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NUMERICAL SIMULATION OF MULTIPHASE FLUID FLOW IN NATURALLY FRACTURED RESERVOIRS

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THE UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

NUMERICAL SIMULATION OF MULTIPHASE FLUID FLOW IN NATURALLY FRACTURED RESERVOIRS

A DISSERTATION

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

degree of

DOCTOR OF PHILOSOPHY

BY

KURUJIT NAKORNTHAP

Norman, Oklahoma

1982

NUMERICAL SIMULATION OF MULTIPHASE FLUID FLOW
IN NATURALLY FRACTURED RESERVOIRS

A DISSERTATION
APPROVED FOR THE SCHOOL OF
PETROLEUM AND GEOLOGICAL ENGINEERING

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Finally, the author wishes to dedicate this dissertation to his parents, Dr. Arth and Mrs. Tapanee Nakornthap. Without their love, support and understanding, this dissertation would not have been possible.

ABSTRACT

A new mathematical flow model is derived for characterizing the multiphase fluid flow phenomenon in naturally fractured reservoirs. This new model treats the reservoir as a double porosity medium consisting of a heterogeneous, isotropic primary rock matrix and an anisotropic, heterogeneous fracture. The statistical distribution in space and orientation of the fracture is manifest in terms of the fracture permeability tensor. The model permits flow through the rock matrix and the fracture to be described simultaneously. The fluid interaction terms coupling flow between the rock matrix and fracture, the gravity effects, the capillary forces and the fracture velocity of fluids are all taken into consideration.

According to this model, the numerical simulation program is developed in FORTRAN IV computer code using the finite difference approximation technique, the fully implicit approach, and the Point Successive Over-Relaxation method. Extension of the simulator capability to incorporate the Monte Carlo technique for randomly generating fracture locations is also discussed.

The simulator is run and tested with data from a field example. The results show that the phase pressures respond to each other more spontaneously in the fracture than they do

to the phase pressures in the rock matrix, and vice versa. Furthermore, the velocity of the fuilds in the fractures have negligible effect on the results. The results suggest that the conventional way of assuming that fluids first flow from the rock matrix into the fracture and then flow through the fracture toward the wellbore may not be an adequate description of the flow phenomenon in a naturally fractured reservoir.

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CHAPTER I

INTRODUCTION

Numerical simulation is recognized as a valuable tool for reservoir engineering studies. Simulation enables one to forecast field performance under a variety of production schemes. An oil field can only be produced one time; and once the production scheme is selected, it is often irreversible. The advantage of reservoir simulation lies in the fact that the simulation model can be run many times at relatively low cost, allowing engineers to experiment with several sets of input data. Observation of model results helps engineers choose the best set of well locations and production schemes for the reservoir.

Understanding the fluid flow behavior is particularly essential for the successful development of a naturally fractured reservoir. It is estimated that substantial amount of oil reserves lies underground in naturally fractured reservoirs. Because of the usually low primary production from these reservoirs and the increasing scarceness of new oil fields, the application of Enhanced Oil Recovery processes in naturally fractured reservoirs is now receiving a greater attention from researchers. Yet, the fluid flow phenomema in such reservoirs are not adequately understood; and considerably more research needs to be done in this area. Hence, there is a need for developing new mathematical schemes that encompass many complex features of these reservoirs.

Consequently, the purpose of this study is to develop a three-dimensional, finite-difference simulation scheme based on a new mathematical model for describing multiphase fluid flow in the naturally fractured porous media.

CHAPTER II

LITERATURE REVIEW

A naturally fractured reservoir can be considered as a system of two physical domains. The primary rock matrix which contains large amount of fluids has a rather low permeability; and the fracture which constitutes a small volume but has the ability to transmit a large portion of flow through the porous medium. As a result, researchers tend to describe the fractured reservoir as a double-porosity medium. The study of the naturally fractured reservoir has been the subject of numerous papers over the past several years.

According to Warren and Root[24] the double-porosity medium has two classes of porosity. The primary porosity is intergranular and controlled by deposition and lithification. The void systems of sands, sandstones and oolitic limestones are typical of this class. The secondary porosity, on the other hand, is foramenular and is controlled by fracturing, jointing and/or solution in circulating water. Vugs, joints, fissures or fractures which occur in formations such as shale, siltstone, schist, limestone or dolomite are typical of this class of porosity.

The actual naturally fractured reservoir may be visualized as shown in Figure 1. Kazemi et al[14], Duguid and Lee[8],

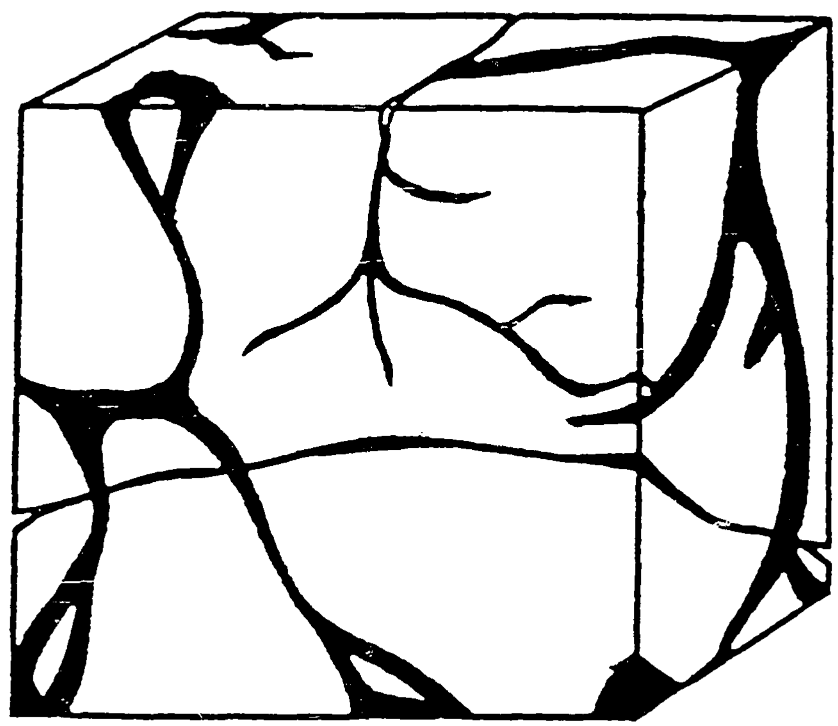

Figure 1. Actual naturally fractured reservoir.

Thomas et al,[22] and Evans[9,10] have shown that any mathematical model for it must include the fluid interaction terms to describe the mass flux of fluid from the primary rock matrix into the fracture. Furthermore, since the flow of fluid in the fracture may be described as continuum flow, it is possible that turbulent flow may occur when abnormally large fractures are found in the vicinity of large pressure gradients such as in the early phases of well drawdown.[2] The term turbulent flow implies that Darcy's law is not adequate to describe the flow phenomena. When flow deviates from the Darcy's law, the Forchheimer equation is normally used to describe the flow phenomena.[10]

The development of fracture flow models has proceeded along two different approaches. These are the statistical approach and the enumerative approach.[9,10] The statistical approach characterizes a fractured rock mass as a statistically homogeneous medium consisting of a combination of fractures and porous rock matrix. The probability of finding a fracture at any point in the system is the same as finding one at any other point. The enumerative approach, however, attempts to model the actual geometry of both the fractures and the porous rock matrix. The location, orientation, and aperture width of fractures become very important in this approach. An extensive discussion of both approaches as well as references are reported by Evans.[9,10].

Since the title of this study deals with the numerical simulation of fractured reservoir, a brief review of mathematical development on this subject seems appropriate and serves the further purpose of laying out the background that led to this study.

A few models have emerged during the past two decades to describe the behavior of naturally fractured reservoirs. Most notably are the models proposed by Warren and Root[24] in 1963 and Kazemi[13] in 1969. Both of these models also describe the fractured reservoir as a double-porosity medium.

In the Warren and Root model the matrix rock containing the primary porosity is homogeneous and isotropic and is contained within a systematic array of identical, rectangular blocks. Superimposed on this system is an orthogonal system of continuous, uniform fractures which are oriented such that each fracture is parallel to one of the principal axes of permeability (See Figure 2). Fluid flow in the reservoir occurs through the fractures, which are anisotropic, with local exchange of fluids between the fracture system and matrix blocks, but flow communication between matrix blocks does not occur.

The Kazemi model differs from the Warren and Root model in that the reservoir consists of a set of uniformly spaced horizontal matrix layers with a set of horizontal fractures as spacers (See Figure 3). The fractures are arranged horizontally whereby fluids flow from matrix layers

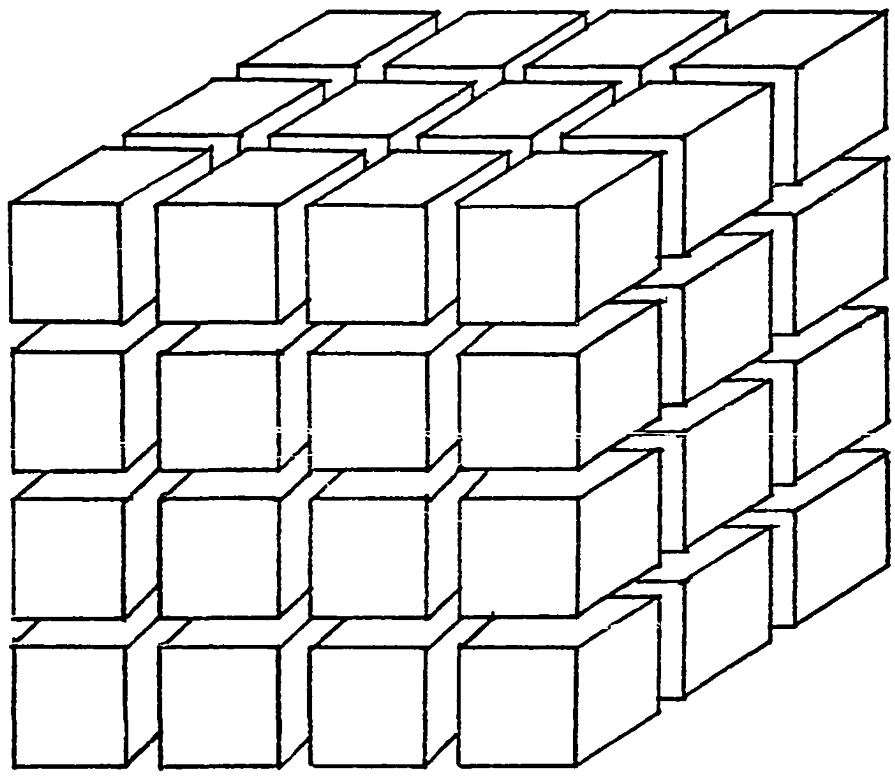

Figure 2. Idealization of a naturally fractured porous medium (Warren and Root model).

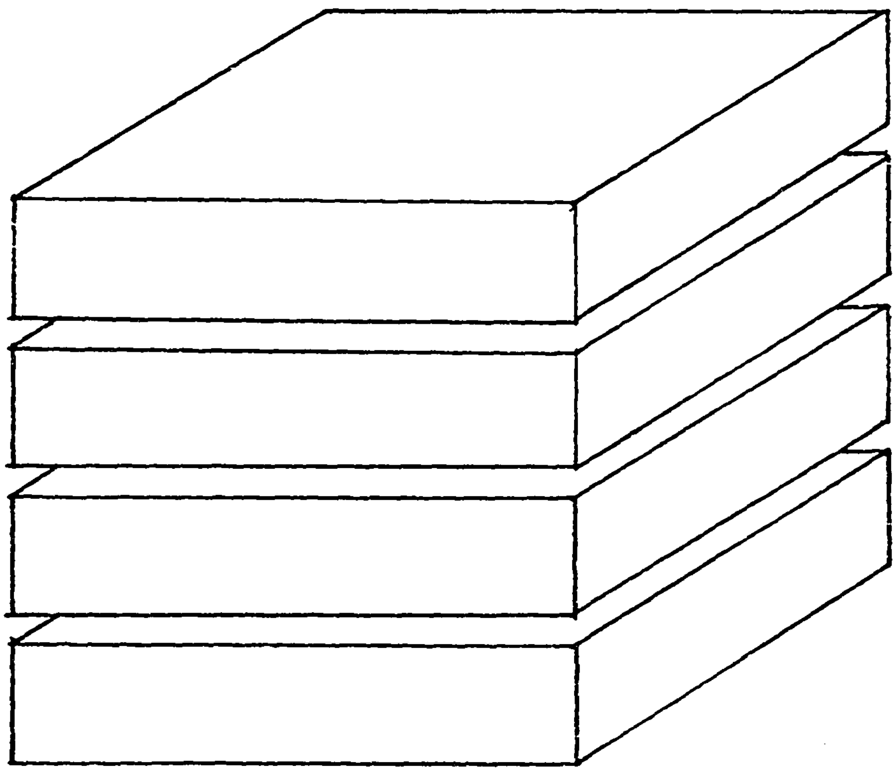

Figure 3. Idealization of a naturally fractured porous medium (Kazemi model).

into the fractures and then the flow converges radially toward the wellbore. This model is used mainly in pressure transient analysis.

Numerical simulation studies of fractured reservoirs have been reported by several researchers. Yamamoto et al[25] developed a gas-oil compositional model of a single matrix block with a fracture system located along the mid-depth of the block. The fracture represented the boundary conditions around the block and flow along the fracture was not considered. Recovery mechanisms for various size blocks were studied.

Kazemi et al[14] used the Warren and Root model to develop a three-dimensional simulator for a single phase or two-phase flow of water and oil in fractured reservoirs. Their models accounted for imbibition, gravity effects, relative mobility and variations in reservoir properties. The block Gauss-Seidel method was used to obtain solutions. Results of the simulation runs were given for a quadrant of a five-spot pattern and a five-well reservoir having a dip and natural water influx.

Rossen[16] presented the simulation of naturally fractured reservoir with semi-implicit source terms. The model treated only the flow in the fracture system while considering the rock matrix blocks as source terms. The source terms were functions of the rock matrix and the fluid properties, with fracture saturations and pressures defining the boundary conditions. Matrix blocks surrounded by gas were assumed not to transfer water from the matrix rock to the fracture and matrix blocks surrounded by water were assumed not to transfer gas from the matrix rock to the fracture.

Duguid and Lee[8] studied the flow of a single-phase fluid through fractured porous media. Their governing equations are derived from the Darcy's law for fluid flow in the primary pores, equations of motion for fluid flow in the fractures, and two continuity equations. The results were two sets of governing equations, one for each type of porosity. These two sets of equations were coupled by the flow interaction terms between fluid in the primary pores and fluid in the fracture. The finite-element Galerkin method was used to solve this coupled system of equations for transient flow of water in a confined leaky aquifer. Duguid and Lee's work was significant in that it attempted to model simultaneously the flow in both the matrix rock and the fracture, and in their recognition that acceleration terms might have an effect on the equation of motion in the fracture.

Thomas et al[22] described the development of a three-dimensional, three-phase model for simulating water, oil and gas flow in a naturally fractured reservoir. The reservoir was assumed to be comprised of a continuous fracture system filled with discontinuous matrix blocks. Therefore, flow in the reservoir occurred through fracture system with local transfer of fluids between the fractures and the matrix blocks; and there was no communication between the matrix blocks. As a result, the governing equations were derived from three fracture flow equations, one for each phase, coupled with three matrix-fracture flow terms. The mathematical formulation was implicit in pressure, water saturation, and gas saturation or saturation pressure for both the fracture flow and the matrix-fracture flow. A geometrical factor was used in the matrix-fracture flow terms to account for the surface area of the matrix blocks per unit volume and a characteristic length associated with the terms. Hysteresis on relative permeability and capillary pressures as well as the variation of the gas-oil interfacial tension were incorporated into the model. Several examples were given to demonstrate the utility of their simulation model.

Bossie-Codreanu et al[4] described a new approach for modeling fluid flow in fully or partially fractured reservoir. The approach also assumed that continuous flow paths existed only in the fracture system; and the flow in the matrix rock was accounted for by the matrix-fracture flow terms. The matrix-fracture flows were directly calculated by the model, taking into account capillarity, gravity, pressure difference between the matrix blocks and fractures and pressure gradients across the matrix blocks. The basic feature of their model was the chessboard arrangement of the fracture and matrix cells: every matrix cell was surrounded by the fracture cells. An example was given for simulation of a reservoir cross section with bottom water injection.

In summary, simulation of multiphase flow through naturally fractured reservoirs is a challenging task and these existing models represent significant advances toward the understanding of this phenomenon. It is believed, however, that certain physical aspects must also be taken into consideration to adequately describe this behavior. For instance, fluids do flow in both the fractures and the matrix rock; and not all the fractures are interconnected. In addition, because of high permeability, flow conductivity in the fractures is much higher than that in the matrix rock. Consequently, fracture flow sometimes resembles flow in a conduit in which the acceleration (or inertial term) plays an important role in governing the flow. Thus, the use of Darcy's law for flow in fractures may be inadequate.

Recently, Evans[9,10] has introduced a general mathematical model for multiphase flow through naturally fractured reservoirs which addresses the above shortcomings. It is believed to be the most general analytical model published to date. The model treats fractures as a general statistical entity that exists throughout the reservoir. This permits flow through the primary rock matrix and the fractures to be described simultaneously with a fluid interaction term coupling the flow between the rock matrix blocks and the fractures. The equations are general in that they allow time and space variations in all fluid and rock properties.

The primary objectives of this dissertation are to derive from the analytical work of Evans a set of diffusivity flow equations and then develop a finite-difference, three-dimensional multiphase simulator for flow of fluids through naturally fractured reservoirs.

CHAPTER III

MATHEMATICAL FORMULATION

3.1 Background and Assumptions

The new mathematical model as proposed by Evans[9,10] for describing behavior of the naturally fractured reservoirs is based upon the statistical approach. Evans introduces the fracture matrix function $f(\overline{r},\Omega)$ to represent the distribution of fractures throughout the reservoir system. Furthermore, he shows that the intrinsic permeability tensor for the fracture ($\overline{\overline{K}}_f$) is related to the fracture matrix function. Hence, the presence or absence of fracture at any point in the reservoir system, as well as the orientation and anisotropy of fracture can be accounted for by manipulating elements in the permeability tensor for that point.

With regard to the model, the following assumptions are made.

1. The reservoir is treated as a double porosity medium. One porosity is associated with the primary rock matrix and the second porosity is associated with the fractures.
2. The rock is an elastic incompressible solid; and the changes in the rock matrix and fracture

porisities are due to reordering and/or reorientation of rock grains.

3. The primary rock matrix is isotropic and heterogeneous, whereas the fractures are anisotropic and heterogeneous.
4. Fluid velocities in both the primary pores and the fractures are assumed to be small.
5. Primary rock matrix pore volume is independent of fracture pressure and conversely for the fracture pore volume.

Other assumptions are introduced as necessary.

3.2 Summary of Governing Equations

The equations necessary for derivations of the multiphase flow equations are summarized below from Evans' paper.[9,10]

3.2.1 Continuity Equations:

Fracture:

$$\nabla\cdot[\sum_j C_{ijf}\rho_{jf}\vec{V}_{fj}] - \sum_j \Gamma_j - \frac{\rho_{is}q_{isf}}{\Delta x\cdot\Delta y\cdot\Delta z}$$

$$+ \frac{\partial}{\partial t}[\phi_f \sum_j C_{ijf}\rho_{jf}S_{jf}] = 0$$

Rock Matrix:

$$\nabla\cdot[\sum_j C_{ij1}\rho_{j1}\vec{V}_{1j}] + \sum_j \Gamma_j - \frac{\rho_{is}q_{is1}}{\Delta x\cdot\Delta y\cdot\Delta z}$$

$$+ \frac{\partial}{\partial t}[\phi_1 \sum_j C_{ij1}\rho_{j1}S_{j1}] = 0$$

3.2.2 Equations of Motion:

Fracture:

$$\vec{V}_{fj} = - \frac{k_{rjf}\,\overline{\overline{K}}_f}{\mu_{jf}} \cdot [\nabla P_{fj} + \rho_{jf}\frac{1}{g_c}\frac{\partial \overline{V}_{jf}}{\partial t} - \rho_{jf}\frac{g}{g_c}\nabla D]$$

Rock Matrix:

$$\vec{V}_{1j} = - \frac{K_1 k_{r1j}}{\mu_{j1}}[\nabla P_{1j} - \rho_{j1}\frac{g}{g_c}\nabla D]$$

where

$$\overline{\overline{K}}_f = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix}$$

3.2.3 Fluid Interaction Terms:

$$\Gamma_j = \frac{\beta_j}{\mu_{j1}}[(P_{1j} - P_{fj}) + 2\sum_{n=1}^{\infty}(-1)^n P_{1j}\, e^{-B_j} - 2\sum_{n=1}^{\infty} P_{fj} e^{-B_j}]$$

or the steady state condition:

$$\Gamma_j = \frac{\beta_j}{\mu_{j1}}[P_{1j} - P_{fj}]$$

where

$$\beta_j = \frac{K_1 k_{r1j}\phi_f C_{ij1}\rho_{j1}}{r_H \ell}$$

$$B_j = \frac{K_1 k_{r1j}\, n^2 \Pi^2 t}{2\ell^2 \mu_{j1}\phi_1 c_1}$$

3.2.4 Porosity Equations:

Fracture:

$$\frac{\partial \phi_f}{\partial t} = \phi_f(1-\phi_f)C_f\frac{\partial P_f}{\partial t} - \phi_1\phi_f C_1\frac{\partial P_1}{\partial t}$$

Rock Matrix:

$$\frac{\partial \phi_1}{\partial t} = \Phi_1(1 - \Phi_1)C_1 \frac{\partial P_1}{\partial t} - \phi_1\phi_f C_f \frac{\partial P_f}{\partial t}$$

3.2.5 Required Auxilary Equations:

Saturations:

$S_{gf} + S_{wf} + S_{of} = 1$ (fracture)

$S_{g1} + S_{w1} + S_{o1} = 1$ (rock matrix)

Capillary Pressures:

$P_{cgof} = P_{fg} - P_{fo}$ (fracture)

$P_{cowf} = P_{fo} - P_{fw}$ (fracture)

$P_{cgo1} = P_{1g} - P_{1o}$ (rock matrix)

$P_{cow1} = P_{1o} - P_{1w}$ (rock matrix)

Conservation of mass of each fluid phase:

$\sum_i C_{ig1} = 1$ (rock matrix)

$\sum_i C_{io1} = 1$ (rock matrix)

$\sum_i C_{iw1} = 1$ (rock matrix)

$\sum_i C_{igf} = 1$ (fracture)

$\sum_i C_{iof} = 1$ (fracture)

$\sum_i C_{iwf} = 1$ (fracture)

3.3 Black Oil Model

The multiphase fluid flow in porous medium refers to the simultaneous flow of three fluid phases: gas, oil, and water phases. In a fully general compositional model there are N chemical species or components, each of which may exist in any or all of the three phases. However, this very general compositional model is extremely difficult to set up and solve. Accordingly, a simplified black oil model (or two-component hydrocarbon system)[15] is used in this simulation study. It is assumed that no mass transfer occurs between the water phase, and the gas and oil phases. There are three components involved: water, oil and gas components (i.e., the hydrocarbon system has only two components: oil and gas). The oil component is the residual liquid at atmospheric pressure left after a differential vaporization and the gas component is the remaining fluid. To avoid confusion, the capital letter subscripts will be used to identify components (i's) and the lower-case subscripts will be used to identify phases (j's). Further, the subscript S will be used to indicate standard conditions.

Let ρ_{OS} be the density of the oil component, and ρ_{GS} be the density of the gas component, both measured at standard conditions. If the formation volume factor for each phase is denoted by B_j, and the dissolved gas-oil ratio by R_{so}, it can be demonstrated that the respective mass fractions C_{ij} in the governing equations for the black oil model are:

For fracture flow:

$$C_{Wgf} = 0 \quad ; \quad C_{Ogf} = 0 \quad ; \quad C_{Ggf} = 1$$

$$C_{Wof} = 0 \quad ; \quad C_{Oof} = \frac{\rho_{OSf}}{B_{of}\rho_{of}} \quad ; \quad C_{Gof} = \frac{R_{sof}\rho_{GSf}}{B_{of}\rho_{of}}$$

$$C_{Wwf} = 1 \quad ; \quad C_{Owf} = 0 \quad ; \quad C_{Gwf} = 0$$

For rock matrix flow:

$$C_{Wgl} = 0 \quad ; \quad C_{Ogl} = 0 \quad ; \quad C_{Ggl} = 1$$

$$C_{Wol} = 0 \quad ; \quad C_{Ool} = \frac{\rho_{OSl}}{B_{ol}\rho_{ol}} \quad ; \quad C_{Gol} = \frac{R_{sol}\rho_{GSl}}{B_{ol}\rho_{ol}}$$

$$C_{Wwl} = 1 \quad ; \quad C_{Owl} = 0 \quad ; \quad C_{Gwl} = 0$$

Furthermore,

$$\rho_{GSl} = \rho_{GSf} = \rho_{GS}$$

$$\rho_{OSl} = \rho_{OSf} = \rho_{OS}$$

$$\rho_{WSl} = \rho_{WSf} = \rho_{WS}$$

and

$$\rho_{gf} = \frac{\rho_{GSF}}{B_{gf}} \quad ; \quad \rho_{of} = \frac{(R_{sof}\rho_{GSf}+\rho_{OSF})}{B_{of}} \quad ; \quad \rho_{wf} = \frac{\rho_{WSf}}{B_{wf}}$$

$$\rho_{gl} = \frac{\rho_{GSL}}{B_{gl}} \quad ; \quad \rho_{ol} = \frac{(R_{sol}\rho_{GSl}+\rho_{OSl})}{B_{ol}} \quad ; \quad \rho_{wl} = \frac{\rho_{WSl}}{B_{wl}}$$

3.4 Tilted Reservoir

The effects of gravity on fluid flow in a tilted reservoir are manifest in terms of ∇D in the governing equations. In the present coordinate convention, as shown in Figure 4, the X, Y and Z are principal axes of the reservoir stratum, and D is the vertical elevation from datum plane (positive downward). Let's define (see Figure 4)

α = angle of the x axis with the horizontal plane

β = angle of the y axis with the horizontal plane

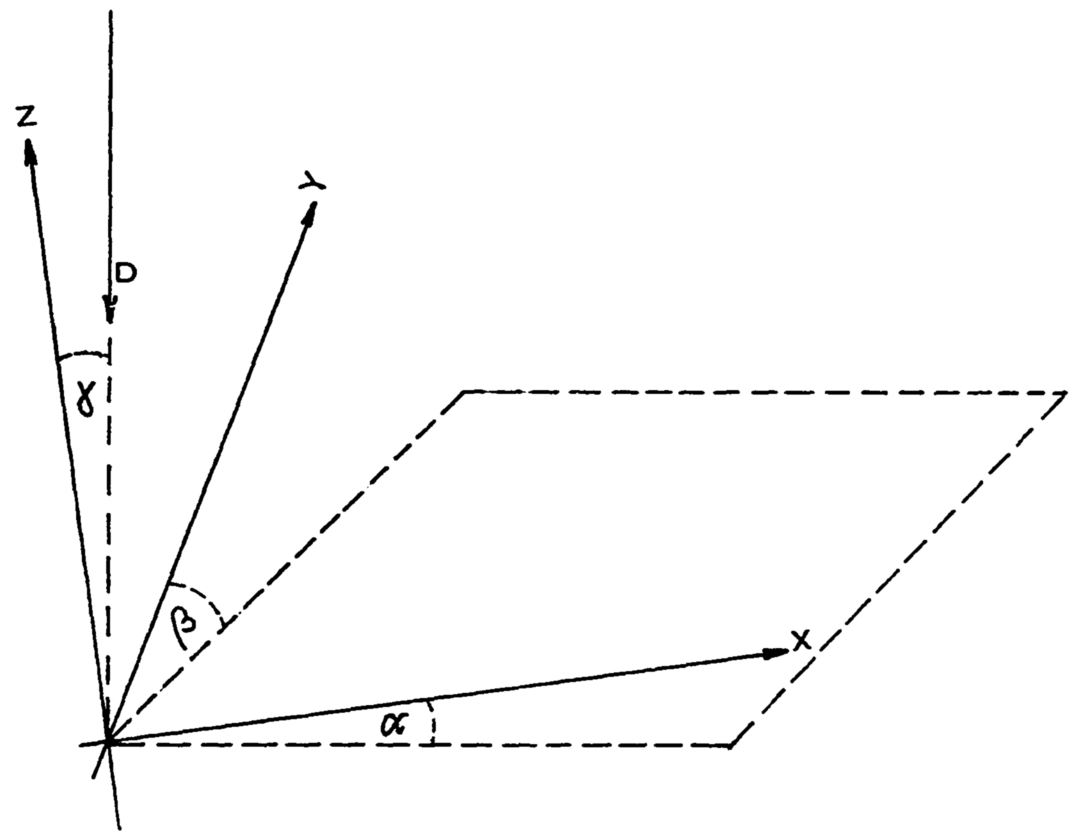

Figure 4. Coordinate convention.

γ = angle of the z axis with the vertical plane

Hence,

$$D = -x\sin\alpha - y\sin\beta - z\cos\gamma$$

And since

$$\nabla D = \frac{\partial D}{\partial x}\hat{i} + \frac{\partial D}{\partial y}\hat{j} + \frac{\partial D}{\partial z}\hat{k}$$

Thus,

$$\frac{\partial D}{\partial x} = -\sin\alpha$$

$$\frac{\partial D}{\partial y} = -\sin\beta$$

$$\frac{\partial D}{\partial z} = -\cos\gamma$$

For the special case when the reservoir is horizontal:

$$\alpha = 0, \ \beta = 0, \ \gamma = 0.$$

Thus,

$$\frac{\partial D}{\partial x} = 0$$

$$\frac{\partial D}{\partial y} = 0$$

$$\frac{\partial D}{\partial z} = -1$$

3.5 Derivation of the Flow Equations

3.5.1 Rock Matrix

The continuity equation for rock matrix in its general form is written as:

$$\nabla\cdot[\sum_j C_{ij1}\rho_{j1}\vec{V}_{1j}] + \sum_j \Gamma_j - \frac{\rho_{is}q_{is1}}{\Delta x\cdot\Delta y\cdot\Delta z}$$

$$+ \frac{\partial}{\partial t}[\phi_1 \sum_j C_{ij1}\rho_{j1}S_{j1}] = 0 \qquad (1)$$

for the components: i = oil, water, and gas. This equation may be written as:

$$\nabla \cdot [C_{ig1}\rho_{g1}\vec{V}_{1g} + C_{io1}\rho_{o1}\vec{V}_{1o} + C_{iw1}\rho_{w1}\vec{V}_{1w}] + [\Gamma_g + \Gamma_o + \Gamma_w]_i$$

$$- \frac{\rho_{is}q_{is1}}{\Delta x \cdot \Delta y \cdot \Delta z} + \frac{\partial}{\partial t}[\phi_1(C_{ig1}\rho_{g1}S_{g1} + C_{io1}\rho_{o1}S_{o1} + C_{iw1}\rho_{w1}S_{w1})] = 0 \tag{2}$$

Upon substitution of the appropriate mass fractions (C_{ij}) for the black oil model we have:

<u>For Water Component</u>

$$\nabla \cdot [\frac{\rho_{WS}\vec{V}_{1w}}{B_{w1}}] + [\Gamma_g + \Gamma_o + \Gamma_w]_W - \frac{\rho_{WS}q_{WS1}}{\Delta x \cdot \Delta y \cdot \Delta z}$$

$$+ \frac{\partial}{\partial t}[\phi_1 \rho_{WS} S_{w1}/B_{w1}] = 0 \tag{3}$$

<u>For Oil Component</u>

$$\nabla \cdot [\frac{\rho_{OS}}{B_{o1}}\vec{V}_{1o}] + [\Gamma_g + \Gamma_o + \Gamma_w]_O - \frac{\rho_{OS}q_{OS1}}{\Delta x \cdot \Delta y \cdot \Delta z}$$

$$+ \frac{\partial}{\partial t}[\frac{\phi_1 \rho \quad S_{o1}}{B_{o1}}] = 0 \tag{4}$$

<u>For Gas Component</u>

$$\nabla \cdot [\frac{\rho_{GS}}{B_{g1}}\vec{V}_{1g} + \frac{R_{so1}\rho_{GS}}{B_{o1}}\vec{V}_{1o}] + [\Gamma_g + \Gamma_o + \Gamma_w]_G - \frac{\rho_{GS}q_{GS1}}{\Delta x \cdot \Delta y \cdot \Delta z}$$

$$+ \frac{\partial}{\partial t}[\phi_1(\frac{\rho_{GS}S_{g1}}{B_{g1}} + \frac{R_{so1}\rho_{GS}S_{o1}}{B_{o1}})] = 0 \tag{5}$$

At this point it is assumed that water is an incompressible fluid (i.e., $B_{w1} = B_{wf} = 1$ and thus $\rho_{w1} = \rho_{wf} = \rho_{ws}$). Further, the fluid interaction terms are assumed to be steady state and follow the form:

$$[\Gamma_j]_i = \frac{\beta_j}{\mu_{j1}} [P_{1j} - P_{fj}] \tag{6}$$

Although the mass flow rate from the rock matrix into the fracture is considered in its original form to be unsteady, this assumption is justified by the fact that the interaction equation shows the rate approaching steady state as time becomes larger. Thus, upon substitution of appropriate C_{ij}'s for the black oil model, it follows that:

<u>For Water Component</u>

$$[\Gamma_g]_W = 0 \tag{7}$$

$$[\Gamma_o]_W = 0 \tag{8}$$

$$[\Gamma_w]_W = \frac{K_1 k_{r1w} \phi_f \rho_{WS}}{r_H 1 \mu_{w1} B_{w1}} (P_{1w} - P_{fw}) \tag{9}$$

<u>For Oil Component</u>

$$[\Gamma_g]_O = 0 \tag{10}$$

$$[\Gamma_o]_O = \frac{K_1 k_{r1o} \phi_f \rho_{OS}}{r_H 1 \mu_{o1} B_{o1}} (P_{1o} - P_{fo}) \tag{11}$$

$$[\Gamma_w]_O = 0 \tag{12}$$

<u>For Gas Component</u>

$$[\Gamma_g]_G = \frac{K_1 k_{r1g} \phi_f \rho_{GS}}{r_H 1 \mu_{g1} B_{g1}} (P_{1g} - P_{fg}) \tag{13}$$

$$[\Gamma_o]_G = \frac{K_1 k_{r1o} \phi_f R_{so1} \rho_{GS}}{r_h 1 \mu_{o1} B_{o1}} (P_{1o} - P_{fo}) \tag{14}$$

$$[\Gamma_w]_G = 0 \tag{15}$$

These fluid interaction terms together with the equations of motion in rock matrix are substituted into the respective continuity equations.

For Water Component

$$\nabla\cdot\left[\frac{K_1 k_{r1w}}{B_{w1}\mu_{w1}}\{\nabla P_{1w}-\rho_{w1}\frac{g}{g_c}\nabla D\}\right]-\left[\frac{K_1 k_{r1w}\phi_f}{r_H l\mu_{w1}B_{w1}}(P_{1w}-P_{fw})\right]$$

$$+\frac{q_{WS1}}{\Delta x\cdot\Delta y\cdot\Delta z}=\phi_1\frac{\partial(S_{w1}/B_{w1})}{\partial t} \tag{16}$$

For Oil Component

$$\nabla\cdot\left[\frac{K_1 k_{r1o}}{B_{o1}\mu_{o1}}\{\nabla P_{1o}-\rho_{o1}\frac{g}{g_c}\nabla D\}\right]-\left[\frac{K_1 k_{r1o}\phi_f}{r_H l\mu_{o1}B_{o1}}(P_{1o}-P_{fo})\right]$$

$$+\frac{q_{OS1}}{\Delta x\cdot\Delta y\cdot\Delta z}=\phi_1\frac{\partial(S_{o1}/B_{o1})}{\partial t} \tag{17}$$

For Gas Component

$$\nabla\cdot\left[\frac{K_1 k_{r1g}}{B_{g1}\mu_{g1}}\{\nabla P_{1g}-\rho_{g1}\frac{g}{g_c}\nabla D\}\right]$$

$$+\nabla\cdot\left[\frac{R_{so1}K_1 k_{r1o}}{B_{o1}\mu_{o1}}\{\nabla P_{1o}-\rho_{o1}\frac{g}{g_c}\nabla D\}\right]$$

$$-\left[\frac{K_1 k_{r1g}\phi_f}{r_H l\,\mu_{g1}B_{g1}}(P_{1g}-P_{fg})+\frac{K_1 k_{r1o}\phi_f R_{so1}}{r_H l\mu_{o1}B_{o1}}(P_{1o}-P_{fo})\right]$$

$$+\frac{q_{GS1}}{\Delta x\cdot\Delta y\cdot\Delta z}=\phi_1\frac{\partial}{\partial t}(S_{g1}/B_{g1}+R_{so1}S_{o1}/B_{o1}) \tag{18}$$

3.5.2 Fracture

Similar to the rock matrix, the continuity equation for fracture in its general form can be written as:

$$\nabla\cdot\left[\sum_j C_{ijf}\rho_{jf}\vec{V}_{fj}\right]-\sum_j\Gamma_j-\frac{\rho_{jsf}q_{isf}}{\Delta x\cdot\Delta y\cdot\Delta z}+\frac{\partial}{\partial t}\left[\phi_f\sum_j C_{ijf}\rho_{jf}S_{jf}\right]$$

$$=0 \tag{19}$$

The substitution of the appropriate mass fractions (C_{ij}) for the black oil model produce:

For Water Component

$$\nabla \cdot \left[\frac{\rho_{WS}\vec{V}_{fw}}{B_{wf}}\right] - [\Gamma_g + \Gamma_o + \Gamma_w]_W - \frac{\rho_{WS}q_{WS1}}{\Delta x \cdot \Delta y \cdot \Delta z}$$

$$+ \frac{\partial}{\partial t}[\phi_f \rho_{WS} S_{wf}/B_{wf}] = 0 \tag{20}$$

For Oil Component

$$\nabla \cdot \left[\frac{\rho_{OS}\vec{V}_{fo}}{B_{of}}\right] - [\Gamma_g + \Gamma_o + \Gamma_w]_O - \frac{\rho_{OS}q_{OS1}}{\Delta x \cdot \Delta y \cdot \Delta z}$$

$$+ \frac{\partial}{\partial t}[\phi_f \rho_{OS} S_{of}/B_{of}] = 0 \tag{21}$$

For Gas Component

$$\nabla \cdot \left[\frac{\rho_{GS}\vec{V}_{fg}}{B_{gf}} + \frac{R_{sof}\rho_{GS}\vec{V}_{fo}}{B_{of}}\right] - [\Gamma_g + \Gamma_o + \Gamma_w]_G - \frac{\rho_{GS}q_{GS1}}{\Delta x \cdot \Delta y \cdot \Delta z}$$

$$+ \frac{\partial}{\partial t}[\phi_f(\rho_{GS}S_{gf}/B_{gf} + R_{sof}\rho_{GS}S_{of}/B_{of})] = 0 \tag{22}$$

The equation of motion in the fracture contains the tensor as well as the vector terms, and can be written in the form below (for phases: j = oil, water and gas).

$$\vec{V}_{fj} = -\frac{k_{rjf}}{\mu_{jf}} \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix} \cdot \begin{bmatrix} \frac{\partial P_{fj}}{\partial x} + \rho_{jf}\frac{1}{g_c}\frac{\partial V_{fjx}}{\partial t} - \rho_{jf}\frac{g}{g_c}\frac{\partial D}{\partial x} \\ \frac{\partial P_{fj}}{\partial y} + \rho_{jf}\frac{1}{g_c}\frac{\partial V_{fjy}}{\partial t} - \rho_{jf}\frac{g}{g_c}\frac{\partial D}{\partial y} \\ \frac{\partial P_{fj}}{\partial z} + \rho_{jf}\frac{1}{g_c}\frac{\partial V_{fjz}}{\partial t} - \rho_{jf}\frac{g}{g_c}\frac{\partial D}{\partial z} \end{bmatrix}$$

$$= -\frac{k_{rjf}}{\mu_{jf}}\,[\hat{i}\{K_{xx}(\frac{\partial P_{fj}}{\partial x} + \frac{\rho_{jf}}{g_c}\frac{\partial V_{fjx}}{\partial t} - \rho_{jf}\frac{g}{g_c}\frac{\partial D}{\partial x})$$

$$+ K_{xy}\;(\frac{\partial P_{fj}}{\partial y} + \frac{\rho_{jf}}{g_c}\frac{\partial V_{fjy}}{\partial t} - \rho_{jf}\frac{g}{g_c}\frac{\partial D}{\partial y})$$

$$+ K_{xz}\;(\frac{\partial P_{fj}}{\partial z} + \frac{\rho_{jf}}{g_c}\frac{\partial V_{fjz}}{\partial t} - \rho_{jf}\frac{g}{g_c}\frac{\partial D}{\partial z})\}$$

$$+ \hat{j}\;\{K_{yx}\;(\frac{\partial P_{fj}}{\partial x} + \frac{\rho_{jf}}{g_c}\frac{\partial V_{fjx}}{\partial t} - \rho_{jf}\frac{g}{g_c}\frac{\partial D}{\partial x})$$

$$+ K_{yy}\;(\frac{\partial P_{fj}}{\partial y} + \frac{\rho_{jf}}{g_c}\frac{\partial V_{fjy}}{\partial t} - \rho_{jf}\frac{g}{g_c}\frac{\partial D}{\partial y})$$

$$+ K_{yz}\;(\frac{\partial P_{fj}}{\partial z} + \frac{\rho_{jf}}{g_c}\frac{\partial V_{fjz}}{\partial t} - \rho_{jf}\frac{g}{g_c}\frac{\partial D}{\partial z})\}$$

$$+ \hat{k}\;\{K_{zx}(\frac{\partial P_{fj}}{\partial x} + \frac{\rho_{jf}}{g_c}\frac{\partial V_{fjx}}{\partial t} - \rho_{jf}\frac{g}{g_c}\frac{\partial D}{\partial x})$$

$$+ K_{zy}(\frac{\partial P_{fj}}{\partial y} + \frac{\rho_{jf}}{g_c}\frac{\partial V_{fjy}}{\partial t} - \rho_{jf}\frac{g}{g_c}\frac{\partial D}{\partial y})$$

$$+ K_{zz}(\frac{\partial P_{fj}}{\partial z} + \frac{\rho_{jf}}{g_c}\frac{\partial V_{fjz}}{\partial t} - \rho_{jf}\frac{g}{g_c}\frac{\partial D}{\partial z})\}] \qquad (23)$$

Upon substitution of the above expressions and the fluid interaction terms into the respective continuity equations for water, oil and gas components the fracture equations (20, (21) and (22) become

<u>For Water Component</u>

$$\nabla\cdot[\frac{k_{rwf}}{B_{wf}\mu_{wf}}\,[\hat{i}\;\{K_{xx}(\frac{\partial P_{fw}}{\partial x} + \frac{\rho_{wf}}{g_c}\frac{\partial V_{fwx}}{\partial t} - \rho_{wf}\frac{g}{g_c}\frac{\partial D}{\partial x}) + K_{xy}(\frac{\partial P_{fw}}{\partial y}$$

$$+ \frac{\rho_{wf}}{g_c}\frac{\partial V_{fwy}}{\partial t} - \rho_{wf}\frac{g}{g_c}\frac{\partial D}{\partial y}) + K_{xz}(\frac{\partial P_{fw}}{\partial z} + \frac{\rho_{wf}}{g_c}\frac{\partial V_{fwz}}{\partial t} - \rho_{wf}\frac{g}{g_c}\frac{\partial D}{\partial z})\}$$

$$+ \hat{j} \; \{K_{yx}(\frac{\partial P_{fw}}{\partial x} + \frac{\rho_{wf}}{g_c} \frac{\partial V_{fwx}}{\partial t} - \rho_{wf} \frac{g}{g_c} \frac{\partial D}{\partial x}) + K_{yy}(\frac{\partial P_{fw}}{\partial y} + \frac{\rho_{wf}}{g_c} \frac{\partial V_{fwy}}{\partial t}$$

$$- \rho_{wf} \frac{g}{g_c} \frac{\partial D}{\partial y}) \;\; + K_{yz}(\frac{\partial P_{fw}}{\partial z} + \frac{\rho_{wf}}{g_c} \frac{\partial V_{fwz}}{\partial t} - \rho_{wf} \frac{g}{g_c} \frac{\partial D}{\partial z})\}$$

$$+ \hat{k} \; \{K_{zx} \; (\frac{\partial P_{fw}}{\partial x} + \frac{\rho_{wf}}{g_c} \frac{\partial V_{fwx}}{\partial t} - \rho_{wf} \frac{g}{g_c} \frac{\partial D}{\partial x})$$

$$+ K_{zy}(\frac{\partial P_{fw}}{\partial y} + \frac{\rho_{wf}}{g_c} \frac{\partial V_{fwy}}{\partial t} - \rho_{wf} \frac{g}{g_c} \frac{\partial D}{\partial y})$$

$$+ K_{zz}(\frac{\partial P_{fw}}{\partial z} + \frac{\rho_{wf}}{g_c} + \frac{\partial V_{fwz}}{\partial t} - \rho_{wf} \frac{g}{g_c} \frac{\partial D}{\partial z})\}]]$$

$$+ [\frac{K_1 k_{r1w} \phi_f}{r_H l \mu_{w1} B_{w1}} (P_{1w} - P_{fw})] + \frac{q_{WSf}}{\Delta x \cdot \Delta y \cdot \Delta z} = \phi_f \frac{\partial}{\partial t} [S_{wf}/B_{wf}] \quad (24)$$

<u>For Oil Component</u>

$$\nabla \cdot [\frac{k_{rof}}{B_{of} \mu_{of}} [\hat{i} \{ K_{xx}(\frac{\partial P_{fo}}{\partial x} + \frac{\rho_{of}}{g_c} \frac{\partial V_{fox}}{\partial t} - \rho_{of} \frac{g}{g_c} \frac{\partial D}{\partial x}) + K_{xy}(\frac{\partial P_{fo}}{\partial y} +$$

$$\frac{\rho_{of}}{g_c} \frac{\partial V_{foy}}{\partial t} - \rho_{of} \frac{g}{g_c} \frac{\partial D}{\partial y}) + K_{xz}(\frac{\partial P_{fo}}{\partial z} + \frac{\rho_{of}}{g_c} \frac{\partial V_{foz}}{\partial t} - \rho_{of} \frac{g}{g_c} \frac{\partial D}{\partial z})\}$$

$$+ \hat{j} \; \{K_{yx}(\frac{\partial P_{fo}}{\partial x} + \frac{\rho_{of}}{g_c} \frac{\partial V_{fox}}{\partial t} - \rho_{of} \frac{g}{g_c} \frac{\partial D}{\partial x}) +$$

$$K_{yy}(\frac{\partial P_{fo}}{\partial y} + \frac{\rho_{of}}{g_c} \frac{\partial V_{foy}}{\partial t} - \rho_{of} \frac{g}{g_c} \frac{\partial D}{\partial y})$$

$$+ K_{yz}(\frac{\partial P_{fo}}{\partial z} + \frac{\rho_{of}}{g_c} \frac{\partial V_{foz}}{\partial t} - \rho_{of} \frac{g}{g_c} \frac{\partial D}{\partial z})\}$$

$$+ \hat{k} \; \{K_{zx}(\frac{\partial P_{fo}}{\partial x} + \frac{\rho_{of}}{g_c} \frac{\partial V_{fox}}{\partial t} - \rho_{of} \frac{g}{g_c} \frac{\partial D}{\partial x})$$

$$+ K_{zy} \; (\frac{\partial P_{fo}}{\partial y} + \frac{\rho_{of}}{g_c} \frac{\partial V_{foy}}{\partial t} - \rho_{of} \; \frac{g}{g_c} \frac{\partial D}{\partial y})$$

$$+ K_{zz} \; (\frac{\partial P_{fo}}{\partial z} + \frac{\rho_{of}}{g_c} \frac{\partial V_{foz}}{\partial t} - \rho_{of} \frac{g}{g_c} \frac{\partial D}{\partial z})\}]]$$

$$+ \left[\frac{K_1 k_{r1o} \phi_f}{r_H l \mu_{o1} B_{o1}} (P_{1o} - P_{fo})\right] + \frac{q_{OSf}}{\Delta x \cdot \Delta y \cdot \Delta z} = \phi_f \frac{\partial}{\partial t} [S_{of}/B_{of}] \quad (25)$$

<u>For Gas Component</u>

$$\nabla \cdot [\frac{k_{rgf}}{B_{gf}\mu_{gf}} [\hat{i}\{K_{xx}(\frac{\partial P_{fg}}{\partial x} + \frac{\rho_{of}}{g_c}\frac{\partial V_{fgx}}{\partial t} - \rho_{gf}\frac{g}{g_c}\frac{\partial D}{\partial x}) + K_{xy}(\frac{\partial P_{fg}}{\partial y}$$

$$+ \frac{\rho_{gf}}{g_c}\frac{\partial V_{fgy}}{\partial t} - \rho_{gf}\frac{g}{g_c}\frac{\partial D}{\partial y}) + K_{xz}(\frac{\partial P_{fg}}{\partial z} + \frac{\rho_{gf}}{g_c}\frac{\partial V_{fgz}}{\partial t} - \rho_{gf}\frac{g}{g_c}\frac{\partial D}{\partial z})\}$$

$$+ \hat{j}\ \{K_{yx}(\frac{\partial P_{fg}}{\partial x} + \frac{\rho_{gf}}{g_c}\frac{\partial V_{fgx}}{\partial t} - \rho_{gf}\frac{g}{g_c}\frac{\partial D}{\partial x}) + K_{yy}(\frac{\partial P_{fg}}{\partial y} + \frac{g}{g_c}\frac{\partial V_{fgy}}{\partial T}$$

$$- \rho_{gf}\frac{g}{g_c}\frac{\partial D}{\partial y}) + K_{yz}(\frac{\partial P_{fg}}{\partial z} + \frac{\rho_{gf}}{g_c}\frac{\partial V_{fgz}}{\partial t} - \rho_{gf}\frac{g}{g_c}\frac{\partial D}{\partial z})\} + \hat{k}\ \{K_{zx}(\frac{\partial P_{fg}}{\partial x}$$

$$+ \frac{\rho_{gf}}{g_c}\frac{\partial V_{fgx}}{\partial t} - \rho_{gf}\frac{g}{g_c}\frac{\partial D}{\partial x}) + K_{zy}(\frac{\partial P_{fg}}{\partial y} + \frac{\rho_{gf}}{g_c}\frac{\partial V_{fgy}}{\partial t} - \rho_{gf}\frac{g}{g_c}\frac{\partial D}{\partial y})$$

$$+ K_{zz}(\frac{\partial P_{fg}}{\partial z} + \frac{\rho_{gf}}{g_c}\frac{\partial V_{fgz}}{\partial t} - \rho_{gf}\frac{g}{g_c}\frac{\partial D}{\partial z})\}]] + \nabla \cdot [\frac{R_{sof}K_{rof}}{B_{of}\mu_{of}} [\hat{i}\{K_{xx}(\frac{\partial P_{fo}}{\partial x}$$

$$+ \frac{\rho_{of}}{g_c}\frac{\partial V_{fox}}{\partial t} - \rho_{of}\frac{g}{g_c}\frac{\partial D}{\partial x}) + K_{xy}(\frac{\partial P_{fo}}{\partial y} + \frac{\rho_{of}}{g_c}\frac{\partial V_{foy}}{\partial t} - \rho_{of}\frac{g}{g_c}\frac{\partial D}{\partial y})$$

$$+ K_{xz}(\frac{\partial P_{fo}}{\partial z} + \frac{\rho_{of}}{g_c}\frac{\partial V_{foz}}{\partial t} - \rho_{of}\frac{g}{g_c}\frac{\partial D}{\partial z})\} + \hat{j}\ \{K_{yx}(\frac{\partial P_{fo}}{\partial x} + \frac{\rho_{of}}{g_c}\frac{\partial V_{fox}}{\partial t}$$

$$- \rho_{of}\frac{g}{g_c}\frac{\partial D}{\partial x}) + K_{yy}(\frac{\partial P_{fo}}{\partial y} + \frac{\rho_{of}}{g_c}\frac{\partial V_{foy}}{\partial t} - \rho_{of}\frac{g}{g_c}\frac{\partial D}{\partial y}) + K_{yz}(\frac{\partial P_{fo}}{\partial z}$$

$$+ \frac{\rho_{of}}{c}\frac{\partial V_{foz}}{\partial t} - \rho_{of}\frac{g}{g_c}\frac{\partial D}{\partial z}) + \hat{k}\{K_{zx}(\frac{\partial P_{fo}}{\partial x} + \frac{\rho_{of}}{g_c}\frac{\partial V_{fox}}{\partial t} - \rho_{of}\frac{g}{g_c}\frac{\partial D}{\partial x})$$

$$+ K_{zy}(\frac{\partial P_{fo}}{\partial y} + \frac{\rho_{of}}{g_c}\frac{\partial V_{foy}}{\partial t} - \rho_{of}\frac{g}{g_c}\frac{\partial D}{\partial y}) + K_{zz}(\frac{\partial P_{fo}}{\partial z} + \frac{\rho_{of}}{g_c}\frac{\partial V_{foz}}{\partial t}$$

$$- \rho_{of}\frac{g}{g_c}\frac{\partial D}{\partial z})\}]] + [\frac{K_1 K_{r1g}\phi_f}{r_H l \mu_{g1} B_{g1}}(P_{1g} - P_{fg}) + \frac{K_1 k_{r1o}\phi_f R_{so1}}{r_H l \mu_{o1} B_{o1}}(P_{1o}$$

$$- P_{fo})] + \frac{q_{GSf}}{\Delta x \cdot \Delta y \cdot \Delta z} = \phi_f \frac{\partial}{\partial t} [S_{gf}/B_{gf} + R_{sof}S_{of}/B_{of}] \quad (26)$$

3.6 The Flow Equations in Three-Dimensional Forms

The flow equations for water, oil and gas components derived in Section 3.3 constitute the six governing diffusivity equations for multiphase, black-oil, fluid flow in a fractured porous media. By utilizing the auxillary equations of capillary pressures, saturations and tilted reservoir, these six equations can be written in three-dimensional forms as follows.

It should be pointed out that the parameters in these equations have their dimensions in SI units. However, the input data are usually obtained in practical oilfield units. Accordingly, some conversion factors have to be included. The conversion factors between these two unit systems are shown in Appendix A. The comparisons of the equations under the SI units and the oilfield units are given in Appendix B.

3.6.1 The Water Diffusivity Equation in the Matrix Rock

$$\frac{\partial}{\partial x}\left[\frac{K_1 k_{r1w}}{B_{w1}\mu_{w1}}\left\{\frac{\partial P_{1w}}{\partial x}+\frac{\rho_{ws}}{B_{w1}}\frac{g}{g_c}\sin\alpha\right\}\right]+\frac{\partial}{\partial y}\left[\frac{K_1 k_{r1w}}{B_{w1}\mu_{w1}}\left\{\frac{\partial P_{1w}}{\partial y}+\frac{\rho_{ws}}{B_{w1}}\frac{g}{g_c}\sin\beta\right\}\right]$$

$$+\frac{\partial}{\partial z}\left[\frac{K_1 k_{r1w}}{B_{w1}\mu_{w1}}\left\{\frac{\partial P_{1w}}{\partial z}+\frac{\rho_{ws}}{B_{w1}}\frac{g}{g_c}\cos\gamma\right\}\right]-\left[\frac{K_1 k_{r1w}\phi_f}{r_H l\mu_{w1}B_{w1}}(P_{1w}-P_{fw})\right]+\frac{q_{ws1}}{\Delta x\Delta y\Delta z}$$

$$=\phi_1\left[\frac{1}{B_{w1}}\frac{\partial S_{w1}}{\partial P_{cow1}}\left(\frac{\partial P_{1o}}{\partial t}-\frac{\partial P_{1w}}{\partial t}\right)+S_{w1}\frac{\partial\left(\frac{1}{B_{w1}}\right)}{\partial P_{1w}}\frac{\partial P_{1w}}{\partial t}\right]^{*} \qquad (27)$$

3.6.2 The Oil Diffusivity Equation in the Matrix Rock

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*Since we assume that water is incompressible, this last term becomes zero $\left(\frac{\partial(1/B_{w1})}{\partial P_{1w}}=0\right)$.

$$\frac{\partial}{\partial x}\left[\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}}\left\{\frac{\partial P_{lo}}{\partial x}+\rho_{ol}\frac{g}{g_c}\sin\alpha\right\}\right]+\frac{\partial}{\partial y}\left[\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}}\frac{\partial P_{lo}}{\partial y}+\rho_{ol}\frac{g}{g_c}\sin\beta\}\right]$$

$$+\frac{\partial}{\partial z}\left[\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}}\left\{\frac{\partial P_{lo}}{\partial z}+\rho_{ol}\frac{g}{g_c}\cos\gamma\right\}\right]-\left[\frac{K_1 k_{rlo}\phi_f}{r_H l\mu_{ol}B_{ol}}(P_{lo}-P_{fo})\right]+\frac{q_{osl}}{\Delta x\cdot\Delta y\cdot\Delta z}$$

$$=\phi_1\left[\frac{1}{B_{ol}}\frac{\partial S_{ol}}{\partial t}+S_{ol}\frac{\partial(\frac{1}{B_{ol}})}{\partial P_{lo}}\frac{\partial P_{lo}}{\partial t}\right] \qquad (28)$$

3.6.3 The Gas Diffusivity Equation in the Matrix Rock

$$\frac{\partial}{\partial x}\left[\frac{K_1 k_{rlg}}{B_{gl}\mu_{gl}}\left\{\frac{\partial P_{lg}}{\partial x}+\frac{\rho_{Gs}}{B_{gl}}\frac{g}{g_c}\sin\alpha\right\}\right]+\frac{\partial}{\partial y}\left[\frac{K_1 k_{rlg}}{B_{gl}\mu_{gl}}\left\{\frac{\partial P_{lg}}{\partial y}+\frac{\rho_{Gs}}{B_{gl}}\frac{g}{g_c}\sin\beta\right\}\right]$$

$$+\frac{\partial}{\partial z}\left[\frac{K_1 k_{rlg}}{B_{gl}\mu_{gl}}\left\{\frac{\partial P_{lg}}{\partial z}+\frac{\rho_{Gs}}{B_{gl}}\frac{g}{g_c}\cos\gamma\right\}\right]+\frac{\partial}{\partial x}\left[\frac{R_{sol}K_1 k_{rlo}}{B_{ol}\mu_{ol}}\left\{\frac{\partial P_{lo}}{\partial x}+\rho_{ol}\frac{g}{g_c}\sin\alpha\right\}\right]$$

$$+\frac{\partial}{\partial y}\left[\frac{R_{sol}K_1 k_{rlo}}{B_{ol}\mu_{ol}}\left\{\frac{\partial P_{lo}}{\partial y}+\rho_{ol}\frac{g}{g_c}\sin\beta\right\}\right]+\frac{\partial}{\partial z}\left[\frac{R_{sol}K_1 k_{rlo}}{B_{ol}\mu_{ol}}\left\{\frac{\partial P_{lo}}{\partial z}+\rho_{ol}\frac{g}{g_c}\cos\gamma\right\}\right]$$

$$-\left[\frac{K_1 k_{rlg}\phi_f}{r_H l\mu_{gl}B_{Gl}}(P_{lg}-P_{fg})+\frac{K_1 k_{rlo}\phi_f R_{sol}}{r_H l\mu_{ol}B_{ol}}(P_{lo}-P_{fo})\right]+\frac{q_{Gsl}}{\Delta x\Delta y\Delta z}$$

$$=\phi_1\left[\left\{\frac{1}{B_{gl}}\frac{\partial S_{gl}}{\partial P_{cgol}}\left(\frac{\partial P_{lg}}{\partial t}-\frac{\partial P_{lo}}{\partial t}\right)+S_{gl}\frac{\partial(\frac{1}{B_{gl}})}{\partial P_{lg}}\frac{\partial P_{lg}}{\partial t}\right\}+\left\{\frac{R_{sol}}{B_{ol}}\frac{\partial S_{ol}}{\partial t}\right.\right.$$

$$\left.\left.+R_{sol}S_{ol}\frac{\partial(\frac{1}{B_{ol}})}{\partial P_{lo}}\frac{\partial P_{lo}}{\partial t}+\frac{S_{ol}}{B_{ol}}\frac{\partial R_{sol}}{\partial P_{lo}}\frac{\partial P_{lo}}{\partial t}\right\}\right] \qquad (29)$$

3.6.4 The Water Diffusivity Equation in the Fractures

$$\frac{\partial}{\partial x}\left[\frac{k_{rwf}K_{xx}}{B_{wf}\mu_{wf}}\left\{\frac{\partial P_{fw}}{\partial x}+\frac{\rho_{ws}}{B_{wf}g_c}\frac{\partial V_{fwx}}{\partial t}+\frac{\rho_{ws}}{B_{wf}}\frac{g}{g_c}\sin\alpha\right\}\right]$$

$$+\frac{\partial}{\partial x}\left[\frac{k_{rwf}K_{xy}}{B_{wf}\mu_{wf}}\left\{\frac{\partial P_{fw}}{\partial y}+\frac{\rho_{ws}}{B_{wf}g_c}\frac{\partial V_{fwy}}{\partial t}+\frac{\rho_{ws}}{B_{wf}}\frac{g}{g_c}\sin\beta\right\}\right]$$

$$+ \frac{\partial}{\partial x} \left[\frac{k_{rwf} K_{xz}}{B_{wf} \mu_{wf}} \left\{ \frac{\partial P_{fw}}{\partial z} + \frac{\rho_{ws}}{B_{wf} g_c} \frac{\partial V_{fwz}}{\partial t} + \frac{\rho_{ws}}{B_{wf}} \frac{g}{g_c} \cos\gamma \right\} \right]$$

$$+ \frac{\partial}{\partial y} \left[\frac{k_{rwf} K_{yx}}{B_{wf} \mu_{wf}} \left\{ \frac{\partial P_{fw}}{\partial x} + \frac{\rho_{ws}}{B_{wf} g_c} \frac{\partial V_{fwx}}{\partial t} + \frac{\rho_{ws}}{B_{wf}} \frac{g}{g_c} \sin\alpha \right\} \right]$$

$$+ \frac{\partial}{\partial y} \left[\frac{k_{rwf} K_{yy}}{B_{wf} \mu_{wf}} \left\{ \frac{\partial P_{fw}}{\partial y} + \frac{\rho_{ws}}{B_{wf} g_c} \frac{\partial V_{fwy}}{\partial t} + \frac{\rho_{ws}}{B_{wf}} \frac{g}{g_c} \sin\beta \right\} \right]$$

$$+ \frac{\partial}{\partial y} \left[\frac{k_{rwf} K_{yz}}{B_{wf} \mu_{wf}} \left\{ \frac{\partial P_{fw}}{\partial z} + \frac{\rho_{ws}}{B_{wf} g_c} \frac{\partial V_{fwz}}{\partial t} + \frac{\rho_{ws}}{B_{wf}} \frac{g}{g_c} \cos\gamma \right\} \right]$$

$$+ \frac{\partial}{\partial z} \left[\frac{k_{rwf} K_{zx}}{B_{wf} \mu_{wf}} \left\{ \frac{\partial P_{fw}}{\partial x} + \frac{\rho_{ws}}{B_{wf} g_c} \frac{\partial V_{fwx}}{\partial t} + \frac{\rho_{ws}}{B_{wf}} \frac{g}{g_c} \sin\alpha \right\} \right]$$

$$+ \frac{\partial}{\partial z} \left[\frac{k_{rwf} K_{zy}}{B_{wf} \mu_{wf}} \left\{ \frac{\partial P_{fw}}{\partial y} + \frac{\rho_{ws}}{B_{wf} g_c} \frac{\partial V_{fwy}}{\partial t} + \frac{\rho_{ws}}{B_{wf}} \frac{g}{g_c} \sin\beta \right\} \right]$$

$$+ \frac{\partial}{\partial z} \left[\frac{k_{rwf} K_{zz}}{B_{wf} \mu_{wf}} \left\{ \frac{\partial P_{fw}}{\partial z} + \frac{\rho_{ws}}{B_{wf} g_c} \frac{\partial V_{fwz}}{\partial t} + \frac{\rho_{ws}}{B_{wf}} \frac{g}{g_c} \cos\gamma \right\} \right]$$

$$+ \left[\frac{K_1 k_{r1w} \phi_f}{r_{H1} B_{w1} \mu_{w1}} (P_{1w} - P_{fw}) \right] + \frac{q_{wsf}}{\Delta x \cdot \Delta y \cdot \Delta z}$$

$$= \phi_f \left[\frac{1}{B_{wf}} \frac{\partial S_{wf}}{\partial P_{cowf}} \left(\frac{\partial P_{fo}}{\partial t} - \frac{\partial P_{fw}}{\partial t} \right) + S_{wf} \frac{\partial \left(\frac{1}{B_{wf}} \right)}{\partial P_{fw}} \frac{\partial P_{fw}}{\partial t} \right] \quad (30)$$

3.6.5 The Oil Diffusivity Equation in the Fractures

$$\frac{\partial}{\partial x} \left[\frac{k_{rof} K_{xx}}{B_{of} \mu_{of}} \left\{ \frac{\partial P_{fo}}{\partial x} + \frac{\rho_{o1}}{g_c} \frac{\partial V_{fox}}{\partial t} + \rho_{o1} \frac{g}{g_c} \sin\alpha \right\} \right]$$

$$+ \frac{\partial}{\partial x} \left[\frac{k_{rof} K_{xy}}{B_{of} \mu_{of}} \left\{ \frac{\partial P_{fo}}{\partial y} + \frac{\rho_{o1}}{g_c} \frac{\partial V_{foy}}{\partial t} + \rho_{o1} \frac{g}{g_c} \sin\beta \right\} \right]$$

$$+ \frac{\partial}{\partial x} \left[\frac{k_{rof} K_{xz}}{B_{of} \mu_{of}} \left\{ \frac{\partial P_{fo}}{\partial z} + \frac{\rho_{o1}}{g_c} \frac{\partial V_{foz}}{\partial t} + \rho_{o1} \frac{g}{g_c} \cos\gamma \right\} \right]$$

$$+ \frac{\partial}{\partial y} \left[\frac{k_{rof} K_{yx}}{B_{of} \mu_{of}} \left\{ \frac{\partial P_{fo}}{\partial x} + \frac{\rho_{o1}}{g_c} \frac{\partial V_{fox}}{\partial t} + \rho_{o1} \frac{g}{g_c} \sin\alpha \right\} \right]$$

$$+ \frac{\partial}{\partial y} [\frac{k_{rof}K_{yy}}{B_{of}\mu_{of}} \{ \frac{\partial P_{fo}}{\partial y} + \frac{\rho_{o1}}{g_c} \frac{\partial V_{foy}}{\partial t} + \rho_{o1} \frac{g}{g_c} \sin\beta \}]$$

$$+ \frac{\partial}{\partial y} [\frac{k_{rof}K_{yz}}{B_{of}\mu_{of}} \{ \frac{\partial P_{fo}}{\partial z} + \frac{\rho_{o1}}{g_c} \frac{\partial V_{foz}}{\partial t} + \rho_{o1} \frac{g}{g_c} \cos\gamma \}]$$

$$+ \frac{\partial}{\partial z} [\frac{k_{rof}K_{zx}}{B_{of}\mu_{of}} \{ \frac{\partial P_{fo}}{\partial x} + \frac{\rho_{o1}}{g_c} \frac{\partial V_{fox}}{\partial t} + \rho_{o1} \frac{g}{g_c} \sin\alpha \}]$$

$$+ \frac{\partial}{\partial z} [\frac{k_{rof}K_{zy}}{B_{of}\mu_{of}} \{ \frac{\partial P_{fo}}{\partial y} + \frac{\rho_{o1}}{g_c} \frac{\partial V_{foy}}{\partial t} + \rho_{o1} \frac{g}{g_c} \sin\beta \}]$$

$$+ \frac{\partial}{\partial z} [\frac{k_{rof}K_{zz}}{B_{of}\mu_{of}} \{ \frac{\partial P_{fo}}{\partial z} + \frac{\rho_{o1}}{g_c} \frac{\partial V_{foz}}{\partial t} + \rho_{o1} \frac{g}{g_c} \cos\gamma \}]$$

$$+ [\frac{K_1 k_{r1o} \phi_f}{r_{H1} B_{o1} \mu_{o1}} (P_{1o} - P_{fo})] + \frac{q_{osf}}{\Delta x \Delta y \Delta z}$$

$$= \phi_f [\frac{1}{B_{of}} \frac{\partial S_{of}}{\partial t} + S_{of} \frac{\partial (\frac{1}{B_{of}})}{\partial P_{fo}} \frac{\partial P_{fo}}{\partial t}] \qquad (31)$$

3.6.6 The Gas Diffusivity Equation in the Fractures

$$\frac{\partial}{\partial x} [\frac{k_{rgf}K_{xx}}{B_{gf}\mu_{gf}} \{ \frac{\partial P_{fg}}{\partial x} + \frac{\rho_{Gs}}{B_{gf} g_c} \frac{\partial V_{fgx}}{\partial t} + \frac{\rho_{Gs}}{B_{gf}} \frac{g}{g_c} \sin\alpha \}]$$

$$+ \frac{\partial}{\partial x} [\frac{k_{rgf}K_{xy}}{B_{gf}\mu_{gf}} \{ \frac{\partial P_{fg}}{\partial y} + \frac{\rho_{Gs}}{B_{gf} g_c} \frac{\partial V_{fgy}}{\partial t} + \frac{\rho_{Gs}}{B_{gf}} \frac{g}{g_c} \sin\beta \}]$$

$$+ \frac{\partial}{\partial x} [\frac{k_{rgf}K_{xz}}{B_{gf}\mu_{gf}} \{ \frac{\partial P_{fg}}{\partial z} + \frac{\rho_{Gs}}{B_{gf} g_c} \frac{\partial V_{fgz}}{\partial t} + \frac{\rho_{Gs}}{B_{gf}} \frac{g}{g_c} \cos\gamma \}]$$

$$+ \frac{\partial}{\partial y} [\frac{k_{rgf}K_{yx}}{B_{gf}\mu_{gf}} \{ \frac{\partial P_{fg}}{\partial x} + \frac{\rho_{Gs}}{B_{gf} g_c} \frac{\partial V_{fgx}}{\partial t} + \frac{\rho_{Gs}}{B_{gf}} \frac{g}{g_c} \sin\alpha \}]$$

$$+ \frac{\partial}{\partial y} [\frac{k_{rgf}K_{yy}}{B_{gf}\mu_{gf}} \{ \frac{\partial P_{fg}}{\partial y} + \frac{\rho_{Gs}}{B_{gf} g_c} \frac{\partial V_{fgy}}{\partial t} + \frac{\rho_{Gs}}{B_{gf}} \frac{g}{g_c} \sin\beta \}]$$

$$+ \frac{\partial}{\partial y} \left[\frac{k_{rgf} K_{yz}}{B_{gf} \mu_{gf}} \left\{ \frac{\partial P_{fg}}{\partial z} + \frac{\rho_{Gs}}{B_{gf} g_c} \frac{\partial V_{fgz}}{\partial t} + \frac{\rho_{Gs}}{B_{gf}} \frac{g}{g_c} \cos\gamma \right\} \right]$$

$$+ \frac{\partial}{\partial z} \left[\frac{k_{rgf} K_{zx}}{B_{gf} \mu_{gf}} \left\{ \frac{\partial P_{fg}}{\partial x} + \frac{\rho_{Gs}}{B_{gf} g_c} \frac{\partial V_{fgx}}{\partial t} + \frac{\rho_{Gs}}{B_{gf}} \frac{g}{g_c} \sin\alpha \right\} \right]$$

$$+ \frac{\partial}{\partial z} \left[\frac{k_{rgf} K_{zy}}{B_{gf} \mu_{gf}} \left\{ \frac{\partial P_{fg}}{\partial y} + \frac{\rho_{Gs}}{B_{gf} g_c} \frac{\partial V_{fgy}}{\partial t} + \frac{\rho_{Gs}}{B_{gf}} \frac{g}{g_c} \sin\beta \right\} \right]$$

$$+ \frac{\partial}{\partial z} \left[\frac{k_{rgf} K_{zz}}{B_{gf} \mu_{gf}} \left\{ \frac{\partial P_{fg}}{\partial z} + \frac{\rho_{Gs}}{B_{gf} g_c} \frac{\partial V_{fgz}}{\partial t} + \frac{\rho_{Gs}}{B_{gf}} \frac{g}{g_c} \cos\gamma \right\} \right]$$

$$+ \frac{\partial}{\partial x} \left[\frac{R_{sof} k_{rof} K_{xx}}{B_{of} \mu_{of}} \left\{ \frac{\partial P_{fo}}{\partial x} + \frac{\rho_{ol}}{g_c} \frac{\partial V_{fox}}{\partial t} + \rho_{ol} \frac{g}{g_c} \sin\alpha \right\} \right]$$

$$+ \frac{\partial}{\partial x} \left[\frac{R_{sof} k_{rof} K_{xy}}{B_{of} \mu_{of}} \left\{ \frac{\partial P_{fo}}{\partial y} + \frac{\rho_{ol}}{g_c} \frac{\partial V_{foy}}{\partial t} + \rho_{ol} \frac{g}{g_c} \sin\beta \right\} \right]$$

$$+ \frac{\partial}{\partial x} \left[\frac{R_{sof} k_{rof} K_{xz}}{B_{of} \mu_{of}} \left\{ \frac{\partial P_{fo}}{\partial z} + \frac{\rho_{ol}}{g_c} \frac{\partial V_{foz}}{\partial t} + \rho_{ol} \frac{g}{g_c} \cos\gamma \right\} \right]$$

$$+ \frac{\partial}{\partial y} \left[\frac{R_{sof} k_{rof} K_{yx}}{B_{of} \mu_{of}} \left\{ \frac{\partial P_{fo}}{\partial x} + \frac{\rho_{ol}}{g_c} \frac{\partial V_{fox}}{\partial t} + \rho_{ol} \frac{g}{g_c} \sin\alpha \right\} \right]$$

$$+ \frac{\partial}{\partial y} \left[\frac{R_{sof} k_{rof} K_{yy}}{B_{of} \mu_{of}} \left\{ \frac{\partial P_{fo}}{\partial y} + \frac{\rho_{ol}}{g_c} \frac{\partial V_{foy}}{\partial t} + \rho_{ol} \frac{g}{g_c} \sin\beta \right\} \right]$$

$$+ \frac{\partial}{\partial y} \left[\frac{R_{sof} k_{rof} K_{yz}}{B_{of} \mu_{of}} \left\{ \frac{\partial P_{fo}}{\partial z} + \frac{\rho_{ol}}{g_c} \frac{\partial V_{foz}}{\partial t} + \rho_{ol} \frac{g}{g_c} \cos\gamma \right\} \right]$$

$$+ \frac{\partial}{\partial z} \left[\frac{R_{sof} k_{rof} K_{zx}}{B_{of} \mu_{of}} \left\{ \frac{\partial P_{fo}}{\partial x} + \frac{\rho_{ol}}{g_c} \frac{\partial V_{fox}}{\partial t} + \rho_{ol} \frac{g}{g_c} \sin\alpha \right\} \right]$$

$$+ \frac{\partial}{\partial z} \left[\frac{R_{sof} k_{rof} K_{zy}}{B_{of} \mu_{of}} \left\{ \frac{\partial P_{fo}}{\partial y} + \frac{\rho_{ol}}{g_c} \frac{\partial V_{foy}}{\partial t} + \rho_{ol} \frac{g}{g_c} \sin\beta \right\} \right]$$

$$+ \frac{\partial}{\partial z} \left[\frac{R_{sof} k_{rof} K_{zz}}{B_{of} \mu_{of}} \left\{ \frac{\partial P_{fo}}{\partial z} + \frac{\rho_{ol}}{g_c} \frac{\partial V_{foz}}{\partial t} + \rho_{ol} \frac{g}{g_c} \cos\gamma \right\} \right]$$

$$+[\frac{K_1 k_{r1g}\phi_f}{r_H 1 \mu_{g1} B_{g1}} (P_{1g} - P_{fg}) + \frac{K_1 k_{r1o}\phi_f R_{so1}}{r_H 1 \mu_{o1} B_{o1}} (P_{1o} - P_{fo})] + \frac{q_{Gsf}}{\Delta x \cdot \Delta y \cdot \Delta z}$$

$$= \phi_f \, [\, \{\frac{1}{B_{gf}} \frac{\partial S_{gf}}{\partial P_{cgof}} (\frac{\partial P_{fg}}{\partial t} - \frac{\partial P_{fo}}{\partial t}) + S_{gf} \frac{\partial (\frac{1}{B_{gf}})}{P_{fg}} \frac{\partial P_{fg}}{\partial t} \}$$

$$+ \{ \frac{R_{sof}}{B_{of}} \frac{\partial S_{of}}{\partial t} + \frac{S_{of}}{B_{of}} \frac{\partial R_{sof}}{\partial P_{fo}} \cdot \frac{\partial P_{fo}}{\partial t} + S_{of} R_{sof} \frac{\partial (\frac{1}{B_{of}})}{\partial P_{fo}} \cdot \frac{\partial P_{fo}}{\partial t} \}] \tag{32}$$

Equations (27), (28), (29), (30), (31) and (32) thus form the mathematical model that simulates the fluid flow behavior in naturally fractured reservoirs. In the next chapter, development of the simulation program based on this model will be discussed.

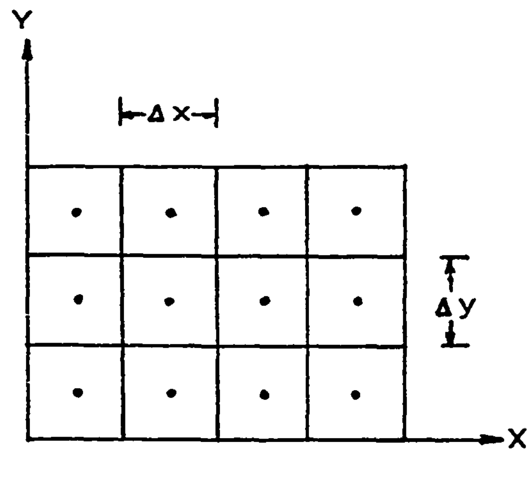
CHAPTER IV

SIMULATOR DEVELOPMENT

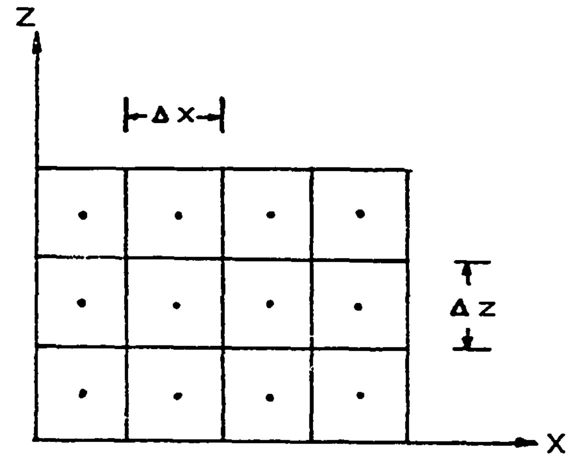
4.1 Finite Difference Approximations

The simulation program in this study is written using the FORTRAN IV computer code. The program is compiled and run on the IBM system 3081 (model D) machine. In order to develop a computer program the derivatives in the governing flow equations have to be replaced by suitable finite difference approximations. This involves discretization of the reservoir spatial domain into a number of grid points (or nodes) by employing, in this case, the block-centered rectangular grid system (See Figure 5). The time domain is also divided into a number of time steps during each of which the system of linear equations is solved to obtain new values of dependent variables. The solution to the equations at any particular time step thus consists of a set of numbers obtained for all grid points within the continuous medium under consideration.

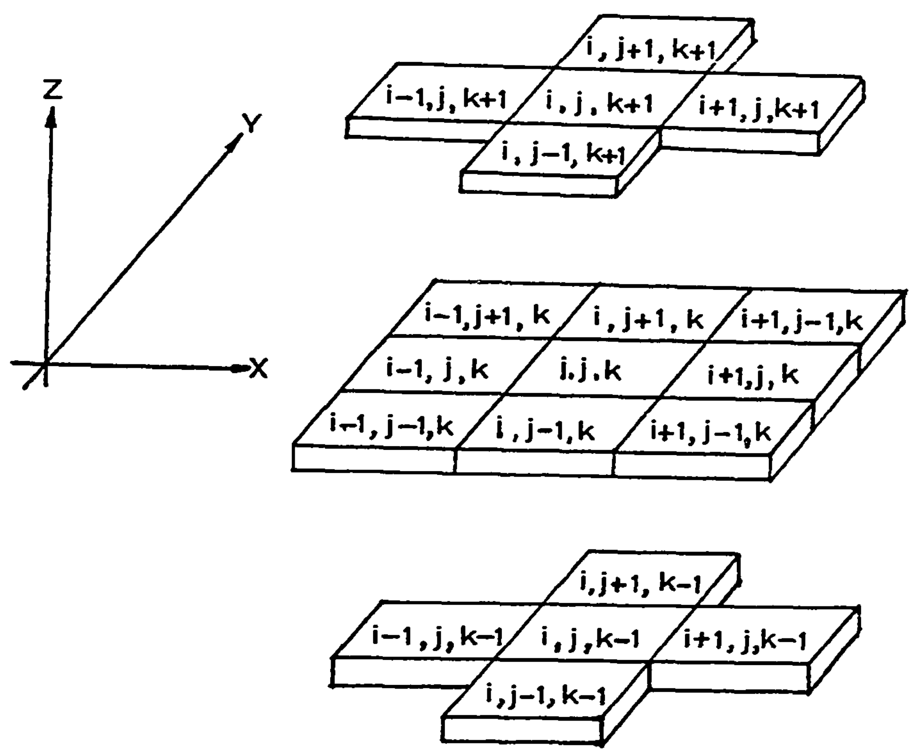
The finite difference approximations are expressions derived from Taylor series and the relationships between the difference and the differential operators. In this study, the derivatives in the six governing flow equations can be approximated by the finite difference formulae



Top View



Side View



Finite Difference Notation

Figure 5. Block-centered grid system

given in Table 1.

The fully implicit approach is used to solve for the new pressure values at all grid points simultaneously. As demonstrated in Chapter III, the capillary pressure equations together with the saturations equations are employed to eliminate S_{wl}, S_{ol}, S_{gl}, S_{wf}, S_{of} and S_{gf} from the six partial differential equations resulting in six equations containing the unknowns P_{lw}, P_{lo}, P_{lg}, P_{fw}, P_{fo} and P_{fg}. These six equations written for all nodes in the grid system are to be solved by one of the numerical methods, preferably an iterative method over a direct method[23]. The calculated pressures are then used in the capillary pressure and saturation equations to compute saturations. This approach is recommended by Faroug Ali[11] as being more stable and accurate than the conventional Implicit-Pressure-Explicit-Saturation (IMPES) approach. Thomas[23] also states that this approach provides a smooth variation of unknowns in spite of saturation discontinuities. However, this approach requires nonzero capillary pressure data. Moreover, the degree of accuracy depends partially on the ways the coefficients of the equations are evaluated. The subject of coefficient evaluation will be discussed in the next section.

The use of formulae similar to the ones in Table 1 to transform the six governing flow equations into six finite difference equations is a very cumbersome and painstaking task. For instance, the number of coefficients involved in these equations amounts to 126 terms, each of which is comprised of a group of parameters. And since the governing flow

Table 1

Finite Difference Formulae

$$\frac{\partial}{\partial x}\left(\lambda \frac{\partial u}{\partial x}\right) = \frac{\lambda_{i+\frac{1}{2},j,k}\dfrac{U_{i+1,j,k}-U_{i,j,k}}{\Delta x} - \lambda_{i-\frac{1}{2},j,k}\dfrac{U_{i,j,k}-U_{i-1,j,k}}{\Delta x}}{\Delta x}$$

$$= \frac{1}{\Delta x^2}[\lambda_{i+\frac{1}{2},j,k}(U_{i+1,j,k}-U_{i,j,k})-\lambda_{i-\frac{1}{2},j,k}(U_{i,j,k}-U_{i-1,j,k})]$$

$$\frac{\partial}{\partial x}\left(\lambda \frac{\partial u}{\partial y}\right) = \frac{\lambda_{i+1,j,k}\dfrac{U_{i+1,j+1,k}-U_{i+1,j-1,k}}{2\Delta y} - \lambda_{i-1,j,k}\dfrac{U_{i-1,j+1,k}-U_{i-1,j-1,k}}{2\Delta y}}{2\Delta x}$$

$$= \frac{1}{4\Delta x\Delta y}[\lambda_{i+1,j,k}(U_{i+1,j+1,k}-U_{i+1,j-1,k})$$

$$-\lambda_{i-1,j,k}(U_{i-1,j+1,k}-U_{i-1,j-1,k})]$$

$$\frac{\partial u}{\partial t} = \frac{U^{n+1}_{i,j,k} - U^{n}_{i,j,k}}{\Delta t}$$

$$\frac{\partial u}{\partial x} = \frac{U_{i+1,j,k}-U_{i-1,j,k}}{2\Delta x}$$

equations are nonlinear partial differential equations, each of these coefficients has to be recomputed every time step. In this context, development of the fractured reservoir simulator is difficult and challenging.

The finite difference forms of the six governing flow equations from section 3.6 constitute a system of simultaneous linear equations and can be written as follows. The expressions for the coefficients of these equations are given in detail in Appendix C.

$$(GW)_{i,j,k}\, P^{n+1}_{1w\; i,j,k-1} + (EW)_{i,j,k}\, P^{n+1}_{1w\; i,j-1,k} + (AW)_{i,j,k}\, P^{n+1}_{1w\; i-1,j,k} + (BW)_{i,j,k}\, P^{n+1}_{1w\; i+1,j,k}$$

$$+ (CW)_{i,j,k}\, P^{n+1}_{1w\; i+1,j,k} + (FW)_{i,j,k}\, P^{n+1}_{1w\; i,j+1,k} + (HW)_{i,j,k}\, P^{n+1}_{1w\; i,j,k+1}$$

$$+ (RW)_{i,j,k}\, P^{n+1}_{fw\; i,j,k} + (UW)_{i,j,k}\, P^{n+1}_{1o\; i,j,k} = DW_{i,j,k} \qquad (33)$$

$$(VO)_{i,j,k}\, P^{n+1}_{1w\; i,j,k} + (GO)_{i,j,k}\, P^{n+1}_{1o\; i,j,k-1} + (EO)_{i,j,k}\, P^{n+1}_{1o\; i,j-1,k}$$

$$+ (AO)_{i,j,k}\, P^{n+1}_{1o\; i-1,j,k} + (BO)_{i,j,k}\, P^{n+1}_{1o\; i,j,k} + (CO)_{i,j,k}\, P^{n+1}_{1o\; i+1,j,k}$$

$$+ (FO)_{i,j,k}\, P^{n+1}_{1o\; i,j+1,k} + (HO)_{i,j,k}\, P^{n+1}_{1o\; i,j,k+1} + (UO)_{i,j,k}\, P^{n+1}_{1g\; i,j,k}$$

$$+ (RO)_{i,j,k}\, P^{n+1}_{fo\; i,j,k} = DO_{i,j,k} \qquad (34)$$

$$(VG)_{i,j,k}\, P^{n+1}_{\substack{1w\\i,j,k}} + (GGO)_{i,j,k}\, P^{n+1}_{\substack{1o\\i,j,k-1}} + (EGO)_{i,j,k}\, P^{n+1}_{\substack{1o\\i,j-1,k}} + (AGO)_{i,j,k}\, P^{n+1}_{\substack{1o\\i-1,j,k}}$$

$$+ (BGO)_{i,j,k}\, P^{n+1}_{\substack{1o\\i,j,k}} + (CGO)_{i,j,k}\, P^{n+1}_{\substack{1o\\i+1,j,k}} + (FGO)_{i,j,k}\, P^{n+1}_{\substack{1o\\i,j+1,k}}$$

$$+ (HGO)_{i,j,k}\, P^{n+1}_{\substack{1o\\i,j,k+1}} + (GG)_{i,j,k}\, P^{n+1}_{\substack{1g\\i,j,k-1}} + (EG)_{i,j,k}\, P^{n+1}_{\substack{1g\\i,j-1,k}}$$

$$+ (AG)_{i,j,k}\, P^{n+1}_{\substack{1g\\i-1,j,k}} + (BG)_{i,j,k}\, P^{n+1}_{\substack{1g\\i,j,k}} + (CG)_{i,j,k}\, P^{n+1}_{\substack{1g\\i+1,j,k}}$$

$$+ (FG)_{i,j,k}\, P^{n+1}_{\substack{1g\\i,j+1,k}} + (HG)_{i,j,k}\, P^{n+1}_{\substack{1g\\i,j,k+1}} + (RGO)_{i,j,k}\, P^{n+1}_{\substack{fo\\i,j,k}}$$

$$+ (RG)_{i,j,k}\, P^{n+1}_{\substack{fg\\i,j,k}} = DG_{i,j,k} \qquad (35)$$

$$(FRW)_{i,j,k}\, P^{n+1}_{\substack{1w\\i,j,k}} + (FGW1)_{i,j,k}\, P^{n+1}_{\substack{fw\\i,j-1,k-1}} + (FGW2)_{i,j,k}\, P^{n+1}_{\substack{fw\\i-1,j,k-1}}$$

$$+ (FGW3)_{i,j,k}\, P^{n+1}_{\substack{fw\\i,j,k-1}} + (FGW4)_{i,j,k}\, P^{n+1}_{\substack{fw\\i+1,j,k-1}}$$

$$+ (FGW5)_{i,j,k}\, P^{n+1}_{\substack{fw\\i,j+1,k-1}} + (FEW1)_{i,j,k}\, P^{n+1}_{\substack{fw\\i-1,j-1,k}}$$

$$+ (FEW2)_{i,j,k}\, P^{n+1}_{\substack{fw\\i,j-1,k}} + (FEW3)_{i,j,k}\, P^{n+1}_{\substack{fw\\i+1,j-1,k}}$$

$$+ (FAW1)_{i,j,k}\, {P^{n+1}_{fw}}_{i-1,j,k} + (FBW)_{i,j,k}\, {P^{n+1}_{fw}}_{i,j,k} + (FCW1)_{i,j,k}\, {P^{n+1}_{fw}}_{i+1,j,k}$$

$$+ (FFW1)_{i,j,k}\, {P^{n+1}_{fw}}_{i-1,j+1,k} + (FFW2)_{i,j,k}\, {P^{n+1}_{fw}}_{i,j+1,k}$$

$$+ (FFW3)_{i,j,k}\, {P^{n+1}_{fw}}_{i+1,j+1,k} + (FHW1)_{i,j,k}\, {P^{n+1}_{fw}}_{i,j-1,k+1}$$

$$+ (FHW2)_{i,j,k}\, {P^{n+1}_{fw}}_{i-1,j,k+1} + (FHW3)_{i,j,k}\, {P^{n+1}_{fw}}_{i,j,k+1}$$

$$+ (FHW4)_{i,j,k}\, {P^{n+1}_{fw}}_{i+1,j,k+1} + (FHW5)_{i,j,k}\, {P^{n+1}_{fw}}_{i,j+1,k+1}$$

$$+ (FUW)_{i,j,k}\, {P^{n+1}_{fo}}_{i,j,k} = DFW_{i,j,k} \qquad (36)$$

$$(FRO)_{i,j,k}\, {P^{n+1}_{lo}}_{i,j,k} + (FVO)_{i,j,k}\, {P^{n+1}_{fw}}_{i,j,k} + (FGO1)_{i,j,k}\, {P^{n+1}_{fo}}_{i,j-1,k-1}$$

$$+ (FGO2)_{i,j,k}\, {P^{n+1}_{fo}}_{i-1,j,k-1} + (FGO3)_{i,j,k}\, {P^{n+1}_{fo}}_{i,j,k-1}$$

$$+ (FGO4)_{i,j,k}\, {P^{n+1}_{fo}}_{i+1,j,k-1} + (FGO5)_{i,j,k}\, {P^{n+1}_{fo}}_{i,j+1,k-1}$$

$$+ (FEO1)_{i,j,k}\, {P^{n+1}_{fo}}_{i-1,j-1,k} + (FEO2)_{i,j,k}\, {P^{n+1}_{fo}}_{i,j-1,k}$$

$$+ (FEO3)_{i,j,k}\, {P^{n+1}_{fo}}_{i+1,j-1,k} + (FAO1)_{i,j.k}\, {P^{n+1}_{fo}}_{i-1,j,k}$$

$$+ (FBO)_{i,j,k} P^{n+1}_{fo\,i,j,k} + (FCO1)_{i,j,k} P^{n+1}_{fo\,i+1,j,k} + (FFO1)_{i,j,k} P^{n+1}_{fo\,i-1,j+1,k}$$

$$+ (FFO2)_{i,j,k} P^{n+1}_{fo\,i,j+1,k} + (FFO3)_{i,j,k} P^{n+1}_{fo\,i+1,j+1,k}$$

$$+ (FHO1)_{i,j,k} P^{n+1}_{fo\,i,j-1,k+1} + (FHO2)_{i,j,k} P^{n+1}_{fo\,i-1,j,k+1}$$

$$+ (FHO3)_{i,j,k} P^{n+1}_{fo\,i,j,k+1} + (FHO4)_{i,j,k} P^{n+1}_{fo\,i+1,j,k+1}$$

$$+ (FHO5)_{i,j,k} P^{n+1}_{fo\,i,j+1,k+1} + (FUO)_{i,j,k} P^{n+1}_{fg\,i,j,k} = DFO_{i,j,k} \quad (37)$$

$$(FRGO)_{i,j,k} P^{n+1}_{lo\,i,j,k} + (FRG)_{i,j,k} P^{n+1}_{lg\,i,j,k} + (FVG)_{i,j,k} P^{n+1}_{fw\,i,j,k}$$

$$+ (FGR1)_{i,j,k} P^{n+1}_{fo\,i,j-1,k-1} + (FGR2)_{i,j,k} P^{n+1}_{fo\,i-1,j,k-1}$$

$$+ (FGR3)_{i,j,k} P^{n+1}_{fo\,i,j,k-1} + (FGR4)_{i,j,k} P^{n+1}_{fo\,i+1,j,k-1}$$

$$+ (FGR5)_{i,j,k} P^{n+1}_{fo\,i,j+1,k-1} + (FER1)_{i,j,k} P^{n+1}_{fo\,i-1,j-1,k}$$

$$+ (FER2)_{i,j,k} P^{n+1}_{fo\,i,j-1,k} + (FER3)_{i,j,k} P^{n+1}_{fo\,i+1,j-1,k}$$

$$+ (FAR1)_{i,j,k} P^{n+1}_{fo\,i-1,j,k} + (FBR)_{i,j,k} P^{n+1}_{fo\,i,j,k} + (FCR1)_{i,j,k} P^{n+1}_{fo\,i+1,j,k}$$

$$+ (FFR1)_{i,j,k}\, P^{n+1}_{fo\;i-1,j+1,k} + (FFR2)_{i,j,k}\, P^{n+1}_{fo\;i,j+1,k}$$

$$+ (FFR3)_{i,j,k}\, P^{n+1}_{fo\;i+1,j+1,k} + (FHR1)_{i,j,k}\, P^{n+1}_{fo\;i,j-1,k+1}$$

$$+ (FHR2)_{i,j,k}\, P^{n+1}_{fo\;i-1,j,k+1} + (FHR3)_{i,j,k}\, P^{n+1}_{fo\;i,j,k+1}$$

$$+ (FHR4)_{i,j,k}\, P^{n+1}_{fo\;i+1,j,k+1} + (FHR5)_{i,j,k}\, P^{N+1}_{fo\;i,j+1,k+1}$$

$$+ (FGG1)_{i,j,k}\, P^{n+1}_{fg\;i,j-1,k-1} + (FGG2)_{i,j,k}\, P^{n+1}_{fg\;i-1,j,k-1}$$

$$+ (FGG3)_{i,j,k}\, P^{n+1}_{fg\;i,j,k-1} + (FGG4)_{i,j,k}\, P^{n+1}_{fg\;i+1,j,k-1}$$

$$+ (FGG5)_{i,j,k}\, P^{n+1}_{fg\;i,j+1,k-1} + (FEG1)_{i,j,k}\, P^{n+1}_{fg\;i-1,j-1,k}$$

$$+ (FEG2)_{i,j,k}\, P^{n+1}_{fg\;i,j-1,k} + (FEG3)_{i,j,k}\, P^{n+1}_{fg\;i+1,j-1,k}$$

$$+ (FAG1)_{i,j,k}\, P^{n+1}_{fg\;i-1,j,k} + (FBG)_{i,j,k}\, P^{n+1}_{fg\;i,j,k}$$

$$+ (FCG1)_{i,j,k}\, P^{n+1}_{fg\;i+1,j,k} + (FFG1)_{i,j,k}\, P^{n+1}_{fg\;i-1,j+1,k}$$

$$+ (FFG2)_{i,j,k}\, P_{fg\; i,j+1,k}^{n+1} + (FFG3)_{i,j,k}\, P_{fg\; i+1,j+1,k}^{n+1}$$

$$+ (FHG1)_{i,j,k}\, P_{fg\; i,j-1,k+1}^{n+1} + (FHG2)_{i,j,k}\, P_{fg\; i-1,j,k+1}^{n+1}$$

$$+ (FHG3)_{i,j,k}\, P_{fg\; i,j,k+1}^{n+1} + (FHG4)_{i,j,k}\, P_{fg\; i+1,j,k+1}^{n+1}$$

$$+ (FHG5)_{i,j,k}\, P_{fg\; i,j+1,k+1}^{n+1} = DFG_{i,j,k} \qquad (38)$$

These equations, written for all N nodes in the reservoir grid system, produce a block 19-band-diagonal coefficient matrix for 6N simultaneous linear equations in 6N unknowns which may be solved by direct or iterative methods. The system of equations can be written as follows in block matrix form (See Figure 6),

where

$$B_r = B_{i,j,k} = \begin{bmatrix} BW_{i,j,k} & UW_{i,j,k} & & RW_{i,j,k} & & \\ VO_{i,j,k} & BO_{i,j,k} & UO_{i,j,k} & & RO_{i,j,k} & \\ VG_{i,j,k} & BGO_{i,j,k} & BG_{i,j,k} & & RGO_{i,j,k} & RG_{i,j,k} \\ FRW_{i,j,k} & & & FBW_{i,j,k} & FUW_{i,j,k} & \\ & FRO_{i,j,k} & & FVO_{i,j,k} & FBO_{i,j,k} & FUO_{i,j,k} \\ & FRGO_{i,j,k} & FRG_{i,j,k} & FVG_{i,j,k} & FBR_{i,j,k} & FBG_{i,j,k} \end{bmatrix}$$

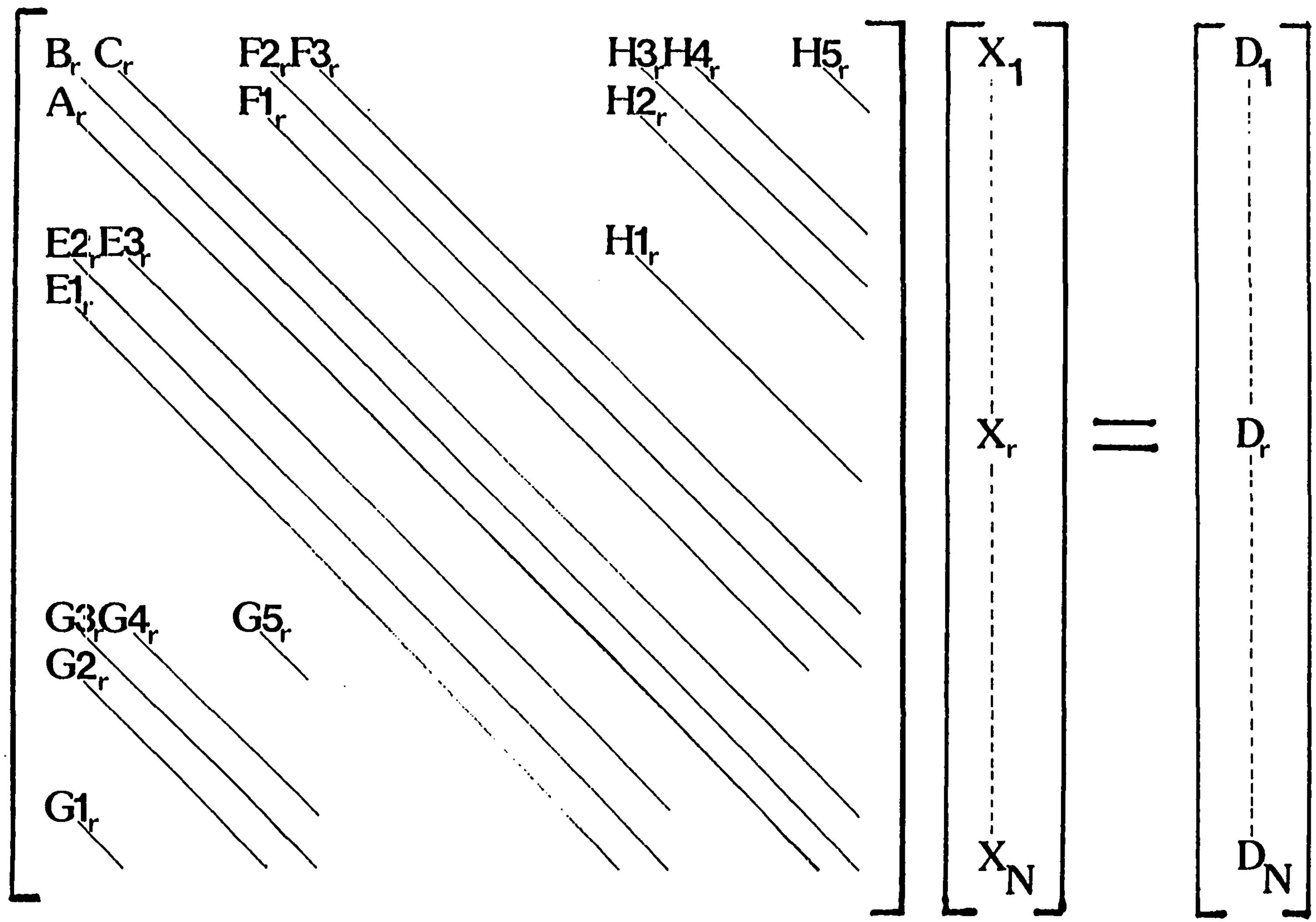


Figure 6. Block matrix form of the pressure equations (19-band diagonal matrix)

$$C_r = C_{i,j,k} = \begin{bmatrix} CW_{i,j,k} & & & & & \\ & CO_{i,j,k} & & & & \\ & CGO_{i,j,k} & CG_{i,j,k} & & & \\ & & & FCW1_{i,j,k} & & \\ & & & & FCO1_{i,j,k} & \\ & & & & FCR1_{i,j,k} & FCG1_{i,j,k} \end{bmatrix}$$

$$A_r = A_{i,j,k} = \begin{bmatrix} AW_{i,j,k} & & & & & \\ & AO_{i,j,k} & & & & \\ & AGO_{i,j,k} & AG_{i,j,k} & & & \\ & & & FAW1_{i,j,k} & & \\ & & & & FAO1_{i,j,k} & \\ & & & & FAR1_{i,j,k} & FAG1_{i,j,k} \end{bmatrix}$$

$$X_{i,j,k} = \begin{bmatrix} P_{lw_{i,j,k}} \\ P_{lo_{i,j,k}} \\ P_{lg_{i,j,k}} \\ P_{fw_{i,j,k}} \\ P_{fo_{i,j,k}} \\ P_{fg_{i,j,k}} \end{bmatrix}$$

$$D_r = D_{i,j,k} = \begin{bmatrix} DW_{i,j,k} \\ DO_{i,j,k} \\ DG_{i,j,k} \\ DFW_{i,j,k} \\ DFO_{i,j,k} \\ DFG_{i,j,k} \end{bmatrix}$$

$$G1_r = G1_{i,j,k} = \begin{bmatrix} 0 & & & & & \\ & 0 & & & & \\ & & 0 & & & \\ & & & FGW1_{i,j,k} & & \\ & & & & FGO1_{i,j,k} & \\ & & & & FGR1_{i,j,k} & FGG1_{i,j,k} \end{bmatrix}$$

$$G2_r = G2_{i,j,k} = \begin{bmatrix} 0 & & & & & \\ & 0 & & & & \\ & & 0 & & & \\ & & & FGW2_{i,j,k} & & \\ & & & & FGO2_{i,j,k} & \\ & & & & FGR2_{i,j,k} & FGG2_{i,j,k} \end{bmatrix}$$

$$G3_r = G3_{i,j,k} = \begin{bmatrix} GW_{i,j,k} & & & & & \\ & GO_{i,j,k} & & & & \\ & GGO_{i,j,k} & GG_{i,j,k} & & & \\ & & & FGW3_{i,j,k} & & \\ & & & & FGO3_{i,j,k} & \\ & & & & FGR3_{i,j,k} & FGG3_{i,j,k} \end{bmatrix}$$

$$G4_r = G4_{i,j,k} = \begin{bmatrix} 0 & & & & & \\ & 0 & & & & \\ & & 0 & & & \\ & & & FGW4_{i,j,k} & & \\ & & & & FGO4_{i,j,k} & \\ & & & & FGR4,_{i,j,k} & FGG4_{i,j,k} \end{bmatrix}$$

$$G5_r = G5_{i,j,k} = \begin{bmatrix} 0 & & & & & \\ & 0 & & & & \\ & & 0 & & & \\ & & & FGW5_{i,j,k} & & \\ & & & & FGO5_{i,j,k} & \\ & & & & FGR5_{i,j,k} & FGG5_{i,j,k} \end{bmatrix}$$

$$E1_r = E1_{i,j,k} = \begin{bmatrix} 0 & & & & & \\ & 0 & & & & \\ & & 0 & & & \\ & & & FEW1_{i,j,k} & & \\ & & & & FEO1_{i,j,k} & \\ & & & & FER1_{i,j,k} & FEG1_{i,j,k} \end{bmatrix}$$

$$E2_r = E2_{i,j,k} = \begin{bmatrix} EW_{i,j,k} & & & & & \\ & EO_{i,j,k} & & & & \\ & EGO_{i,j,k} & EG_{i,j,k} & & & \\ & & & FEW2_{i,j,k} & & \\ & & & & FEO2_{i,j,k} & \\ & & & & FER2_{i,j,k} & FEG2_{i,j,k} \end{bmatrix}$$

0

$$E3_r = E3_{i,j,k} = \begin{bmatrix} 0 & & & & & \\ & 0 & & & & \\ & & 0 & & & \\ & & & FEW3_{i,j,k} & & \\ & & & & FEO3_{i,j,k} & \\ & & & & FER3_{i,j,k} & FEG3_{i,j,k} \end{bmatrix}$$

$$F1_r = F1_{i,j,k} = \begin{bmatrix} 0 & & & & & \\ & 0 & & & & \\ & & 0 & & & \\ & & & FFW1_{i,j,k} & & \\ & & & & FFO1_{i,j,k} & \\ & & & & FFR1_{i,j,k} & FFG1_{i,j,k} \end{bmatrix}$$

$$F2_r = F2_{i,j,k} = \begin{bmatrix} FW_{i,j,k} & & & & & \\ & FO_{i,j,k} & & & & \\ & FGO_{i,j,k} & FG_{i,j,k} & & & \\ & & & FFW2_{i,j,k} & & \\ & & & & FFO2_{i,j,k} & \\ & & & & FFR2_{i,j,k} & FFG2_{i,j,k} \end{bmatrix}$$

$$F3_r = F3_{i,j,k} = \begin{bmatrix} 0 & & & & & \\ & 0 & & & & \\ & & 0 & & & \\ & & & FFW3_{i,j,k} & & \\ & & & & FFO3_{i,j,k} & \\ & & & & FFR3_{i,j,k} & FFG3_{i,j,k} \end{bmatrix}$$

$$H1_r = H1_{i,j,k} = \begin{bmatrix} 0 & & & & & \\ & 0 & & & & \\ & & 0 & & & \\ & & & FHW1_{i,j,k} & & \\ & & & & FHO1_{i,j,k} & \\ & & & & FHR1_{i,j,k} & FHG1_{i,j,k} \end{bmatrix}$$

$$H2_r = H2,_{i,j,k} = \begin{bmatrix} 0 & & & & & \\ & 0 & & & & \\ & & 0 & & & \\ & & & FHW2_{i,j,k} & & \\ & & & & FHO2_{i,j,k} & \\ & & & & FHR2_{i,j,k} & FHG2_{i,j,k} \end{bmatrix}$$

$$H3_r = H3,_{i,j,k} = \begin{bmatrix} HW_{i,j,k} & & & & & \\ & HO_{i,j,k} & & & & \\ & HGO_{i,j,k} & HG_{i,j,k} & & & \\ & & & FHW3_{i,j,k} & & \\ & & & & FHO3_{i,j,k} & \\ & & & & FHR3_{i,j,k} & FHG3_{i,j,k} \end{bmatrix}$$

$$H4_r = H4_{i,j,k} = \begin{bmatrix} 0 & & & & & \\ & 0 & & & & \\ & & 0 & & & \\ & & & FHW4_{i,j,k} & & \\ & & & & FHO4_{i,j,k} & \\ & & & & FHR4_{i,j,k} & FHG4_{i,j,k} \end{bmatrix}$$

$$H5_r = H5_{i,j,k} = \begin{bmatrix} 0 & & & & & \\ & 0 & & & & \\ & & 0 & & & \\ & & & FHW5_{i,j,k} & & \\ & & & & FHO5_{i,j,k} & \\ & & & & FHR5_{i,j,k} & FHG5_{i,j,k} \end{bmatrix}$$

4.2 Evaluation of Coefficients

The coefficients of the derivatives in a nonlinear partial differential equation, in addition to being functions of the independent variables, are also functions of the dependent variables. For the present system of equations, the coefficients include parameters such as formation volume factors, solubility, relative permeability, viscosity, porosity and fracture velocity. These parameters are either pressure- or saturation dependent. Consequently, we are presented with a dilemma: how can we obtain the solution to the pressure equations when the solution depends on the coefficients which themselves depend on these pressures? Crichlow[7] suggests two ways out of this situation. First, these coefficients may be evaluated from the pressures or saturations of the previous time step. Implied in this approach is the belief that these coefficients do not change so rapidly from one time step to the next. This would be true if pressures and saturations are also not changing so rapidly. Second, for an iterative method, these coefficients are evaluated from the most current pressures or saturations of the last iteration within the same time step.

In this study, the first approach with some modification is used. Parameters such as (dS_w/dP_{cow}) and (dS_g/dP_{cgo}) are evaluated from S_w^n and S_g^n, respectively. Other parameters may be evaluated according to the technique shown by Faroug Ali[11]. That is the pressures and/or saturations are averaged in time between the last time step values and the "projected" current values. Then, the parameters B_o, B_g, R_{so}, $d(1/B_o)dP_o$, $d(1/B_g)/dP_g$, dR_{so}/dP_o, μ_o, μ_w and μ_g are evaluated from the $P^{n+\frac{1}{2}}$ values, whereas the parameters k_{row}, k_{rw}, k_{rog} and k_{rg} are evaluated from the $S_w^{n+\frac{1}{2}}$ or $S_g^{n+\frac{1}{2}}$ values. The "projected" values of pressures or saturations may be computed from the following formulae given by Settari and Aziz[18].

$$\tilde{U}^{n+1} = U^n + \frac{\Delta t^{n+1}}{\Delta t^n} (U^n - U^{n-1}) \tag{39}$$

Whereas, the average values in time may be computed from

$$U^{n+\frac{1}{2}} = \frac{\tilde{U}^{n+1} + U^n}{2} \tag{40}$$

Sometimes, when flow between two adjacent grid points are being considered, the parameters have to be evaluated from pressures/saturations at midpoint in space between those two grid points. These midpoint values may be computed from

$$U_{i+\frac{1}{2},j,k} = \frac{U_{i,j,k} + U_{i+1,j,k}}{2} \qquad (41)$$

With regard to relative permeability, the upstream weighting scheme is used[11,18]. This scheme evaluates the relative permeability from saturations at the upstream node, for example

$$k_{rw\ i+\frac{1}{2},j,k} = \begin{cases} k_{rw}(S_{w\ i,j,k}) & \text{if flow is from } (i,j,k) \text{ to } (i+1,j,k) \\ k_{rw}(S_{w\ i+1,j,k}) & \text{if flow is from } (i+1,j,k) \text{ to } (i,j,k) \end{cases}$$

The direction of flow can be determined by comparing the flow potentials of the two grid points.

Therefore, a coefficient such as $(CO)_{i,j,k}$ from Appendix C may be interpreted

$$CO_{i,j,k} = \frac{V_B}{\Delta x^2} \left(\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k}$$

$$= \frac{V_B}{\Delta x^2} \left[\frac{K_{1\ i+\frac{1}{2},j,k}\ k_{rlo}(S^{n+\frac{1}{2}}_{wl}, S^{n+\frac{1}{2}}_{gl})\text{upstream}}{B_{ol}(P^{n+\frac{1}{2}}_{lo\ i+\frac{1}{2},j,k})\,\mu_{ol}(P^{n+\frac{1}{2}}_{lo\ i+\frac{1}{2},j,k})} \right]$$

where

$$K_{1\, i+\frac{1}{2},j,k} = \frac{1}{2}(K_{1\ i,j,k} + K_{1\ i+1,j,k})$$

$$P^{n+\frac{1}{2}}_{lo\ i+\frac{1}{2},j,k} = \frac{1}{2}\left[\frac{P^{n+1}_{lo\ i,j,k} + P^{n}_{lo\ i,j,k}}{2} + \frac{P^{n+1}_{lo\, i+1,j,k} + P^{n}_{lo\, i+1,j,k}}{2}\right]$$

$$k_{rlo} = k_{rlo}(S^{n+\frac{1}{2}}_{wl\ i,j,k}\ ,\ S^{n+\frac{1}{2}}_{gl\ i,j,k})$$

$$\text{if}\quad \Phi^{n+\frac{1}{2}}_{lo\ i,j,k} \geq \Phi^{n+\frac{1}{2}}_{lo\ i+1,j,k}$$

$$= k_{rlo}(S^{n+\frac{1}{2}}_{wl\ i+1,j,k}\ ,\ S^{n+\frac{1}{2}}_{gl\ i+1,j,k})$$

$$\text{if}\ \Phi^{n+\frac{1}{2}}_{lo\ i,j,k} < \Phi^{n+\frac{1}{2}}_{lo\ i,j,k}$$

Finally, in evaluating fluid density it will be assumed that density at the boundary of a grid block may be represented by density evaluated at the center of that grid block, i.e.,

$$\rho_{i+\frac{1}{2},j,k} = \rho_{i-\frac{1}{2},j,k} = \rho_{i,j+\frac{1}{2},k} = \rho_{i,j-\frac{1}{2},k} = \rho_{i,j,k+\frac{1}{2}}$$

$$= \rho_{i,j,k-\frac{1}{2}} = \rho_{i,j,k}$$

4.3 Boundary Conditions

In this study, a closed or no-flow boundary will be used. Hence, the Neumann conditions are specified on the reservoir boundaries.

$$\left.\begin{aligned} \frac{\partial P}{\partial x} &= 0 \\ \frac{\partial P}{\partial y} &= 0 \\ \frac{\partial P}{\partial z} &= 0 \end{aligned}\right\} \quad \text{on } \partial R \qquad (42)$$

where ∂R is the reservoir boundary.

The Neumann conditions can be incorporated into the simulation model in two different ways:[11,23] by means of reflection nodes or by setting permeability (or transmissibility) to zero on the boundary nodes. In reservoir simulation, the latter is used more frequently. For an expression such as

$\nabla \cdot (K \cdot \nabla \Phi)$, the requirement $\nabla \Phi = 0$ on ∂R can be as well accomplished by setting coefficient $K = 0$ on ∂R.

4.4 Three-Phase Relative Permeability

Numerical simulation of multiphase flow requires the use of three-phase relative permeability data. Effort involved in determining these data experimentally generally rules out such a direct approach. However, Stone[20,21] has developed a method for estimating three-phase relative permeability from two sets of more easily obtained two-phase data. The required data consists of a set of water-oil relative permeability data and gas-oil relative permeability data. To allow for hysteresis, the water and gas saturations should be changing in the same direction in the two sets of two-phase data as desired in three-phase system. For example, if both the water and gas saturations are expected to increase in the three-phase system, then imbibition water-oil data and drainage gas-oil data should be used. However, if oil is displacing gas, followed by water displacing oil, the imbibition data should be used for both the gas-oil and water-oil systems.

Stone's method is based on the channel flow theory combined with probability concepts. It states that water relative permeability is a function of water saturation alone regardless of whether the system is two-phase or three-phase. The same is true with gas relative permeability as a function of gas saturation. Thus, only oil relative permeability needs to be redetermined in the three-phase system.
Stone's equation for calculating oil relative permeability

is given as

$$k_{ro} = (k_{row} + k_{rw})(k_{rog} + k_{rg}) - (k_{rw} + k_{rg}) \quad (43)$$

Note that if the above equation yields a negative k_{ro}, it implies complete blockage of oil, or $k_{ro} = 0$. This equation has a desirable property in that it yields the correct two-phase data when only two phases are flowing, and yet provides interpolated data for three-phase flow that is a consistent and continuous function of the phase saturations.

4.5 Injection and Production Rates

Individual phase rates of injection are normally specified explicitly, for the usual practice is to inject one phase, being water or gas, into the reservoir. The rates at the producing wells, however, cannot be specified so explicitly. This is true because two or more phases may be produced simultaneously and the relative productions of those fluid phases are not subject to control. According to Peaceman,[15] they are functions of saturations in the vicinity of the well and should be computed in proportion to the local mobility of those phases. That is

$$q_o = q_t \frac{\lambda_o}{\lambda_t} \quad (44)$$

$$q_w = q_t \frac{\lambda_w}{\lambda_t} \quad (45)$$

$$q_g = q_t \frac{\lambda_g}{\lambda_t} \cdot 5.615 \quad (46)$$

where $\lambda_t = \lambda_o + \lambda_w + \lambda_g$ = total mobility

4.6 Hydraulic Radius of a Fracture Conduit

Evans extended the work of Duguid and Lee for a single phase fluid and derived the fluid interaction terms for multi-phase flow as shown in section 3.2.3. In the derivation, he introducted the parameter r_H to represent the hydraulic radius of the fracture conduit. Comparison between Evans' and Duguid and Lee's derivations shows that r_H can be related to the characteristic half width of the fracture by

$$r_H = \frac{\Pi d}{4} \tag{47}$$

where d = characteristic half width of the fracture.

With regard to the length of the fracture, the characteristic half length ℓ of the fracture is assumed to equal the half dimension of the primary grid block. Thus,

$$\ell = \frac{\Delta x}{2} \tag{48}$$

4.7 Porosity Calculation

In this simulation program, porosity will be evaluated from oil pressures of the previous time step. The assumption here is that porosity varies very slowly as a function of pressures, and thus may be considered constant during the time since the previous time step to the present. The oil pressure is assumed to be representative of the fluid pressure in pore spaces. The justification for this assumption is based upon a finding by Coats, et al[5] that evaluation of certain properties from a single phase pressure produced insignificant error.

Therefore, the finite difference forms of the porosity equations in section 3.2.4 are given as follows.

For the rock matrix:

$$\phi^{n+1}_{1\ i,j,k} = \phi^{n}_{1\ i,j,k}(1-\phi^{n}_{1\ i,j,k})c_1(P^{n+1}_{1o\ i,j,k}-P^{n}_{1o\ i,j,k})$$
$$-\phi^{n}_{1\ i,j,k}\ \phi^{n}_{f\ i,j,k}\ c_f\ (P^{n+1}_{fo\ i,j,k}-P^{n}_{fo\ i,j,k})$$
$$+\phi^{n}_{1\ i,j,k} \qquad (49)$$

For the fractures:

$$\phi^{n+1}_{f\ i,j,k} = \phi^{n}_{f\ i,j,k}(1-\phi^{n}_{f\ i,j,k})c_f(P^{n+1}_{fo\ i,j,k}-P^{n}_{fo\ i,j,k})$$
$$-\phi^{n}_{1\ i,j,k}\ \phi^{n}_{f\ i,j,k})c_1\ (P^{n+1}_{1o\ i,j,k}-P^{n}_{1o\ i,j,k})$$
$$+\phi^{n}_{f\ i,j,k} \qquad (50)$$

4.8 Velocity Calculation

The equation of motion in the fracture from section 3.2.2 for phase j (j = water, oil and gas) can be written in x, y and z coordinates as follows:

$$V_{fjx} = -\frac{k_{rjf}}{\mu_{jf}}\ [K_{xx}(\frac{\partial P_{fj}}{\partial x}+\frac{\rho_{jf}}{g_c}\frac{\partial V_{fjx}}{\partial t}+\rho_{jf}\frac{g}{g_c}\sin\alpha)+K_{xy}\ (\frac{\partial P_{fj}}{\partial y}$$
$$+\frac{\rho_{jf}}{g_c}\frac{\partial V_{fjy}}{\partial t}+\rho_{jf}\frac{g}{g_c}\sin\beta)+K_{xz}(\frac{\partial P_{fj}}{\partial z}+\frac{\rho_{jf}}{g_c}\frac{\partial V_{fjz}}{\partial t}$$
$$+\rho_{jf}\frac{g}{g_c}\cos\gamma)] \qquad (51)$$

$$V_{fjy} = -\frac{k_{rjf}}{\mu_{jf}}\ [K_{yx}(\frac{\partial P_{fj}}{\partial x}+\frac{\rho_{jf}}{g_c}\frac{\partial V_{fjx}}{\partial t}+\rho_{jf}\frac{g}{g_c}\sin\alpha)+K_{yy}(\frac{\partial P_{fj}}{\partial y}$$
$$+\frac{\rho_{jf}}{g_c}\frac{\partial V_{fjy}}{\partial t}+\rho_{jf}\frac{g}{g_c}\sin\beta)+K_{yz}(\frac{\partial P_{fj}}{\partial z}+\frac{\rho_{jf}}{g_c}\frac{\partial V_{fjz}}{\partial t}+\rho_{jf}\frac{g}{g_c}\cos\gamma)]$$
$$(52)$$

$$V_{fjz} = \frac{-k_{rjf}}{\mu_{jf}} [K_{zx}(\frac{\partial P_{fj}}{\partial x} + \frac{\rho_{jf}}{g_c} \frac{\partial V_{fjx}}{\partial t} + \rho_{jf} \frac{g}{g_c} \sin\alpha) + K_{zy}(\frac{\partial P_{fj}}{\partial y} + \frac{\rho_{jf}}{g_c} \frac{\partial V_{fjy}}{\partial t} + \rho_{jf} \frac{g}{g_c} \sin\beta) + K_{zz}(\frac{\partial P_{fj}}{\partial z} + \frac{\rho_{jf}}{g_c} \frac{\partial V_{fjz}}{\partial t} + \rho_{jf} \frac{g}{g_c} \cos\gamma)] \quad (53)$$

In the simulation program these velocities are calculated explicitly from the above equations after pressures and saturations have been determined. The assumption is that the velocity changes slowly from one time step to the next.

For example, the finite difference form of V_{fjx} may be written as:

$$\begin{aligned} V^{n+1}_{fjx\ i,j,k} = (\frac{-k_{rjf}}{\mu_{jf}})^{n+1}_{i,j,k}[K_{xx\ i,j,k}(&\frac{P^{n+1}_{fj\ i+1,j,k} - P^{n+1}_{fj\ i-1,j.k}}{2\Delta x} \\ &+ \frac{\rho^{n+1}_{jf\ i,j,k}}{g_c} \frac{V^{n+1}_{fjx\ i,j,k} - V^{n}_{fjx\ i,j,k}}{\Delta t} + \rho^{n+1}_{jf\ i,j,k} \frac{g}{g_c} \sin\alpha) \\ &+ K_{xy\ i,j,k}(\frac{P^{n+1}_{fj\ i,j+1,k} - P^{n+1}_{fj\ i,j-1,k}}{2\Delta y} \\ &+ \frac{\rho^{n+1}_{jf\ i,j,k}}{g_c} (\frac{\partial V_{fjy}}{\partial t})^{n}_{i,j,k} + \rho^{n+1}_{jf\ i,j,k} \frac{g}{g_c} \sin\beta) \\ &+ K_{xz\ i,j,k}(\frac{P^{n+1}_{fj\ i,j,k+1} - P^{n+1}_{fj\ i,j,k-1}}{2\Delta z} \\ &+ \frac{\rho^{n+1}_{jf\ i,j,k}}{g_c}(\frac{\partial V_{fjz}}{\partial t})^{n}_{i,j,k} + \rho^{n+1}_{jf\ i,j,k} \frac{g}{g_c} \cos\gamma)] \quad (53) \end{aligned}$$

Thus,

$$V^{n+1}_{fjx\ i,j,k} = \frac{1}{1+(\frac{k_{rjf}}{\mu_{jf}} \frac{\rho_{jf}}{g_c} \frac{K_{xx}}{\Delta t})^{n+1}_{i,j,k}} (- \frac{k_{rjf}}{\mu_{jf}})^{n+1}_{i,j,k}$$

$$[K_{xx\ i,j,k}(\frac{P^{n+1}_{fj\ i+1,j,k} - P^{n+1}_{fj\ i-1,j,k}}{2\Delta x} - \frac{\rho^{n+1}_{jf\ i,j,k}}{g_c \Delta t}$$

$$V^{n}_{fjx\ i,j,k} + \rho^{n+1}_{jf\ i,j,k} \frac{g}{g_c} \sin\alpha) + K_{xy\ i,j,k}$$

$$(\frac{P^{n+1}_{fj\ i,j+1,k} - P^{n+1}_{i,j-1,k}}{2\Delta y} + \frac{\rho^{n+1}_{jf\ i,j,k}}{g_c} (\frac{\partial V_{fjy}}{\partial t})^{n}_{i,j,k}$$

$$+ \rho^{n+1}_{jf\ i,j,k} \frac{g}{g_c} \sin\beta) + K_{xz\ i,j,k}(\frac{P^{n+1}_{fj\ i,j,k+1} - P^{n+1}_{fj\ i,j,k-1}}{2\Delta z}$$

$$+ \frac{\rho^{n+1}_{jf\ i,j,k}}{g_c} (\frac{\partial V_{fjz}}{\partial t})^{n}_{i,j,k} + \rho^{n+1}_{jf\ i,j,k} \frac{g}{g_c} \cos\gamma)] \qquad (54)$$

The finite difference forms of V_{fjy} and V_{fjz} are similar to that of V_{fjx} and, therefore, will not be shown here.

It should be pointed out that in its initial state the reservoir is static or undisturbed by outside forces. Consequently, there is no fluid movement within the reservoir. This implies that the initial fluid velocity and acceleration in the fractures are zero.

4.9 Point Successive Over-Relaxation Method (PSOR)

PSOR is one of the various methods available for solving a system of simultaneous linear equations. The discussion of this method has been well documented in many textbooks and the literature.[1,7,12,15,19] The PSOR method is based on solving the equations by successive approximations (or guesses) until the convergence of results to a preselected tolerance limit is achieved or an action due to failure of convergence is taken.

Several reasons were taken into consideration in choosing this method over other ones for the simulation program developed in this dissertation.

1. The PSOR is an iterative method which is more suitable than a direct method for solving a large set of equations that has a sparse coefficient matrix because it takes advantage of this sparseness by requiring computing storage only for the nonzero elements.[12]
2. The roundoff characteristics of an iterative method such as the PSOR are better.[12] With a direct method, roundoff error can be incurred with each mathematical operation and simply accumulates until the final answers are obtained. With an iterative method, however, the presence of roundoff error in the unknowns at the end of any iteration simply results in those unknowns being somewhat poorer estimates for the next iteration. Thus, the roundoff error in the final converged values is only that accumulated in the final iteration.
3. The system of equations in this study has the form of a 19-band diagonal coefficient matrix which is much larger and more complicated than the conventional penta-diagonal or hepta-diagonal matrices. The PSOR is preferred to other iterative methods because its formula is straightforward and can be incorporated into the simulation program without

a great deal of difficulty.

The PSOR method expresses the next approximations of the solution at one grid point explicitly in terms of known estimates of other variables in an equation. Thus, in this study equations (33), (34), (35), (36), (37) and (38) are manipulated in such a way that the 6 unknowns at each grid point ($P^{n+1}_{lw\ i,j,k}$, $P^{n+1}_{lo\ i,j,k}$, $P^{n+1}_{lg\ i,j,k}$, $P^{n+1}_{fw\ i,j,k}$, $P^{n+1}_{fo\ i,j,k}$ and $P^{n+1}_{fg\ i,j,k}$) are expressed in terms of the same phase pressures at other grid points and/or different phase pressures at the same grid point. For example, the water flow equation in rock matrix can be written as:

$$\begin{aligned}\overset{k+1}{\tilde{P}}{}^{n+1}_{lw\ i,j,k} = \frac{1}{(BW)_{i,j,k}} [&(DW)_{i,j,k} - (GW)_{i,j,k} \overset{k+1}{P}{}^{n+1}_{lw\ i,j,k-1} \\ &- (EW)_{i,j,k} \overset{k+1}{P}{}^{n+1}_{lw\ i,j-1,k} - (AW)_{i,j,k} \overset{k+1}{P}{}^{n+1}_{lw\ i-1,j,k} \\ &- (CW)_{i,j,k} \overset{k}{P}{}^{n+1}_{lw\ i+1,j,k} - (FW)_{i,j,k} \overset{k}{P}{}^{n+1}_{lw\ i,j+1,k} \\ &- (HW)_{i,j,k} \overset{k}{P}{}^{n+1}_{lw\ i,j,k+1} - (RW)_{i,j,k} \overset{k}{P}{}^{n+1}_{fw\ i,j,k} \\ &- (UW)_{i,j,k} \overset{k}{P}{}^{n+1}_{lo\ i,j,k}]\end{aligned} \tag{55}$$

where superscript k indicates level of iteration in time step (n+1).

After computation at each grid point, the value $\overset{k+1}{\tilde{P}}{}^{n+1}_{lw\ i,j,k}$ is relaxed by the formula:

$$P_{1w\ i,j,k}^{\overset{k+1}{n+1}} = P_{1w\ i,j,k}^{\overset{k}{n+1}} + \omega(\tilde{P}_{1w\ i,j,k}^{\overset{k+1}{n+1}} - P_{1w\ i,j,k}^{\overset{k}{n+1}}) \quad (56)$$

where ω is a relaxation parameter.

The iterative process continues until the differences between $P_{1w\ i,j,k}^{n+1}$'s of two successive iterations for all grid points are less than a predefined tolerance limit ε.

$$\left| P_{1w\ i,j,k}^{\overset{k+1}{n+1}} - P_{1w\ i,j,k}^{\overset{k}{n+1}} \right| \leq \varepsilon \quad (57)$$

The same procedure discussed above applies to P_{1o}, P_{1g}, P_{fw}, P_{fo} and P_{fg} as well. Equations for these unknowns are similar in form to that of P_{1w}, and for brevity will not be shown here.

With regard to the relaxation parameter ω, its function is to speed up the convergence rate. The selection of the optimum value of ω usually requires some trial-and-error simulation runs with varying ω. The optimum ω is the one that produces the minimum number of iteration per time step. Generally, the more homogeneous the system, the closer the value of ω is to 1.0, and as the degree of anisotropy increases, the more ω approaches 2. And in practice, an overestimation of ω is always better than an underestimation.[7] In this study a value of w = 1.2 was used and gave a reasonable rate of convergence.

CHAPTER V

ALGORITHM

In this chapter, a brief description of the major components of the simulation program is presented. Input data for a case example is also given. The flow diagram of the computational procedure is illustrated in Figure 7.

5.1 Major Program Components

5.1.1 Main Program

The main program starts with defining and dimensioning variables. Parameters such as flow coefficients, fracture velocity and acceleration are initialized. Then, basic data is read via subroutines RESDIM, RESDAT, INCON and CODE. Constant terms in the transmissibilities of the pressure equations are evaluated by subroutine TRAN. Next, the program proceeds to calculate initial fluids in place and reservoir pore volume. The simulation process starts with the reading/establishing of time step size. Saturation changes during the previous time step are checked and a warning printed when they become so excessive that time step size may have to be reduced to smooth the changes. The injection/production rates are determined. The updating of pressures and saturations is done in subroutine EXTRAP which also projects these variables to

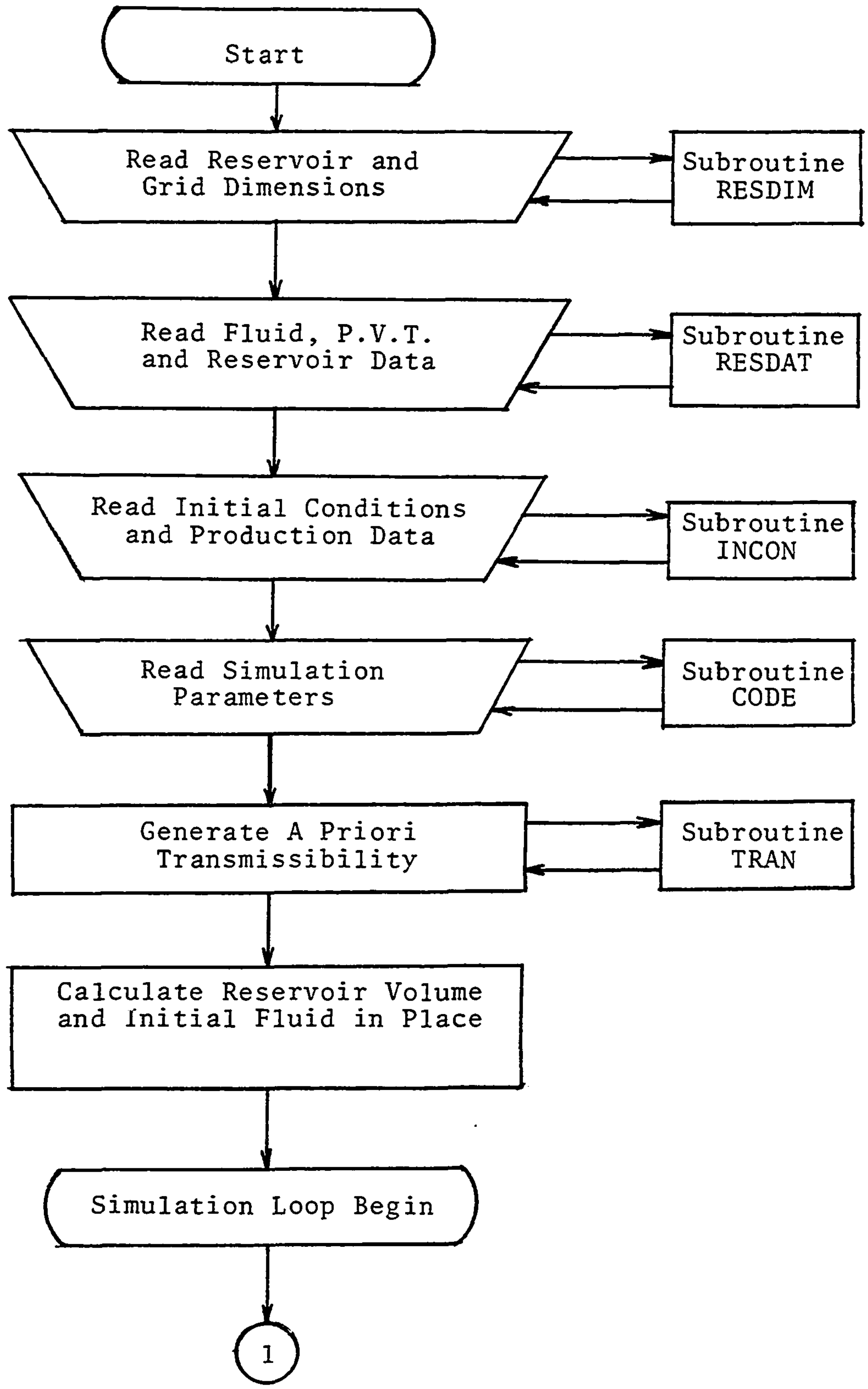


Figure 7. Flow chart of the simulation program.

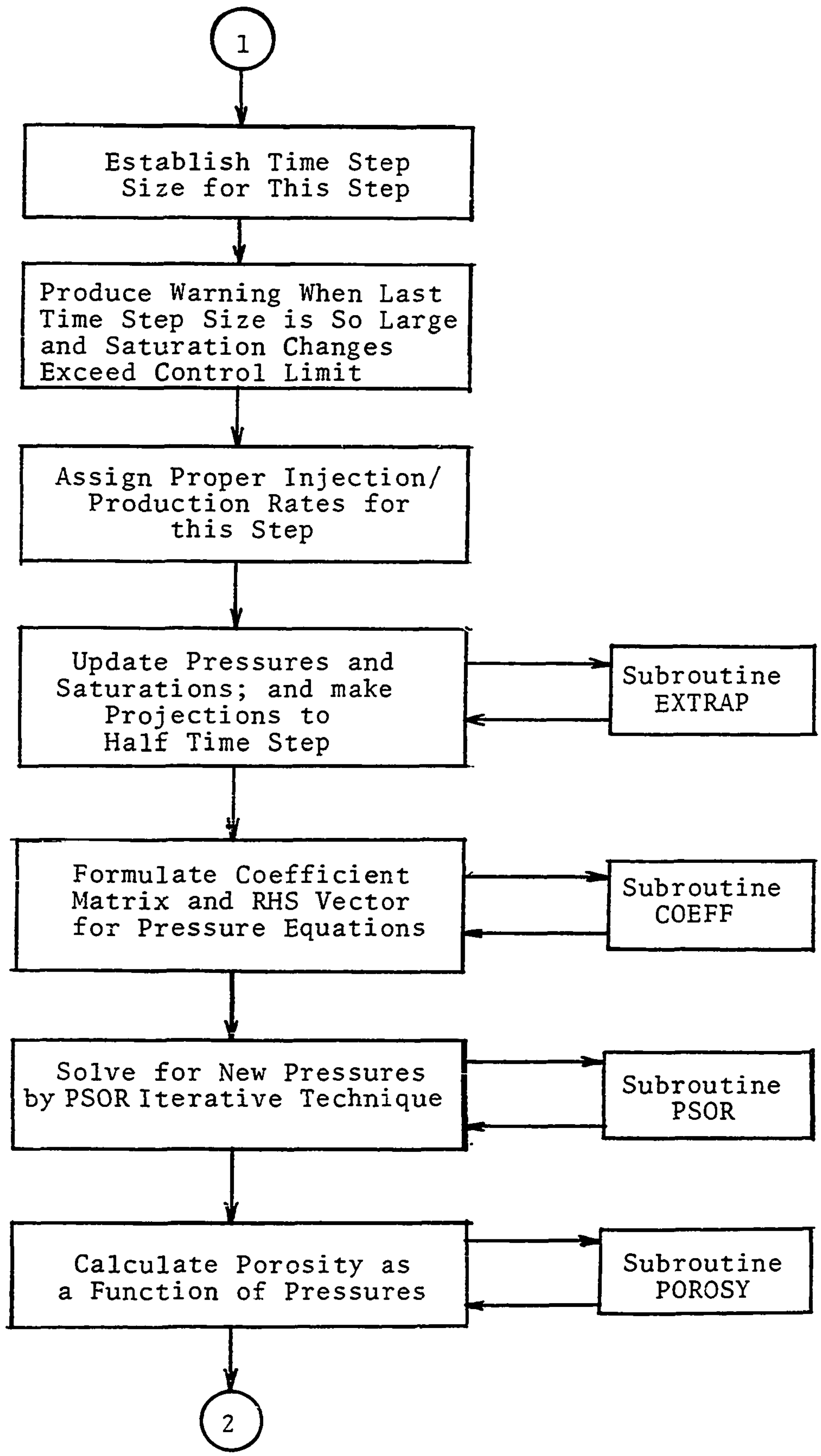

1
Establish Time Step Size for This Step
Produce Warning When Last Time Step Size is So Large and Saturation Changes Exceed Control Limit
Assign Proper Injection/ Production Rates for this Step
Update Pressures and Saturations; and make Projections to Half Time Step
Subroutine EXTRAP
Formulate Coefficient Matrix and RHS Vector for Pressure Equations
Subroutine COEFF
Solve for New Pressures by PSOR Iterative Technique
Subroutine PSOR
Calculate Porosity as a Function of Pressures
Subroutine POROSY
2

Fig. 7 (cont'd)

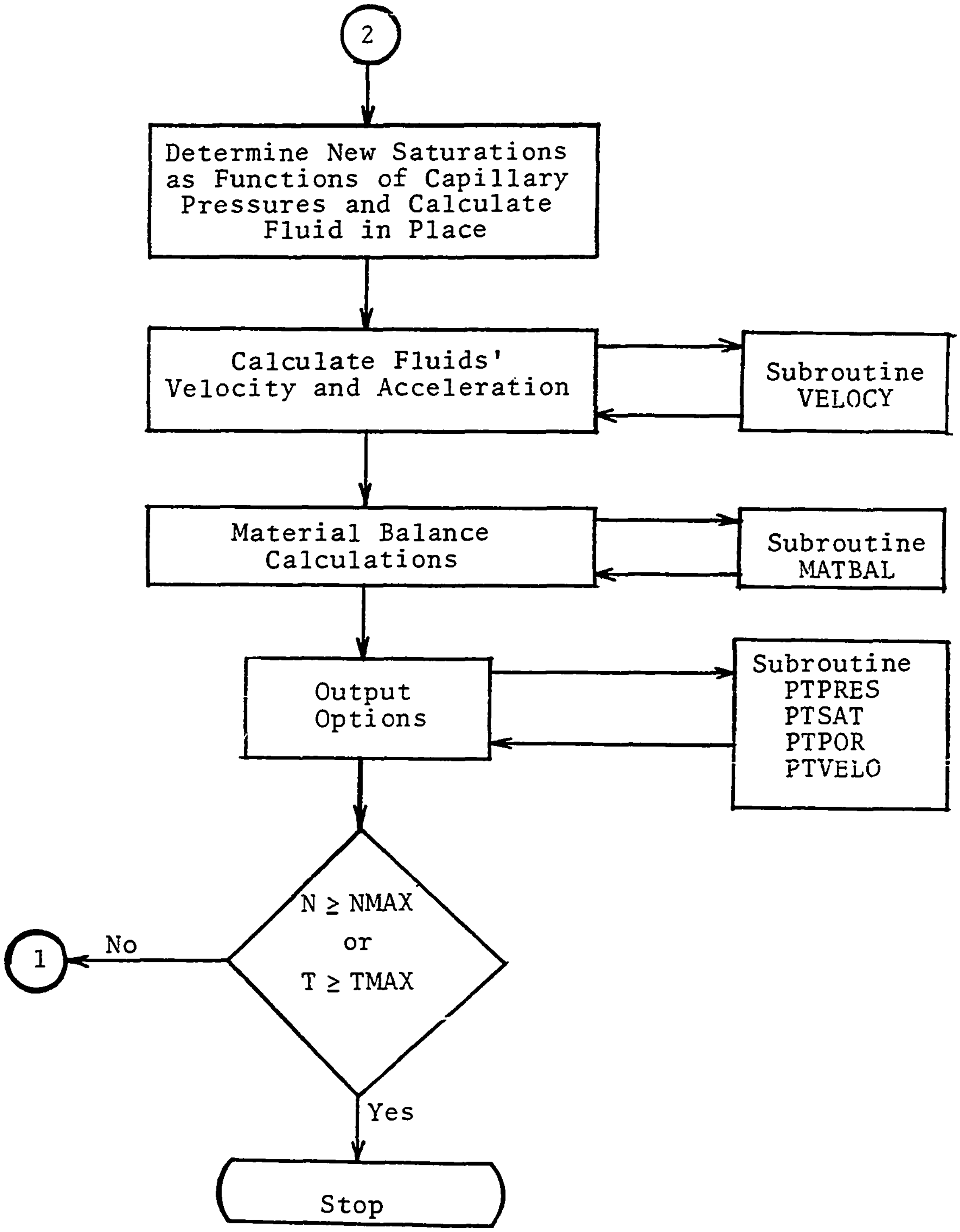

2
Determine New Saturations as Functions of Capillary Pressures and Calculate Fluid in Place
Calculate Fluids' Velocity and Acceleration
Subroutine VELOCY
Material Balance Calculations
Subroutine MATBAL
Output Options
Subroutine PTPRES PTSAT PTPOR PTVELO
N ≥ NMAX or T ≥ TMAX
No
1
Yes
Stop

Fig. 7 (cont'd)

$(n + \frac{1}{2})$ time step to provide a basis from which to evaluate transmissibilities, and to give an initial estimate for the pressure solution.

Transmissibility coefficients and the right-hand-side vector are now calculated in subroutine COEFF. The pressure equations are solved simultaneously in subroutine PSOR. After pressures of this time step are determined, subroutine POROSY evaluates porosity as a function of pressures. Then, new saturations are determined from new capillary pressures using linear interpolation from tables of look-up data. Subroutine VELOCY calculates fracture velocity based on new pressures and saturations.

Toward the end of the time step, material balance calculations are carried out in subroutine MATBAL. Finally, results of this time step are printed out via subroutines PTPRES, PTSAT, PTPOR and PTVELO. Before repeating the same process at a new time step, elapsed time and number of time steps are checked for termination of the simulation.

5.1.2 Subroutine Code

Simulation parameters are read in this subroutine. These parameters include maximum number of time steps, maximum simulation time, tolerance limit for PSOR, maximum number of iterations for PSOR, relaxation parameter, bubble point pressure, abandonment pressure, maximum water-oil ratio, maximum gas-oil ratio, and print codes.

5.1.3 Subroutine COEFF

This subroutine formulates the transmissibility coefficient matrix and the right-hand-side vector for the pressure equations. The subroutine is quite complicated and cumbersome because there are 126 coefficients and 6 governing equations to be evaluated at each grid point. The fact that every coefficient is pressure- and saturation-dependent necessitates the extensive uses of a linear interpolation subroutine (LINTP) to obtain data from tables of look-up. Relative permeabilities are evaluated upstream and therefore flow potentials and directions of flow have to be determined for every fluid phase at every grid point.

5.1.4 Subroutine EXTRAP

This subroutine updates pressures and saturations from the previous time step. It also extrapolates these two variables to time step $(n + \frac{1}{2})$ to provide a basis from which to evaluate the transmissibility coefficients in subroutine COEFF. The extrapolated pressures also serve as an initial approximation of the solution in subroutine PSOR.

5.1.5 Function FAVG

This function simply computes the average value of two numbers.

5.1.6 Subroutine INCON

Initial phase pressures and saturations are read in this subroutine along with grid locations, rates, time-on and time-off of the injectors and producers.

5.1.7 Subroutine LINTP

This subroutine performs linear interpolation from tabulated data.

5.1.8 Subroutine MATBAL

Material balance errors of oil, water and gas during a time step are calculated in this subroutine. Fluid injections/ productions as well as their cumulatives are computed. Water-oil ratio, gas-oil ratio and average reservoir pressures are also computed.

5.1.9 Subroutine POROSY

This subroutine calculates rock matrix porosity and fracture porosity as functions of pressures. (See section 4.7.)

5.1.10 Subroutine PSOR

This subroutine solves the system of pressure equations by the Point-Successive-Over-Relaxation method. (See section 4.9.) A flow chart of this subroutine is shown in Figure 8.

5.1.11 Subroutine PTPRES

This subroutine prints pressure distributions in the rock matrix and fractures. It also prints results from subroutine MATBAL.

5.1.12 Subroutine PTSAT

Saturation distributions in the rock matrix and the

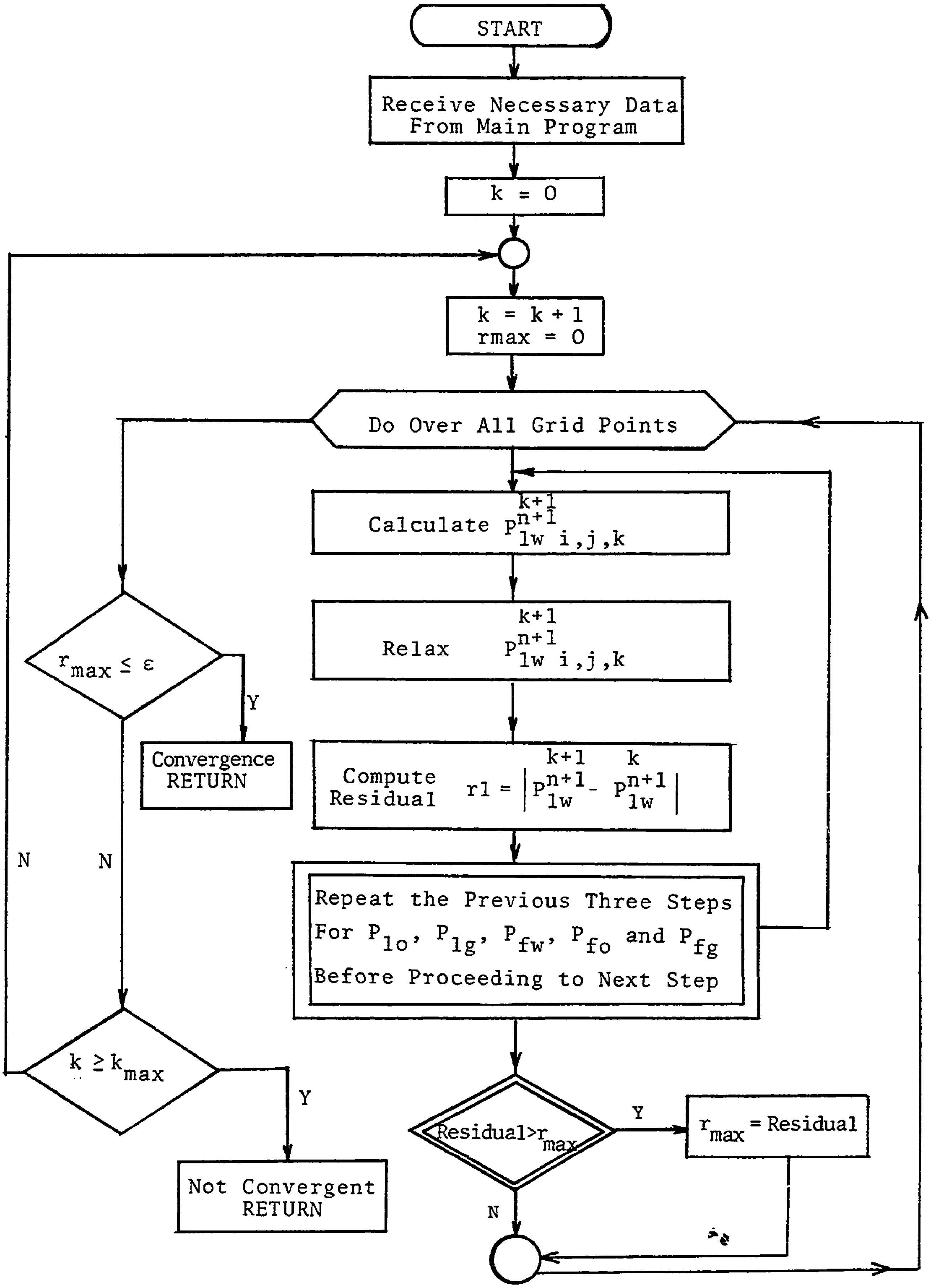


Figure 8. Flow Chart of PSOR subroutine.

fractures are printed in this subroutine.

5.1.13 Subroutine PTPOR

Porosity distributions in the rock matrix and the fracture are printed in this subroutine.

5.1.14 Subroutine PTVELO

Fluid velocity distributions in the fractures are printed in this subroutine.

5.1.15 Subroutine RESDAT

This subroutine reads porosity and permeability data for the rock matrix and the fractures. It should be pointed out that because of its tensor form, there are 9 tensor elements associated with the fracture permeability. The subroutine also reads fluid P.V.T. data for oil, water and gas. These include formation volume factors, viscosities, solution gas-oil ratio, derivatives of the inverses of formation volume factors with respect to pressures, and derivative of solution gas-oil ratio with respect to pressure. Other data read are oil, water and gas densities at standard conditions, fracture and rock matrix compressibilities, and tilt angles of the formation. Gas-oil relative permeability and capillary pressure data and derivatives of gas saturation with respect to gas-oil capillary pressure are read for the rock matrix and the fracture. Similarly, water-oil relative permeability and capillary pressure data and derivatives of water saturation with respect to water-oil capillary pressure are read for the rock matrix and the fractures. For linear interpolation purposes, the water-oil capillary pressure versus water saturation data are to be rearranged such that the water-oil capillary pressures are tabulated in increasing order.

5.1.16 Subroutine RESDIM

This subroutine reads numbers of grid points in x-, y- and z-directions along with length, width, and thickness of the reservoir. This data is used to calculate uniform grid dimensions. In addition, half width of the fracture is read and hydraulic radius calculated.

5.1.17 Subroutine TRAN

This subroutine computes those parts of the transmissibility coefficients that are constant and thus do not need to be reevaluated every time step.

5.1.18 Subroutine VELOCY

This subroutine calculates velocity and acceleration of the fluids in the fracture (see section 4.8).

5.2 Field Example

Data from one of Thomas et al[22] three-dimensional examples was used to demonstrate the utility of the simulation program developed. In the example, a reservoir section between an injection and production well is modeled using a 10 x 2 x 5 grid system.

The rock matrix permeability and porosity are set equal to 1 md and 0.29. The fracture permeability and porosity are 10 md and 0.01. Both the rock matrix and fracture are homogeneous and isotropic. Hence, the following values were used,

$$K_1 = 1.0 \text{ md}$$

$$\phi_1 = 0.29$$

$$\bar{\bar{K}}_f = \begin{bmatrix} 10.0 & 0.0 & 0.0 \\ 0.0 & 10.0 & 0.0 \\ 0.0 & 0.0 & 10.0 \end{bmatrix} \text{ md}$$

$$\phi_f = 0.01$$

In the rock matrix as well as the fracture, the initial reservoir pressure is set at 6214.7 psia for the oil phase, 6164.7 psia for the water phase, and 6214.775 psia for the gas phase. Initial saturations are 0.80 for oil, 0.20 for water and 0.0 for gas.

Both the injection and production wells are perforated in all five layers. The productivity indices of the five layers are all equal. Thus, it is assumed that injection/production rates are divided equally among these five layers. The formation is horizontal, i.e., $\alpha = 0$, $\beta = 0$ and $\gamma = 0$.

In this example, water is injected into the reservoir at an initial rate of 7000 STB/day. Total fluid production rate is set at 4000 STB/day.

In Thomas et al paper, the size/geometry of fracture is implicitly given in terms of the matrix shape factor (σ) which is 0.25 for the example. But in this model, the fracture half width is required data. Since it was not given, the fracture half width (d) of 0.0005 ft was assumed. This rough estimate is obtained from comparison of Thomas et al matrix-fracture flow equation to Evans' fluid interaction term. The comparison is explained and illustrated in Appendix H.

Information on reservoir dimensions and rock/fracture properties is given in Table 2. PVT data for oil, water and gas are shown in Tables 3, 4 and 5, respectively. Table 6 gives fluid densities at standard conditions.

Gas-oil relative permeability and capillary pressure data is given in Table 7. Water-oil relative permeability and capillary pressure data is diven in Table 8. In deviating from Thomas et al approach which assumes straight-line relative permeabilities and zero capillary pressure in the fracture, data in Tables 7 and 8 were applied in both the rock matrix and fractures. This is because the fully implicit approach used in this simulation program requires nonzero capillary pressure data, especially the nonzero slopes of P_c versus saturation.

The bubble point pressure is 5559.7 psia. The abandonment pressure of 1500 psia was used. Abandonment water-oil ratio and gas-oil ratio are 100 STB/STB and 100,000 SFC/STB, respectively. A pressure tolerance limit of 0.2 psi is used in the PSOR subroutine.

An example of input data arrangement is given in Appendix E.

Table 2

RESERVOIR & GRID DIMENSIONS AND ROCK PROPERTIES
****

LENGTH = 2000.0 FEET

WIDTH = 400.0 FEET

THICKNESS = 250.0 FEET

NUMBER OF GRID POINTS IN X-DIRECTION = 10

NUMBER OF GRID POINTS IN Y-DIRECTION = 2

NUMBER OF GRID POINTS IN Z-DIRECTION = 5

DELTA-X (FT) = 200.00

DELTA-Y (FT) = 200.00

DELTA-Z (FT) = 50.00

NATURAL FRACTURE HALF-WIDTH = 0.000500 FEET

HYDRAULIC RADIUS = 0.000393 FEET

FRACTURE COMPRESSIBILITY = 0.3500D-05 PSI-1

MATRIX ROCK COMPRESSIBILITY = 0.3500D-05 PSI-1

TILT ANGLES OF RESERVOIR FORMATION:

ALPHA = 0.0 DEG.

BETA = 0.0 DEG.

GAMMA = 0.0 DEG.

Table 3

OIL PVT DATA
****

PO (PSI)	BO (BBL/STB)	D(1/BO)/DP (STB/BBL/PSI)	RSO (SCF/STB)	DRSO/DP (SCF/STB/PSI)	UO (CP)
14.7	1.0000	-0.13790D-03	0.0	0.2192	0.7200
1714.7	1.3026	-0.57600D-04	372.6	0.2241	0.5260
2114.7	1.3429	-0.57500D-04	463.2	0.2345	0.4800
2614.7	1.3969	-0.57900D-04	581.5	0.2495	0.4300
3014.7	1.4437	-0.58200D-04	681.5	0.2802	0.3960
3614.7	1.5204	-0.59400D-04	846.2	0.3016	0.3480
4214.7	1.6077	-0.60100D-04	1029.7	0.3295	0.3030
4614.7	1.6725	-0.60800D-04	1163.3	0.3632	0.2740
5014.7	1.7442	-0.64000D-04	1311.0	0.4001	0.2440
5314.7	1.8042	-0.60700D-04	1431.2	0.4035	0.2260
5614.7	1.8649	-0.58000D-04	1557.6	0.5012	0.2060
7014.7	2.1978	-0.57900D-04	2259.0	0.5011	0.1090

Table 4

WATER PVT DATA
****

PW (PSI)	UW (CP)
14.7	0.3500
7014.7	0.3500

Table 5

GAS PVT DATA
****

PG (PSI)	BG (BBL/SCF)	D(1/BG)/DP (SCF/BBL/PSI)	UG (CP)
14.7	0.17809D+00	0.29335	0.0120
1714.7	0.19485D-02	0.31438	0.0163
2114.7	0.15667D-02	0.30453	0.0173
2614.7	0.12671D-02	0.28563	0.0186
3014.7	0.11072D-02	0.24074	0.0197
3614.7	0.94930D-03	0.22771	0.0214
4214.7	0.84180D-03	0.20337	0.0233
4614.7	0.78840D-03	0.18849	0.0246
5014.7	0.74450D-03	0.17931	0.0257
5314.7	0.71620D-03	0.16519	0.0266
5614.7	0.69180D-03	0.15808	0.0276
7014.7	0.60000D-03	0.15814	0.0330

Table 6

FLUID DENSITIES AT STANDARD CONDITIONS
****

STANDARD PRESSURE = 14.7000 PSIA

STANDARD TEMPERATURE = 60.0 DEG. F

OIL DENSITY = 51.1400 LBM/CU FT

WATER DENSITY = 65.0000 LBM/CU FT

GAS DENSITY = 0.0580 LBM/CU FT

Table 7

GAS-OIL RELATIVE PERMEABILITY & CAPILLARY PRESSURE DATA

SG	KRG	KROG	PCGO (PSI)	DSG/DPC (PSI-1)
0.0	0.0	1.000	0.075	10.00000
0.10	0.015	0.700	0.085	10.00000
0.20	0.050	0.450	0.095	10.00000
0.30	0.103	0.250	0.115	5.00000
0.40	0.190	0.110	0.145	3.33000
0.50	0.310	0.028	0.255	0.91000
0.55	0.420	0.0	0.386	0.38000
1.00	1.000	0.0	1.565	0.38000

Table 8

WATER-OIL RELATIVE PERMEABILITY & CAPILLARY PRESSURE DATA
****

SW	KRW	KROW	PCOW (PSI)	DSW/DPC (PSI-1)
0.0	0.0	1.000	214.000	-0.00122
0.20	0.0	1.000	50.000	-0.00122
0.25	0.005	0.860	9.000	-0.00122
0.30	0.010	0.723	2.000	-0.00714
0.35	0.020	0.600	0.500	-0.03333
0.40	0.030	0.492	0.0	-0.10000
0.45	0.045	0.392	-0.400	-0.12500
0.50	0.060	0.304	-1.200	-0.06250
0.55	0.082	0.225	-2.600	-0.03570
0.60	0.110	0.154	-4.000	-0.03570
0.65	0.143	0.093	-7.000	-0.01670
0.70	0.180	0.042	-10.000	-0.01670
0.75	0.230	0.0	-40.000	-0.00167
1.00	1.000	0.0	-190.000	-0.00167

CHAPTER VI

DISCUSSION OF RESULTS

In this chapter the results of an example case study are discussed along with recommendations for further improvement of this simulation program.

So far, the development of the fractured reservoir simulator may be summarized by the following steps.

1. The reservoir is discretized three-dimensionally into a series of grid points, each of which consists of two physical domains: the rock matrix and the fractures.
2. Six governing partial differential equations (referred to interchangeably as flow equations, pressure equations or diffusivity equations) are formulated to describe the fluid movement at each gridpoint. The black oil model is assumed to characterize the compositional behavior of oil, water and gas. Physical properties such as gravity effects and capillary forces are taken into consideration.
3. The finite difference scheme and fully implicit approach are used to transform the six governing pressure equations into a system of analogous

difference equations. Thus, for a total of N grid points, there are 6N equations in 6N unknowns. Fluid and rock properties at each grid point are evaluated individually and then used in computing transmissibility coefficients. Relative permeabilities must be evaluated upstream. A computer code is written in accordance with this scheme.

4. The PSOR numerical method is used to solve the resulting system of simultaneous linear equations for the pressures at a new time step.
5. Capillary pressures are computed, and saturations are determined by interpolation from the tables of saturations versus capillary pressures. The pressures are also used in calculating porosity and fluid velocity.

6.1 Simulator Capability

Although the rock matrix and fractures are isotropic as well as homogeneous in the field example, the simulation program developed is capable of handling the isotropic heterogeneous rock matrix and the anisotropic heterogeneous fracture. Hence, a study of anisotropy in fracture can be considered.

In addition, the presence and/or absence of fracture at any grid point can be accounted for by manipulating elements of the permeability tensor. For example, all nine elements of the permeability tensor could have been zero if it had been determined that the fractures at a particular grid point either did not exist or was not interconnected.

The fracture orientation can also be handled in a similar way. For instance, if the preferential direction of the flow deviates from the principal axes, the off-diagonal elements of the permeability tensors may be assigned some real numbers instead of zero.

The above capabilities lend themselves readily to the inclusion of a probabilistic approach such as the Monte Carlo method for generating the statistical distribution of fracture in the reservoir. This application is particularly useful for a naturally fractured reservoir which has been determined (via well testing data, for example) to have networks of fractures, or sand lenses, or shale barriers covering certain percentages of the reservoir area. The Monte Carlo method can then be used to generate randomly the distribution of fractured grid points according to those percentages. For example, Figure 9 illustrates a reservoir area that has been discretized into a 10 x 7 grid system. A 35 percent concentration of fracture is arbitrarily given for this area. This translates to 25 out of 70 grid points containing fractures. And consequently, the remaining 45 grid points will have the permeability tensors of zero. In Figure 9, the fractured grid points are denoted by "1" and the nonfractured by "0." The implication from this is that the Monte Carlo method may be used to generate a priori the locations of grid points containing fractures. This information is used as input data

1	0	1	0	0	0	0	0	1	0
0	1	0	1	1	0	0	0	0	0
0	1	1	0	1	0	1	0	0	0
1	1	0	0	1	0	1	0	0	0
0	0	0	1	0	1	1	0	0	0
1	0	0	1	0	0	1	1	0	0
0	1	0	0	1	1	0	0	1	0

FRACTURED NODES = 1
NON-FRACTURED NODES = 0

Figure 9. Random Generation of Fractured Nodes by Monte Carlo Method.

to the simulation program. An example of the Monte Carlo program is given in Appendix G.

The simulator is also capable of neglecting the calculation of fracture velocity by simply not calling the VELOCY subroutine at the end of each time step. In such a case, the equations of motion in the fractures would be identical to the equations of motion in the rock matrix (i.e., Darcy's law). This allows the study of velocity effects on the fluid movement through the naturally fractured reservoir.

The present simulation program is designed for the 10 x 2 x 5 grid system (100 grid points). However, the COMMON/ DIMENSION statements at the beginning of each program or subroutine can easily be modified to fit any other grid systems.

6.2 Results of the Field Example

The data given in section 5.2 is fed into the simulation program. For comparative study, injection and production rates are delegated to the flow equations for the fractures because Thomas et al[22] assumed that flow through the reservoir occurred primarily through the fracture. However, it should be noted that the simulator is capable of distributing any flow rates to both the rock matrix equations and the fracture equations. An output sample is given in Table 9. The saturation distribution output over extended periods of time are used in plotting the fracture- and the matrix-50-percent water saturation profiles as shown in Figures 10 and 11. Note the gradual gravity effect shown by water

Table 9

Output Sample

```
SIMULATION RESULTS AFTER TIME STEP    40

ELAPSED TIME  =      14.82 DAYS

TIME STEP SIZE (DAY)   =       1.00


AVERAGE RESERVOIR (MATRIX) PRESSURE (PSIA)  =      6214.68

OIL MATERIAL BALANCE THIS STEP (PERCENT)    =      -0.4688
WATER MATERIAL BALANCE THIS STEP (PERCENT)  =       1.0805
GAS MATERIAL BALANCE THIS STEP (PERCENT)    =      -0.4672

CUMULATIVE OIL PRODUCED (STB)               =       59299.
CUMULATIVE WATER PRODUCED (STB)             =           1.
CUMULATIVE WATER INJECTED (STB)             =      103775.
CUMULATIVE GAS PRODUCED (SCF)               =   110132395.
CUMULATIVE GAS INJECTED (SCF)               =           0.

WATER-OIL RATIO                             =          0.0
GAS-OIL RATIO                               =       3714.6

OIL PRODUCTION THIS STEP (STB)              =     -3999.92
WATER PRODUCTION THIS STEP (STB)            =        -0.08
WATER INJECTION THIS STEP (STB)             =      7000.00
GAS PRODUCTION THIS STEP (SCF)              = -7425490.35
GAS INJECTION THIS STEP (SCF)               =         0.0
```

Table 9 (cont'd)

PRESSURE DISTRIBUTIONS IN MATRIX ROCK

****

LAYER NUMBER 5

****

ROW NUMBER 2

PO	6213.5	6213.6	6213.6	6213.6	6213.6	6213.6	6213.6	6213.7	6214.3	6215.1
PW	6163.6	6163.6	6163.6	6163.6	6163.6	6163.6	6163.6	6163.7	6164.4	6165.1
PG	6213.6	6213.6	6213.6	6213.6	6213.6	6213.6	6213.6	6213.7	6214.3	6215.2

ROW NUMBER 1

PO	6210.8	6213.5	6213.6	6213.6	6213.6	6213.6	6213.6	6214.0	6215.0	6215.2
PW	6161.0	6163.6	6163.6	6163.6	6163.6	6163.6	6163.7	6164.1	6165.0	6165.2
PG	6210.7	6213.6	6213.6	6213.6	6213.6	6213.6	6213.6	6214.1	6215.1	6215.3

LAYER NUMBER 4

****

ROW NUMBER 2

PO	6214.6	6214.6	6214.6	6214.6	6214.6	6214.6	6214.6	6214.7	6215.3	6215.3
PW	6164.6	6164.6	6164.6	6164.6	6164.6	6164.6	6164.6	6164.7	6165.3	6165.2
PG	6214.7	6214.7	6214.7	6214.7	6214.7	6214.7	6214.7	6214.8	6215.4	6215.4

ROW NUMBER 1

PO	6211.8	6214.6	6214.6	6214.6	6214.6	6214.6	6214.6	6215.0	6215.2	6215.3
PW	6162.0	6164.6	6164.6	6164.6	6164.6	6164.6	6164.6	6165.0	6165.1	6165.3
PG	6211.8	6214.7	6214.7	6214.7	6214.7	6214.7	6214.7	6215.1	6215.3	6215.4

LAYER NUMBER 3

****

ROW NUMBER 2

PO	6214.7	6214.7	6214.7	6214.7	6214.7	6214.7	6214.7	6214.8	6215.3	6215.2
PW	6164.7	6164.7	6164.7	6164.7	6164.7	6164.7	6164.7	6164.8	6165.3	6165.1
PG	6214.8	6214.8	6214.8	6214.8	6214.8	6214.8	6214.8	6214.9	6215.4	6215.3

ROW NUMBER 1

PO	6211.9	6214.7	6214.7	6214.7	6214.7	6214.7	6214.7	6215.2	6215.1	6215.3
PW	6162.1	6164.7	6164.7	6164.7	6164.7	6164.7	6164.7	6165.2	6165.1	6165.3
PG	6211.9	6214.8	6214.8	6214.8	6214.8	6214.8	6214.8	6215.3	6215.2	6215.4

Table 9 (cont'd)

LAYER NUMBER 2
****

ROW NUMBER 2

PO	6214.8	6214.8	6214.8	6214.8	6214.8	6214.8	6214.8	6214.9	6215.4	6215.1
PW	6164.8	6164.8	6164.8	6164.8	6164.8	6164.6	6164.8	6164.9	6165.3	6165.1
PG	6214.8	6214.9	6214.9	6214.9	6214.9	6214.9	6214.9	6215.0	6215.5	6215.2

ROW NUMBER 1

PO	6212.0	6214.8	6214.8	6214.8	6214.8	6214.6	6214.8	6215.1	6215.1	6215.3
PW	6162.1	6164.8	6164.8	6164.8	6164.8	6164.8	6164.8	6165.1	6165.0	6165.3
PG	6212.0	6214.8	6214.9	6214.9	6214.9	6214.9	6214.9	6215.2	6215.2	6215.4

LAYER NUMBER 1
****

ROW NUMBER 2

PO	6215.8	6215.8	6215.8	6215.8	6215.8	6215.8	6215.8	6215.9	6215.6	6215.3
PW	6165.8	6165.8	6165.8	6165.8	6165.8	6165.8	6165.8	6165.8	6165.5	6165.3
PG	6215.9	6216.0	6216.0	6216.0	6216.0	6216.0	6216.0	6216.0	6215.7	6215.4

ROW NUMBER 1

PO	6213.0	6215.8	6215.8	6215.8	6215.8	6215.8	6215.9	6215.5	6215.2	6215.4
PW	6163.2	6165.8	6165.8	6165.8	6165.8	6165.8	6165.8	6165.4	6165.2	6165.3
PG	6213.1	6215.9	6216.0	6216.0	6216.0	6216.0	6216.0	6215.6	6215.3	6215.5

Table 9 (cont'd)

PRESSURE DISTRIBUTIONS IN FRACTURE
****

LAYER NUMBER 5
****

ROW NUMBER 2

PFO	6213.2	6213.2	6213.2	6213.2	6213.2	6213.2	6213.2	6213.5	6214.4	6215.3
PFW	6163.3	6163.3	6163.3	6163.3	6163.3	6163.3	6174.2	6220.0	6381.4	6574.6
PFG	6212.8	6212.8	6212.8	6212.8	6212.8	6212.8	6212.9	6213.2	6214.3	6215.4

ROW NUMBER 1

PFO	6209.3	6213.2	6213.2	6213.2	6213.2	6213.2	6213.2	6214.2	6215.1	6215.4
PFW	6159.8	6163.3	6163.3	6163.3	6163.3	6163.4	6190.8	6246.3	6474.7	6900.2
PFG	6207.9	6212.8	6212.8	6212.8	6212.8	6212.8	6212.9	6214.0	6215.3	6215.7

LAYER NUMBER 4
****

ROW NUMBER 2

PFO	6214.6	6214.6	6214.6	6214.6	6214.6	6214.6	6214.6	6214.9	6215.4	6215.4
PFW	6164.6	6164.6	6164.6	6164.6	6164.6	6164.6	6172.3	6224.6	6401.5	6596.9
PFG	6214.6	6214.6	6214.6	6214.6	6214.6	6214.6	6214.6	6215.0	6215.6	6215.7

ROW NUMBER 1

PFO	6210.7	6214.6	6214.6	6214.6	6214.6	6214.6	6214.6	6215.2	6215.3	6215.4
PFW	6161.1	6164.6	6164.6	6164.6	6164.6	6164.7	6192.2	6264.9	6496.9	6922.6
PFG	6209.7	6214.6	6214.6	6214.6	6214.6	6214.6	6214.7	6215.4	6215.5	6215.8

Table 9 (cont'd)

LAYER NUMBER 3
****

ROW NUMBER 2

PFO	6214.7	6214.7	6214.7	6214.7	6214.7	6214.7	6214.7	6215.1	6215.4	6215.3
PFW	6164.7	6164.7	6164.7	6164.7	6164.7	6164.7	6176.3	6227.5	6420.7	6619.0
PFG	6214.7	6214.8	6214.8	6214.8	6214.8	6214.8	6214.8	6215.2	6215.7	6215.5

ROW NUMBER 1

PFO	6210.9	6214.7	6214.7	6214.7	6214.7	6214.7	6214.7	6215.4	6215.2	6215.4
PFW	6161.2	6164.7	6164.7	6164.7	6164.7	6164.8	6198.2	6297.8	6519.3	6945.0
PFG	6209.9	6214.7	6214.8	6214.8	6214.8	6214.8	6214.8	6215.6	6215.4	6215.8

LAYER NUMBER 2
****

ROW NUMBER 2

PFO	6214.8	6214.8	6214.8	6214.8	6214.8	6214.8	6214.8	6215.1	6215.5	6215.3
PFW	6164.8	6164.8	6164.9	6164.8	6164.8	6164.8	6178.9	6232.2	6440.5	6641.2
PFG	6214.9	6214.9	6214.9	6214.9	6214.9	6214.9	6214.9	6215.3	6215.8	6215.5

ROW NUMBER 1

PFO	6211.0	6214.8	6214.8	6214.8	6214.8	6214.8	6214.9	6215.2	6215.2	6215.4
PFW	6161.3	6164.8	6164.8	6164.8	6164.8	6165.0	6218.0	6321.9	6541.7	6967.4
PFG	6210.0	6214.9	6214.9	6214.9	6214.9	6214.9	6215.0	6215.4	6215.4	6215.8

LAYER NUMBER 1
****

ROW NUMBER 2

PFO	6216.2	6216.2	6216.2	6216.2	6216.2	6216.2	6216.2	6216.3	6215.7	6215.4
PFW	6166.1	6166.1	6166.1	6166.1	6166.1	6166.1	6179.8	6235.6	6461.3	6663.6
PFG	6216.7	6216.7	6216.7	6216.7	6216.7	6216.7	6216.7	6216.8	6216.1	6215.7

ROW NUMBER 1

PFO	6212.4	6216.2	6216.2	6216.2	6216.2	6216.2	6216.3	6215.6	6215.3	6215.5
PFW	6162.6	6166.1	6166.1	6166.1	6166.1	6168.4	6216.9	6343.5	6564.0	6989.9
PFG	6211.8	6216.7	6216.7	6216.7	6216.7	6216.7	6216.8	6215.9	6215.6	6215.9

Table 9 (cont'd)

SATURATION DISTRIBUTIONS IN MATRIX ROCK
****

LAYER NUMBER 5
****

ROW NUMBER 2

SO	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
SW	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
SG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ROW NUMBER 1

SO	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
SW	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
SG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

LAYER NUMBER 4
****

ROW NUMBER 2

SO	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
SW	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
SG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ROW NUMBER 1

SO	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
SW	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
SG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

LAYER NUMBER 3
****

ROW NUMBER 2

SO	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
SW	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
SG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ROW NUMBER 1

SO	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
SW	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
SG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 9 (cont'd)

LAYER NUMBER 2
****

ROW NUMBER 2

SO	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
SW	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
SG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ROW NUMBER 1

SO	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
SW	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
SG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

LAYER NUMBER 1
****

ROW NUMBER 2

SO	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
SW	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
SG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ROW NUMBER 1

SO	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
SW	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
SG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 9 (cont'd)

SATURATION DISTRIBUTIONS IN FRACTURE
****

LAYER NUMBER 5
****

ROW NUMBER 2

SOF	0.80	0.80	0.80	0.80	0.80	0.80	0.79	0.36	0.04	0.0
SWF	0.20	0.20	0.20	0.20	0.20	0.20	0.21	0.64	0.96	1.00
SGF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ROW NUMBER 1

SOF	0.80	0.80	0.80	0.80	0.80	0.80	0.77	0.26	0.0	0.0
SWF	0.20	0.20	0.20	0.20	0.20	0.20	0.23	0.74	1.00	1.00
SGF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

LAYER NUMBER 4
****

ROW NUMBER 2

SOF	0.80	0.80	0.80	0.80	0.80	0.80	0.79	0.31	0.01	0.0
SWF	0.20	0.20	0.20	0.20	0.20	0.20	0.21	0.69	0.99	1.00
SGF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ROW NUMBER 1

SOF	0.80	0.80	0.80	0.80	0.80	0.80	0.77	0.23	0.0	0.0
SWF	0.20	0.20	0.20	0.20	0.20	0.20	0.23	0.77	1.00	1.00
SGF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

LAYER NUMBER 3
****

ROW NUMBER 2

SOF	0.80	0.80	0.80	0.80	0.80	0.80	0.79	0.30	0.0	0.0
SWF	0.20	0.20	0.20	0.20	0.20	0.20	0.21	0.70	1.00	1.00
SGF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 9 (cont'd)

ROW NUMBER 1

SOF	0.80	0.80	0.80	0.80	0.80	0.80	0.76	0.18	0.0	0.0
SWF	0.20	0.20	0.20	0.20	0.20	0.20	0.24	0.82	1.00	1.00
SGF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

LAYER NUMBER 2
****

ROW NUMBER 2

SOF	0.80	0.80	0.80	0.80	0.80	0.80	0.78	0.29	0.0	0.0
SWF	0.20	0.20	0.20	0.20	0.20	0.20	0.22	0.71	1.00	1.00
SGF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ROW NUMBER 1

SOF	0.80	0.80	0.80	0.80	0.80	0.80	0.43	0.14	0.0	0.0
SWF	0.20	0.20	0.20	0.20	0.20	0.20	0.57	0.86	1.00	1.00
SGF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

LAYER NUMBER 1
****

ROW NUMBER 2

SOF	0.80	0.80	0.80	0.80	0.80	0.80	0.78	0.28	0.0	0.0
SWF	0.20	0.20	0.20	0.20	0.20	0.20	0.22	0.72	1.00	1.00
SGF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ROW NUMBER 1

SOF	0.80	0.80	0.80	0.80	0.80	0.80	0.53	0.10	0.0	0.0
SWF	0.20	0.20	0.20	0.20	0.20	0.20	0.47	0.90	1.00	1.00
SGF	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 9 (cont'd)

FLUID VELOCITY DISTRIBUTIONS IN FRACTURES
****

LAYER NUMBER 5
****

ROW NUMBER 2

VOX	0.0	-0.2076D-04	-0.1894D-06	-0.1169D-08	-0.3290D-07	-0.2551D-04	-0.3481D-03	-0.1210D-03	0.0	0.0
VOY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VOZ	-0.9354D-01	-0.9354D-01	-0.9354D-01	-0.9354D-01	-0.9354D-01	-0.9354D-01	-0.9007D-01	-0.9697D-02	0.0	0.0
VWX	0.0	-0.1388D-09	-0.1272D-11	-0.7836D-14	-0.2025D-11	-0.7479D-07	-0.3442D-04	-0.1286D-01	-0.1413D+00	0.0
VWY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VWZ	-0.1248D-05	-0.1235D-05	-0.1235D-05	-0.1235D-05	-0.1235D-05	-0.1238D-05	-0.1095D-03	-0.1120D-01	-0.7197D-01	-0.8161D-01
VGX	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VGY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VGZ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ROW NUMBER 1

VOX	0.0	-0.3684D-02	-0.2067D-04	-0.9566D-07	-0.4298D-06	-0.7342D-04	-0.9114D-03	-0.2002D-04	0.0	0.0
VOY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VOZ	-0.9331D-01	-0.9354D-01	-0.9354D-01	-0.9354D-01	-0.9354D-01	-0.9351D-01	-0.8479D-01	-0.1044D-02	0.0	0.0
VWX	0.0	-0.2429D-07	-0.1382D-09	-0.6525D-12	-0.6070D-09	-0.3218D-06	-0.1258D-03	-0.2781D-01	-0.2956D+00	0.0
VWY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VWZ	-0.4418D-05	-0.1248D-05	-0.1235D-05	-0.1235D-05	-0.1235D-05	-0.2114D-05	-0.2740D-03	-0.1769D-01	-0.8161D-01	-0.8161D-01
VGX	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VGY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VGZ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

LAYER NUMBER 4
****

ROW NUMBER 2

VOX	0.0	-0.2079D-04	-0.1897D-06	-0.1167D-06	-0.2629D-07	-0.1849D-04	-0.3286D-03	-0.3663D-04	0.0	0.0
VOY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VOZ	-0.8775D-01	-0.8775D-01	-0.8775D-01	-0.8775D-01	-0.8775D-01	-0.8775D-01	-0.8542D-01	-0.4239D-02	0.0	0.0
VWX	0.0	-0.2950D-10	-0.2706D-12	-0.1662D-14	-0.3592D-12	-0.1138D-07	-0.2557D-04	-0.1817D-01	-0.1649D+00	0.0
VWY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VWZ	-0.2689D-06	-0.2555D-06	-0.2554D-06	-0.2554D-06	-0.2554D-06	-0.2574D-06	-0.7349D-04	-0.1194D-01	-0.1028D-01	-0.1202D-02
VGX	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VGY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VGZ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ROW NUMBER 1

Table 9 (cont'd)

VOX	0.0	-0.3688D-02	-0.2069D-04	-0.9513D-07	-0.1716D-06	-0.3062D-04	-0.5718D-03	0.0	0.0	0.0
VOY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VOZ	-0.8752D-01	-0.8775D-01	-0.8775D-01	-0.8775D-01	-0.8775D-01	-0.8773D-01	-0.7958D-01	0.0	0.0	0.0
VWX	0.0	-0.5356D-08	-0.2936D-10	-0.1362D-12	-0.9944D-10	-0.1436D-06	-0.1524D-03	-0.3852D-01	-0.2973D+00	0.0
VWY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VWZ	-0.3613D-05	-0.2689D-06	-0.2554D-06	-0.2554D-06	-0.2554D-06	-0.9107D-06	-0.2293D-03	0.3251D-02	-0.9016D-03	-0.5161D-03
VGX	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VGY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VGZ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

LAYER NUMBER 3
****

ROW NUMBER 2

VOX	0.0	-0.2079D-04	-0.1898D-06	-0.1274D-08	-0.8420D-07	-0.3122D-04	-0.3461D-03	-0.2454D-04	0.0	0.0
VOY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VOZ	-0.9270D-01	-0.9270D-01	-0.9270D-01	-0.9270D-01	-0.9270D-01	-0.9269D-01	-0.8904D-01	-0.3585D-02	0.0	0.0
VWX	0.0	-0.3041D-11	-0.2780D-13	-0.1861D-15	-0.1094D-11	-0.6328D-08	-0.3994D-04	-0.2034D-01	-0.1770D+00	0.0
VWY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VWZ	-0.4107D-07	-0.2707D-07	-0.2696D-07	-0.2695D-07	-0.2695D-07	-0.9830D-07	-0.9803D-04	-0.1247D-01	-0.1101D-01	-0.1395D-02
VGX	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VGY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VGZ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ROW NUMUER 1

VOX	0.0	-0.3688D-02	-0.2070D-04	-0.9543D-07	-0.2746D-06	-0.4750D-04	-0.5882D-03	0.0	0.0	0.0
VOY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VOZ	-0.9246D-01	-0.9270D-01	-0.9270D-01	-0.9270D-01	-0.9270D-01	-0.9267D-01	-0.8191D-01	0.0	0.0	0.0
VWX	0.0	-0.7944D-09	-0.3020D-11	-0.1402D-13	-0.1206D-10	-0.1531D-06	-0.2455D-03	-0.6499D-01	-0.2925D+00	0.0
VWY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VWZ	-0.3516D-05	-0.4101D-07	-0.2701D-07	-0.2695D-07	-0.2696D-07	-0.8188D-06	-0.1430D-03	0.9591D-02	-0.6489D-03	-0.5750D-03
VGX	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VGY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VGZ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

LAYER NUMBER 2
****

ROW NUMBER 2

VOX	0.0	-0.2080D-04	-0.1899D-06	-0.1296D-08	-0.8444D-07	-0.2089D-04	-0.2795D-03	-0.1985D-04	0.0	0.0
VOY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VOZ	-0.8776D-01	-0.8776D-01	-0.8776D-01	-0.8776D-01	-0.8776D-01	-0.8776D-01	-0.8364D-01	-0.2850D-02	0.0	0.0
VWX	0.0	0.0	0.0	0.0	0.0	-0.1360D-08	-0.5237D-04	-0.2268D-01	-0.1849D+00	0.0
VWY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VWZ	0.0	0.0	0.0	0.0	0.0	-0.1685D-07	-0.1293D-03	-0.1285D-01	-0.8340D-02	-0.1122D-02
VGX	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VGY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VGZ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 9 (cont'd)

ROW NUMBER 1

VOX	0.0	-0.3689D-02	-0.2071D-04	-0.9651D-07	-0.6618D-06	-0.8477D-04	-0.7983D-04	0.0	0.0	0.0
VOY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VOZ	-0.8754D-01	-0.8776D-01	-0.8776D-01	-0.8776D-01	-0.8776D-01	-0.8770D-01	-0.1776D-01	0.0	0.0	0.0
VWX	0.0	0.0	0.0	0.0	0.0	-0.5009D-06	-0.6452D-02	-0.8373D-01	-0.2918D+00	0.0
VWY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VWZ	-0.3332D-05	0.0	0.0	0.0	0.0	-0.1565D-05	-0.4347D-02	0.5370D-03	-0.7068D-03	-0.4850D-03
VGX	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VGY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VGZ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

LAYER NUMBER 1
****

ROW NUMBER 2

VOX	0.0	-0.2083D-04	-0.1901D-06	-0.1301D-08	-0.5727D-07	-0.4517D-05	-0.6700D-04	0.1478D-04	0.0	0.0
VOY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VOZ	-0.9369D-01	-0.9369D-01	-0.9369D-01	-0.9369D-01	-0.9369D-01	-0.9369D-01	-0.8935D-01	-0.2714D-02	0.0	0.0
VWX	0.0	0.0	0.0	0.0	0.0	0.0	-0.5204D-04	-0.2487D-01	-0.1934D+00	0.0
VWY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VWZ	0.0	0.0	0.0	0.0	0.0	0.0	-0.1352D-03	-0.1596D-01	-0.8161D-01	-0.8161D-01
VGX	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VGY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VGZ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

ROW NUMBER 1

VOX	0.0	-0.3693D-02	-0.2073D-04	-0.1045D-06	-0.3423D-05	-0.3596D-04	0.2356D-03	0.0	0.0	0.0
VOY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VOZ	-0.9347D-01	-0.9369D-01	-0.9369D-01	-0.9369D-01	-0.9369D-01	-0.9299D-01	-0.3394D-01	0.0	0.0	0.0
VWX	0.0	0.0	0.0	0.0	0.0	-0.6093D-05	-0.3963D-02	-0.1069D+00	-0.2922D+00	0.0
VWY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VWZ	-0.2524D-05	0.0	0.0	0.0	0.0	-0.2164D-04	-0.4087D-02	-0.5561D-01	-0.8161D-01	-0.8161D-01
VGX	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VGY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VGZ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

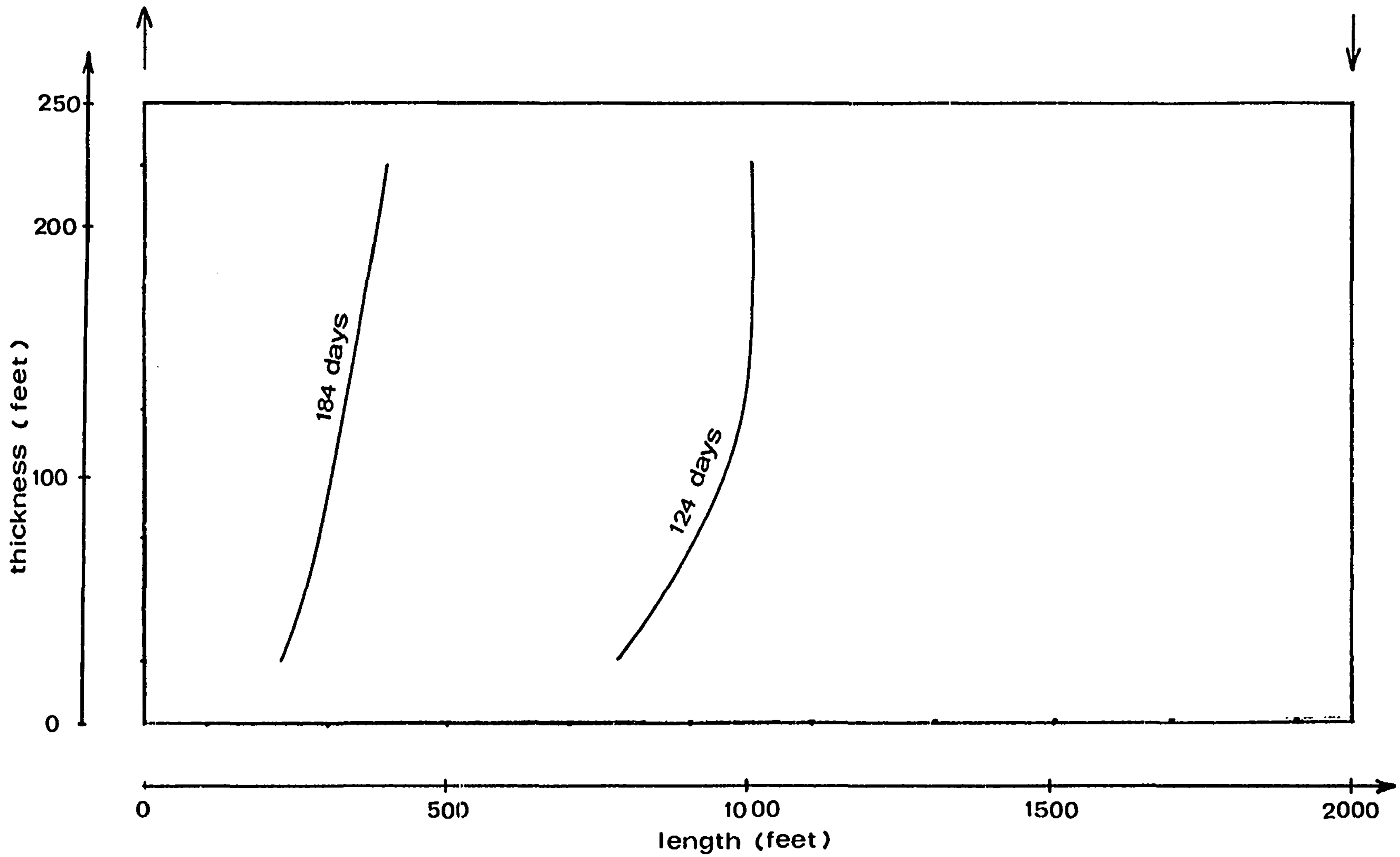


Figure 10. Fracture 50% Water Saturation Profile (center cross-section).

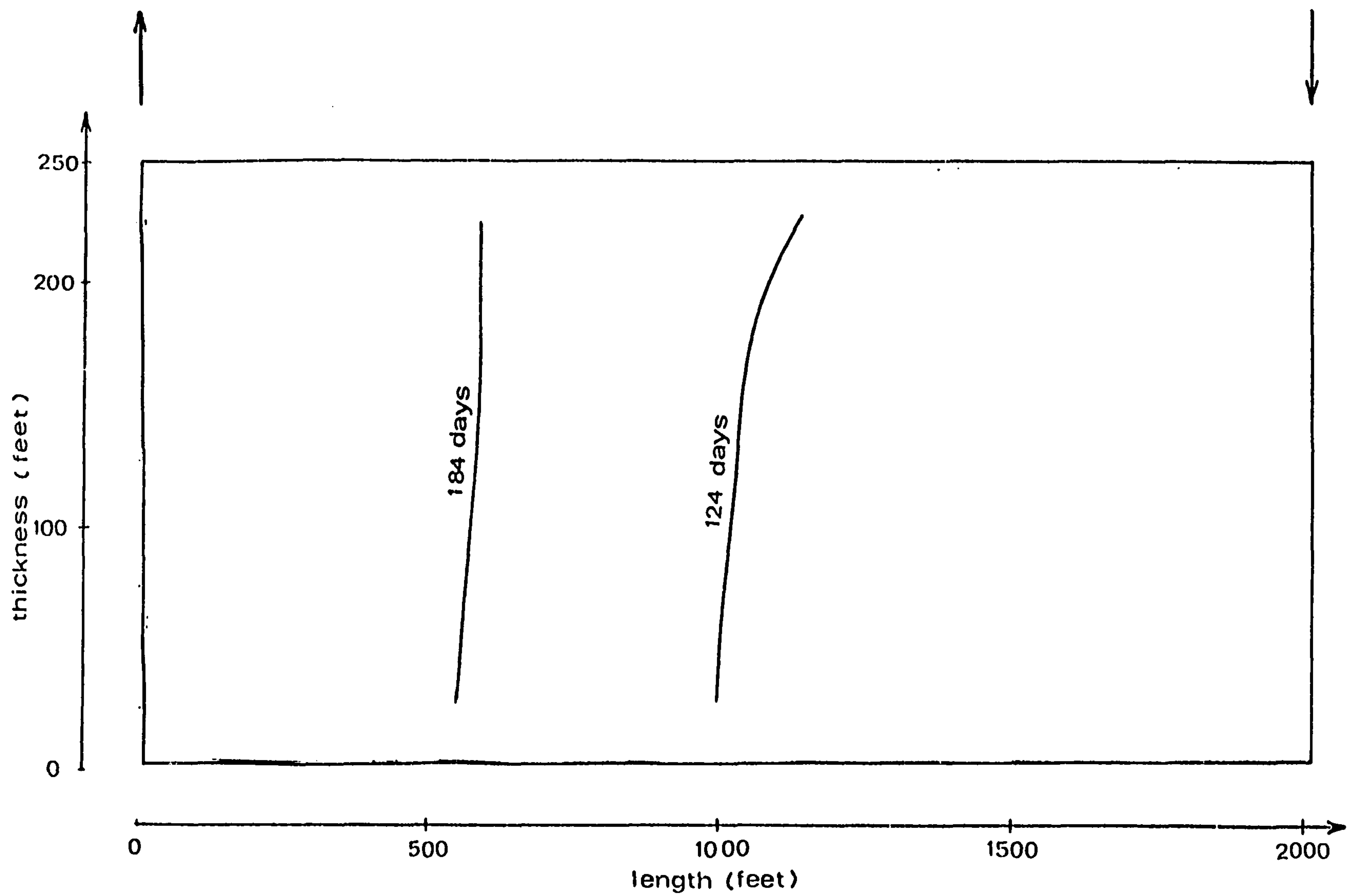


Figure 11. Matrix 50% Water Saturation Profile (Center cross-section)

underrunning oil. The water fronts in the rock matrix move slower than the ones in the fractures. Water-oil ratio reaches 100 (condition for water breakthrough) in approximately 257 days as shown in Figure 12.

Thomas et al original results are illustrated in Figure 13. Comparisons between the two results indicate that water moves much faster and thus breaks through earlier in this study than what had been reported by Thomas et al.

The reason for these discrepancies may be explained as follows.

6.2.1 Difference in the Injection Rates

Thomas et al set initial water injection rate at 7000 STB/day with a constraint that the rate would be adjusted and reduced as time progressed so that the flowing bottomhole pressure would not exceed 7400 psig. In this study, however, the constant water injection rate of 7000 STB/day and production rate of 4000 STB/day are used due to the incomplete data given on productivity indices and rate schedules. This produces a net effect of adding 3000 STB/day which inevitably leads to a build-up of the reservoir pressure. In reality, the reservoir as well as the wellbore equipment cannot accommodate such a build-up for a long period of time without adjustment of the rates.

This difference in injection rate schedule, therefore, contributes to the earlier water breakthrough reported in this study.

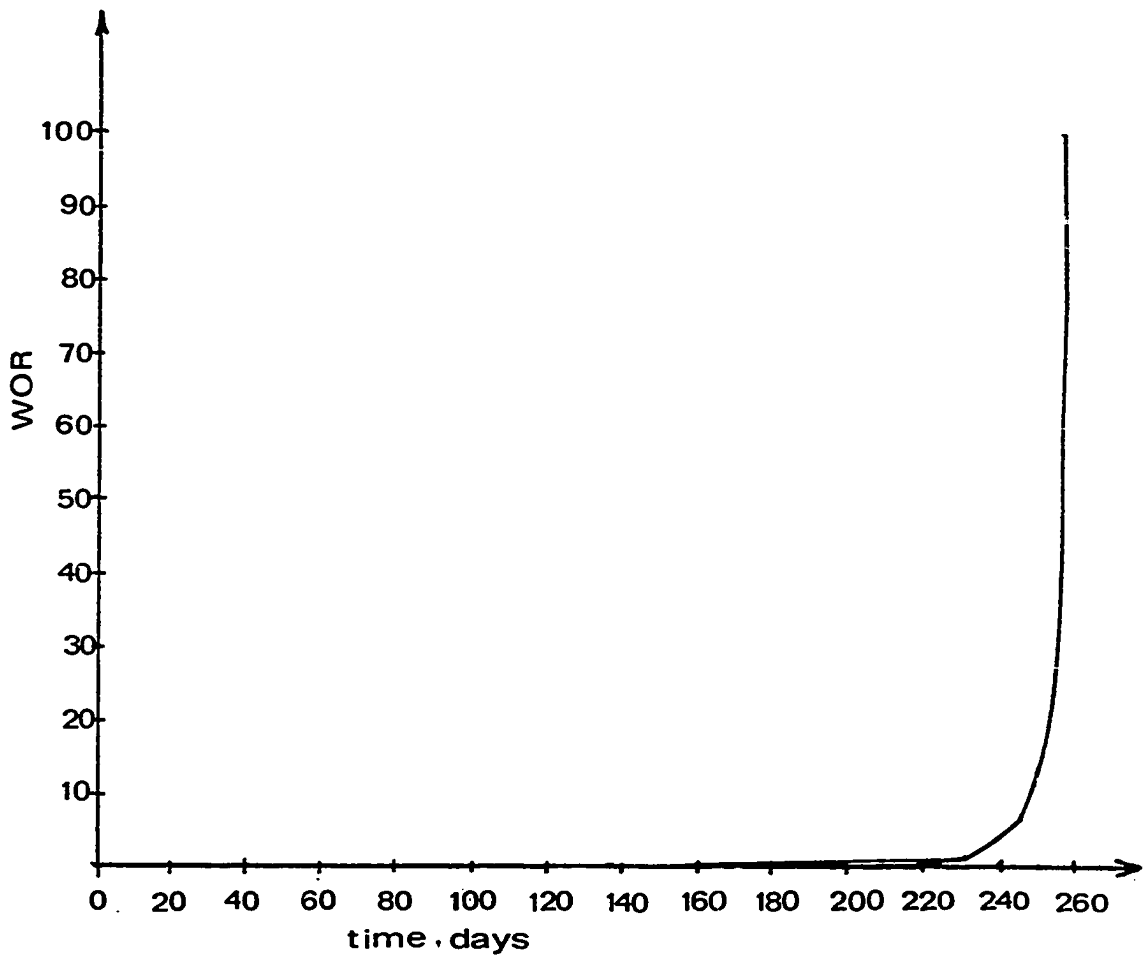


Figure 12   Water-Oil Ratio versus time.

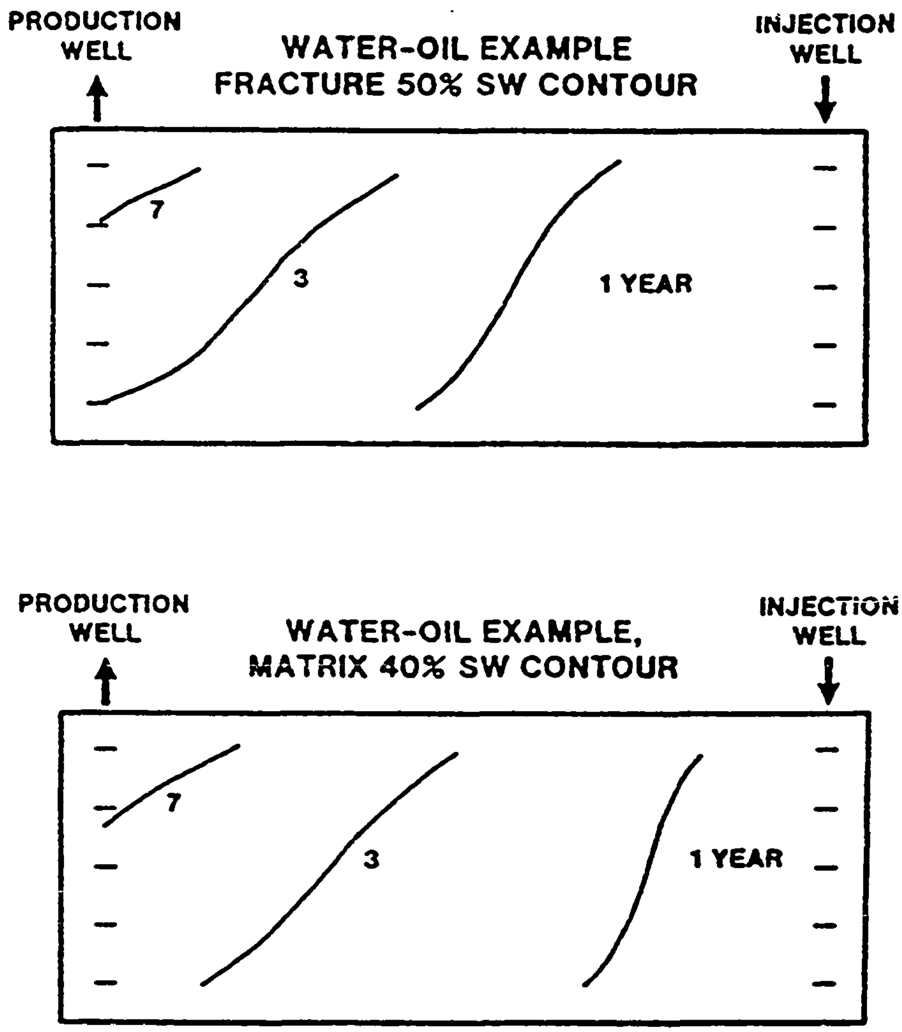


Figure 13. Fracture 50% Water Saturation Profile and Matrix 40% Water Saturation Profile (after Thomas et al. example).

6.2.2 Difference in the Capillary Pressure Data

Thomas et al set the fracture capillary pressure to zero and used straight-line fracture relative permeabilities in their study. They were able to neglect capillary pressures in the fracture by virtue of their solution technique. Their scheme reduced the flow equations into three equations in three fractured unknowns: pressure, water saturation and gas saturation. In this study, the formulation scheme produces six equations in six unknowns. The six unknowns are oil-, water-, and gas-pressures in the rock matrix and the fractures. This type of formulation requires nonzero capillary pressure data, particularly the nonzero slopes of P_c versus saturation.

This basic difference in problem formulation together with Thomas et al assumptions of zero fracture capillary pressures are believed to be partially responsible for the differences between the two results. In the following section it will be shown that the solution to the pressure equations is, in fact, influenced largely by the capillary-pressure-related terms.

6.2.3 Dominance of the Capillary-pressure-related Coefficients

One advantage of using the PSOR method to solve the pressure equations is the fact that the method expresses an unknown explicitly in terms of known estimates of other variables. Therefore, it is easy to observe the relationships among variables and how much impact a certain variable has on the final solution.

To illustrate this point, a portion of the coefficient matrix of one grid point at a certain time step (grid 5,1,1 at time step 20) is listed and shown in Figures 14, 15, 16 and 17 for the water and oil equations in the rock matrix, and the water and oil equations in the fractures, respectively.

In Figure 14, besides coefficients (BW) and (DW), the coefficient (UW) has the largest magnitude among all other coefficients. Since the coefficient (UW) belongs to the variable P_{1o}, the solution for P_{1w} will be solely dominated by the value of P_{1o}. As shown in Appendix C, this (UW) is basically a function of (dS_{w1}/dP_{cow1}). Thus, it is apparent that the value of this capillary-pressure-related term plays a major role in influencing the answer.

Similarly, in Figure 15, aside from (BO) and (DO), the coefficient (UO) has the largest magnitude. (RO), which is the next largest coefficient, is several orders of magnitude less than (UO). Hence, the solution for P_{1o} will be dominated mostly by the values of P_{1g} which has the coefficient (UO). In other words, the oil pressure in the rock matrix is related more closely to the other phase pressures in the rock matrix than to the oil pressure in the fractures. This is why fluids in the rock matrix move at a slower pace than they do in the fractures.

After inspecting Figures 16 and 17, similar findings

```
BW    ****************************** | -0.5601d3 |
DW    ****************************************  0.2801d5
GW    **  0.0
EW    **  0.0
AW    **  0.0
CW    **  0.0
FW    **  0.0
HW    **  0.0
RW    **  0.0
UW    ******************************    0.5601d3
```

$$
\begin{aligned}
P^{n+1}_{lw\ i,j,k} = \frac{1}{BW_{i,j,k}} \big(& DW_{i,j,k} - GW_{i,j,k} P^{n+1}_{lw\ i,j,k-1} - EW_{i,j,k} P^{n+1}_{lw\ i,j-1,k} - AW_{i,j,k} P^{n+1}_{lw\ i-1,j,k} \\
& - CW_{i,j,k} P^{n+1}_{lw\ i+1,j,k} - FW_{i,j,k} P^{n+1}_{lw\ i,j+1,k} - HW_{i,j,k} P^{n+1}_{lw\ i,j,k+1} \\
& - RW_{i,j,k} P^{n+1}_{fw\ i,j,k} - UW_{i,j,k} P^{n+1}_{lo\ i,j,k} \big)
\end{aligned}
$$

Figure 14. Water Equation in Rock Matrix and Relative Magnitudes of its Coefficients.

```
BO   ********************************************  ! -0.2289d7 !
DO   ***************************************  0.2952d6
VO   ***********************  0.2790d3
GO   **  0.0
EO   **  0.0
AO   ****  0.1707d0
CO   ****  0.1707d0
FO   ****  0.1707d0
HO   ******************  0.2731d2
UO   ********************************************     0.2287d7
RO   ***************************  0.1739d4
```

$$
\begin{aligned}
P^{n+1}_{lo\ i,j,k} = \frac{1}{BO_{i,j,k}} \Big(& DO_{i,j,k} - VO_{i,j,k}P^{n+1}_{lw\ i,j,k} - GO_{i,j,k}P^{n+1}_{lo\ i,j,k-1} - EO_{i,j,k}P^{n+1}_{lo\ i,j-1,k} \\
& - AO_{i,j,k}P^{n+1}_{lo\ i-1,j,k} - CO_{i,j,k}P^{n+1}_{lo\ i+1,j,k} - FO_{i,j,k}P^{n+1}_{lo\ i,j+1,k} \\
& - HO_{i,j,k}P^{n+1}_{lo\ i,j,k+1} - UO_{i,j,k}P^{n+1}_{lg\ i,j,k} - RO_{i,j,k}P^{n+1}_{fo\ i,j,k} \Big)
\end{aligned}
$$

Figure 15. Oil Equation in Rock Matrix and Relative Magnitudes of its Coefficients.

```
FBW    ************************  | -0.1931d2 |
DFW    ********************************  0.9669d3
FRW    **  0.0
FGW1   **  0.0
FGW2   **  0.0
FGW3   **  0.0
FGW4   **  0.0
FGW5   **  0.0
FEW1   **  0.0
FEW2   **  0.0
FEW3   **  0.0
FAW1   **  0.0
FCW1   **  0.0
FFW1   **  0.0
FFW2   **  0.0
FFW3   **  0.0
FHW1   **  0.0
FHW2   **  0.0
FHW3   **  0.0
FHW4   **  0.0
FHW5   **  0.0
FUW    ************************      0.1931d2
```

$$P^{n+1}_{fw\ i,j,k} = \frac{1}{FBW_{i,j,k}} \Big(DFW_{i,j,k} - FRW_{i,j,k} P^{n+1}_{lw\ i,j,k} - FGW1_{i,j,k} P^{n+1}_{fw\ i,j-1,k-1}$$

$$- FGW2_{i,j,k} P^{n+1}_{fw\ i-1,j,k-1} - FGW3_{i,j,k} P^{n+1}_{fw\ i,j,k-1} - FGW4_{i,j,k} P^{n+1}_{fw\ i+1,j,k} - FGW5_{i,j,k} P^{n+1}_{fw\ i,j+1,k-1}$$

$$- FEW1_{i,j,k} P^{n+1}_{fw\ i-1,j-1,k} - FEW2_{i,j,k} P^{n+1}_{fw\ i,j-1,k} - FEW3_{i,j,k} P^{n+1}_{fw\ i+1,j-1,k} - FAW1_{i,j,k} P^{n+1}_{fw\ i-1,j,k}$$

$$- FCW1_{i,j,k} P^{n+1}_{fw\ i+1,j,k} - FFW1_{i,j,k} P^{n+1}_{fw\ i-1,j+1,k} - FFW2_{i,j,k} P^{n+1}_{fw\ i,j+1,k} - FFW3_{i,j,k} P^{n+1}_{fw\ i+1,j+1,k}$$

$$- FHW1_{i,j,k} P^{n+1}_{fw\ i,j-1,k+1} - FHW2_{i,j,k} P^{n+1}_{fw\ i-1,j,k+1} - FHW3_{i,j,k} P^{n+1}_{fw\ i,j,k+1} - FHW4_{i,j,k} P^{n+1}_{fw\ i+1,j,k+1}$$

$$- FHW5_{i,j,k} P^{n+1}_{fw\ i,j+1,k+1} - FUW_{i,j,k} P^{n+1}_{fo\ i,j,k} \Big)$$

Figure 16. Water Equation in Fracture and Relative Magnitudes of its Coefficients.

FBO	***	| -0.8063d5 |
DFO	**************************************	0.1441d5
FRO	**********************************	0.1739d4
FVO	******************	0.9620d1
FG01	**	0.0
FG02	**	0.0
FG03	**	0.0
FG04	**	0.0
FG05	**	0.0
FE01	**	0.0
FE02	**	0.0
FE03	**	0.0
FA01	**************	0.1707d1
FC01	**************	0.1707d1
FF01	**	0.0
FF02	**************	0.1707d1
FF03	**	0.0
FH01	**	0.0
FH02	**	0.0
FH03	**********************	0.2731d2
FH04	**	0.0
FH05	**	0.0
FUO	***	0.7885d5

$$
\begin{aligned}
P^{n+1}_{fo\ i,j,k} = \frac{1}{FBO_{i,j,k}} \Big(& DFO_{i,j,k} - FRO_{i,j,k} P^{n+1}_{lo\ i,j,k} - FVO_{i,j,k} P^{n+1}_{fw\ i,j,k} \\
& - FG01_{i,j,k} P^{n+1}_{fo\ i,j-1,k-1} - FG02_{i,j,k} P^{n+1}_{fo\ i-1,j,k-1} - FG03_{i,j,k} P^{n+1}_{fo\ i,j,k-1} \\
& - FG04_{i,j,k} P^{n+1}_{fo\ i+1,j,k-1} - FG05_{i,j,k} P_{fo\ i,j+1,k-1} - FE01_{i,j,k} P^{n+1}_{fo\ i-1,j-1,k} \\
& - FE02_{i,j,k} P^{n+1}_{fo\ i,j-1,k} - FE03_{i,j,k} P_{fo\ i+1,j-1,k} - FA01_{i,j,k} P^{n+1}_{fo\ i-1,j,k} \\
& - FC01_{i,j,k} P^{n+1}_{fo\ i+1,j,k} - FF01_{i,j,k} P^{n+1}_{fo\ i-1,j+1,k} - FF02_{i,j,k} P^{n+1}_{fo\ i,j+1,k} \\
& - FF03_{i,j,k} P^{n+1}_{fo\ i+1,j+1,k} - FH01_{i,j,k} P^{n+1}_{fo\ i,j-1,k+1} - FH02_{i,j,k} P^{n+1}_{fo\ i-1,j,k+1} \\
& - FH03_{i,j,k} P^{n+1}_{fo\ i,j,k+1} - FH04_{i,j,k} P^{n+1}_{fo\ i+1,j,k+1} - FH05_{i,j,k} P^{n+1}_{fo\ i,j+1,k+1} \\
& - FUO_{i,j,k} P^{n+1}_{fg\ i,j,k} \Big)
\end{aligned}
$$

Figure 17. Oil Equation in Fracture and Relative Magnitudes of its Coefficients.

emerge. The variable largely responsible for the P_{fw} solution is P_{fo} which has the coefficient (FUW) related to (dS_{wf}/dP_{cowf}). As for the variable P_{fo}, its solution is largely affected by the value of P_{fg} which has the coefficient (FUO) related to (dS_{gf}/dP_{cgof}).

The implication is that the phase pressures in the fractures relate to each other more rapidly and spontaneously than they do to the phase pressure in the rock matrix, and vice versa. So, the fracture injection/production rates would be felt faster in the fractures than in the rock matrix, and conversely for the rock matrix.

Consequently, one can make the following deduction: the conventional way of assuming that fluids first flow from the rock matrix into the fractures and then flow through the fractures toward the wellbore may not be an adequate description of the flow phenomenon in the naturally fractured reservoir. What is likely to occur is that a portion of fluids would converge to the wellbore through the rock matrix while another portion is converging through the fractures. However, the ratio of the rock matrix flow to the fracture flow is difficult, if not impossible, to determine.

6.3 Effect of Lowering Injection Rate

As discussed earlier, the use of constant 7000 STB/day water injection rate inevitably leads to unrealistic pressure build-up in the reservoir, and may result in a convergence problem. In order to investigate this rate effect, the water injection rate is reduced to 4000 STB/day. The simulation program is run with this new rate and the results are shown in Figures 18 and 19. It is noted that water breakthrough occurs at approximately 288 days, an indication that water moves through the reservoir at a slower pace than the case in Figures 10 and 11.

This suggests that in order to keep the reservoir pressure from growing out of control, a reasonable rate schedule should employ a stair-step pattern in which one rate would be maintained at a constant for a certain period of time followed by a new lowered rate which would be constant for another period of time, and so on.

6.4 Effect of Fluid Velocity in the Fracture

The fracture velocity distributions such as the one shown in Table 9 are observed over an extended period of time. It is noted that the absolute values of these velocities are less than 3.5 ft/day. With such a small value, one tends to think that fluid flow through the fractures would be in a laminar region, and therefore would not be affected much by the fracture velocity.

To check this point, the simulation program is rerun without calling the VELOCY subroutine at the end of each time step. This amounts to keeping velocity and acceleration at their initial conditions of zero, and in effect, neglecting the fluid velocity in the fractures. The results of this run turn out to be identical to the first run (Figures 10 and 11).

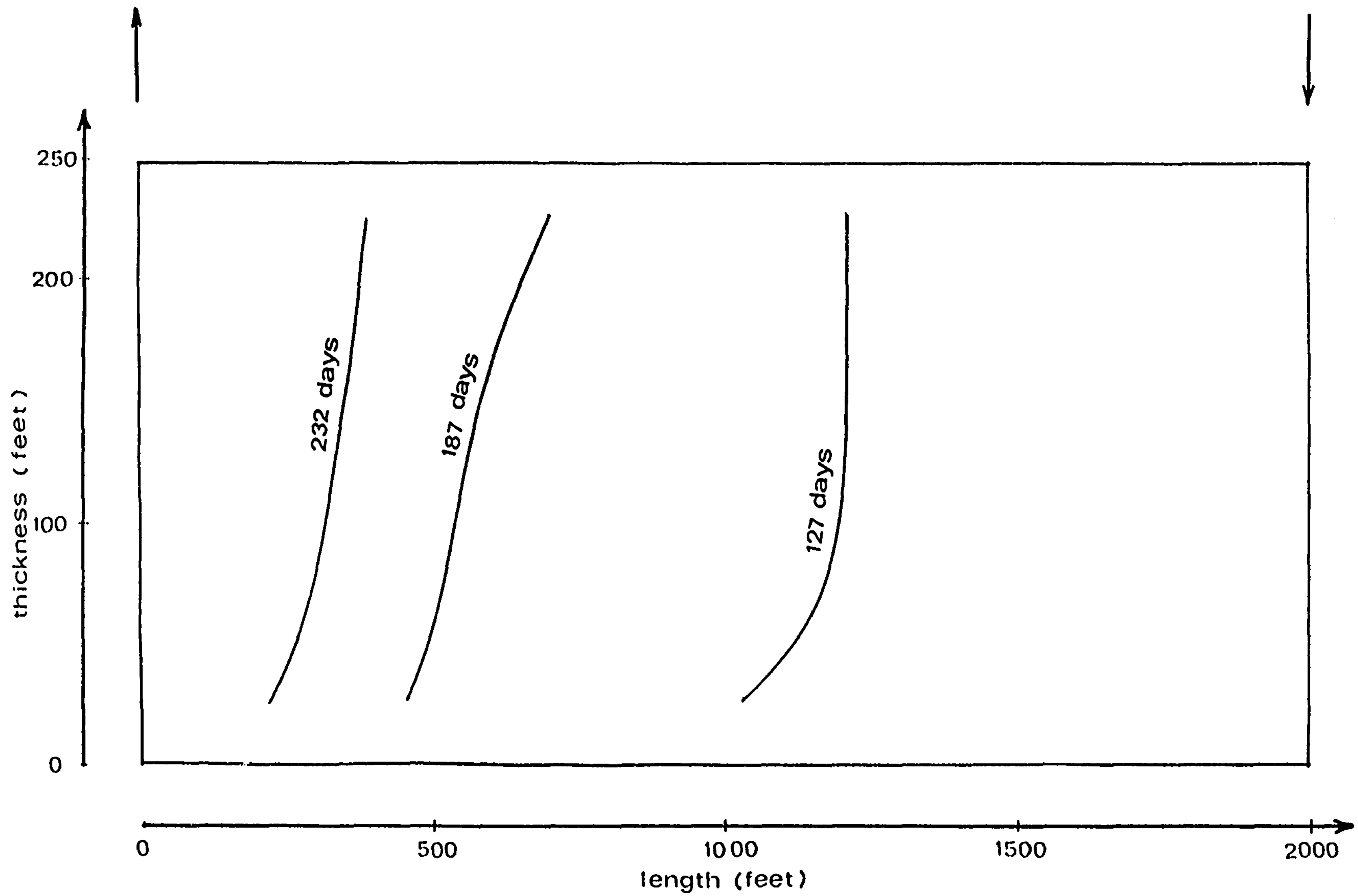


Figure 18. Fracture 50% Water Saturation Profile (Center cross-section; water injection rate = 4000 STB/day)

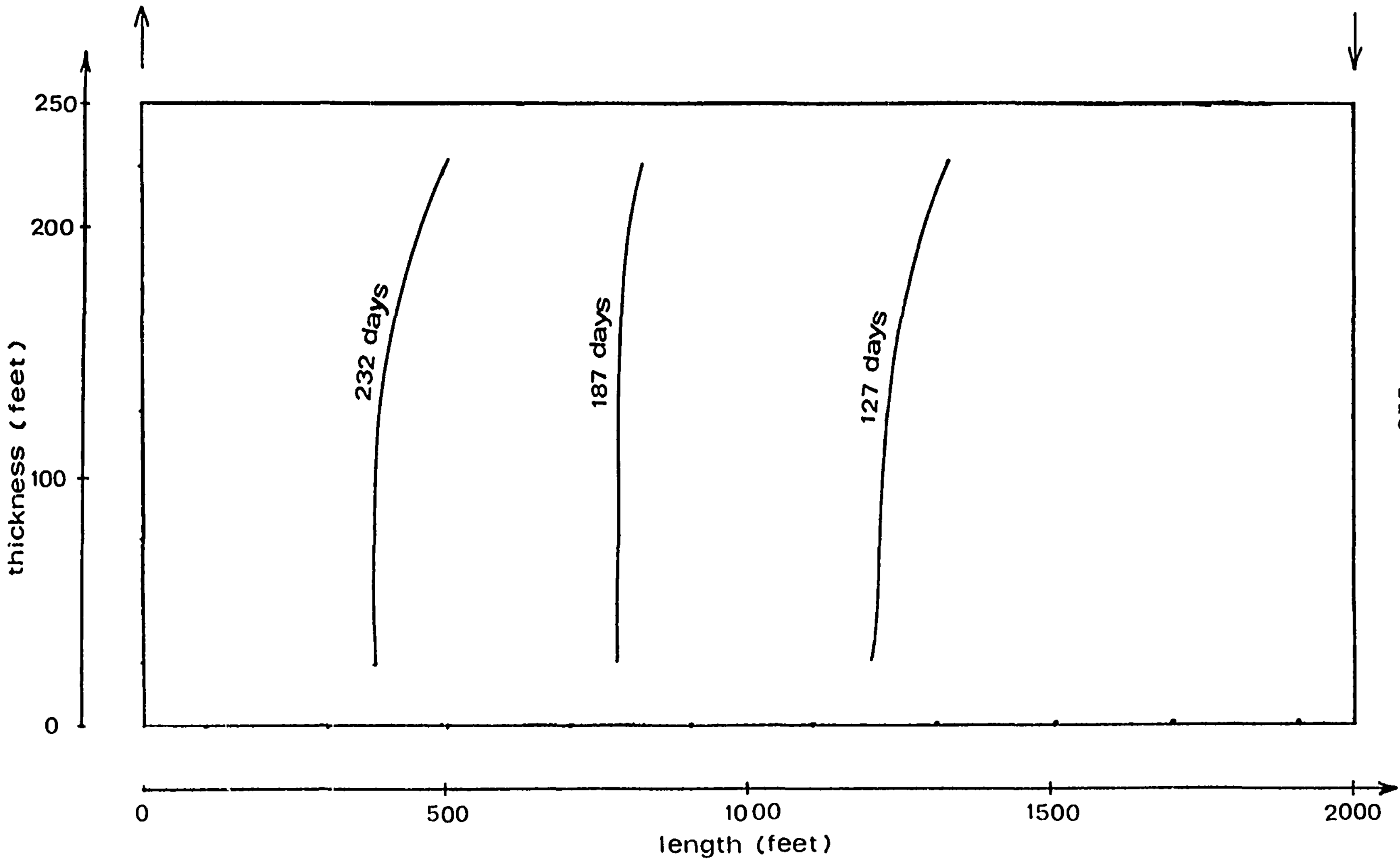


Figure 19. Matrix 50% Water Saturation Profile (center cross-section, water injection rate = 4000 STB/day).

This indicates that for the permeability data and production data used, the effect of fluid velocity in the fractures is negligible.

Incidentally, with regard to porosity, it should be mentioned that porosity distributions in both the rock matrix and the fracture remains relatively unchanged throughout the simulation period.

6.5 Recommendations for Further Improvements

The simulation program developed in this study represents a significant step toward a better understanding of the naturally fractured reservoir. However, because of the complexity of its mathematical model, the simulator may have some flaws inadvertently hidden in it. And certainly, it will take more programming tests with more field examples to perfect the simulator. In this section, suggestions for improvement of the simulation program are discussed.

The range and magnitude of a certain data set is very important in insuring the stability of the problem. For instance, the injection/production rates should not be so unrealistically high that the formation cannot sustain it. An improvement can be made in this regard by adding new statements into the program which specify maximum/minimum flowing bottomhole pressures and relate them with the block pressure and productivity index to compute the flow rates.

Another improvement can be achieved by adding statements which automatically decrease the time step size if the saturation changes during the previous time step are too large.

It should be pointed out that the largest time step size used in this study is 1 day, for a convergence problem is experienced when a larger step size is used.

A long-term improvement may be the development of a similar program for a limited compositional hydrocarbon model. Moreover, instead of a linear interpolation routine, the use of other types of interpolation technique should be explored.

Finally, it must be emphasized that the quality of the simulation results is only as good as the quality and accuracy of the input data. Therefore, special care should be taken in obtaining or measuring data for the simulator.

CHAPTER VII

CONCLUSIONS

This study presents the development of a numerical simulator for naturally fractured reservoirs. The principal conclusions can be summarized as follows.

1. The new mathematical flow model is derived for characterizing the multiphase fluid flow through naturally fractured reservoirs. This model permits flow through the rock matrix and the fracture to be described simultaneously. The fluid interaction terms, the gravity effects, the capillary forces and the fracture velocity of fluids are all taken into consideration.
2. A finite-difference, three-dimensional, black oil simulator has been developed according to this new model.
3. The simulator is capable of handling the isotropic, heterogeneous rock matrix and the anisotropic, heterogeneous fracture as well as the fracture orientation.
4. The presence/absence of fractures at any particular location in the reservoir can be statistically generated a priori by the Monte Carlo method; this

randomly generated location can then be inputted in the simulation program.

5. For the data used in this study, the phase pressures respond to each other more rapidly and spontaneously in the fractures than they do to the phase pressures in the rock matrix, and vice versa.
6. The conventional way of assuming that fluids first flow from the rock matrix into the fracture and then flow through the fracture toward the wellbore may not be an adequate description of the flow phenomenon in the naturally fractured reservoirs.
7. For the data used in this study, it appears that the fracture velocity of fluids has a negligible effect on the results.
8. The simulator developed represents significant advances toward a better understanding of the fluid flow phenomenon in the naturally fractured reservoirs.

NOMENCLATURE

B	=	Nondimensional constant; or formation volume factor (bbl/STB or bbl/SCF)
C_{ij}	=	Mass fraction of component i in phase j
c	=	Compressibility (psi^{-1})
D	=	Depth measured positive downward (ft)
d	=	Fracture half width (ft)
$f(\overline{r},\overline{\Omega})$	=	Fracture distribution function
g	=	Acceleration of gravity
g_c	=	Unit conversion factor (32.174 lbm-ft/lbf sec^2)
K	=	Absolute permeability (md)
$\overline{\overline{K}}_f$	=	Fracture permeability tensor (md)
k_{rj}	=	Relative permeability of phase j
ℓ or l	=	Characteristic half length of a fracture (ft)
N	=	Total number of grid points
P	=	Fluid pressure (psi)
q	=	Flow rate, positive for injection and negative for Production (STB/day or SCF/day)
R	=	Solution gas-oil ratio (SCF/STB)
r_H	=	Hydraulic radius for fracture (ft)
S	=	Phase saturation
t	=	Time (day)
V_B	=	Bulk volume (ft^3) = $\Delta x \cdot \Delta y \cdot \Delta z$
V_j	=	Velocity of fluid phase j (ft/day)

x,y,z = Rectangular coordinates

α = Angle of the x-axis to the horizontal plane

β = Angle of the y-axis to the horizontal plane; or parameter in fluid interaction term

Γ = Fluid interaction term between the fracture and the rock matrix

γ = Angle of the z-axis to the vertical plane

ε = Tolerance limit

λ = Fluid mobility

μ = Fluid viscosity (cp)

ρ = Fluid density (lbm/ft^3)

Φ = Flow potential (psi)

ϕ = Porosity

ω = Relaxation parameter

Note: Units, if given, are in oil field units.

Subscripts

c = Capillary pressure

f = Fracture

G or g = Gas

i = Hydrocarbon component; or grid point in x-direction

j = Hydrocarbon phase; or grid point in y-direction

k = Grid point in z-direction

l = Rock matrix

O or o = Oil

r = Relative value

S = Standard conditions

W or w = Water

Superscripts

k = Iteration level

n = Time step level

Symbols

$\rightharpoonup$ = Vector

$=$ = Tensor

∇ = Nabla differential operator

Δ = Delta or increment

$\hat{i}$ = Unit vector in x-direction

$\hat{j}$ = Unit vector in y-direction

$\hat{k}$ = Unit vector in z-direction

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APPENDIX A

Comparison of Units and Conversion Factors

Symbol	Definition	SI* Units	Darcy or cgs units	Oilfield Units	Conversion** Factors
q	Flow Rate	m^3/S	cm^3/S	STB/day	5.434396×10^5
q_g	Gas Flow Rate	m^3/S	cm^3/S	SFC/day	3.051187×10^6
k	Permeability	m^2	darcy	md	1.01325×10^{15}
μ	Viscosity	Pa.S	cp	cp	1×10^3
P	Pressure	Pa	atm	psi	1.450377×10^{-4}
x,y,z	Distances	m	cm	ft	3.28084
t	Time	S	S	day	$\frac{1}{86400}$
c	Compressibility	Pa^{-1}	atm^{-1}	psi^{-1}	6.894757×10^3
T	Temperature	K	K	R	1.8
ρ	Density	kg/m^3	gm/cm^3	lb_m/ft^3	6.242797×10^{-2}
g	Gravitational Acceleration	m/S^2	cm/S^2	ft/S^2	3.28084
g_c	Conversion Constant	$1 \frac{kg\text{-}m}{N \cdot S^2}$ or $1 \frac{kg}{Pa \cdot S^2 \cdot m}$	$1 \frac{gm\ cm}{dyne\ S^2}$	$32.17 \frac{lb_m\text{-}ft}{lb_f \cdot S^2}$	32.17
h	Thickness	m	cm	ft	3.28084
V	Velocity	m/S	cm/s	ft/day	2.834646×10^5

* The SI is a coherent unit, so equations written in this unit do not need numerical conversion factor.

** To convert from the SI unit to the oilfield unit, multiply the SI unit by the corresponding conversion factor.

Some Useful Conversion Factors

Area:	1 acre	$= 43560\ ft^2$
Permeability:	1 darcy	$= 1000$ md
		$= 9.86923 \times 10^{-13}\ m^2$
		$\doteq 9.86923 \times 10^{-9}\ cm^2$
Viscosity:	1 poise	$= 1\ \frac{gm}{cm \cdot s}$
		$= 100$ cp
		$= 0.1$ Pa•S
		$= 6.719689 \times 10^{-2}\ \frac{lb_m}{ft \cdot S}$
		$= 2.088543 \times 10^{-3}\ \frac{lb_f \cdot S}{ft^2}$
Volume:	1 bbl	$= 5.614583\ ft^3$
		= 42 gal
	1 gal	$= 3785.43\ cm^3$
		$= 231\ in^3$
	$1\ ft^3$	= 7.4805 gal
		= 28.317 liter
	$1\ m^3$	= 6.2898 bbl
Pressure:	1 atm	= 760 mm Hg. (0°c)
		= 33.8995 ft water (4°c)
		= 14.696 psi
		= 1.01325 bar
		$= 1.01325 \times 10^5$ Pa (pascal or N/m^2)
Mass:	$1\ lb_m$	= 453.59243 gm.

APPENDIX B

COMPARISON OF EQUATIONS UNDER SI UNITS AND OILFIELD UNITS

SI UNITS	OILFIELD UNITS
Darcy's Law For Flow in Rock Matrix	
$\vec{V}_{1j} = -\frac{K_1 k_{r1j}}{\mu_{j1}} [\nabla P_{1j} - \rho_{j1} \frac{g}{g_c} \nabla D]$	$\vec{V}_{1j} = -0.0063283 \frac{K_1 k_{r1j}}{\mu_{j1}} [\nabla P_{1j} - \frac{1}{144} \rho_{j1} \nabla D]$
Equation of Motion In Fracture	
$\vec{V}_{fj} = \frac{k_{rjf} \bar{\bar{K}}_f}{\mu_{jf}} \cdot [\nabla P_{fj} + \rho_{jf} \frac{1}{g_c} \frac{\partial \bar{V}_{fj}}{\partial t} - \rho_{jf} \frac{g}{g_c} \nabla D]$	$\vec{V}_{fj} = -0.0063283 \frac{k_{rjf} \bar{\bar{K}}_f}{\mu_{jf}} \cdot [\nabla P_{fj} + 2.891738 \times 10^{-14} \rho_{jf} \frac{\partial \bar{V}_{fj}}{\partial t} - \frac{1}{144} \rho_{jf} \nabla D]$
Water Equation for Flow in Rock Matrix	
$\nabla \cdot [\frac{K_1 k_{r1w}}{B_{w1} \mu_{w1}} \{\nabla P_{1w} - \frac{\rho_{ws}}{B_{w1}} \nabla D\}] - [\frac{K_1 k_{r1w} \phi_f}{r_H 1 \mu_{w1} B_{w1}} (P_{1w} - P_{fw})] + \frac{q_{ws}}{\Delta x \cdot \Delta y \cdot \Delta z} = \phi_1 \frac{\partial}{\partial t} (S_{w1}/B_{w1})$	$0.001127 \nabla \cdot [\frac{K_1 k_{r1w}}{B_{w1} \mu_{w1}} \{\nabla P_{1w} - \frac{1}{144} \frac{\rho_{ws}}{B_{w1}} \nabla D\}] - 0.001127 [\frac{K_1 k_{r1w} \phi_f}{r_H 1 \mu_{w1} B_{w1}} (P_{1w} - P_{fw})] + \frac{q_{ws}}{\Delta x \cdot \Delta y \cdot \Delta z} = \frac{1}{5.615} \phi_1 \frac{\partial}{\partial t} (S_{w1}/B_{w1})$

SI UNITS	OILFIELD UNITS

Oil Equation for Flow in Rock Matrix

SI UNITS

$$\nabla\cdot\left[\frac{K_1 k_{r1o}}{B_{o1}\mu_o}\{\nabla P_{1o} - \rho_{o1}\frac{g}{g_c}\nabla D\}\right] - \left[\frac{K_1 k_{r1o}\phi_f}{r_H 1\mu_{o1}B_{o1}}(P_{1o}-P_{fo})\right] + \frac{q_{os}}{\Delta x\cdot\Delta y\cdot\Delta z} = \phi_1\frac{\partial}{\partial t}(S_{o1}/B_{o1})$$

OILFIELD UNITS

$$0.001127\ \nabla\cdot\left[\frac{K_1 k_{r1o}}{B_{o1}\mu_o}\{\nabla P_{1o} - \frac{1}{144}\rho_{o1}\nabla D\}\right] - 0.001127\left[\frac{K_1 k_{r1o}\Phi_f}{r_H 1\mu_{o1}B_{o1}}(P_{1o}-P_{fo})\right] + \frac{q_{os}}{\Delta x\cdot\Delta y\cdot\Delta z} = \frac{1}{5.615}\phi_1\frac{\partial}{\partial t}(S_{o1}/B_{o1})$$

Gas Equation for Flow in Rock Matrix

SI UNITS

$$\nabla\cdot\left[\frac{K_1 k_{r1g}}{B_{g1}\mu_{g1}}\{\nabla P_{1g} - \rho_{g1}\frac{g}{g_c}\nabla D\}\right] + \nabla\cdot\left[\frac{R_{so1}K_1 k_{r1o}}{B_{o1}\mu_{o1}}\{\Delta P_{1o} - \rho_{o1}\frac{g}{g_c}\nabla D\}\right] - \left[\frac{K_1 k_{r1g}\phi_f}{r_H 1\mu_{g1}B_{g1}}(P_{1g}-P_{fg})\right] - \left[\frac{K_1 k_{r1o}\phi_f R_{so1}}{r_H 1\mu_{o1}B_{o1}}(P_{1o}-P_{fo})\right] + \frac{q_{gs}}{\Delta x\cdot\Delta y\cdot\Delta z} = \phi_1\frac{\partial}{\partial t}\left[\frac{S_{g1}}{B_{g1}} + \frac{R_{so1}S_{o1}}{B_{o1}}\right]$$

OILFIELD UNITS

$$0.001127\nabla\cdot\left[\frac{K_1 k_{r1g}}{B_{g1}\mu_{g1}}\{\nabla P_{1g} - \frac{1}{144}\rho_{g1}\nabla D\}\right] + 0.001127\ \nabla\cdot\left[\frac{R_{so1}K_1 k_{r1o}}{B_{o1}\mu_{o1}}\{\Delta P_{1o} - \frac{1}{144}\rho_{o1}\nabla D\}\right] - 0.001127\left[\frac{K_1 k_{r1g}\phi_f}{r_H 1\mu_{g1}B_{g1}}(P_{1g}-P_{fg})\right] - 0.001127\left[\frac{K_1 k_{r1o}\phi_f R_{so1}}{r_H 1\mu_{o1}B_{o1}}(P_{1o}-P_{fo})\right] + \frac{q_{gs}}{\Delta x\cdot\Delta y\cdot\Delta z} = \frac{1}{5.615}\phi_1\frac{\partial}{\partial t}\left[\frac{S_{g1}}{B_{g1}} + \frac{R_{so1}S_{o1}}{B_{o1}}\right]$$

SI UNITS | **OILFIELD UNITS**

Water Equation for Flow in Fracture

SI UNITS

$$\nabla \cdot \left[\frac{k_{rwf}\overline{\overline{K}}_f}{B_{wf}\,{}_{wf}} \cdot \{\nabla P_{fw} + \frac{\rho_{ws}}{B_{wf}} \frac{1}{g_c} \frac{\partial \overline{V}_{fw}}{\partial t}\right.$$

$$\left. - \frac{\rho_{ws}}{B_{wf}} \frac{g}{g_c} \nabla D\}\right]$$

$$+\left[\frac{K_1 k_{r1w}\phi_f}{r_H 1\ B_{w1}\mu_{w1}} (P_{1w} - P_{fw})\right]$$

$$+ \frac{q_{wsf}}{\Delta x \cdot \Delta y \cdot \Delta z} = \phi_f \frac{\partial}{\partial t}\left[\frac{S_{wf}}{B_{wf}}\right]$$

OILFIELD UNITS

$$0.001127\,\Delta \cdot \left[\frac{k_{rwf}\overline{\overline{K}}_f}{B_{wf}\mu_{wf}} \cdot \{\nabla P_{fw}\right.$$

$$+ 2.891738 \times 10^{-14} \frac{\rho_{ws}}{B_{wf}} \frac{\partial \overline{V}_{fw}}{\partial t}$$

$$\left. - \frac{1}{144} \frac{\rho_{ws}}{B_{wf}} \nabla D\}\right]$$

$$+ 0.001127 \left[\frac{K_1 k_{r1w}\phi_f}{r_H 1 \mu_{w1} B_{w1}} (P_{1w} - P_{fw})\right]$$

$$+ \frac{q_{wsf}}{\Delta x \cdot \Delta y \cdot \Delta z} = \frac{1}{5.615} \phi_f \frac{\partial}{\partial t}\left[\frac{S_{wf}}{B_{wf}}\right]$$

Oil Equation for Flow in Fracture

SI UNITS

$$\nabla \cdot \left[\frac{k_{rof}\overline{\overline{K}}_f}{B_{of}\mu_{of}} \cdot \{\nabla P_{fo} + \rho_{o1} \frac{g}{g_c} \frac{\partial \overline{V}_{fo}}{\partial t}\right.$$

$$\left. - \rho_{o1} \frac{g}{g_c} \nabla D\}\right]$$

$$+ \left[\frac{K_1 k_{r1o}\phi_f}{r_H 1\ B_{o1}\mu_{o1}} (P_{1o} - P_{fo})\right]$$

$$+ \frac{q_{osf}}{\Delta x \cdot \Delta y \cdot \Delta z} = \phi_f \frac{\partial}{\partial t}\left[\frac{S_{of}}{B_{of}}\right]$$

OILFIELD UNITS

$$0.001127\nabla \cdot \left[\frac{k_{rof}\overline{\overline{K}}_f}{B_{of}\mu_{of}} \cdot \{\nabla P_{fo}\right.$$

$$+ 2.891738 \times 10^{-14} \rho_{o1} \frac{\partial \overline{V}_{fo}}{\partial t}$$

$$\left. - \frac{1}{144} \rho_{o1} \nabla D\}\right]$$

$$+ 0.001127 \left[\frac{K_1 k_{r1o}\phi_f}{r_H 1\ B_{o1}\mu_{o1}} (P_{1o} - P_{fo})\right]$$

$$+ \frac{q_{osf}}{\Delta x \cdot \Delta y \cdot \Delta z} = \frac{1}{5.615} \phi_f \frac{\partial}{\partial t}\left[\frac{S_{of}}{B_{of}}\right]$$

Gas Equation for Flow in Fracture

SI UNITS

$$\nabla\cdot\left[\frac{k_{rgf}\overline{\overline{K}}_f}{B_{gf}\mu_{gf}}\cdot\left\{\nabla P_{fg}+\rho_{g1}\frac{g}{g_c}\frac{\partial\overline{V}_{fg}}{\partial t}-\rho_{g1}\frac{g}{g_c}\nabla D\right\}\right]$$

$$+\nabla\cdot\left[\frac{R_{sof}k_{rof}\overline{\overline{K}}_f}{B_{of}\mu_{of}}\cdot\left\{\nabla P_{fo}+\rho_{o1}\frac{1}{g_c}\frac{\partial\overline{V}_{fo}}{\partial t}-\rho_{o1}\frac{g}{g_c}\nabla D\right\}\right]$$

$$+\left[\frac{K_1 k_{r1g}\phi_f}{r_H 1\mu_{g1}B_{g1}}(P_{1g}-P_{fg})\right]$$

$$+\left[\frac{K_1 k_{r1o}\phi_f R_{so1}}{r_H 1\,\mu_{o1}B_{o1}}(P_{1o}-P_{fo})\right]$$

$$+\frac{q_{Gsf}}{\Delta x\cdot\Delta y\cdot\Delta z}=\phi_f\frac{\partial}{\partial t}\left[\frac{S_{gf}}{B_{gf}}+\frac{R_{sof}S_{of}}{B_{of}}\right]$$

OILFIELD UNITS

$$0.001127\ \nabla\cdot\left[\frac{k_{rgf}\overline{\overline{K}}_f}{B_{gf}\mu_{gf}}\cdot\left\{\nabla P_{fg}+2.891738\times10^{-14}\rho_{g1}\frac{\partial\overline{V}_{fg}}{\partial t}-\frac{1}{144}\rho_{g1}\nabla D\right\}\right]$$

$$+0.001127\nabla\cdot\left[\frac{R_{sof}k_{rof}\overline{\overline{K}}_f}{B_{of}\mu_{of}}\cdot\left\{\nabla P_{fo}+2.891738\times10^{-14}\rho_{o1}\frac{\partial\overline{V}_{fo}}{\partial t}-\frac{1}{144}\rho_{o1}\nabla D\right\}\right]$$

$$+0.001127\left[\frac{K_1 k_{r1g}\phi_f}{r_H 1\,\mu_{g1}B_{g1}}(P_{1g}-P_{fg})\right]$$

$$+0.001127\left[\frac{K_1 k_{r1o}\phi_f R_{so1}}{r_H 1\,\mu_{o1}B_{o1}}(P_{1o}-P_{fo})\right]$$

$$+\frac{q_{Gsf}}{\Delta x\cdot\Delta y\cdot\Delta z}=\frac{1}{5.615}\phi_f\frac{\partial}{\partial t}\left[\frac{S_{gf}}{B_{gf}}+\frac{R_{sof}S_{of}}{B_{of}}\right]$$

APPENDIX C

EXPRESSIONS FOR THE COEFFICIENTS

Water Equation in Matrix Rock ($B_{wl} = 1$ when water is incompressible)

$$GW_{i,j,k} = \frac{V_B}{\Delta z^2} \left(\frac{K_l k_{rlw}}{B_{wl}\mu_{wl}} \right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}}$$

$$EW_{i,j,k} = \frac{V_B}{\Delta y^2} \left(\frac{K_l k_{rlw}}{B_{wl}\mu_{wl}} \right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k}$$

$$AW_{i,j,k} = \frac{V_B}{\Delta x^2} \left(\frac{K_l k_{rlw}}{B_{wl}\mu_{wl}} \right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k}$$

$$BW_{i,j,k} = - V_B \Big[\frac{1}{\Delta z^2} \left(\frac{K_l k_{rlw}}{B_{wl}\mu_{wl}} \right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}} + \frac{1}{\Delta z^2} \left(\frac{K_l k_{rlw}}{B_{wl}\mu_{wl}} \right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}}$$

$$+ \frac{1}{\Delta y^2} \left(\frac{K_l k_{rlw}}{B_{wl}\mu_{wl}} \right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k} + \frac{1}{\Delta y^2} \left(\frac{K_l k_{rlw}}{B_{wl}\mu_{wl}} \right)_{i,j+\frac{1}{2},k}$$

$$+ \frac{1}{\Delta x^2} \left(\frac{K_l k_{rlw}}{B_{wl}\mu_{wl}} \right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k} + \frac{1}{\Delta x^2} \left(\frac{K_l k_{rlw}}{B_{wl}\mu_{wl}} \right)_{i+\frac{1}{2},j,k}$$

$$+ \frac{\phi^n_{f_{i,j,k}}}{r_H l} \left(\frac{K_l k_{rlw}}{B_{wl}\mu_{wl}} \right)^{n+\frac{1}{2}}_{i,j,k} - \frac{(\phi_l)^n_{i,j,k}}{\Delta t} \frac{1}{B^{n+\frac{1}{2}}_{wl_{i,j,k}}} (S'_{wl})^n_{i,j,k}$$

$$+ \frac{\phi^n_{l_{i,j,k}}}{\Delta t} S^{n+\frac{1}{2}}_{wl_{i,j,k}} \left(\frac{1}{B_{wl}} \right)'^{n+\frac{1}{2}}_{i,j,k} \Big]^*$$

*This last term is zero when water is assumed incompressible.

$$CW_{i,j,k} = \frac{V_B}{\Delta x^2} \left(\frac{K_1 k_{r1w}}{B_{w1}\mu_{w1}} \right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k}$$

$$FW_{i,j,k} = \frac{V_B}{\Delta y^2} \left(\frac{K_1 k_{r1w}}{B_{w1}\mu_{w1}} \right)^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k}$$

$$HW_{i,j,k} = \frac{V_B}{\Delta z^2} \left(\frac{K_1 k_{r1w}}{B_{w1}\mu_{w1}} \right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}}$$

$$RW_{i,j,k} = \frac{V_B (\phi_f)^n_{i,j,k}}{r_H l} \left(\frac{K_1 k_{r1w}}{B_{w1}\mu_{w1}} \right)^{n+\frac{1}{2}}_{i,j,k}$$

$$UW_{i,j,k} = \frac{V_B (\phi_1)^n_{i,j,k} (S_{w1}')^n_{i,j,k}}{\Delta t \; B^{n+\frac{1}{2}}_{w1_{i,j,k}}}$$

$$\begin{aligned} DW_{i,j,k} = &- (q_{ws1})_{i,j,k} - \frac{(\phi_1)^n_{i,j,k} V_B}{\Delta t} \Big[\frac{(S_{w1})^n_{i,j,k}}{B^{n+\frac{1}{2}}_{w1_{i,j,k}}} (P^n_{1o} - P^n_{1w_{i,j,k}}) \\ &+ S^{n+\frac{1}{2}}_{w1_{i,j,k}} \left(\frac{1}{B_{w1}} \right)'^{\,n+\frac{1}{2}}_{i,j,k} P^n_{1w_{i,j,k}} \Big]^{*} \\ &- \frac{V_B}{\Delta x} \rho^{n+\frac{1}{2}}_{w1_{i,j,k}} \frac{g}{g_c} \sin\alpha \Big[\left(\frac{K_1 k_{r1w}}{B_{w1}\mu_{w1}} \right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} - \left(\frac{K_1 k_{r1w}}{B_{w1}\mu_{w1}} \right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k} \Big] \\ &- \frac{V_B}{\Delta y} \rho^{n+\frac{1}{2}}_{w1_{i,j,k}} \frac{g}{g_c} \sin\beta \Big[\left(\frac{K_1 k_{r1w}}{B_{w1}\mu_{w1}} \right)^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} - \left(\frac{K_1 k_{r1w}}{B_{w1}\mu_{w1}} \right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k} \Big] \\ &- \frac{V_B}{\Delta z} \rho^{n+\frac{1}{2}}_{w1_{i,j,k}} \frac{g}{g_c} \cos\gamma \Big[\left(\frac{K_1 k_{r1w}}{B_{w1}\mu_{w1}} \right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} - \left(\frac{K_1 k_{r1w}}{B_{w1}\mu_{w1}} \right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}} \Big] \end{aligned}$$

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*This term is zero when water is assumed incompressible.

Oil Equation in Matrix Rock

$$VO_{i,j,k} = - \frac{V_B(\phi_1)^n_{i,j,k}}{\Delta t\ B^{n+\frac{1}{2}}_{ol_{i,j,k}}} (S'_{wl})_{i,j,k}$$

$$GO_{i,j,k} = \frac{V_B}{\Delta z^2} \left(\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}}$$

$$EO_{i,j,k} = \frac{V_B}{\Delta y^2} \left(\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k}$$

$$AO_{i,j,k} = \frac{V_B}{\Delta x^2} \left(\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k}$$

$$\begin{aligned} BO_{i,j,k} = -V_B \Big[& \frac{1}{\Delta z^2} \left(\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}} + \frac{1}{\Delta y^2} \left(\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k} \\ & + \frac{1}{\Delta x^2} \left(\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k} + \frac{1}{\Delta x^2} \left(\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} \\ & + \frac{1}{\Delta y^2} \left(\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} + \frac{1}{\Delta z^2} \left(\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} \\ & + \frac{(\phi_f)^n_{i,j,k}}{r_H l} \left(\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j,k} + \frac{(\phi_1)^n_{i,j,k}}{\Delta t} \Big\{ \frac{(S'_{gl})^n_{i,j,k}}{B^{n+\frac{1}{2}}_{ol_{i,j,k}}} \\ & - \frac{(S'_{wl})^n}{B^{n+\frac{1}{2}}_{ol_{i,j,k}}} + (1 - S^{n+\frac{1}{2}}_{gl_{i,j,k}} - S^{n+\frac{1}{2}}_{wl_{i,j,k}}) \left(\frac{1}{B_{ol}} \right)'^{n+\frac{1}{2}}_{i,j,k} \Big\} \Big] \end{aligned}$$

$$CO_{i,j,k} = \frac{V_B}{\Delta x^2} \left(\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k}$$

$$FO_{i,j,k} = \frac{V_B}{\Delta y^2} \left(\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k}$$

$$HO_{i,j,k} = \frac{V_B}{\Delta z^2} \left(\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}}$$

$$UO_{i,j,k} = \frac{V_B(\phi_1)^n_{i,j,k}(S'_{gl})^n_{i,j,k}}{\Delta T \; B^{n+\frac{1}{2}}_{ol_{i,j,k}}}$$

$$RO_{i,j,k} = \frac{V_B(\phi_f)^n_{i,j,k}}{r_H l} \left(\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j,k}$$

$$DO_{i,j,k} = -(q_{osl})_{i,j,k} - \frac{V_B(\phi_1)^n_{i,j,k}}{\Delta t} \Bigg[\Bigg\{ \frac{(S'_{gl})^n_{i,j,k}}{B^{n+\frac{1}{2}}_{ol_{i,j,k}}}$$

$$- \frac{(S'_{wl})^n_{i,j,k}}{B^{n+\frac{1}{2}}_{ol_{i,j,k}}} + (1 - S^{n+\frac{1}{2}}_{gl_{i,j,k}} - S^{n+\frac{1}{2}}_{wl_{i,j,k}}) \left(\frac{1}{B_{ol}} \right)'^{\,n+\frac{1}{2}} \Bigg\} P^n_{lo_{i,j,k}}$$

$$- \frac{(S'_{gl})^n_{i,j,k}}{B^{n+\frac{1}{2}}_{ol_{i,j.k}}} P^n_{lg_{i,j,k}} + \frac{(S'_{wl})^n_{i,j,k}}{B^{n+\frac{1}{2}}_{i,j,k}} P^n_{lw_{i,j,k}} \Bigg]$$

$$- \frac{V_B}{\Delta x}(\rho_{ol})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\alpha \left[\left(\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} - \left(\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k} \right]$$

$$- \frac{V_B}{\Delta y}(\rho_{ol})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\beta \left[\left(\frac{K_1 r_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} - \left(\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k} \right]$$

$$- \frac{V_B}{\Delta z}(\rho_{ol})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \cos\gamma \left[\left(\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} - \left(\frac{K_1 k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}} \right]$$

Gas Equation in Matrix Rock

$$VG_{i,j,k} = \frac{-V_B(\phi_1)^n_{i,j,k}}{\Delta t\ B^{n+\frac{1}{2}}_{ol_{i,j,k}}} R^{n+\frac{1}{2}}_{sol_{i,j,k}} (S'_{wl})^n_{i,j,k}$$

$$GGO_{i,j,k} = \frac{V_B}{\Delta z^2} \left(\frac{R_{sol}K_l k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}}$$

$$EGO_{i,j,k} = \frac{V_B}{\Delta y^2} \left(\frac{R_{sol}K_l k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k}$$

$$AGO_{i,j,k} = \frac{V_B}{\Delta x^2} \left(\frac{R_{sol}K_l k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k}$$

$$\begin{aligned} BGO_{i,j,k} = -\ V_B \Bigg[& \frac{1}{\Delta z^2} \left(\frac{R_{sol}K_l k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}} + \frac{1}{\Delta y^2} \left(\frac{R_{sol}K_l k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k} \\ & + \frac{1}{\Delta x^2} \left(\frac{R_{sol}K_l k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k} + \frac{1}{\Delta x^2} \left(\frac{R_{sol}K_l k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} \\ & + \frac{1}{\Delta y^2} \left(\frac{R_{sol}K_l k_{flo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} + \frac{1}{\Delta z^2} \left(\frac{R_{sol}K_l k_{rlo}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} \\ & + \frac{(\phi_f)^n_{i,j,k}}{r_H l} \left(\frac{K_l k_{rlo} R_{sol}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j,k} + \frac{(\phi_1)^n_{i,j,k}}{\Delta t} \Bigg\{ \frac{-(S'_{gl})^n_{i,j,k}}{B^{n+\frac{1}{2}}_{gl_{i,j,k}}} \\ & + \frac{R^{n+\frac{1}{2}}_{sol_{i,j,k}}}{B^{n+\frac{1}{2}}_{ol_{i,j,k}}} (S'_{gl})^n_{i,j,k} - \frac{R^{n+\frac{1}{2}}_{sol_{i,j,k}} (S'_{wl})^n_{i,j,k}}{B^{n+\frac{1}{2}}_{ol_{i,j,k}}} \\ & + R^{n+\frac{1}{2}}_{sol_{i,j,k}} (1 - S^{n+\frac{1}{2}}_{gl,i,j,k} - S^{n+\frac{1}{2}}_{wl_{i,j,k}}) \left(\frac{1}{B_{ol}} \right)'^{\,n+\frac{1}{2}}_{i,j,k} \\ & + (1 - S^{n+\frac{1}{2}}_{gl_{i,j,k}} - S^{n+\frac{1}{2}}_{wl_{i,j,k}}) \frac{(R'_{sol})^{n+\frac{1}{2}}_{i,j,k}}{B^{n+\frac{1}{2}}_{ol_{i,j,k}}} \Bigg\} \Bigg] \end{aligned}$$

$$CGO_{i,j,k} = \frac{V_B}{\Delta x^2} \left(\frac{R_{sol} K_l k_{rlo}}{B_{ol} \mu_{ol}} \right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k}$$

$$FGO_{i,j,k} = \frac{V_B}{\Delta y^2} \left(\frac{R_{sol} K_l k_{rlo}}{B_{ol} \mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k}$$

$$HGO_{i,j,k} = \frac{V_B}{\Delta z^2} \left(\frac{R_{sol} K_l k_{rlo}}{B_{ol} \mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}}$$

$$GG_{i,j,k} = \frac{V_B}{\Delta z^2} \left(\frac{K_l k_{rlg}}{B_{gl} \mu_{gl}} \right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}}$$

$$EG_{i,j,k} = \frac{V_B}{\Delta y^2} \left(\frac{K_l k_{rlg}}{B_{gl} \mu_{gl}} \right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k}$$

$$AG_{i,j,k} = \frac{V_B}{\Delta x^2} \left(\frac{K_l k_{rlg}}{B_{gl} \mu_{gl}} \right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k}$$

$$\begin{aligned} BG_{i,j,k} = - V_B \Bigg[& \frac{1}{\Delta z^2} \left(\frac{K_l k_{rlg}}{B_{gl} \mu_{gl}} \right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}} + \frac{1}{\Delta y^2} \left(\frac{K_l k_{rlg}}{B_{gl} \mu_{gl}} \right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k} \\ & + \frac{1}{\Delta x^2} \left(\frac{K_l k_{rlg}}{B_{gl} \mu_{gl}} \right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k} + \frac{1}{\Delta x^2} \left(\frac{K_l k_{rlg}}{B_{gl} \mu_{gl}} \right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} \\ & + \frac{1}{\Delta y^2} \left(\frac{K_l k_{rlg}}{B_{gl} \mu_{gl}} \right)^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} + \frac{1}{\Delta z^2} \left(\frac{K_l k_{rlg}}{B_{gl} \mu_{gl}} \right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} \\ & + \frac{(\phi_f)^n_{i,j,k}}{r_H l} \left(\frac{K_l k_{rlg}}{B_{gl} \mu_{gl}} \right)^{n+\frac{1}{2}}_{i,j,k} + \frac{(\phi_l)^n_{i,j,k}}{\Delta t} \Bigg\{ \frac{(S'_{gl})^n_{i,j,k}}{B^{n+\frac{1}{2}}_{gl_{i,j,k}}} \\ & + S^{n+\frac{1}{2}}_{gl_{i,j,k}} \left(\frac{1}{B_{gl}} \right)'^{\,n+\frac{1}{2}}_{i,j,k} - \frac{R^{n+\frac{1}{2}}_{sol\ i,j,k} (S'_{gl})^n}{B^{n+\frac{1}{2}}_{ol_{i,j,k}}} \Bigg\} \Bigg] \end{aligned}$$

$$CG_{i,j,k} = \frac{V_B}{\Delta x^2} \left(\frac{K_1 k_{rlg}}{B_{gl}\mu_{gl}} \right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k}$$

$$FG_{i,j,k} = \frac{V_B}{\Delta y^2} \left(\frac{K_1 k_{rlg}}{B_{gl}\mu_{gl}} \right)^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k}$$

$$HG_{i,j,k} = \frac{V_B}{\Delta z^2} \left(\frac{K_1 k_{rlg}}{B_{gl}\mu_{gl}} \right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}}$$

$$RGO_{i,j,k} = \frac{V_B(\phi_f)^n_{i,j,k}}{r_H l} \left(\frac{K_1 k_{rlo} R_{sol}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j,k}$$

$$RG_{i,j,k} = \frac{V_B(\phi_f)^n_{i,j,k}}{r_H l} \left(\frac{K_1 k_{rlg}}{B_{gl}\mu_{gl}} \right)^{n+\frac{1}{2}}_{i,j,k}$$

$$DG_{i,j,k} = -(q_{Gsl})_{i,j,k} - \frac{V_B(\phi_l)^n_{i,j,k}}{\Delta t} \Bigg[\Bigg\{ \frac{(S'_{gl})^n_{i,j,k}}{B^{n+\frac{1}{2}}_{gl_{i,j,k}}}$$

$$+ S^{n+\frac{1}{2}}_{gl_{i,j,k}} \left(\frac{1}{B_{gl}} \right)'^{n+\frac{1}{2}}_{i,j,k} - \frac{R^{n+\frac{1}{2}}_{sol\ i,j,k}}{B^{n+\frac{1}{2}}_{ol\ i,j,k}} (S'_{gl})^n_{i,j,k} \Bigg\} P^n_{lg_{i,j,k}}$$

$$+ \Bigg\{ \frac{-(S_{gl})^n_{i,j,k}}{B^{n+\frac{1}{2}}_{gl\ i,j,k}} + \frac{R^{n+\frac{1}{2}}_{sol\ i,j,k}}{B^{n+\frac{1}{2}}_{ol\ i,j,k}} (S'_{gl})^n_{i,j,k} - \frac{R^{n+\frac{1}{2}}_{sol\ i,j,k} (S'_{wl})^n_{i,j,k}}{B^{n+\frac{1}{2}}_{ol\ i,j,k}}$$

$$+ R^{n+\frac{1}{2}}_{sol\ i,j,k} \left(1 - S^{n+\frac{1}{2}}_{gl_{i,j,k}} - S^{n+\frac{1}{2}}_{wl_{i,j,k}}\right) \left(\frac{1}{B_{ol}} \right)'^{n+\frac{1}{2}}_{i,j,k}$$

$$+ \left(1 - S^{n+\frac{1}{2}}_{gl_{i,j,k}} - S^{n+\frac{1}{2}}_{wl_{i,j,k}}\right) \frac{1}{B^{n+\frac{1}{2}}_{ol}} (R'_{sol})^{n+\frac{1}{2}}_{i,j,k} \Bigg\} P^n_{lo\ i,j,k}$$

$$+ \frac{R^{n+\frac{1}{2}}_{sol\ i,j,k}}{B^{n+\frac{1}{2}}_{ol\ i,j,k}} (S'_{wl})^n_{i,j,k} P^n_{lw\ i,j,k} \Bigg]$$

$$- \frac{V_B(\rho_{gl})^{n+\frac{1}{2}}_{i,j,k}}{\Delta x} \frac{g}{g_c} \sin\alpha [(\frac{K_1 k_{rlg}}{B_{gl}\mu_{gl}})^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} - (\frac{K_1 k_{rlg}}{B_{gl}\mu_{gl}})^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k}]$$

$$- \frac{V_B}{\Delta x} (\rho_{ol})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\alpha [(\frac{R_{sol} K_1 k_{rlo}}{B_{ol}\mu_{ol}})^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} - (\frac{R_{sol} K_1 k_{rlo}}{B_{ol}\mu_{ol}})^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k}]$$

$$- \frac{V_B}{\Delta y} (\rho_{gl})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\beta [(\frac{K_1 k_{rlg}}{B_{gl}\mu_{gl}})^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} - (\frac{K_1 k_{rlg}}{B_{gl}\mu_{gl}})^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k}]$$

$$- \frac{V_B}{\Delta y} (\rho_{ol})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\beta [(\frac{R_{sol} K_1 k_{rlo}}{B_{ol}\mu_{ol}})^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} - (\frac{R_{sol} K_1 k_{rlo}}{B_{ol}\mu_{ol}})^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k}]$$

$$- \frac{V_B}{\Delta z} (\rho_{gl})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \cos\gamma [(\frac{K_1 k_{rlg}}{B_{gl}\mu_{gl}})^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} - (\frac{K_1 k_{rlg}}{B_{gl}\mu_{gl}})^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}}]$$

$$- \frac{V_B}{\Delta z} (\rho_{ol})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \cos\gamma [(\frac{R_{sol} K_1 k_{rlo}}{B_{ol}\mu_{ol}})^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} - (\frac{R_{sol} K_1 k_{rlo}}{B_{ol}\mu_{ol}})^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}}]$$

<u>Water Equation in Fracture</u> ($B_{wf}=1$ when water is incompressible)

$$FGW1_{i,j,k} = \frac{V_B}{4\Delta y \Delta z} [(\frac{K_{yz} k_{rwf}}{B_{wf}\mu_{wf}})^{n+\frac{1}{2}}_{i,j-1,k} + (\frac{K_{zy} k_{rwf}}{B_{wf}\mu_{wf}})^{n+\frac{1}{2}}_{i,j,k-1}]$$

$$FGW2_{i,j,k} = \frac{V_B}{4\Delta x \Delta z} [(\frac{K_{xz} k_{rwf}}{B_{wf}\mu_{wf}})^{n+\frac{1}{2}}_{i-1,j,k} + (\frac{K_{zx} k_{rwf}}{B_{wf}\mu_{wf}})^{n+\frac{1}{2}}_{i,j,k-1}]$$

$$FGW3_{i,j,k} = \frac{V_B}{\Delta z^2} (\frac{K_{zz} k_{rwf}}{B_{wf}\mu_{wf}})^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}}$$

$$FGW4_{i,j,k} = \frac{-V_B}{4\Delta x \Delta z} [(\frac{K_{xz} k_{rwf}}{B_{wf}\mu_{wf}})^{n+\frac{1}{2}}_{i+1,j,k} + (\frac{K_{zx} k_{rwf}}{B_{wf}\mu_{wf}})^{n+\frac{1}{2}}_{i,j,k-1}]$$

$$FGW5_{i,j,k} = \frac{-V_B}{4\Delta y \Delta z} [(\frac{K_{yz} k_{rwf}}{B_{wf}\mu_{wf}})^{n+\frac{1}{2}}_{i,j+1,k} + (\frac{K_{zy} k_{rwf}}{B_{wf}\mu_{wf}})^{n+\frac{1}{2}}_{i,j,k-1}]$$

$$FEW1_{i,j,k} = \frac{V_B}{4\Delta x\Delta y}\left[\left(\frac{K_{xy}k_{rwf}}{B_{wf}\mu_{wf}}\right)^{n+\frac{1}{2}}_{i-1,j,k} + \left(\frac{K_{yx}k_{rwf}}{B_{wf}\mu_{wf}}\right)^{n+\frac{1}{2}}_{i,j-1,k}\right]$$

$$FEW2_{i,j,k} = \frac{V_B}{\Delta y^2}\left(\frac{K_{yy}k_{rwf}}{B_{wf}\mu_{wf}}\right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k}$$

$$FEW3_{i,j,k} = \frac{V_B}{4\Delta x\Delta y}\left[\left(\frac{K_{xy}k_{rwf}}{B_{wf}\mu_{wf}}\right)^{n+\frac{1}{2}}_{i+1,j,k} + \left(\frac{K_{yx}k_{rwf}}{B_{wf}\mu_{wf}}\right)^{n+\frac{1}{2}}_{i,j-1,k}\right]$$

$$FAW1_{i,j,k} = \frac{V_B}{\Delta x^2}\left(\frac{K_{xx}k_{rwf}}{B_{wf}\mu_{wf}}\right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k}$$

$$\begin{aligned}FBW_{i,j,k} = -V_B\Bigg[&\frac{1}{\Delta x^2}\left(\frac{K_{xx}k_{rwf}}{B_{wf}\mu_{wf}}\right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} + \frac{1}{\Delta x^2}\left(\frac{K_{xx}k_{rwf}}{B_{wf}\mu_{wf}}\right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k}\\ &+ \frac{1}{\Delta y^2}\left(\frac{K_{yy}k_{rwf}}{B_{wf}\mu_{wf}}\right)^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} + \frac{1}{\Delta y^2}\left(\frac{K_{yy}k_{rwf}}{B_{wf}\mu_{wf}}\right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k}\\ &+ \frac{1}{\Delta z^2}\left(\frac{K_{zz}k_{rwf}}{B_{wf}\mu_{wf}}\right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} + \frac{1}{\Delta z^2}\left(\frac{K_{zz}k_{rwf}}{B_{wf}\mu_{wf}}\right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}}\\ &+ \frac{(\phi_f)^n_{i,j,k}}{r_H l}\left(\frac{K_l k_{rlw}}{B_{wl}\mu_{wl}}\right)^{n+\frac{1}{2}}_{i,j,k} - \frac{(\phi_f)^n_{i,j,k}}{\Delta t\, B^{n+\frac{1}{2}}_{wf_{i,j,k}}}(S'_{wf})^n_{i,j,k}\\ &+ \frac{(\phi_f)^n_{i,j,k}}{\Delta t} S^{n+\frac{1}{2}}_{wf\ i,j,k}\left(\frac{1}{B_{wf}}\right)'^{n+\frac{1}{2}}_{i,j,k}\Bigg]^*\end{aligned}$$

$$FCW1_{i,j,k} = \frac{V_B}{\Delta x^2}\left(\frac{K_{xx}k_{rwf}}{B_{wf}\mu_{wf}}\right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k}$$

$$FFW1_{i,j,k} = -\frac{V_B}{4\Delta x\Delta y}\left[\left(\frac{K_{xy}k_{rwf}}{B_{wf}\mu_{wf}}\right)^{n+\frac{1}{2}}_{i-1,j,k} + \left(\frac{K_{yx}k_{rwf}}{B_{wf}\mu_{wf}}\right)^{n+\frac{1}{2}}_{i,j+1,k}\right]$$

$$FFW2_{i,j,k} = \frac{V_B}{\Delta y^2}\left(\frac{K_{yy}k_{rwf}}{B_{wf}\mu_{wf}}\right)^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k}$$

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*This term is zero when water is incompressible.

$$FFW3_{i,j,k} = \frac{V_B}{4\Delta x\Delta y} \left[\left(\frac{K_{xy}k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i+1,j,k} + \left(\frac{K_{yx}k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j+1,k}\right]$$

$$FHW1_{i,j,k} = \frac{-V_B}{4\Delta y\Delta z} \left[\left(\frac{K_{yz}k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j-1,k} + \left(\frac{K_{zy}k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j,k+1}\right]$$

$$FHW2_{i,j,k} = \frac{-V_B}{4\Delta x\Delta z} \left[\left(\frac{K_{xz}k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i-1,j,k} + \left(\frac{K_{zx}k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j,k+1}\right]$$

$$FHW3_{i,j,k} = \frac{V_B}{\Delta z^2} \left(\frac{K_{zz}k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}}$$

$$FHW4_{i,j,k} = \frac{V_B}{4\Delta x\Delta z} \left[\left(\frac{K_{xz}k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i+1,j,k} + \left(\frac{K_{zx}k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j,k+1}\right]$$

$$FHW5_{i,j,k} = \frac{V_B}{4\Delta y\Delta z} \left[\left(\frac{K_{yz}k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j+1,k} + \left(\frac{K_{zy}k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j,k+1}\right]$$

$$FRW_{i,j,k} = \frac{V_B(\phi_f)^n_{i,j,k}}{r_H l} \left(\frac{K_l k_{rlw}}{B_{wl}\mu_{wl}} \right)^{n+\frac{1}{2}}_{i,j,k}$$

$$FUW_{i,j,k} = \frac{-V_B(\phi_f)^n_{i,j,k}}{\Delta t\, B^{n+\frac{1}{2}}_{wf_{i,j,k}}} (S'_{wf})^n_{i,j,k}$$

$$\begin{aligned}
DFW_{i,j,k} = {} & (q_{wsf})_{i,j,k} - \frac{V_B(\phi_f)^n_{i,j,k}}{\Delta t\, B^{n+\frac{1}{2}}_{wf_{i,j,k}}}(S'_{wf})^n_{i,j,k}(P^n_{fo\ i,j,k} \\
& - P^n_{fw\ i,j,k}) - \frac{V_B(\phi_f)^n_{i,j,k}}{\Delta t} S^{n+\frac{1}{2}}_{wf\ i,j,k} \left(\frac{1}{B_{wf}} \right)'^{n+\frac{1}{2}}_{i,j,k} P^n_{fw_{i,j,k}}{}^{*} \\
& - \frac{V_B}{2\Delta x\, g_c} \left(\frac{\rho_{wf}K_{xx}k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j,k} \left[\left(\frac{\partial V_{fwx}}{\partial t} \right)^n_{i+1,j,k} - \left(\frac{\partial V_{fwx}}{\partial t} \right)^n_{i-1,j,k}\right] \\
& - \frac{V_B(\rho_{wf})^{n+\frac{1}{2}}_{i,j,k}}{\Delta x} \frac{g}{g_c} \sin\alpha\left[\left(\frac{K_{xx}k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} - \left(\frac{K_{xx}k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k}\right]
\end{aligned}$$

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*This term is zero when water is assumed incompressible.

$$- \frac{V_B}{2\Delta x\, g_c} \left(\frac{\rho_{wf} K_{xy} k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j,k} \left[\left(\frac{\partial V_{fwy}}{\partial t} \right)^{n}_{i+1,j,k} - \left(\frac{\partial V_{fwy}}{\partial t} \right)^{n}_{i-1,j,k} \right]$$

$$- \frac{V_B}{\Delta x} (\rho_{wf})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\beta \left[\left(\frac{K_{xy} k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} - \left(\frac{K_{xy} k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k} \right]$$

$$- \frac{V_B}{2\Delta x\, g_c} \left(\frac{\rho_{wf} K_{xz} k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j,k} \left[\left(\frac{\partial V_{fwz}}{\partial t} \right)^{n}_{i+1,j,k} - \left(\frac{\partial V_{fwz}}{\partial t} \right)^{n}_{i-1,j,k} \right]$$

$$- \frac{V_B}{\Delta x} (\rho_{wf})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \cos\gamma \left[\left(\frac{K_{xz} k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} - \left(\frac{K_{xz} k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k} \right]$$

$$- \frac{V_B}{2\Delta y\, g_c} \left(\frac{\rho_{wf} K_{yx} k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j,k} \left[\left(\frac{\partial V_{fwx}}{\partial t} \right)^{n}_{i,j+1,k} - \left(\frac{\partial V_{fwx}}{\partial t} \right)^{n}_{i,j-1,k} \right]$$

$$- \frac{V_B}{\Delta y} (\rho_{wf})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\alpha \left[\left(\frac{K_{yx} k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} - \left(\frac{K_{yx} k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k} \right]$$

$$- \frac{V_B}{2\Delta y\, g_c} \left(\frac{K_{yy} k_{rwf} \rho_{wf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j,k} \left[\left(\frac{\partial V_{fwy}}{\partial t} \right)^{n}_{i,j+1,k} - \left(\frac{\partial V_{fwy}}{\partial t} \right)^{n}_{i,j-1,k} \right]$$

$$- \frac{V_B}{\Delta y} \frac{g}{g_c} (\rho_{wf})^{n+\frac{1}{2}}_{i,j,k} \sin\beta \left[\left(\frac{K_{yy} k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} - \left(\frac{K_{yy} k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k} \right]$$

$$- \frac{V_B}{2\Delta y\, g_c} \left(\frac{\rho_{wf} K_{yz} k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j,k} \left[\left(\frac{\partial V_{fwz}}{\partial t} \right)^{n}_{i,j+1,k} - \left(\frac{\partial V_{fwz}}{\partial t} \right)^{n}_{i,j-1,k} \right]$$

$$- \frac{V_B}{\Delta y} (\rho_{wf})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \cos\gamma \left[\left(\frac{K_{yz} k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} - \left(\frac{K_{yz} k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k} \right]$$

$$- \frac{V_B}{2\Delta z\, g_c} \left(\frac{\rho_{wf} K_{zx} k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j,k} \left[\left(\frac{\partial V_{fwx}}{\partial t} \right)^{n}_{i,j,k+1} - \left(\frac{\partial V_{fwx}}{\partial t} \right)^{n}_{i,j,k-1} \right]$$

$$- \frac{V_B}{\Delta z} (\rho_{wf})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\alpha\left[\left(\frac{K_{zx}k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} - \left(\frac{K_{zx}k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}} \right]$$

$$- \frac{V_B}{2\Delta z\ g_c} \left(\frac{\rho_{wf}K_{zy}k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j,k} \left[\left(\frac{\partial V_{fwy}}{\partial t} \right)^{n}_{i,j,k+1} - \left(\frac{\partial V_{fwy}}{\partial t} \right)^{n}_{i,j,k-1} \right]$$

$$- \frac{V_B}{\Delta z} (\rho_{wf})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\beta\left[\left(\frac{K_{zy}k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} - \left(\frac{K_{zy}k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}} \right]$$

$$- \frac{V_B}{2\Delta z\ g_c} \left(\frac{\rho_{wf}K_{zz}k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j,k} \left[\left(\frac{\partial V_{fwz}}{\partial t} \right)^{n}_{i,j,k+1} - \left(\frac{\partial V_{fwz}}{\partial t} \right)^{n}_{i,j,k-1} \right]$$

$$- \frac{V_B}{\Delta z} (\rho_{wf})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \cos\gamma\left[\left(\frac{K_{zz}k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} - \left(\frac{K_{zz}k_{rwf}}{B_{wf}\mu_{wf}} \right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}} \right]$$

<u>Oil Equation in Fracture</u>

$$FGO1_{i,j,k} = \frac{V_B}{4\Delta y\Delta z} \left[\left(\frac{K_{yz}K_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i,j-1,k} + \left(\frac{K_{zy}k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i,j,k-1} \right]$$

$$FGO2_{i,j,k} = \frac{V_B}{4\Delta x\Delta z} \left[\left(\frac{K_{xz}k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i-1,j,k} + \left(\frac{K_{zx}k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i,j,k-1} \right]$$

$$FGO3_{i,j,k} = \frac{V_B}{\Delta z^2} \left(\frac{K_{zz}k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}}$$

$$FGO4_{i,j,k} = \frac{-V_B}{4\Delta x\Delta z} \left[\left(\frac{K_{xz}k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i+1,j,k} + \left(\frac{K_{zx}k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i,j,k-1} \right]$$

$$FGO5_{i,j,k} = \frac{-V_B}{4\Delta y\Delta z} \left[\left(\frac{K_{yz}k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i,j+1,k} + \left(\frac{K_{zy}k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i,j,k-1} \right]$$

$$FEO1_{i,j,k} = \frac{V_B}{4\Delta x\Delta y} \left[\left(\frac{K_{xy}k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i-1,j,k} + \left(\frac{K_{yx}k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i,j-1,k} \right]$$

$$FEO2_{i,j,k} = \frac{V_B}{\Delta y^2} \left(\frac{K_{yy}k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k}$$

$$FEO3_{i,j,k} = \frac{-V_B}{4\Delta x\Delta y} [(\frac{K_{yx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i+1,j,k} + (\frac{K_{yx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j-1,k}]$$

$$FAO1_{i,j,k} = \frac{V_B}{\Delta x^2} (\frac{K_{xx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k}$$

$$FBO_{i,j,k} = -V_B [\frac{1}{\Delta x^2} (\frac{K_{xx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} + \frac{1}{\Delta x^2} (\frac{K_{xx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k}$$

$$+ \frac{1}{\Delta y^2} (\frac{K_{yy}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} + \frac{1}{\Delta y^2} (\frac{K_{yy}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k}$$

$$+ \frac{1}{\Delta z^2} (\frac{K_{zz}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} + \frac{1}{\Delta z^2} (\frac{K_{zz}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}}$$

$$+ \frac{(\phi_f)^n_{i,j,k}}{r_H{}^1} (\frac{K_1k_{rlo}}{B_{ol}\mu_{ol}})^{n+\frac{1}{2}}_{i,j,k} + \frac{(\phi_f)^n_{i,j,k}}{\Delta t} \{(1-S^{n+\frac{1}{2}}_{wf\ i,j,k} -$$

$$- S^{n+\frac{1}{2}}_{gf\ i,j,k}) (\frac{1}{B_{of}})^{'n+\frac{1}{2}}_{i,j,k} - \frac{1}{B^{n+\frac{1}{2}}_{of\ i,j,k}} ((S'_{wf})^n_{i,j,k} - (S'_{gf})^n_{i,j,k})\}]$$

$$FCO1_{i,j,k} = \frac{V_B}{\Delta x^2} (\frac{K_{xx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k}$$

$$FFO1_{i,j,k} = \frac{-V_B}{4\Delta x\Delta y} [(\frac{K_{xy}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i-1,j,k} + (\frac{K_{yx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j+1,k}]$$

$$FFO2_{i,j,k} = \frac{V_B}{\Delta y^2} (\frac{K_{yy}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k}$$

$$FFO3_{i,j,k} = \frac{V_B}{4\Delta x\Delta y} [(\frac{K_{xy}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i+1,j,k} + (\frac{K_{yx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j+1,k}]$$

$$FHO1_{i,j,k} = \frac{-V_B}{4\Delta y\Delta z} [(\frac{K_{yz}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j-1,k} + (\frac{K_{zy}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j,k+1}]$$

$$FHO2_{i,j,k} = \frac{-V_B}{4\Delta x\Delta z} [(\frac{K_{xz}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i-1,j,k} + (\frac{K_{zx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j,k+1}]$$

$$FHO3_{i,j,k} = \frac{V_B}{\Delta z^2} (\frac{K_{zz}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}}$$

$$FHO4_{i,j,k} = \frac{V_B}{4\Delta x\Delta z} [(\frac{K_{xz}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i+1,j,k} + (\frac{K_{zx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j,k+1}]$$

$$FHO5_{i,j,k} = \frac{V_B}{4\Delta y\Delta z} [(\frac{K_{yz}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j+1,k} + (\frac{K_{zy}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j,k+1}]$$

$$FRO_{i,j,k} = \frac{V_B(\phi_f)^n_{i,j,k}}{r_H l} (\frac{K_l\, k_{rlo}}{B_{ol}\mu_{ol}})^{n+\frac{1}{2}}_{i,j,k}$$

$$FUO_{i,j,k} = \frac{V_B(\phi_f)^n_{i,j,k}}{\Delta t\ B^{n+\frac{1}{2}}_{of\ i,j,k}} (S'_{gf})^n_{i,j,k}$$

$$FVO_{i,j,k} = \frac{-V_B(\phi_f)^n_{i,j,k}}{\Delta t\ B^{n+\frac{1}{2}}_{of\ i,j,k}} (S'_{wf})^n_{i,j,k}$$

$$DFO_{i,j,k} = -\ (q_{osf})_{i,j,k} - \frac{V_B(\phi_f)^n_{i,j,k}}{\Delta t}$$

$$[\{(1-S^{n+\frac{1}{2}}_{wf\ i,j,k} - S^{n+\frac{1}{2}}_{gf\ i,j,k})(\frac{1}{B_{of}})^{'n+\frac{1}{2}}_{i,j,k}$$

$$- \frac{1}{B^{n+\frac{1}{2}}_{of\ i,j,k}} ((S'_{wf})^n_{i,j,k} - (S'_{gf})^n_{i,j,k})\}\ P^n_{fo\ i,j,k}$$

$$+ \frac{1}{B^{n+\frac{1}{2}}_{of\ i,j,k}} \{(S'_{wf})^n_{i,j,k}P^n_{fw\ i,j,k} - (S'_{gf})^n_{i,j,k}P^n_{fg\ i,j,k}\}\ ]$$

$$- \frac{V_B}{2\Delta x\, g_c} (\frac{\rho_{wl}K_{xx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j,k} [(\frac{\partial V_{fox}}{\partial t})^n_{i+1,j,k} - (\frac{\partial V_{fox}}{\partial t})^n_{i-1,j,k}]$$

$$- \frac{V_B(\rho_{of})^{n+\frac{1}{2}}_{i,j,k}}{\Delta x} \frac{g}{g_c} \sin\alpha[(\frac{K_{xx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} - (\frac{K_{xx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k}]$$

$$- \frac{V_B}{2\Delta x\ g_c} (\frac{\rho_{of}K_{xy}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j,k} [(\frac{\partial V_{foy}}{\partial t})^{n}_{i+1,j,k} - (\frac{\partial V_{foy}}{\partial t})^{n}_{i-1,j,k}]$$

$$- \frac{V_B}{\Delta x} (\rho_{of})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\beta[(\frac{K_{xy}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} - (\frac{K_{xy}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k}]$$

$$- \frac{V_B}{2\Delta x\ g_c} (\frac{\rho_{of}K_{xz}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j,k} [(\frac{\partial V_{foz}}{\partial t})^{n}_{i+1,j,k} - (\frac{\partial V_{foz}}{\partial t})^{n}_{i-1,j,k}]$$

$$- \frac{V_B}{\Delta x} (\rho_{of})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \cos\gamma[(\frac{K_{xz}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} - (\frac{K_{xz}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k}]$$

$$- \frac{V_B}{2\Delta y\ g_c} (\frac{\rho_{of}K_{yx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j,k} [(\frac{\partial V_{fox}}{\partial t})^{n}_{i,j+1,k} - (\frac{\partial V_{fox}}{\partial t})^{n}_{i,j-1,k}]$$

$$- \frac{V_B}{\Delta y} (\rho_{of})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\alpha[(\frac{K_{yx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} - (\frac{K_{yx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k}]$$

$$- \frac{V_B}{2\Delta y\ g_c} (\frac{\rho_{of}K_{yy}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j,k} [(\frac{\partial V_{foy}}{\partial t})^{n}_{i,j+1,k} - (\frac{\partial V_{foy}}{\partial t})^{n}_{i,j-1,k}]$$

$$- \frac{V_B}{\Delta y} (\rho_{of})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\beta[(\frac{K_{yy}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} - (\frac{K_{yy}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k}]$$

$$- \frac{V_B}{2\Delta y\ g_c} (\frac{\rho_{of}K_{yz}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j,k} [(\frac{\partial V_{foz}}{\partial t})^{n}_{i,j+1,k} - (\frac{\partial V_{foz}}{\partial t})^{n}_{i,j-1,k}]$$

$$- \frac{V_B}{\Delta y} (\rho_{of})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \cos\gamma[(\frac{K_{yz}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} - (\frac{K_{yz}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k}]$$

$$- \frac{V_B}{2\Delta z\ g_c} (\frac{\rho_{of}K_{zx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j,k} [(\frac{\partial V_{fox}}{\partial t})^{n}_{i,j,k+1} - (\frac{\partial V_{fox}}{\partial t})^{n}_{i,j,k-1}]$$

$$- \frac{V_B}{\Delta z} (\rho_{of})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\alpha \left[\left(\frac{K_{zx} k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} - \left(\frac{K_{zx} k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}} \right]$$

$$- \frac{V_B}{2\Delta z\, g_c} \left(\frac{\rho_{of} K_{zy} k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i,j,k} \left[\left(\frac{\partial V_{foy}}{\partial t} \right)^{n}_{i,j,k+1} - \left(\frac{\partial V_{foy}}{\partial t} \right)^{n}_{i,j,k-1} \right]$$

$$- \frac{V_B}{\Delta z} (\rho_{of})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\beta \left[\left(\frac{K_{zy} k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} - \left(\frac{K_{zy} k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}} \right]$$

$$- \frac{V_B}{2\Delta z\, g_c} \left(\frac{\rho_{of} K_{zz} k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i,j,k} \left[\left(\frac{\partial V_{foz}}{\partial t} \right)^{n}_{i,j,k+1} - \left(\frac{\partial V_{foz}}{\partial t} \right)^{n}_{i,j,k-1} \right]$$

$$- \frac{V_B}{\Delta z} (\rho_{of})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \cos\gamma \left[\left(\frac{K_{zz} k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} - \left(\frac{K_{zz} k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}} \right]$$

<u>Gas Equation in fracture</u>

$$FGG1_{i,j,k} = \frac{V_B}{4\Delta y \Delta z} \left[\left(\frac{K_{yz} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j-1,k} + \left(\frac{K_{zy} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j,k-1} \right]$$

$$FGG2_{i,j,k} = \frac{V_B}{4\Delta x \Delta z} \left[\left(\frac{K_{xz} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i-1,j,k} + \left(\frac{K_{zx} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j,k-1} \right]$$

$$FGG3_{i,j,k} = \frac{V_B}{\Delta z^2} \left(\frac{K_{zz} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}}$$

$$FGG4_{i,j,k} = \frac{-V_B}{4\Delta x \Delta z} \left[\left(\frac{K_{xz} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i+1,j,k} + \left(\frac{K_{zx} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j,k-1} \right]$$

$$FGG5_{i,j,k} = \frac{-V_B}{4\Delta y \Delta z} \left[\left(\frac{K_{yz} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j+1,k} + \left(\frac{K_{zy} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j,k-1} \right]$$

$$FEG1_{i,j,k} = \frac{V_B}{4\Delta x \Delta y} \left[\left(\frac{K_{xy} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i-1,j,k} + \left(\frac{K_{yx} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j-1,k} \right]$$

$$FEG2_{i,j,k} = \frac{V_B}{\Delta y^2} \left(\frac{K_{yy} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k}$$

$$FEG3_{i,j,k} = \frac{-V_B}{4\Delta x\Delta y}\left[\left(\frac{K_{xy}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i+1,j,k} + \left(\frac{K_{yx}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i,j-1,k}\right]$$

$$FAG1_{i,j,k} = \frac{V_B}{\Delta x^2}\left(\frac{K_{xx}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k}$$

$$\begin{aligned} FBG_{i,j,k} = -V_B \Bigg[& \frac{1}{\Delta x^2}\left(\frac{K_{xx}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} + \frac{1}{\Delta x^2}\left(\frac{K_{xx}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k} \\ & + \frac{1}{\Delta y^2}\left(\frac{K_{yy}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} + \frac{1}{\Delta y^2}\left(\frac{K_{yy}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k} \\ & + \frac{1}{\Delta z^2}\left(\frac{K_{zz}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} + \frac{1}{\Delta z^2}\left(\frac{K_{zz}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}} \\ & + \frac{(\phi_f)^n_{i,j,k}}{\Delta t}\left\{\frac{(S'_{gf})^n_{i,j,k}}{B^{n+\frac{1}{2}}_{gf\,i,j,k}} + S^{n+\frac{1}{2}}_{gf_{i,j,k}}\left(\frac{1}{B_{gf}}\right)^{\prime n+\frac{1}{2}}_{i,j,k} \right. \\ & \left. - R^{n+\frac{1}{2}}_{sof_{i,j,k}} \frac{1}{B^{n+\frac{1}{2}}_{of_{i,j,k}}}(S'_{gf})^n_{i,j,k}\right\} + \frac{(\phi_f)^n_{i,j,k}}{r_H{}^1}\left(\frac{K_1\,k_{rlg}}{B_{gl}\mu_{gl}}\right)^{n+\frac{1}{2}}_{i,j,k}\Bigg] \end{aligned}$$

$$FCG1_{i,j,k} = \frac{V_B}{\Delta x^2}\left(\frac{K_{xx}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k}$$

$$FFG1_{i,j,k} = \frac{-V_B}{4\Delta x\Delta y}\left[\left(\frac{K_{xy}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i-1,j,k} + \left(\frac{K_{yx}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i,j+1,k}\right]$$

$$FFG2_{i,j,k} = \frac{V_B}{\Delta y^2}\left(\frac{K_{yy}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k}$$

$$FFG3_{i,j,k} = \frac{V_B}{4\Delta x\Delta y}\left[\left(\frac{K_{xy}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i+1,j,k} + \left(\frac{K_{yx}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i,j+1,k}\right]$$

$$FHG1_{i,j,k} = \frac{-V_B}{4\Delta y\Delta z}\left[\left(\frac{K_{yz}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i,j-1,k} + \left(\frac{K_{zy}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i,j,k+1}\right]$$

$$FHG2_{i,j,k} = \frac{-V_B}{4\Delta x\Delta z}\left[\left(\frac{K_{xz}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i-1,j,k} + \left(\frac{K_{zx}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i,j,k+1}\right]$$

$$FHG3_{i,j,k} = \frac{V_B}{\Delta z^2}\left(\frac{K_{zz}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}}$$

$$FHG4_{i,j,k} = \frac{V_B}{4\Delta x\Delta z}\left[\left(\frac{K_{xz}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i+1,j,k} + \left(\frac{K_{zx}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i,j,k+1}\right]$$

$$FHG5_{i,j,k} = \frac{V_B}{4\Delta y\Delta z}\left[\left(\frac{K_{yz}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i,j+1,k} + \left(\frac{K_{zy}k_{rgf}}{B_{gf}\mu_{gf}}\right)^{n+\frac{1}{2}}_{i,j,k+1}\right]$$

$$FGR1_{i,j,k} = \frac{V_B}{4\Delta y\Delta z}\left[\left(\frac{R_{sof}K_{yz}k_{rof}}{B_{of}\mu_{of}}\right)^{n+\frac{1}{2}}_{i,j-1,k} + \left(\frac{R_{sof}K_{zy}k_{rof}}{B_{of}\mu_{of}}\right)^{n+\frac{1}{2}}_{i,j,k-1}\right]$$

$$FGR2_{i,j,k} = \frac{V_B}{4\Delta x\Delta z}\left[\left(\frac{R_{sof}K_{xz}k_{rof}}{B_{of}\mu_{of}}\right)^{n+\frac{1}{2}}_{i-1,j,k} + \left(\frac{R_{sof}K_{zx}k_{rof}}{B_{of}\mu_{of}}\right)^{n+\frac{1}{2}}_{i,j,k-1}\right]$$

$$FGR3_{i,j,k} = \frac{V_B}{\Delta z^2}\left(\frac{R_{sof}K_{zz}k_{rof}}{B_{of}\mu_{of}}\right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}}$$

$$FGR4_{i,j,k} = \frac{-V_B}{4\Delta x\Delta z}\left[\left(\frac{R_{sof}K_{xz}k_{rof}}{B_{of}\mu_{of}}\right)^{n+\frac{1}{2}}_{i+1,j,k} + \left(\frac{R_{sof}K_{zx}K_{rof}}{B_{of}\mu_{of}}\right)^{n+\frac{1}{2}}_{i,j,k-1}\right]$$

$$FGR5_{i,j,k} = \frac{-V_B}{4\Delta y\Delta z}\left[\left(\frac{R_{sof}K_{yz}k_{rof}}{B_{of}\mu_{of}}\right)^{n+\frac{1}{2}}_{i,j+1,k} + \left(\frac{R_{sof}K_{zy}k_{rof}}{B_{of}\mu_{of}}\right)^{n+\frac{1}{2}}_{i,j,k-1}\right]$$

$$FER1_{i,j,k} = \frac{V_B}{4\Delta x\Delta y}\left[\left(\frac{R_{sof}K_{xy}k_{rof}}{B_{of}\mu_{of}}\right)^{n+\frac{1}{2}}_{i-1,j,k} + \left(\frac{R_{sof}K_{yx}k_{rof}}{B_{of}\mu_{of}}\right)^{n+\frac{1}{2}}_{i,j-1,k}\right]$$

$$FER2_{i,j,k} = \frac{V_B}{\Delta y^2}\left(\frac{R_{sof}K_{xy}k_{rof}}{B_{of}\mu_{of}}\right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k}$$

$$FER3_{i,j,k} = \frac{-V_B}{4\Delta x\Delta y}\left[\left(\frac{R_{sof}K_{xy}k_{rof}}{B_{of}\mu_{of}}\right)^{n+\frac{1}{2}}_{i+1,j,k} + \left(\frac{R_{sof}K_{yx}k_{rof}}{B_{of}\mu_{of}}\right)^{n+\frac{1}{2}}_{i,j-1,k}\right]$$

$$FAR1_{i,j,k} = \frac{V_B}{\Delta x^2} \left(\frac{R_{sof} K_{xx} k_{rof}}{B_{of} \mu_{of}} \right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k}$$

$$FBR_{i,j,k} = -V_B \left[\frac{1}{\Delta x^2} \left(\frac{R_{sof} K_{xx} k_{rof}}{B_{of} \mu_{of}} \right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} + \frac{1}{\Delta x^2} \left(\frac{R_{sof} K_{xx} k_{rof}}{B_{of} \mu_{of}} \right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k} \right.$$

$$+ \frac{1}{\Delta y^2} \left(\frac{R_{sof} K_{yy} k_{rof}}{B_{of} \mu_{of}} \right)^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} + \frac{1}{\Delta y^2} \left(\frac{R_{sof} K_{yy} k_{rof}}{B_{of} \mu_{of}} \right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k}$$

$$+ \frac{1}{\Delta z^2} \left(\frac{R_{sof} K_{zz} k_{rof}}{B_{of} \mu_{of}} \right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} + \frac{1}{\Delta z^2} \left(\frac{R_{sof} K_{zz} k_{rof}}{B_{of} \mu_{of}} \right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}}$$

$$- \frac{(\phi_f)^n_{i,j,k}}{\Delta t} \left\{ \frac{(S'_{gf})^n_{i,j,k}}{B^{n+\frac{1}{2}}_{gf\ i,j,k}} + \frac{R^{n+\frac{1}{2}}_{sof\ i,j,k}}{B^{n+\frac{1}{2}}_{of\ i,j,k}} \left((S'_{wf})^n_{i,j,k} - (S'_{gf})^n_{i,j,k} \right) \right.$$

$$\left. - (1 - S^{n+\frac{1}{2}}_{wf\ i,j,k} - S^{n+\frac{1}{2}}_{gf\ i,j,k}) \left(\frac{(R'_{sof})^{n+\frac{1}{2}}_{i,j,k}}{B^{n+\frac{1}{2}}_{of\ i,j,k}} + R^{n+\frac{1}{2}}_{sof\ i,j,k} \left(\frac{1}{B_{of}} \right)'^{\,n+\frac{1}{2}}_{i,j,k} \right) \right\}$$

$$\left. + \frac{(\phi_f)^n_{i,j,k}}{r_H l} \left(\frac{K_l k_{rlo} R_{sol}}{B_{ol} \mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j,k} \right]$$

$$FCR1_{i,j,k} = \frac{V_B}{\Delta x^2} \left(\frac{R_{sof} K_{xx} k_{rof}}{B_{of} \mu_{of}} \right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k}$$

$$FFR1_{i,j,k} = \frac{-V_B}{4\Delta x \Delta y} \left[\left(\frac{R_{sof} K_{xy} k_{rof}}{B_{of} \mu_{of}} \right)^{n+\frac{1}{2}}_{i-1,j,k} + \left(\frac{R_{sof} K_{yx} k_{rof}}{B_{of} \mu_{of}} \right)^{n+\frac{1}{2}}_{i,j+1,k} \right]$$

$$FFR2_{i,j,k} = \frac{V_B}{\Delta y^2} \left(\frac{R_{sof} K_{yy} k_{rof}}{B_{of} \mu_{of}} \right)^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k}$$

$$FFR3_{i,j,k} = \frac{V_B}{4\Delta x \Delta y} \left[\left(\frac{R_{sof} K_{xy} k_{rof}}{B_{of} \mu_{of}} \right)^{n+\frac{1}{2}}_{i+1,j,k} + \left(\frac{R_{sof} K_{yx} k_{rof}}{B_{of} \mu_{of}} \right)^{n+\frac{1}{2}}_{i,j+1,k} \right]$$

$$FHR1_{i,j,k} = \frac{-V_B}{4\Delta y \Delta z} \left[\left(\frac{R_{sof} K_{yz} k_{rof}}{B_{of} \mu_{of}} \right)^{n+\frac{1}{2}}_{i,j-1,k} + \left(\frac{R_{sof} K_{zy} k_{rof}}{B_{of} \mu_{of}} \right)^{n+\frac{1}{2}}_{i,j,k+1} \right]$$

$$FHR2_{i,j,k} = \frac{-V_B}{4\Delta x \Delta z} \left[\left(\frac{R_{sof} K_{xz} k_{rof}}{B_{of} \mu_{of}} \right)^{n+\frac{1}{2}}_{i-1,j,k} + \left(\frac{R_{sof} K_{zx} k_{rof}}{B_{of} \mu_{of}} \right)^{n+\frac{1}{2}}_{i,j,k+1} \right]$$

$$FHR3_{i,j,k} = \frac{V_B}{\Delta z^2} \left(\frac{R_{sof}K_{zz}k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}}$$

$$FHR4_{i,j,k} = \frac{V_B}{4\Delta x\Delta z} \left[\left(\frac{R_{sof}K_{xz}k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i+1,j,k} + \left(\frac{R_{sof}K_{zx}k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i,j,k+1} \right]$$

$$FHR5_{i,j,k} = \frac{V_B}{4\Delta y\Delta z} \left[\left(\frac{R_{sof}K_{yz}k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i,j+1,k} + \left(\frac{R_{sof}K_{zy}k_{rof}}{B_{of}\mu_{of}} \right)^{n+\frac{1}{2}}_{i,j,k+1} \right]$$

$$FRG_{i,j,k} = \frac{V_B(\phi_f)^n_{i,j,k}}{r_H l} \left(\frac{K_l k_{rlg}}{B_{gl}\mu_{gl}} \right)^{n+\frac{1}{2}}_{i,j,k}$$

$$FRGO_{i,j,k} = \frac{V_B(\phi_f)^n_{i,j,k}}{r_H l} \left(\frac{K_l k_{rlo} R_{sol}}{B_{ol}\mu_{ol}} \right)^{n+\frac{1}{2}}_{i,j,k}$$

$$FVG_{i,j,k} = \frac{-V_B(\phi_f)^n_{i,j,k}}{\Delta t} \frac{R^{n+\frac{1}{2}}_{sof\ i,j,k}}{B^{n+\frac{1}{2}}_{of\ i,j,k}} (S'_{wf})^n_{i,j,k}$$

$$\begin{aligned}
DFG_{i,j,k} = &- (q_{Gsf}) - \frac{(\phi_f)^n_{i,j,k} V_B}{\Delta t} \Bigg[\Bigg\{ \frac{(S'_{gf})^n_{i,j,k}}{B^{n+\frac{1}{2}}_{gf\ i,j,k}} \\
&+ S^{n+\frac{1}{2}}_{gf\ i,j,k} \left(\frac{1}{B_{of}} \right)'^{\,n+\frac{1}{2}}_{i,j,k} - \frac{R^{n+\frac{1}{2}}_{sof\ i,j,k}}{B^{n+\frac{1}{2}}_{of\ i,j,k}} (S'_{gf})^n_{i,j,k} \Bigg\} P^n_{fg\ i,j,k} \\
&- \Bigg\{ \frac{(S'_{gf})^n_{i,j,k}}{B^{n+\frac{1}{2}}_{gf\ i,j,k}} + \frac{R^{n+\frac{1}{2}}_{sof\ i,j,k}}{B^{n+\frac{1}{2}}_{of\ i,j,k}} \left((S'_{wf})^n - (S'_{gf})^n_{i,j,k} \right) \\
&- \left(1 - S^{n+\frac{1}{2}}_{wf\ i,j,k} - S^{n+\frac{1}{2}}_{gf\ i,j,k}\right) \left(\frac{(R'_{sof})^{n+\frac{1}{2}}_{i,j,k}}{B^{n+\frac{1}{2}}_{of\ i,j,k}} + R^{n+\frac{1}{2}}_{sof\ i,j,k} \left(\frac{1}{B_{of}} \right)'^{\,n+\frac{1}{2}}_{i,j,k} \right) \Bigg\} \\
&P^n_{fo\ i,j,k} + \frac{R^{n+\frac{1}{2}}_{sof\ i,j,k}}{B^{n+\frac{1}{2}}_{of\ i,j,k}} (S'_{wf})^n_{i,j,k} P^n_{fw\ i,j,k} \Bigg] \\
&- \frac{V_B}{2\Delta x\, g_c} \left(\frac{\rho_{gf} K_{xx} k_{rgf}}{B_{gl}\mu_{gl}} \right)^{n+\frac{1}{2}}_{i,j,k} \left[\left(\frac{\partial V_{fgx}}{\partial t} \right)^n_{i+1,j,k} - \left(\frac{\partial V_{fgx}}{\partial t} \right)^n_{i-1,j,k} \right] \\
&- \frac{V_B}{\Delta x} (\rho_{gf})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\alpha \left[\left(\frac{K_{xx} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} - \left(\frac{K_{xx} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k} \right]
\end{aligned}$$

$$- \frac{-V_B}{2\Delta x\, g_c} \left(\frac{\rho_{gf} K_{xy} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j,k} \left[\left(\frac{\partial V_{fgy}}{\partial t} \right)^{n}_{i+1,j,k} - \left(\frac{\partial V_{fgy}}{\partial t} \right)^{n}_{i-1,j,k} \right]$$

$$- \frac{V_B}{\Delta x} (\rho_{gf})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\beta \left[\left(\frac{K_{xy} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} - \left(\frac{K_{xy} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k} \right]$$

$$- \frac{V_B}{2\Delta x\, g_c} \left(\frac{\rho_{gf} K_{xz} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j,k} \left[\left(\frac{\partial V_{fgz}}{\partial t} \right)^{n}_{i+1,j,k} - \left(\frac{\partial V_{fgz}}{\partial t} \right)^{n}_{i-1,j,k} \right]$$

$$- \frac{V_B}{\Delta x} (\rho_{gf})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \cos\gamma \left[\left(\frac{K_{xz} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} - \left(\frac{K_{xz} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k} \right]$$

$$- \frac{V_B}{2\Delta y\, g_c} \left(\frac{\rho_{gf} K_{yx} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j,k} \left[\left(\frac{\partial V_{fgx}}{\partial t} \right)^{n}_{i,j+1,k} - \left(\frac{\partial V_{fgx}}{\partial t} \right)^{n}_{i,j-1,k} \right]$$

$$- \frac{V_B}{\Delta y} (\rho_{gf})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\alpha \left[\left(\frac{K_{yx} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} - \left(\frac{K_{yx} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k} \right]$$

$$- \frac{V_B}{2\Delta y\, g_c} \left(\frac{\rho_{gf} K_{yy} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j,k} \left[\left(\frac{\partial V_{fgy}}{\partial t} \right)^{n}_{i,j+1,k} - \left(\frac{\partial V_{fgy}}{\partial t} \right)^{n}_{i,j-1,k} \right]$$

$$- \frac{V_B}{\Delta y} (\rho_{gf})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\beta \left[\left(\frac{k_{yy} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} - \left(\frac{K_{yy} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k} \right]$$

$$- \frac{V_B}{2\Delta y\, g_c} \left(\frac{\rho_{gf} K_{yz} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j,k} \left[\left(\frac{\partial V_{fgz}}{\partial t} \right)^{n}_{i,j+1,k} - \left(\frac{\partial V_{fgz}}{\partial t} \right)^{n}_{i,j-1,k} \right]$$

$$- \frac{V_B}{\Delta y} (\rho_{gf})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \cos\gamma \left[\left(\frac{K_{yz} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} - \left(\frac{K_{yz} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k} \right]$$

$$- \frac{V_B}{2\Delta z\, g_c} \left(\frac{\rho_{gf} K_{zx} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j,k} \left[\left(\frac{\partial V_{fgx}}{\partial t} \right)^{n}_{i,j,k+1} - \left(\frac{\partial V_{fgx}}{\partial t} \right)^{n}_{i,j,k-1} \right]$$

$$- \frac{V_B}{\Delta z} (\rho_{gf})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\alpha \left[\left(\frac{K_{zx} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} - \left(\frac{K_{zx} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}} \right]$$

$$- \frac{V_B}{2\Delta z\, g_c} \left(\frac{\rho_{gf} K_{zy} k_{rgf}}{B_{gf}\mu_{gf}} \right)^{n+\frac{1}{2}}_{i,j,k} \left[\left(\frac{\partial V_{fgy}}{\partial t} \right)^{n}_{i,j,k+1} - \left(\frac{\partial V_{fgy}}{\partial t} \right)^{n}_{i,j,k-1} \right]$$

$$- \frac{V_B}{\Delta z} (\rho_{gf})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\beta[(\frac{K_{zy}k_{rgf}}{B_{gf}\mu_{gf}})^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} - (\frac{K_{zy}k_{rgf}}{B_{gf}\mu_{gf}})^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}}]$$

$$- \frac{V_B}{2\Delta z\ g_c} (\frac{\rho_{gf}K_{zz}k_{rgf}}{B_{gf}\mu_{gf}})^{n+\frac{1}{2}}_{i,j,k} [(\frac{\partial V_{fgz}}{\partial t})^{n}_{i,j,k+1} - (\frac{\partial V_{fgz}}{\partial t})^{n}_{i,j,k-1}]$$

$$- \frac{V_B}{\Delta z} (\rho_{gf})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \cos\gamma[(\frac{K_{zz}k_{rgf}}{B_{gf}\mu_{gf}})^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} - (\frac{K_{zz}k_{rgf}}{B_{gf}\mu_{gf}})^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}}]$$

$$- \frac{V_B}{2\Delta x\ g_c} (\frac{\rho_{of}R_{sof}K_{xx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j,k} [(\frac{\partial V_{fox}}{\partial t})^{n}_{i+1,j,k} - (\frac{\partial V_{fox}}{\partial t})^{n}_{i-1,j,k}]$$

$$- \frac{V_B}{\Delta x} (\rho_{of})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\alpha[(\frac{R_{sof}K_{xx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} - (\frac{R_{sof}K_{xx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k}]$$

$$- \frac{V_B}{2\Delta x\ g_c} (\frac{\rho_{of}R_{sof}K_{xy}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j,k} [(\frac{\partial V_{foy}}{\partial t})^{n}_{i+1,j,k} - (\frac{\partial V_{foy}}{\partial t})^{n}_{i-1,j,k}]$$

$$- \frac{V_B}{\Delta x} (\rho_{of})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\beta[(\frac{R_{sof}K_{xy}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} - (\frac{R_{sof}K_{xy}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k}]$$

$$- \frac{V_B}{2\Delta x\ g_c} (\frac{\rho_{of}R_{sof}K_{xz}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j,k} [(\frac{\partial V_{foz}}{\partial t})^{n}_{i+1,j,k} - (\frac{\partial V_{foz}}{\partial t})^{n}_{i-1,j,k}]$$

$$- \frac{V_B}{\Delta x} (\rho_{of})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \cos\gamma[(\frac{R_{sof}K_{xz}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} - (\frac{R_{sof}K_{xz}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k}]$$

$$- \frac{V_B}{2\Delta y\ g_c} (\frac{\rho_{of}R_{sof}K_{yx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j,k} [(\frac{\partial V_{fox}}{\partial t})^{n}_{i,j+1,k} - (\frac{\partial V_{fox}}{\partial t})^{n}_{i,j-1,k}]$$

$$- \frac{V_B}{\Delta y} (\rho_{of})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\alpha[(\frac{R_{sof}K_{yx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} - (\frac{R_{sof}K_{yx}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k}]$$

$$- \frac{V_B}{2\Delta y\ g_c} (\frac{\rho_{of}R_{sof}K_{yy}k_{rof}}{B_{of}\mu_{of}})^{n+\frac{1}{2}}_{i,j,k} [(\frac{\partial V_{foy}}{\partial t})^{n}_{i,j+1,k} - (\frac{\partial V_{foy}}{\partial t})^{n}_{i,j-1,k}]$$

$$- \frac{V_B}{\Delta y} (\rho_{of})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\beta [(\frac{R_{sof} K_{yy} k_{rof}}{B_{of} \mu_{of}})^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} - (\frac{R_{sof} K_{yy} k_{rof}}{B_{of} \mu_{of}})^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k}]$$

$$- \frac{V_B}{2\Delta y\, g_c} (\frac{\rho_{of} R_{sof} K_{yz} k_{rof}}{B_{of} \mu_{of}})^{n+\frac{1}{2}}_{i,j,k} [(\frac{\partial V_{foz}}{\partial t})^{n}_{i,j+1,k} - (\frac{\partial V_{foz}}{\partial t})^{n}_{i,j-1,k}]$$

$$- \frac{V_B}{\Delta y} (\rho_{of})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \cos\gamma [(\frac{R_{sof} K_{yz} k_{rof}}{B_{of} \mu_{of}})^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} - (\frac{R_{sof} K_{yz} k_{rof}}{B_{of} \mu_{of}})^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k}]$$

$$- \frac{V_B}{2\Delta z\, g_c} (\frac{\rho_{of} R_{sof} K_{zx} k_{rof}}{B_{of} \mu_{of}})^{n+\frac{1}{2}}_{i,j,k} [(\frac{\partial V_{fox}}{\partial t})^{n}_{i,j,k+1} - (\frac{\partial V_{fox}}{\partial t})^{n}_{i,j,k-1}]$$

$$- \frac{V_B}{\Delta z} (\rho_{of})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\alpha [(\frac{R_{sof} K_{zx} k_{rof}}{B_{of} \mu_{of}})^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} - (\frac{R_{sof} K_{zx} k_{rof}}{B_{of} \mu_{of}})^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}}]$$

$$- \frac{V_B}{2\Delta z\, g_c} (\frac{\rho_{of} R_{sof} K_{zy} k_{rof}}{B_{of} \mu_{of}})^{n+\frac{1}{2}}_{i,j,k} [(\frac{\partial V_{foy}}{\partial t})^{n}_{i,j,k+1} - (\frac{\partial V_{foy}}{\partial t})^{n}_{i,j,k-1}]$$

$$- \frac{V_B}{\Delta z} (\rho_{of})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \sin\beta [(\frac{R_{sof} K_{zy} k_{rof}}{B_{of} \mu_{of}})^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} - (\frac{R_{sof} K_{zy} k_{rof}}{B_{of} \mu_{of}})^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}}]$$

$$- \frac{V_B}{2\Delta z\, g_c} (\frac{\rho_{of} R_{sof} K_{zz} k_{rof}}{B_{of} \mu_{of}})^{n+\frac{1}{2}}_{i,j,k} [(\frac{\partial V_{foz}}{\partial t})^{n}_{i,j,k+1} - (\frac{\partial V_{foz}}{\partial t})^{n}_{i,j,k-1}]$$

$$- \frac{V_B}{\Delta z} (\rho_{of})^{n+\frac{1}{2}}_{i,j,k} \frac{g}{g_c} \cos\gamma [(\frac{R_{sof} K_{zz} k_{rof}}{B_{of} \mu_{of}})^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} - (\frac{R_{sof} K_{zz} k_{rof}}{B_{of} \mu_{of}})^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}}]$$

APPENDIX D

DATA PREPARATION

The instructions for preparing input data for this simulation program are given below. The data cards must be read in the following order of subroutines.

Set 1. RESDIM

Set 2. RESDAT

Set 3. INCON

Set 4. CODE

Set 5. MAIN PROGRAM

An example of input data arrangement is given in Appendix E.

Set 1. Input data for subroutine RESDIM

1. Title card _ _ _ _ _ _ _ _ _ _ _ _ _ FORMAT (40A2)

2. Grid sizes and reservoir dimensions_ _ _ _ _FORMAT (3I5,3F10·0)

NX	cols 1-5	Number of grid points in X-direction
NY	6-10	Number of grid points in Y-direction
NZ	11-15	Number of grid points in Z-direction
XL	16-25	Reservoir length (feet)
YL	26-35	Reservoir width (feet)
ZL	36-45	Reservoir thickness (feet)

3. Fracture half width _ _ _ _ _ _ _ _ FORMAT (F10.0)

WF cols 1-10 Fracture half width (feet)

Set 2. Input data for subroutine RESDAT

1. Title card _ _ _ _ _ _ _ _ _ _ _ _ FORMAT (40A2)
2. Code numbers for rock matrix porosity and permeability_____FORMAT (2I5)

   KPHIL cols 1-5 Code number for rock matrix porosity

   KPERL 6-10 Code number for rock matrix permeability

   If KPHIL = 0, porosity is uniform throughout the reservoir.

   If KPERL = 0, permeability is uniform throughout the reservoir.
3. Title card (if KPHIL = 0)_ _ _ _ FORMAT (40A2)
4. Rock matrix porosity (if KPHIL = 0)_ _ _ FORMAT (F10.0)

   PHIL cols 1-10 Uniform rock matrix porosity (fraction)
5. Title card (if KPHIL ≠ 0)_ _ _ _ FORMAT (40A2)
6. Porosity distribution in rock matrix (if KPHIL ≠ 0) _ _ _ _ _ _ FORMAT (10F7.0)

   PHI (I,J,K) cols 1-7 Porosity distribution for the
   8-14 J'th row. NX values must be
   15-21 read -- continue on additional
   ---- cards if necessary. The row
   ---- order must be NY, NY-1, NY-2,
   -- ----1. The layer order must
   64-70 be NZ, NZ-1, NZ-2, ----1.

Note: New row or layer has to be started on a new card.

6. Title card (if KPERL = 0) _ _ _ _ _ FORMAT(40A2)

7. Rock matrix permeability (if KPERL = 0)_ _ FORMAT (F10.0)

PERL cols. 1-10 Uniform rock matrix permeability (md.)

8. Title card (if KPERL ≠ 0) _ _ _ _ _ _FORMAT(40A2)

9. Permeability distribution in rock matrix (if KPERL ≠ 0) _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ FORMAT(10F7.0)

KL(I,J,K) cols	1-7	Permeability distribution for
	8-14	the J'th row. NX values must
	15-21	be read -- continue on addi-
	---	tional cards if necessary.
	---	The row order must be NY, NY-1,
	---	NY-2, ...1. The layer order
	64-70	must be NZ, NZ-1, NZ-2, ...1.

Note: New row or layer has to be started on a new card.

10. Title card _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ FORMAT(40A2)

11. Code numbers for fracture porosity and permeability _ _ _ _ _ FORMAT(2I5)

KPHIF cols 1-5 Code number for rock matrix porosity

NUMKF cols 6-10 Code number for fracture permeability.

Note: For uniform distributions KPHIF = 0/NUMKF = 0. As for permeability tensor, if not uniform (NUMKF ≠ 0), one set of tensor values will be assigned to all nodes; then NUMKF sets of permeability tensor will be read for nodes that are different.

12. Title card (if KPHIF = 0) _ _ _ _ _ _ FORMAT(40A2)

13. Fracture porosity (if KPHIF = 0) _ _ _ FORMAT(F10.0)

    PHIF cols 1-10 Uniform fracture porosity (fraction)

14. Title card (if KPHIF ≠ 0) _ _ _ _ _ _ FORMAT(40A2)

15. Porosity distribution in fracture (if KPHIF ≠ 0) _ _ _ _ _ _ FORMAT(10F7.0)

FPHI(I,J,K)	cols	1-7	Porosity distribution for
		8-14	the J'th row. NX values
		---	must be read -- continue on
		---	additional cards if necessary.
		---	The row order must be NY, NY-1,
		---	NY-2, ...1. The layer order
		---	must be NZ, NZ-1, NZ-2,....1.

Note: New row or layer has to be started on a new card.

16. Title card _ _ _ _ _ _ _ _ _ _ _ _ _ _ FORMAT(40A2)

17. Fracture permeability Tensor _ _ _ _ _ FORMAT(9F8.0)

CFKXX	cols	1-8	Elements of the permeability
CFKXY		9-16	tensor (md.)
CFKXZ		17-24	
CFKYX		25-32	
CFKYY		33-40	
CFKYZ		41-48	
CFKZX		49-56	
CFKZY		57-64	
CFKZZ		65-72	

18. Title card (if NUMKF $\neq$ 0)

19. Fracture permeability tensor and grid point locations (if NUMKF $\neq$ 0) _ _ _ FORMAT(3I5, 9F6.0)

I	cols 1-5	Grid point locations
J	6-10	
K	11-15	
FKXX(I,J,K)	16-21	Elements of the permeability tensor (md.)
FKXY(I,J,K)	22-27	
FKXZ(I,J,K)	28-33	
FKYX(I,J,K)	34-39	
FKYY(I,J,K)	40-45	
FKYZ(I,J,K)	46-51	
FKZX(I,J,K)	52-57	
FKZY(I,J,K)	58-63	
FKZZ(I,J,K)	64-69	

Note: NUMKF cards are read.

20. Title card _ _ _ _ _ _ _ _ _ _ _ _ FORMAT(40A2)

21. Maximum values of pressures and saturations for tabulated data _ _ _ _ _ _ _ _ _ _ FORMAT(8F10.0)

PMAXO	cols. 1-10	Maximum oil pressure in table (psia)
PMAXW	11-20	Maximum water pressure in table (psia)
PMAXG	21-30	Maximum gas pressure in table (psia)
SGMAX	31-40	Maximum gas saturation in table (fraction)

SWMAX cols. 41-50 Maximum water saturation in table (fraction)

22. Title card _ _ _ _ _ _ _ _ _ _ _ _ FORMAT(40A2)

23. Oil PVT tabulated data _ _ _ _ _ _ FORMAT(6F12.0)

POT(I)	cols. 1-12	Oil pressure (psia)
BOT(I)	13-24	Oil formation volume factor (bbl/STB)
DIBOT(I)	25-36	$d(1/B_o)/dP_o$ (STB/bbl/psi)
RSOT(I)	37-48	Solution gas-oil ratio (SCF/STB)
DRSOT(I)	49-60	dR_S/dP_o (SCF/STB/psi)
UOT(I)	61-72	Oil viscosity (cp)

Note: Repeat this card until all tabulated data are read. The POT(I) must be arranged in increasing order, with the last card having POT(I) = PMAXO to signal the end of data.

24. Title card _ _ _ _ _ _ _ _ _ _ _ _ FORMAT(40A2)

25. Water PVT tabulated data _ _ _ _ _ FORMAT(6F12.0)

PWT(I)	cols. 1-12	Water pressure (psia)
UWT(I)	13-24	Water viscosity (cp)

Note: Repeat this card until all tabulated data are read. The PWT(I) must be arranged in increasing order, with the last card having PWT(I) = PMAXW to signal the end of data.

26. Title card _ _ _ _ _ _ _ _ _ _ _ _ FORMAT(40A2)

27. Gas PVT tabulated data _ _ _ _ _ _ FORMAT(6F12.0)

PGT(I)	cols 1-12	Gas pressure (psia)
BGT(I)	13-24	Gas formation volume factor (bbl/SCF)

DIBGT(I) cols 25-36 $d(1/B_g)/dP_g$ (SCF/bbl/psi)

UGT(I) 37-48 Gas viscosity (cp)

Note: Repeat this card until all tabulated data are read. The PGT(I) must be arranged in increasing order, with the last card having PGT(I) = PMAXG to signal the end of data.

28. Title card _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ FORMAT(40A2)

29. Oil, water and gas densities at standard conditions _ _ FORMAT(6F12.0)

RHOSO cols 1-12 Oil density at standard conditions (lbm/cu.ft)

RHOSW 13-24 Water density at standard conditions (lbm/cu.ft)

RHOSG 25-36 Gas density at standard consitions (lbm/cu.ft)

PSC 37-48 Standard pressure (psia)

TSC 49-60 Standard temperature (°F)

30. Title card _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ FORMAT(40A2)

31. Fracture and rock matrix compressibility_ _FORMAT(2D12.4)

CF cols. 1-12 Fracture compressibility (psi^{-1})

CL 13-24 Rock matrix compressibility (psi^{-1})

32. Title card _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ FORMAT(40A2)

33. Tilting angles of the formation _ _ _ _ _ (6F12.0)

ALPHA cols. 1-12 Angle between X-axis and horizontal plane (DEGREE)

BETA 13-24 Angle between Y-axis and horizontal plane (DEGREE)

GAMMA cols. 25-36 Angle between Z-axis and vertical plane (DEGREE)

34. Title card _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ FORMAT(40A2)

35. Gas-oil relative permeability data for rock matrix _ _ _ _ _ _ MATRIX (6F12.0)

SGT(I)	cols. 1-12	Gas saturation (fraction)
KRGT(I)	13-24	Gas relative permeability (fraction)
KROGT(I)	25-36	Oil relative permeability (fraction)
PCGOT(I)	37-48	Gas-oil capillary pressure (psi)
DSGT(I)	49-60	dS_g/dP_{cgo} (psi^{-1})

Note: Repeat this card until all tabulated data are read. The SGT(I) must be arranged in increasing order, with the last card having SGT(I) = SGMAX to signal the end of data.

36. Title card _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ FORMAT(40A2)

37. Water-oil relative permeability data for rock matrix _ _ _ FORMAT(6F12.0)

SWT(I)	cols. 1-12	Water saturation (fraction)
KRWT(I)	13-24	Water relative permeability (fraction)
KROWT(I)	25-36	Oil relative permeability (fraction)
PCOWT(I)	37-48	Water-oil capillary pressure (psi)
DSWT(I)	49-60	dS_w/dP_{cow} (psi^{-1})

Note: Repeat this card until all tabulated data are read. The SWT(I) must be arranged in increasing order, with the last card having SWT(I) = SWMAX to signal the end of data.

38. Title card _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ FORMAT(40A2)

39. Gas-oil relative permeability data for fracture _ _ _ _ _ FORMAT(6F12.0)

FSGT(I)	cols. 1-12	Gas saturation (fraction)
FKRGT(I)	13-24	Gas relative permeability (fraction)
FKROGT(I)	25-36	Oil relative permeability (fraction)
FPCGOT(I)	37-48	Gas-oil capillary pressure (psi)
DSGT(I)	49-60	$d\ S_g/d\ P_{cgo}$ (psi^{-1})

Note: Repeat this card until all tabulated data are read. The FSGT(I) must be arranged in increasing order, with the last card having FSGT(I) = SGMAX to signal the end of data.

40. Title card _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ FORMAT(40A2)

41. Water-oil relative permeability for fracture _ _ _ _ FORMAT(6F12.0)

FSWI(I)	cols. 1-12	Water saturation (fraction)
FKRWT(I)	13-24	Water relative permeability (fraction)
FKROWT(I)	25-36	Oil relative permeability (fraction)
FPCOWT(I)	37-48	Water-oil capillary pressure (psi)
FDSWT(I)	49-60	$d\ S_w/d\ P_{cow}$ (psi^{-1})

Note: Repeat this card until all tabulated data are read. The FSWT(I) must be arranged in increasing order, with the last card having GSWT(I) = SWMAX to signal the end of data.

Set 3 Input data for subroutine INCON

1. Title card _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ FORMAT(40A2)
2. Initial reservoir pressures _ _ _ _ FORMAT(6F10.0)

PI	cols. 1-10	Initial oil pressure in rock matrix (psia)
PWI	11-20	Initial water pressure in rock matrix (psia)
PGI	21-30	Initial gas pressure in rock matrix (psia)
PFI	31-40	Initial oil pressure in fracture (psia)
PWFI	41-50	Initial water pressure in fracture (psia)
PGFI	51-60	Initial gas pressure in fracture (psia)

3. Initial saturations _ _ _ _ _ _ _ _ _ _ FORMAT(6F10.0)

SOI	cols. 1-10	Initial oil saturation in rock matrix (fraction)
SWI	11-20	Initial water saturation in rock matrix (fraction)
SGI	21-30	Initial gas saturation in rock matrix (fraction)
SOFI	31-40	Initial oil saturation in fracture (fraction)
SWFI	41-50	Initial water saturation in fracture (fraction)
SGFI	51-60	Initial gas saturation in fracture (fraction)

4. Title card _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ FORMAT(40A2)
5. Number of variable rate nodes _ _ _ _ _ _ FORMAT(I5)

   NVQN cols. 1-5 Number of variable rate nodes

6.* Location of node and its active time _ _ _ FORMAT (3I5,4F10.0)

QN1(I)	cols	1-5	Location of the gridpoint
QN2(I)		6-10	
QN3(I)		11-15	
TQ1(I)		16-25	Time the rate is on (day)
TQ2(I)		26-35	Time the rate is off (day)

7.* Rates at this node _ _ _ _ _ _ _ _ FORMAT(8F9.0)

QVO(I)	cols.	1-9	Oil rate in rock matrix (STB/day)
QVW(I)		10-18	Water rate in rock matrix (STB/day)
QVG(I)		19-27	Gas rate in rock matrix (SCF/day)
QVT(I)		28-36	Total fluid rate in rock matrix (STB/day)
QVO(I)		37-45	Oil rate in fracture (STB/day)
QVWF(I)		46-54	Water rate in fracture (STB/day)
QVGF(I)		55-63	Gas rate in fracture (SCF/day)
QVTF(I)		64-72	Total fluid rate in fracture (STB/day)

*Notes:

(1) Cards 6 and 7 are read in sequence. NVQN sequences are read.

(2) Injection rate has positive sign, whereas production rate has negative sign.

(3) If the rates are to be determined based on phases' mobilities, QVT(I) and/or QVTF(I) must not be zero.

(4) If the rates of oil, water, and gas are to be explicitly defined, QVT(I) and/or QVTF(I) must be zero.

Set 4 Input data for subroutine code

1. Title card _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ FORMAT(40A2)
2. Simulation parameters _ _ _ _ _ _ _ _ FORMAT(I5,5F10.0)

NMAX	cols. 1-5	Maximum number of time steps
TMAX	6-15	Maximum simulation time (day)
WORMAX	16-25	Maximum allowable water-oil ratio
GORMAX	26-35	Maximum allowable gas-oil ratio (SCF/STB)
PBP	36-45	Bubble point pressure (psia)
PMIN	46-55	Abandonment pressure (psia)

3. Iterative parameters and print codes _ _ FORMAT(5I5,2F10.0)

MITER	cols. 1-5	Maximum number of iterations for PSOR
LPT	6-10	Pressure distributions will be printed every LPT'th time step
LST	11-15	Saturation distributions will be printed every LST'th time step
LPOR	16-20	Porosity distributions will be printed every LPOR'th time step
LVELO	21-25	Velocity distributions will be printed every LVELO'th time step.
OMEGA	26-35	Relaxation parameter
TOL	36-45	Tolerance limit for PSOR

Set 5 Input data for the MAIN program

1. Time step size _ _ _ _ _ _ _ _ _ _ FORMAT(F10.0)

DELT cols. 1-10 Time step size (day)

Note: At least one time step size must be read. If N cards are read, all time steps after step N will have the same size as step N.

APPENDIX E

ARRANGEMENT OF INPUT DATA

```
NUMBER OF GRIDS(NX, NY, NZ) AND RESERVOIR LENGTH, WIDTH, THICKNESS
   10     2     5  2000.     400.        250.
FRACTURE HALF WIDTH (FT)
 0.0500
CODE NUMBERS FOR MATRIX POROSITY AND PERMEABILITY
    0     0
INITIAL MATRIX POROSITY
 0.29
MATRIX PERMEABILITY (MD)
 1.0
CODE NUMBERS FOR FRACTURE POROSITY AND PERMEABILITY
    0     0
INITIAL FRACTURE POROSITY
 0.0005
FRACTURE PERMEABILITY TENSOR ELEMENTS
10.0     0.0     0.0     0.0     10.0     0.0     0.0     0.0      10.0
MAXIMUM PRESSURES AND SATURATIONS FOR PVT DATA TABLES
 7014.7    7014.7    7014.7    1.0       1.0
OIL PVT TABLES
 14.7        1.0         -0.0001379   0.0        0.21924    0.72
 1714.7      1.3026      -0.0000576   372.8      0.22411    0.526
 2114.7      1.3429      -0.0000575   463.2      0.23447    0.48
 2614.7      1.3909      -0.0000579   531.5      0.24947    0.43
 3014.7      1.4437      -0.0000582   681.5      0.26020    0.396
 3614.7      1.5204      -0.0000594   846.2      0.30159    0.343
 4214.7      1.6077      -0.0000601   1029.7     0.32943    0.303
 4614.7      1.6725      -0.0000608   1163.3     0.36316    0.274
 5014.7      1.7442      -0.0000640   1311.0     0.40007    0.244
 5314.7      1.8042      -0.0000607   1431.2     0.40346    0.226
 5614.7      1.8649      -0.0000580   1557.6     0.50122    0.206
 7014.7      2.1978      -0.0000579   2259.0     0.50111    0.169
WATER PVT TABLE
 14.7        0.35
 7014.7      0.35
GAS PVT TABLES
 14.7        0.17309      0.29835     0.01205
 1714.7      0.0019485    0.31458     0.0163
 2114.7      0.0015567    0.30453     0.0173
 2614.7      0.0012671    0.28563     0.0186
 3014.7      0.0011072    0.24074     0.0197
 3614.7      0.0009493    0.22771     0.0214
 4214.7      0.0008418    0.20337     0.0233
 4614.7      0.0007834    0.18349     0.0246
 5014.7      0.0007445    0.17931     0.0257
 5314.7      0.0007162    0.16519     0.0266
 5614.7      0.0006918    0.15808     0.0276
 7014.7      0.0006       0.15814     0.0330
OIL WATER GAS DENSITIES AT STANDARD PRESSURE AND TEMPERATURE
 51.14       65.0         0.058       14.7        60.0
```

```
FRACTURE AND MATRIX ROCK COMPRESSIBILITY
      3.5D-4       3.5D-6
TILTING ANGLES : ALPHA, BETA, GAMMA (DEGREES)
 0.0           0.0          0.0
GAS OIL RELATIVE PERMEABILITY IN ROCK MATRIX
   0.0          0.0          1.0          0.075        10.0
   0.10         0.015        0.70         0.085        10.0
   0.20         0.050        0.45         0.095        10.0
   0.30         0.103        0.25         0.115        5.0000
   0.40         0.190        0.11         0.145        3.3300
   0.50         0.310        0.028        0.255        0.9100
   0.55         0.420        0.0          0.386        0.3800
   1.0          1.0          0.0          1.565        0.3800
WATER-OIL RELATIVE PERMEABILITY IN ROCK MATRIX
   0.0          0.0          1.0          214.0        -0.00122
   0.20         0.0          1.0           50.0        -0.00122
   0.25         0.005        0.86           9.0        -0.00122
   0.30         0.01         0.723          2.0        -0.00714
   0.35         0.02         0.60           0.5        -0.03333
   0.40         0.03         0.492          0.0        -0.1
   0.45         0.045        0.392         -0.4        -0.125
   0.50         0.06         0.304         -1.2        -0.0625
   0.55         0.082        0.225         -2.6        -0.0357
   0.60         0.110        0.154         -4.0        -0.0357
   0.65         0.143        0.093         -7.0        -0.0167
   0.70         0.160        0.042        -10.0        -0.0167
   0.75         0.230        0.0          -40.0        -0.00167
   1.0          1.0          0.0         -190.0        -0.00167
GAS OIL RELATIVE PERMEABILITY IN FRACTURE
   0.0          0.0          1.0          0.075        10.0
   0.10         0.015        0.70         0.085        10.0
   0.20         0.050        0.45         0.095        10.0
   0.30         0.103        0.25         0.115        5.0000
   0.40         0.190        0.11         0.145        3.3300
   0.50         0.310        0.028        0.255        0.9100
   0.55         0.420        0.0          0.385        0.3800
   1.0          1.0          0.0          1.565        0.3800
WATER-OIL RELATIVE PERMEABILITY IN FRACTURE
   0.0          0.0          1.0          214.0        -0.00122
   0.20         0.0          1.0           50.0        -0.00122
   0.25         0.005        0.86           9.0        -0.00122
   0.30         0.01         0.723          2.0        -0.00714
   0.35         0.02         0.60           0.5        -0.03333
   0.40         0.03         0.492          0.0        -0.1
   0.45         0.045        0.392         -0.4        -0.125
   0.50         0.06         0.304         -1.2        -0.0625
   0.55         0.082        0.225         -2.6        -0.0357
   0.60         0.110        0.154         -4.0        -0.0357
   0.65         0.143        0.093         -7.0        -0.0167
   0.70         0.160        0.042        -10.0        -0.0167
   0.75         0.230        0.0          -40.0        -0.00167
   1.0          1.0          0.0         -190.0        -0.00167
INITIAL PHASE PRESSURES IN ROCK MATRIX AND FRACTURE
 6214.7        6164.7   6214.775   6214.7      6164.7      6214.775
 0.80          0.20     0.0        0.80        0.20        0.0
```

```
NUMBER OF VARIABLE RATE NODES
   10     0
    1     1     1  0.0       500.0
0.0      0.0       0.0       0.0        0.0        0.0        0.0          -800.0
    1     1     2  0.0       500.0
0.0      0.0       0.0       0.0        0.0        0.0        0.0          -800.0
    1     1     3  0.0       500.0
0.0      0.0       0.0       0.0        0.0        0.0        0.0          -800.0
    1     1     4  0.0       500.0
0.0      0.0       0.0       0.0        0.0        0.0        0.0          -800.0
    1     1     5  0.0       500.0
0.0      0.0       0.0       0.0        0.0        0.0        0.0          -800.0
   10     1     1  0.0       500.0
0.0      0.0       0.0       0.0        0.0        1400.0     0.0        0.0
   10     1     2  0.0       500.0
0.0      0.0       0.0       0.0        0.0        1400.0     0.0        0.0
   10     1     3  0.0       500.0
0.0      0.0       0.0       0.0        0.0        1400.0     0.0        0.0
   10     1     4  0.0       500.0
0.0      0.0       0.0       0.0        0.0        1400.0     0.0        0.0
   10     1     5  0.0       500.0
0.0      0.0       0.0       0.0        0.0        1400.0     0.0        0.0
SIMULATION PARAMETERS
  400 500.0        100.0     100000.0   5559.7      1500.0
  100    20    20    30    40   1.2          0.2
  0.05
  0.05
  0.05
  0.05
  0.05
  0.075
  0.075
  0.075
  0.075
  0.075
  0.075
  0.10
  0.10
  0.10
  0.10
  0.15
  0.15
  0.15
  0.15
  0.225
  0.225
  0.225
  0.225
  0.225
  0.375
  0.375
  0.375
  0.375
  0.50
  0.50
  0.50
  1.0
  1.0
```

APPENDIX F

COMPUTER LISTING OF THE SIMULATION PROGRAM

```
0001          IMPLICIT REAL*8(A-H,K,O-Z)
0002          INTEGER K
         C
         C
         C   *******************************************************************
         C   *                                                                 *
         C   *  THREE-DIMENSIONAL, THREE-PHASE, BLACK OIL RESERVOIR SIMULATOR *
         C   *  FOR FLUID FLOW IN NATURALLY FRACTURED RESERVOIR                *
         C   *                                                                 *
         C   *       AUTHOR:  KURUJIT NAKURNTHAP                               *
         C   *       ADVISOR: DR. RONALD D. EVANS                              *
         C   *                                                                 *
         C   *       SCHOOL OF PETROLEUM AND GEOLOGICAL ENGINEERING            *
         C   *       UNIVERSITY OF OKLAHOMA                                    *
         C   *       NOVEMBER 1982                                             *
         C   *                                                                 *
         C   *******************************************************************
         C
         C
0003          COMMON /PRESS/ PO(10,2,5),PW(10,2,5),PG(10,2,5),PFO(10,2,5),
             & PFW(10,2,5),PFG(10,2,5),PON(10,2,5),PWN(10,2,5),PGN(10,2,5),
             & PFON(10,2,5),PFWN(10,2,5),PFGN(10,2,5)
0004          COMMON /SAT/ SO(10,2,5),SW(10,2,5),SG(10,2,5),SOF(10,2,5),
             & SWF(10,2,5),SGF(10,2,5),SON(10,2,5),SWN(10,2,5),SGN(10,2,5),
             & SOFN(10,2,5),SWFN(10,2,5),SGFN(10,2,5)
0005          COMMON /PROD/ QO(10,2,5),QW(10,2,5),QG(10,2,5),QOF(10,2,5),
             & QWF(10,2,5),QGF(10,2,5)
0006          COMMON /VELO/ VOX(10,2,5),VOY(10,2,5),VOZ(10,2,5),VWX(10,2,5),
             &VWY(10,2,5),VWZ(10,2,5),VGX(10,2,5),VGY(10,2,5),VGZ(10,2,5)
0007          COMMON /ACCL/ DVOXDT(10,2,5),DVOYDT(10,2,5),DVOZDT(10,2,5),
             & DVWXDT(10,2,5),DVWYDT(10,2,5),DVWZDT(10,2,5),DVGXDT(10,2,5),
             & DVGYDT(10,2,5),DVGZDT(10,2,5)
0008          COMMON /CMTX1/ GW(10,2,5),EW(10,2,5),AW(10,2,5),BW(10,2,5),
             &CW(10,2,5),FW(10,2,5),HW(10,2,5),RW(10,2,5),UWM(10,2,5),DW(10,2,5)
0009          COMMON /CMTX2/ VO(10,2,5),GO(10,2,5),EO(10,2,5),AO(10,2,5),
             & BO(10,2,5),CO(10,2,5),FO(10,2,5),HO(10,2,5),UOM(10,2,5),
             & RO(10,2,5),DO(10,2,5)
0010          COMMON /CMTX3/ VG(10,2,5),GGO(10,2,5),EGO(10,2,5),AGO(10,2,5),
             & BGO(10,2,5),CGO(10,2,5),FGO(10,2,5),HGO(10,2,5),GG(10,2,5),
             & EG(10,2,5),AG(10,2,5),BG(10,2,5),CG(10,2,5),FG(10,2,5),
             & HG(10,2,5),RGO(10,2,5),RG(10,2,5),DG(10,2,5)
0011          COMMON /CMTX4/ FRW(10,2,5),FGW1(10,2,5),FGW2(10,2,5),FGW3(10,2,5)
             &,FGW4(10,2,5),FGW5(10,2,5),FEW1(10,2,5),FEW2(10,2,5),FEW3(10,2,5)
             &,FAW1(10,2,5),FBW(10,2,5),FCW1(10,2,5),FFW1(10,2,5),FFW2(10,2,5)
             &,FFW3(10,2,5),FHW1(10,2,5),FHW2(10,2,5),FHW3(10,2,5),FHW4(10,2,5)
             &,FHW5(10,2,5),FOW(10,2,5),DFW(10,2,5)
0012          COMMON /CMTX5/ FRO(10,2,5),FVO(10,2,5),FGO1(10,2,5),FGO2(10,2,5),
             & FGO3(10,2,5),FGO4(10,2,5),FGO5(10,2,5),FEO1(10,2,5),FEO2(10,2,5)
             &,FEO3(10,2,5),FAO1(10,2,5),FBO(10,2,5),FCO1(10,2,5),FFO1(10,2,5),
             & FFO2(10,2,5),FFO3(10,2,5),FHO1(10,2,5),FHO2(10,2,5),FHO3(10,2,5)
             &,FHO4(10,2,5),FHO5(10,2,5),FOO(10,2,5),DFO(10,2,5)
0013          COMMON /CMTX6/ FPGO(10,2,5),FRG(10,2,5),FVG(10,2,5),FGR1(10,2,5),
             & FGR2(10,2,5),FGR3(10,2,5),FGR4(10,2,5),FGR5(10,2,5),FER1(10,2,5)
             &,FER2(10,2,5),FER3(10,2,5),FAR1(10,2,5),FBR(10,2,5),FCR1(10,2,5),
             & FFR1(10,2,5),FFR2(10,2,5),FFR3(10,2,5),FHR1(10,2,5),FHR2(10,2,5)
             &,FHR3(10,2,5),FHR4(10,2,5),FHR5(10,2,5),FGG1(10,2,5),FGG2(10,2,5)
             &,FGG3(10,2,5),FGG4(10,2,5),FGG5(10,2,5),FEG1(10,2,5),FEG2(10,2,5)
             &,FEG3(10,2,5),FAG1(10,2,5),FBG(10,2,5),FCG1(10,2,5),FFG1(10,2,5),
```

```
                  & FFG2(10,2,5),FFG3(10,2,5),FHG1(10,2,5),FHG2(10,2,5),FHG3(10,2,5) 00000580
                  &,FHG4(10,2,5),FHG5(10,2,5),DFG(10,2,5)                            00000590
0014               COMMON /TR1/ TGW(10,2,5),TEW(10,2,5),TAW(10,2,5),TCW(10,2,5),    00000600
                  & TFW(10,2,5),THW(10,2,5),TRW(10,2,5),TUW(10,2,5),TVO(10,2,5),    00000610
                  & TGO(10,2,5),TEO(10,2,5),TAO(10,2,5),TCO(10,2,5),TFO(10,2,5),    00000620
                  & THO(10,2,5),TUO(10,2,5),TRO(10,2,5)                             00000630
0015               COMMON /TR2/ TVG(10,2,5),TGGO(10,2,5),TEGO(10,2,5),TAGO(10,2,5), 00000640
                  & TCGO(10,2,5),TFGO(10,2,5),THGO(10,2,5),TGG(10,2,5),TEG(10,2,5), 00000650
                  & TAG(10,2,5),TCG(10,2,5),TFG(10,2,5),THG(10,2,5),THGO(10,2,5),   00000660
                  & TRG(10,2,5)                                                     00000670
0016               COMMON /TR3/ TFGW1(10,2,5),TFGW2(10,2,5),TFGW3(10,2,5),TFGW4(10,2 00000680
                  &,5),TFGW5(10,2,5),TFEW1(10,2,5),TFEW2(10,2,5),TFEW3(10,2,5),TFAW1(00000690
                  & 10,2,5),TFCW1(10,2,5),TFFW1(10,2,5),TFFW2(10,2,5),TFFW3(10,2,5), 00000700
                  & TFHW1(10,2,5),TFHW2(10,2,5),TFHW3(10,2,5),TFHW4(10,2,5),        00000710
                  & TFHW5(10,2,5),TFRW(10,2,5),TFUW(10,2,5)                         00000720
0017               COMMON /TR4/ TFGO1(10,2,5),TFGO2(10,2,5),TFGO3(10,2,5),TFGO4(10,2,00000730
                  &5),TFGO5(10,2,5),TFEO1(10,2,5),TFEO2(10,2,5),TFEO3(10,2,5),TFAO1( 00000740
                  & 10,2,5),TFCO1(10,2,5),TFFO1(10,2,5),TFFO2(10,2,5),TFFO3(10,2,5), 00000750
                  & TFHO1(10,2,5),TFHO2(10,2,5),TFHO3(10,2,5),TFHO4(10,2,5),TFHO5(10,00000760
                  & 2,5),TFRO(10,2,5),TFUO(10,2,5),TFVO(10,2,5)                     00000770
0018               COMMON /TR5/ TFGG1(10,2,5),TFGG2(10,2,5),TFGG3(10,2,5),TFGG4(10,2,00000780
                  &5),TFGG5(10,2,5),TFEG1(10,2,5),TFEG2(10,2,5),TFEG3(10,2,5),TFAG1( 00000790
                  &10,2,5),TFCG1(10,2,5),TFFG1(10,2,5),TFFG2(10,2,5),TFFG3(10,2,5),  00000800
                  &TFHG1(10,2,5),TFHG2(10,2,5),TFHG3(10,2,5),TFHG4(10,2,5),TFHG5(10, 00000810
                  &2,5),TFGR1(10,2,5),TFGR2(10,2,5),TFGR3(10,2,5),TFGR4(10,2,5),     00000820
                  & TFGR5(10,2,5),TFER1(10,2,5),TFER2(10,2,5),TFER3(10,2,5),TFAR1(   00000830
                  &10,2,5),TFCR1(10,2,5),TFFR1(10,2,5),TFFR2(10,2,5),TFFR3(10,2,5),  00000840
                  & TFHR1(10,2,5),TFHR2(10,2,5),TFHR3(10,2,5),TFHR4(10,2,5),TFHR5(   00000850
                  &10,2,5),TFRG(10,2,5),TFRGO(10,2,5),TFVG(10,2,5)                   00000860
0019               COMMON /SET2/ VB,DELX,DELY,DELZ,DELT,RH                          00000870
0020               COMMON /SET3/ CON1,CON2,CON3,CON4                                00000880
0021               COMMON /SET1/ RHOSO,RHOSW,RHOSG,PSC,TSC,ALPHA,BETA,GAMMA         00000890
0022               COMMON /LIMIT/ MPOT,MPWT,MPGT,MSGT,MSWT,MFSGT,MFSWT              00000900
0023               COMMON /PARM1/ CL,CF,PHI(10,2,5),FPHI(10,2,5)                    00000910
0024               COMMON /PARM2/ KL(10,2,5),FKXX(10,2,5),FKXY(10,2,5),FKXZ(10,2,5), 00000920
                  & FKYX(10,2,5),FKYY(10,2,5),FKYZ(10,2,5),FKZX(10,2,5),            00000930
                  & FKZY(10,2,5),FKZZ(10,2,5)                                       00000940
0025               COMMON /PARM3/  POT(15),BOT(15),DIBUT(15),                       00000950
                  & RSUT(15),DRSUT(15),UOT(15),PWT(15),UWT(15),PGT(15),BGT(15),     00000960
                  & DIUGT(15),UGT(15),SGT(15),KRGT(15),KROGT(15),PCGOT(15),DSGT(15), 00000970
                  & SWT(15),KRWT(15),KROWT(15),PCOWT(15),DSWT(15),FSGT(15),FKRGT(15),00000980
                  & FKROGT(15),FPCGOT(15),FDSGT(15),FSWT(15),FKRWT(15),FKROWT(15),  00000990
                  & FPCOWT(15),FDSWT(15),RSWT(15),RFSWT(15)                         00001000
0026               COMMON /FLOW/QVO(10),QVW(10),QVG(10),QVT(10),QVOF(10),QVWF(10),  00001010
                  & QVGF(10),QVTF(10),TO1(10),TO2(10),TP1(10),TP2(10),PV,DP,QN1(10), 00001020
                  & QN2(10),QN3(10),PN1(10),PN2(10),PN3(10)                         00001030
0027               INTEGER*2 QN1,QN2,QN3,PN1,PN2,PN3                                00001040
0028               REAL*8 MOEO,MOLW,MOEG                                            00001050
0029               DIMENSION VPM(10,2,5),VPF(10,2,5)                                00001060
0030               DATA ID,LPN,LSN/0,0,0/                                           00001070
0031               DATA CUMOIL,CUMWAT,CUMWI,CUMGAS,CUMGI/5*0.0/                     00001080
             C                                                                      00001090
             C    INPUT RESERVOIR AND GRID DIMENSIONS                               00001100
             C                                                                      00001110
0032               CALL RESDIM(NX,NY,NZ,XL,YL,ZL,DELX,DELY,DELZ,RH)                 00001120
             C                                                                      00001130
             C    INPUT FLUID; P.V.T.; AND RESERVOIR DATA                           00001140
             C                                                                      00001150
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0033          CALL RESDAT(NX,NY,NZ)
        C
        C  INPUT INITIAL PRESSURES AND SATURATIONS AND PRODUCTION DATA
        C
0034          CALL INCON(NX,NY,NZ,NVON)
        C
        C   INPUT SIMULATOR PARAMETERS
        C
0035          CALL CODE(NMAX,TMAX,TOL,LPT,LST,MITER,OMEGA,PUP,PMIN,WORMAX,
             & GORMAX,LPUR,LVELO)
        C
        C   CALCULATE PRE-SIMULATION CONSTANT TRANSMISSIBILITY
        C
0036          VB=DELX*DELY*DELZ
0037          CALL TRAN(NX,NY,NZ,KL,FKXX,FKYY,FKZZ)
        C
        C   CALCULATE INITIAL RESERVOIR VOLUME
        C
0038          RVOLM=0.0
0039          RVOLF=0.0
0040          SCFO=0.0
0041          SCFW=0.0
0042          SCFG=0.0
0043          SCFGR=0.0
0044          DO 801 K=1,NZ
0045          DO 801 J=1,NY
0046          DO 801 I=1,NX
0047          VPM(I,J,K)=VB*PHI(I,J,K)
0048          RVOLM=RVOLM+VPM(I,J,K)
0049          VPF(I,J,K)=VB*FPHI(I,J,K)
0050          RVOLF=RVOLF+VPF(I,J,K)
0051          CALL LINTP(MPOT,PO(I,J,K),BBO,POT,BOT)
0052          CALL LINTP(NPOT,PFO(I,J,K),BFO,POT,BOT)
0053          CALL LINTP(MPGT,PG(I,J,K),BBG,PGT,BGT)
0054          CALL LINTP(MPGT,PFG(I,J,K),BFG,PGT,BGT)
0055          CALL LINTP(NPOT,PO(I,J,K),RSO,POT,RSOT)
0056          CALL LINTP(NPOT,PFO(I,J,K),RSF,POT,RSOT)
0057          SCFO=SCFO+VPM(I,J,K)*SO(I,J,K)/BBO+VPF(I,J,K)*SOF(I,J,K)/BFO
0058          SCFW=SCFW+VPM(I,J,K)*SW(I,J,K)+VPF(I,J,K)*SWF(I,J,K)
0059          SCFG=SCFG+VPM(I,J,K)*SG(I,J,K)/(BBG*5.615) +
             &            VPF(I,J,K)*SGF(I,J,K)/(BFG*5.615)
0060          SCFGR=SCFGR+VPM(I,J,K)*SO(I,J,K)*RSO/(BBO*5.615) +
             &              VPF(I,J,K)*SOF(I,J,K)*RSF/(BFO*5.615)
0061      801 CONTINUE
0062          STBON=SCFO/5.615
0063          STBWN=SCFW/5.615
0064          SCFTN=SCFG+SCFGR
0065          TOTVOL=RVOLM+RVOLF
0066          PRINT 2004,TOTVOL,STBON,STBWN,SCFTN
        C
        C   SIMULATION LOOP BEGIN
        C
0067          LTIME=0.0
0068          STIME=0.0
0069          LPN=LPT
0070          LSN=LST
0071          LPURN=LPUR
0072          LVELON=LVELO
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      LVELON=LVELO
      NITER=0
C
      DO 9000 N=1,NMAX
      IF(N.GT.1) DELTN=DELT
      IF(N.GT.1) LTIME=ETIME+DELT
      IF(ID.EQ.0) READ(5,2009,END=777) DELT
  778 STIME=STIME+DELT
      IF(ETIME.GE.TMAX) GO TO 9999
      IF(NITER.GE.25) DELT=DELT*0.5
      IF(NITER.LE.5.AND.N.GT.30)  DELT=DELT*2.0
      IF(DELT.LE.0.001) PRINT 2333
      IF(DELT.LE.0.001) STOP
C
C   CHECK MAXIMUM SATURATION CHANGE FOR LAST TIME STEP
C
      IF(N.EQ.1) GO TO 302
      DSMAX=0.0
      DSFMAX=0.0
      DO 800 K=1,NZ
      DO 800 J=1,NY
      DO 800 I=1,NX
      DSO=SO(I,J,K)-SON(I,J,K)
      DSW=SW(I,J,K)-SWN(I,J,K)
      DSG=SG(I,J,K)-SGN(I,J,K)
      DSOF=SOF(I,J,K)-SOFN(I,J,K)
      DSWF=SWF(I,J,K)-SWFN(I,J,K)
      DSGF=SGF(I,J,K)-SGFN(I,J,K)
      IF(DABS(DSO).GT.DSMAX) DSMAX=DABS(DSO)
      IF(DABS(DSW).GT.DSMAX) DSMAX=DABS(DSW)
      IF(DABS(DSG).GT.DSMAX) DSMAX=DABS(DSG)
      IF(DABS(DSOF).GT.DSFMAX) DSFMAX=DABS(DSOF)
      IF(DABS(DSWF).GT.DSFMAX) DSFMAX=DABS(DSWF)
      IF(DABS(DSGF).GT.DSFMAX) DSFMAX=DABS(DSGF)
  800 CONTINUE
      IF(DSMAX.GT.0.30) PRINT 2002
      IF(DSFMAX.GT.0.30) PRINT 2003
  302 CONTINUE
C
C   DETERMINE FLOW RATES FOR ALL NODES
C
      DO 807 K=1,NZ
      DO 807 J=1,NY
      DO 807 I=1,NX
      QO(I,J,K)=0.0
      QW(I,J,K)=0.0
      QG(I,J,K)=0.0
      QOF(I,J,K)=0.0
      QWF(I,J,K)=0.0
      QGF(I,J,K)=0.0
  807 CONTINUE
      IF(NVQN.EQ.0) GO TO 315
      DO 802 I=1,NVQN
      IF(STIME.LE.TQ1(I).OR.STIME.GT.TQ2(I)) GO TO 802
C
C   CHECK IF FLOW RATE FOR EACH PHASE IS SPECIFIED EXPLICITLY OR HAS
C   TO BE DETERMINED FROM PHASE MOBILITY
C
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0119           IF(QVT(I).NE.0.0) GO TO 306                                     00002490
0120           QO(QN1(I),QN2(I),QN3(I))=QVO(I)                                 00002500
0121           QW(QN1(I),QN2(I),QN3(I))=QVW(I)                                 00002510
0122           QG(QN1(I),QN2(I),QN3(I))=QVG(I)                                 00002520
0123           GO TO 307                                                       00002530
0124       306 PP=PO(QN1(I),QN2(I),QN3(I))                                     00002540
0125           PPW=PW(QN1(I),QN2(I),QN3(I))                                    00002550
0126           PPG=PG(QN1(I),QN2(I),QN3(I))                                    00002560
0127           SSW=SW(QN1(I),QN2(I),QN3(I))                                    00002570
0128           SSG=SG(QN1(I),QN2(I),QN3(I))                                    00002580
0129           CALL LINTP(MPOT,PP,UO,POT,UOT)                                  00002590
0130           CALL LINTP(MPWT,PPW,UW,PWT,UWT)                                 00002600
0131           CALL LINTP(MPGT,PPG,UG,PGT,UGT)                                 00002610
0132           CALL LINTP(MPOT,PP,RSO,POT,RSOT)                                00002620
0133           CALL LINTP(MPOT,PP,BBO,POT,BOT)                                 00002630
0134           CALL LINTP(MPGT,PPG,BBG,PGT,BGT)                                00002640
0135           CALL LINTP(MSWT,SSW,AKRW,SWT,KRWT)                              00002650
0136           CALL LINTP(MSWT,SSW,AKROW,SWT,KROWT)                            00002660
0137           CALL LINTP(MSGT,SSG,AKRG,SGT,KRGT)                              00002670
0138           CALL LINTP(MSGT,SSG,AKROG,SGT,KROGT)                            00002680
0139           WMOB=AKRW/UW                                                    00002690
0140           GMOB=AKRG/UG                                                    00002700
0141           AKRO=(AKROW+AKRW)*(AKROG+AKRG)-(AKRW+AKRG)                      00002710
0142           IF(AKRO.LT.0.0) AKRO=0.0                                        00002720
0143           OMOB=AKRO/UO                                                    00002730
0144           TMOB=OMOB+WMOB+GMOB                                             00002740
0145           QO(QN1(I),QN2(I),QN3(I))=QVT(I)*OMOB/TMOB                       00002750
0146           QW(QN1(I),QN2(I),QN3(I))=QVT(I)*WMOB/TMOB                       00002760
0147           QG(QN1(I),QN2(I),QN3(I))=QVT(I)*GMOB*5.615/TMOB +               00002770
         &                               RSO*QO(QN1(I),QN2(I),QN3(I))          00002780
      C                                                                        00002790
      C   AT THIS POINT WE CAN CALCULATE FLOWING BOTTOM HOLE PRESSURE          00002800
      C   IF PRODUCTIVITY INDEX IS GIVEN                                       00002810
      C                                                                        00002820
0148       307 IF(QVTF(I).NE.0.0) GO TO 308                                    00002830
0149           QOF(QN1(I),QN2(I),QN3(I))=QVOF(I)                               00002840
0150           QWF(QN1(I),QN2(I),QN3(I))=QVWF(I)                               00002850
0151           QGF(QN1(I),QN2(I),QN3(I))=QVGF(I)                               00002860
0152           GO TO 802                                                       00002870
0153       308 PF=PFO(QN1(I),QN2(I),QN3(I))                                    00002880
0154           PWF=PFW(QN1(I),QN2(I),QN3(I))                                   00002890
0155           PGF=PFG(QN1(I),QN2(I),QN3(I))                                   00002900
0156           SSWF=SWF(QN1(I),QN2(I),QN3(I))                                  00002910
0157           SSGF=SGF(QN1(I),QN2(I),QN3(I))                                  00002920
0158           CALL LINTP(MPOT,PF,UOF,POT,UOT)                                 00002930
0159           CALL LINTP(MPWT,PWF,UWF,PWT,UWT)                                00002940
0160           CALL LINTP(MPGT,PGF,UGF,PGT,UGT)                                00002950
0161           CALL LINTP(MPOT,PF,RSF,POT,RSOT)                                00002960
0162           CALL LINTP(MPOT,PF,BFO,POT,BOT)                                 00002970
0163           CALL LINTP(MPGT,PGF,BFG,PGT,BGT)                                00002980
0164           CALL LINTP(MFSWT,SSWF,AKRWF,FSWT,FKRWT)                         00002990
0165           CALL LINTP(MFSWT,SSWF,AKROWF,FSWT,FKROWT)                       00003000
0166           CALL LINTP(MFSGT,SSGF,AKRGF,FSGT,FKRGT)                         00003010
0167           CALL LINTP(MFSGT,SSGF,AKROGF,FSGT,FKROGT)                       00003020
0168           WMOBF=AKRWF/UWF                                                 00003030
0169           GMOBF=AKRGF/UGF                                                 00003040
0170           AKROF=(AKROWF+AKRWF)*(AKROGF+AKRGF)-(AKRWF+AKRGF)               00003050
0171           IF(AKROF.LT.0.0) AKROF=0.0                                      00003060
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0172          GMOBF=AKROF/UOF                                          00003070
0173          TMOBF=OMOBF+WMOBF+GMOBF                                  00003080
0174          QOF(QN1(I),QN2(I),QN3(I))=QVTF(I)*OMOBF/TMOBF            00003090
0175          QWF(QN1(I),QN2(I),QN3(I))=QVTF(I)*WMOBF/TMOBF            00003100
0176          QGF(QN1(I),QN2(I),QN3(I))=QVTF(I)*GMOBF*5.615/TMOBF +    00003110
             &                         RSF*QOF(QN1(I),QN2(I),QN3(I))   00003120
        C                                                              00003130
        C   AT THIS POINT WE CAN CALCULATE FLOWING BOTTOM HOLE PRESSURE 00003140
        C   IF PRODUCTIVITY INDEX IS GIVEN                             00003150
        C                                                              00003160
0177      302 CONTINUE                                                 00003200
        C                                                              00003210
        C   UPDATE PRESSURES AND SATURATIONS;                          00003220
        C   THEN EXPRAPOLATE THEM TO HALF TIME STEP AHEAD              00003230
        C                                                              00003240
0178      315 IF(N.EQ.1) GO TO 316                                     00003250
0179          CALL EXTRAP(NX,NY,NZ,PON,PO,DELT,DELTN)                  00003260
0180          CALL EXTRAP(NX,NY,NZ,PWN,PW,DELT,DELTN)                  00003270
0181          CALL EXTRAP(NX,NY,NZ,PGN,PG,DELT,DELTN)                  00003280
0182          CALL EXTRAP(NX,NY,NZ,PFON,PFO,DELT,DELTN)                00003290
0183          CALL EXTRAP(NX,NY,NZ,PFWN,PFW,DELT,DELTN)                00003300
0184          CALL EXTRAP(NX,NY,NZ,PFGN,PFG,DELT,DELTN)                00003310
0185          CALL EXTRAP(NX,NY,NZ,SON,SO,DELT,DELTN)                  00003320
0186          CALL EXTRAP(NX,NY,NZ,SWN,SW,DELT,DELTN)                  00003330
0187          CALL EXTRAP(NX,NY,NZ,SGN,SG,DELT,DELTN)                  00003340
0188          CALL EXTRAP(NX,NY,NZ,SOFN,SOF,DELT,DELTN)                00003350
0189          CALL EXTRAP(NX,NY,NZ,SWFN,SWF,DELT,DELTN)                00003360
0190          CALL EXTRAP(NX,NY,NZ,SGFN,SGF,DELT,DELTN)                00003370
0191      316 CONTINUE                                                 00003380
        C                                                              00003390
        C   FORMULATE COEFFICIENT MATRIX AND RHS VECTOR                00003400
        C   FOR THE SIX GOVERNING EQUATIONS                            00003410
        C                                                              00003420
0192          CALL COEFF(NX,NY,NZ)                                     00003430
        C                                                              00003900
        C   CALCULATE NEW PRESSURE DISTRIBUTIONS USING PSOR METHOD     00003910
        C                                                              00003920
0193          CALL PSOR(NX,NY,NZ,MITER,TOL,OMEGA,ITER)                 00003930
        C                                                              00003940
        C   CALCULATE NEW POROSITY AS A FUNCTION OF PRESSURE           00003950
        C                                                              00003960
0194          CALL POROSY(NX,NY,NZ,RVOLM,RVOLF,VB,VPM,VPF)             00003970
        C                                                              00003980
        C   DETERMINE NEW SATURATION DISTRIBUTIONS                     00003990
        C                                                              00004000
0195          SCFO=0.0                                                 00004010
0196          SCFW=0.0                                                 00004020
0197          SCFG=0.0                                                 00004030
0198          SCFGR=0.0                                                00004040
0199          DO 803 K=1,NZ                                            00004050
0200          DO 803 J=1,NY                                            00004060
0201          DO 803 I=1,NX                                            00004070
        C                                                              00004080
        C   CALCULATE CAPILLARY PRESSURES                              00004090
        C                                                              00004100
0202          PCWO=PO(I,J,K)-PW(I,J,K)                                 00004110
0203          PCWOF=PFO(I,J,K)-PFW(I,J,K)                              00004120
0204          PCGO=PG(I,J,K)-PO(I,J,K)                                 00004130
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0205          PCGUF=PFG(I,J,K)-PFO(I,J,K)                                   00004140
0206          IF(PCWO.LT.PCOWT(1)) PCWO=PCOWT(1)                            00004181
0207          IF(PCWOF.LT.FPCOWT(1)) PCWOF=FPCOWT(1)                        00004182
0208          IF(PCGO.LT.PCGOT(1)) PCGO=PCGOT(1)                            00004190
0209          IF(PCGOF.LT.FPCGOT(1)) PCGOF=FPCGOT(1)                        00004200
0210          CALL LINTP(MSWT,PCWO,SW(I,J,K),PCOWT,RSWT)                    00004210
0211          CALL LINTP(MFSWT,PCWOF,SWF(I,J,K),FPCOWT,RFSWT)               00004220
0212          CALL LINTP(MSGT,PCGO,SG(I,J,K),PCGOT,SGT)                     00004230
0213          CALL LINTP(MFSGT,PCGOF,SGF(I,J,K),FPCGOT,SGT)                 00004240
0214          IF(PO(I,J,K).GT.PBP) SG(I,J,K)=0.0                            00004250
0215          IF(PFO(I,J,K).GT.PBP) SGF(I,J,K)=0.0                          00004260
0216          SO(I,J,K)=1.0-SW(I,J,K)-SG(I,J,K)                             00004270
0217          SOF(I,J,K)=1.0-SWF(I,J,K)-SGF(I,J,K)                          00004280
0218          CALL LINTP(MPOT,PO(I,J,K),BBO,POT,BOT)                        00004290
0219          CALL LINTP(MPOT,PFO(I,J,K),BFO,POT,BOT)                       00004300
0220          CALL LINTP(MPGT,PG(I,J,K),BBG,PGT,BGT)                        00004310
0221          CALL LINTP(MPGT,PFG(I,J,K),BFG,PGT,BGT)                       00004320
0222          CALL LINTP(MPOT,PO(I,J,K),RSO,POT,RSOT)                       00004330
0223          CALL LINTP(MPOT,PFO(I,J,K),RSF,POT,RSOT)                      00004340
0224          SCFO=SCFO+VPM(I,J,K)*SO(I,J,K)/BBO+VPF(I,J,K)*SOF(I,J,K)/BFO  00004350
0225          SCFW=SCFW+VPM(I,J,K)*SW(I,J,K)+VPF(I,J,K)*SWF(I,J,K)          00004360
0226          SCFG=SCFG+VPM(I,J,K)*SG(I,J,K)/(BBG*5.615) +                  00004370
             &           VPF(I,J,K)*SGF(I,J,K)/(BFG*5.615)                  00004380
0227          SCFGR=SCFGR+VPM(I,J,K)*SO(I,J,K)*RSO/(BBO*5.615) +            00004390
             &           VPF(I,J,K)*SOF(I,J,K)*RSF/(BFO*5.615)              00004400
0228      303 CONTINUE                                                      00004410
0229          STBO=SCFO/5.615                                               00004420
0230          STBW=SCFW/5.615                                               00004430
0231          SCFT=SCFG+SCFGR                                               00004440
        C                                                                   00004480
        C   CALCULATE FLUID VELOCITY IN FRACTURE                            00004490
        C                                                                   00004500
0232          CALL VELOCY(NX,NY,NZ)                                         00004520
        C                                                                   00004534
        C   DETERMINE AVERAGE RESERVOIR PRESSURE AND MATERIAL BALANCL ERRORS 00004535
        C   FOR THE PREVIOUS TIME STEP                                      00004536
        C                                                                   00004537
0233          CALL MATBAL(NX,NY,NZ,STBO,STBON,STBW,STBWN,SCFT,SCFTN,MBEO,MBEW, 00004538
             & MBEG,WOR,GOR,VPM,VPF,CUMOIL,CUMWAT,CUMWI,CUMGAS,CUMGI,RVOLM, 00004539
             & RVOLF,PAVG,DELT ,OILP,WATP,WATI,GASP,GASI)                   00004540
0234          IF(PAVG.LT.PMIN) GO TO 9004                                   00004541
0235          IF(WOR.GT.WORMAX) GO TO 9005                                  00004542
0236          IF(GOR.GT.GORMAX) GO TO 9006                                  00004543
        C                                                                   00004544
        C   OUTPUT RESULTS OF THE PREVIOUS TIME STEP                        00004545
        C                                                                   00004546
0237          IF(N.NE.0.AND.N.NE.LPN) GO TO 312                             00004547
0238          CALL PTPRES(NX,NY,NZ,N,PAVG,MBEO,MBEW,MBEG,CUMOIL,CUMWAT,CUMWI, 00004548
             & CUMGAS,CUMGI,OILP,WATP,WATI,GASP,GASI,WOR,GOR,STIME,DELT)    00004549
0239      312 IF(N.NE.0.AND.N.NE.LSN) GO TO 313                             00004550
0240          CALL PTSAT(NX,NY,NZ,N,STIME)                                  00004551
0241      313 IF(N.NE.0.AND.N.NE.LPORN) GO TO 372                           00004552
0242          CALL PTPOR(NX,NY,NZ,N,STIME)                                  00004553
0243      372 IF(N.NE.0.AND.N.NE.LVELON) GO TO 373                          00004554
0244          CALL PTVELO(NX,NY,NZ,N,STIME,DELT)                            00004555
0245      373 IF(N.EQ.LPN) LPN=LPN+LPT                                      00004556
0246          IF(N.EQ.LSN) LSN=LSN+LST                                      00004557
0247          IF(N.EQ.LPORN) LPORN=LPORN+LPOR                               00004558
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0248            IF(N.EQ.LVELON) LVELON=LVELON+LVELO                               00004559
           C                                                                      00004560
           C                                                                      00004561
0249        9000 CONTINUE                                                         00004562
                 GO TO 9999                                                       00004563
0250
0251         777 ID=1                                                             00004570
0252             GO TO 778                                                        00004580
0253        9004 PRINT 2311                                                       00004590
0254             GO TO 9999                                                       00004600
0255        9005 PRINT 2312                                                       00004610
0256             GO TO 9999                                                       00004620
0257        9006 PRINT 2313                                                       00004630
0258        2002 FORMAT('0WARNING: SATURATION CHANGE OF ONE OR MORE NODES EXCEED  00004640
                &LIMIT DURING LAST TIME STEP')                                    00004650
0259        2003 FORMAT('0WARNING: SATURATION IN FRACTURE OF ONE OR MORE NODES    00004660
                &EXCEED LIMIT DURING LAST TIME STEP')                             00004670
0260        2004 FORMAT('0INITIAL RESERVOIR VOLUME(MATRIX+FRACTURE) =',F15.2,     00004680
                &' CU.FT.',///' INITIAL OIL IN PLACE               =',F15.2,      00004690
                &' STB',/,   ' INITIAL WATER IN PLACE             =',F15.2,       00004700
                &' STB',/,   ' INITIAL GAS IN PLACE               =',F15.2,       00004710
                &' SCF'////)                                                      00004720
0261        2009 FORMAT(F10.0)                                                    00004730
0262        2311 FORMAT('0AVERAGE RESERVOIR PRESSURE  BELOW ABANDONMENT PRESSURE') 00004780
0263        2312 FORMAT('0STOP BECAUSE WATER-OIL RATIO LIMIT IS EXCEEDED')        00004790
0264        2313 FORMAT('0STOP BECAUSE GAS-OIL RATIO LIMIT IS EXCEEDED')          00004800
0265        2333 FORMAT('0STOP BECAUSE OF UNREALISTICALLY SMALL TIME STEPS')      00004801
0266        9999 STOP                                                             00004810
0267             END                                                              00004820
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FORTRAN IV G1  RELEASE 2.0          BLK DATA          DATE = 82333          20/46/55          PAGE 0001

0001        BLOCK DATA                                                                   00004830
0002        IMPLICIT REAL*8(A-H,O-Z)                                                     00004840
0003        COMMON /SET3/ CON1,CON2,CON3,CON4                                            00004850
0004        COMMON /CMTX1/ GW(10,2,5),EW(10,2,5),AW(10,2,5),BW(10,2,5),                  00004860
           &CW(10,2,5),FW(10,2,5),HW(10,2,5),RW(10,2,5),UWM(10,2,5),DW(10,2,5)00004870
0005        COMMON /CMTX2/ VO(10,2,5),GO(10,2,5),EO(10,2,5),AO(10,2,5),                  00004880
           & BO(10,2,5),CO(10,2,5),FO(10,2,5),HO(10,2,5),UOM(10,2,5),                    00004890
           & RO(10,2,5),DO(10,2,5)                                                      00004900
0006        COMMON /CMTX3/ VG(10,2,5),GGO(10,2,5),EGO(10,2,5),AGO(10,2,5),               00004910
           & BGO(10,2,5),CGO(10,2,5),FGO(10,2,5),HGO(10,2,5),GG(10,2,5),                 00004920
           & EG(10,2,5),AG(10,2,5),BG(10,2,5),CG(10,2,5),FG(10,2,5),                     00004930
           & HG(10,2,5),RGO(10,2,5),RG(10,2,5),DG(10,2,5)                                00004940
0007        COMMON /CMTX4/ FRW(10,2,5),FGW1(10,2,5),FGW2(10,2,5),FGW3(10,2,5)            00004950
           &,FGW4(10,2,5),FGW5(10,2,5),FEW1(10,2,5),FEW2(10,2,5),FEW3(10,2,5)            00004960
           &,FAW1(10,2,5),FBW(10,2,5),FCW1(10,2,5),FFW1(10,2,5),FFW2(10,2,5)             00004970
           &,FFW3(10,2,5),FHW1(10,2,5),FHW2(10,2,5),FHW3(10,2,5),FHW4(10,2,5)            00004980
           &,FHW5(10,2,5),FUW(10,2,5),DFW(10,2,5)                                        00004990
0008        COMMON /CMTX5/ FRO(10,2,5),FVO(10,2,5),FGO1(10,2,5),FGO2(10,2,5),            00005000
           & FGO3(10,2,5),FGO4(10,2,5),FGO5(10,2,5),FEO1(10,2,5),FEO2(10,2,5)            00005010
           &,FEO3(10,2,5),FAO1(10,2,5),FBO(10,2,5),FCO1(10,2,5),FFO1(10,2,5),            00005020
           & FFO2(10,2,5),FFO3(10,2,5),FHO1(10,2,5),FHO2(10,2,5),FHO3(10,2,5)            00005030
           &,FHO4(10,2,5),FHO5(10,2,5),FUO(10,2,5),DFO(10,2,5)                           00005040
0009        COMMON /CMTX6/ FRGO(10,2,5),FRG(10,2,5),FVG(10,2,5),FGR1(10,2,5),            00005050
           & FGR2(10,2,5),FGR3(10,2,5),FGR4(10,2,5),FGR5(10,2,5),FER1(10,2,5)            00005060
           &,FER2(10,2,5),FER3(10,2,5),FAR1(10,2,5),FBR(10,2,5),FCR1(10,2,5),            00005070
           & FFR1(10,2,5),FFR2(10,2,5),FFR3(10,2,5),FHR1(10,2,5),FHR2(10,2,5)            00005080
           &,FHR3(10,2,5),FHR4(10,2,5),FHR5(10,2,5),FGG1(10,2,5),FGG2(10,2,5)            00005090
           &,FGG3(10,2,5),FGG4(10,2,5),FGG5(10,2,5),FEG1(10,2,5),FEG2(10,2,5)            00005100
           &,FEG3(10,2,5),FAG1(10,2,5),FBG(10,2,5),FCG1(10,2,5),FFG1(10,2,5),            00005110
           & FFG2(10,2,5),FFG3(10,2,5),FHG1(10,2,5),FHG2(10,2,5),FHG3(10,2,5)            00005120
           &,FHG4(10,2,5),FHG5(10,2,5),DFG(10,2,5)                                       00005130
0010        COMMON /VELO/ VOX(10,2,5),VOY(10,2,5),VOZ(10,2,5),VWX(10,2,5),               00005140
           &VWY(10,2,5),VWZ(10,2,5),VGX(10,2,5),VGY(10,2,5),VGZ(10,2,5)                  00005150
0011        COMMON /ACCL/ DVOXDT(10,2,5),DVOYDT(10,2,5),DVOZDT(10,2,5),                  00005160
           & DVWXDT(10,2,5),DVWYDT(10,2,5),DVWZDT(10,2,5),DVGXDT(10,2,5),                00005170
           & DVGYDT(10,2,5),DVGZDT(10,2,5)                                               00005180
0012        DATA CON1/0.001127/,CON2/0.1781/,CON3/2.8917D-14/,CON4/0.0063283/            00005190
0013        DATA GW/100*0.0/,EW/100*0.0/,AW/100*0.0/,BW/100*0.0/,CW/100*0.0/,            00005200
           &FW/100*0.0/,HW/100*0.0/,RW/100*0.0/,UWM/100*0.0/,VO/100*0.0/,                00005210
           &GO/100*0.0/,EO/100*0.0/,AO/100*0.0/,BO/100*0.0/,CO/100*0.0/,                 00005220
           & FO/100*0.0/,HO/100*0.0/,UOM/100*0.0/,RO/100*0.0/                            00005230
0014        DATA VG/100*0.0/,GGO/100*0.0/,EGO/100*0.0/,AGO/100*0.0/,                     00005240
           & BGO/100*0.0/,CGO/100*0.0/,FGO/100*0.0/,HGO/100*0.0/,GG/100*0.0/,            00005250
           & EG/100*0.0/,AG/100*0.0/,BG/100*0.0/,CG/100*0.0/,FG/100*0.0/,                00005260
           & HG/100*0.0/,RGO/100*0.0/,RG/100*0.0/                                        00005270
0015        DATA FGW1/100*0.0/,FGW2/100*0.0/,FGW3/100*0.0/,FGW4/100*0.0/,                00005280
           & FGW5/100*0.0/,FEW1/100*0.0/,FEW2/100*0.0/,FEW3/100*0.0/,                    00005290
           & FAW1/100*0.0/,FBW/100*0.0/,FCW1/100*0.0/,FFW1/100*0.0/, FFW2/100*00005300
           &0.0/,FFW3/100*0.0/,FHW1/100*0.0/,FHW2/100*0.0/,FHW3/100*0.0/,                00005310
           & FHW4/100*0.0/,FHW5/100*0.0/,FRW/100*0.0/,FUW/100*0.0/                       00005320
0016        DATA FGO1/100*0.0/,FGO2/100*0.0/,FGO3/100*0.0/,FGO4/100*0.0/,                00005330
           & FGO5/100*0.0/,FEO1/100*0.0/,FEO2/100*0.0/,FEO3/100*0.0/,                    00005340
           & FAO1/100*0.0/,FCO1/100*0.0/,FFO1/100*0.0/,FFO2/100*0.0/,                    00005350
           & FFO3/100*0.0/,FHO1/100*0.0/,FHO2/100*0.0/,FHO3/100*0.0/,                    00005360
           & FHO4/100*0.0/,FHO5/100*0.0/,FRO/100*0.0/,FUO/100*0.0/,                      00005370
           & FBO/100*0.0/,FVO/100*0.0/                                                   00005380
0017        DATA FGG1/100*0.0/,FGG2/100*0.0/,FGG3/100*0.0/,FGG4/100*0.0/,                00005390
           & FGG5/100*0.0/,FEG1/100*0.0/,FEG2/100*0.0/,FEG3/100*0.0/,                    00005400
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                    & FAG1/100*0.0/,FCG1/100*0.0/,FFG1/100*0.0/,FFG2/100*0.0/,         00005410
                    & FFG3/100*0.0/,FHG1/100*0.0/,FHG2/100*0.0/,FHG3/100*0.0/,         00005420
                    & FHG4/100*0.0/,FHG5/100*0.0/,FGR1/100*0.0/,FGR2/100*0.0/,         00005430
                    & FGR3/100*0.0/,FGR4/100*0.0/,FGR5/100*0.0/,FER1/100*0.0/,         00005440
                    & FER2/100*0.0/,FER3/100*0.0/,FAR1/100*0.0/,FCR1/100*0.0/,         00005450
                    & FFR1/100*0.0/,FFR2/100*0.0/,FFR3/100*0.0/,FHR1/100*0.0/,         00005460
                    & FHR2/100*0.0/,FHR3/100*0.0/,FHR4/100*0.0/,FHR5/100*0.0/,         00005470
                    &FBG/100*0.0/,FBR/100*0.0/,FRG/100*0.0/,FRGO/100*0.0/,FVG/100*0.0/ 00005480
0018                 DATA VOX/100*0.0/,VOY/100*0.0/,VOZ/100*0.0/,VWX/100*0.0/,         00005490
                    & VWY/100*0.0/,VWZ/100*0.0/,VGX/100*0.0/,VGY/100*0.0/,VGZ/100*0.0/ 00005500
0019                 DATA DVOXDT/100*0.0/,DVOYDT/100*0.0/,DVOZDT/100*0.0/,             00005510
                    & DVWXDT/100*0.0/,DVWYDT/100*0.0/,DVWZDT/100*0.0/,DVGXDT/100*0.0/, 00005520
                    & DVGYDT/100*0.0/,DVGZDT/100*0.0/                                  00005530
0020                  END                                                              00005540
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                 SUBROUTINE CODE(NMAX,TMAX,TOL,LPT,LST,MITER,OMEGA,PBP,PMIN,
                & WORMAX,GORMAX,LPOR,LVELO)
          C
          C   SUBROUTINE TO SIMULATION PARAMETERS
          C
                 IMPLICIT REAL*8(A-H,O-Z)
                 INTEGER*2 TITLE(40)
                 READ(5,100) TITLE
             100 FORMAT(40A2)
          C
          C  RUN TIME PARAMETERS
          C
                 READ(5,101) NMAX,TMAX,WORMAX,GORMAX,PBP,PMIN
             101 FORMAT(I5,5F10.0)
                 PRINT 102,NMAX,TMAX,WORMAX,GORMAX,PBP,PMIN
             102 FORMAT(//'0MAXIMUM NUMBER OF TIME STEPS =',I5,/,
                &'0MAXIMUM SIMULATION TIME (DAYS) =',F10.0,/,
                &'0MAXIMUM WATER-OIL RATIO  =',F10.0,/,
                &'0MAXIMUM GAS-OIL RATIO  =',F12.0,/,'0BUBBLE POINT PRESSURE =',
                &F10.1,' PSIA',/,'0ABANDONMENT PRESSURE  =',F10.1,' PSIA')
          C
          C  PRINT CODES AND TOLERANCE LIMITS
          C
                 READ(5,103) MITER,LPT,LST,LPOR,LVELO,OMEGA,TOL
             103 FORMAT(5I5,2F10.0)
                 PRINT 104,MITER,LPT,LST,LPOR,LVELO,OMEGA,TOL
             104 FORMAT('0MAXIMUM ALLOWABLE ITERATIONS FOR PSUR =',I5,/,
                &  '0PRESSURE DISTRIBUTION WILL BE PRINTED EVERY',I5,
                &' TIME STEP',/'0SATURATION DISTRBUTION WILL BE PRINTED EVERY',
                &I4,' TIME STEP',/'0POROSITY DISTRIBUTION WILL BE PRINTED EVERY',
                &I5,' TIME STEP',/'0VELOCITY DISTRIBUTION WILL BE PRINTED EVERY',
                & I5,' TIME STEP',/'0RELAXATION PARAMETER =',F10.2,//,
                & ' TOLERANCE LIMIT FOR PSUR =',F15.6,//)
                 RETURN
                 END
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0001          SUBROUTINE COEFF(NX,NY,NZ)
         C
         C   SUBROUTINE TO FORMULATE COEFFICIENT MATRIX AND RHS VECTOR
         C
0002          IMPLICIT REAL*8(A-H,K,O-Z)
0003          INTEGER K
0004          COMMON /PRESS/ PO(10,2,5),PW(10,2,5),PG(10,2,5),PFO(10,2,5),
             & PFW(10,2,5),PFG(10,2,5),PON(10,2,5),PWN(10,2,5),PGN(10,2,5),
             & PFON(10,2,5),PFWN(10,2,5),PFGN(10,2,5)
0005          COMMON /SAT/ SO(10,2,5),SW(10,2,5),SG(10,2,5),SOF(10,2,5),
             & SWF(10,2,5),SGF(10,2,5),SON(10,2,5),SWN(10,2,5),SGN(10,2,5),
             & SOFN(10,2,5),SWFN(10,2,5),SGFN(10,2,5)
0006          COMMON /PROD/ QO(10,2,5),QW(10,2,5),QG(10,2,5),QOF(10,2,5),
             & QWF(10,2,5),QGF(10,2,5)
0007          COMMON /ACCL/ DVOXDT(10,2,5),DVOYDT(10,2,5),DVOZDT(10,2,5),
             & DVWXDT(10,2,5),DVWYDT(10,2,5),DVWZDT(10,2,5),DVGXDT(10,2,5),
             & DVGYDT(10,2,5),DVGZDT(10,2,5)
0008          COMMON /CMTX1/ GW(10,2,5),EW(10,2,5),AW(10,2,5),BW(10,2,5),
             &CW(10,2,5),FW(10,2,5),HW(10,2,5),RW(10,2,5),UWM(10,2,5),DW(10,2,5)
0009          COMMON /CMTX2/ VO(10,2,5),GO(10,2,5),EO(10,2,5),AO(10,2,5),
             & BO(10,2,5),CO(10,2,5),FO(10,2,5),HO(10,2,5),UOM(10,2,5),
             & RO(10,2,5),DO(10,2,5)
0010          COMMON /CMTX3/ VG(10,2,5),GGO(10,2,5),EGO(10,2,5),AGO(10,2,5),
             & BGO(10,2,5),CGO(10,2,5),FGO(10,2,5),HGO(10,2,5),GG(10,2,5),
             & EG(10,2,5),AG(10,2,5),UG(10,2,5),CG(10,2,5),FG(10,2,5),
             & HG(10,2,5),RGO(10,2,5),RG(10,2,5),DG(10,2,5)
0011          COMMON /CMTX4/ FRW(10,2,5),FGW1(10,2,5),FGW2(10,2,5),FGW3(10,2,5)
             &,FGW4(10,2,5),FGW5(10,2,5),FEW1(10,2,5),FEW2(10,2,5),FEW3(10,2,5)
             &,FAW1(10,2,5),FBW(10,2,5),FCW1(10,2,5),FFW1(10,2,5),FFW2(10,2,5)
             &,FFW3(10,2,5),FHW1(10,2,5),FHW2(10,2,5),FHW3(10,2,5),FHW4(10,2,5)
             &,FHW5(10,2,5),FUW(10,2,5),DFW(10,2,5)
0012          COMMON /CMTX5/ FRO(10,2,5),FVO(10,2,5),FGO1(10,2,5),FGO2(10,2,5),
             & FGO3(10,2,5),FGO4(10,2,5),FGO5(10,2,5),FEO1(10,2,5),FEO2(10,2,5)
             &,FEO3(10,2,5),FAO1(10,2,5),FBO(10,2,5),FCO1(10,2,5),FFO1(10,2,5),
             & FFO2(10,2,5),FFO3(10,2,5),FHO1(10,2,5),FHO2(10,2,5),FHO3(10,2,5)
             &,FHO4(10,2,5),FHO5(10,2,5),FUO(10,2,5),DFO(10,2,5)
0013          COMMON /CMTX6/ FRGO(10,2,5),FRG(10,2,5),FVG(10,2,5),FGR1(10,2,5),
             & FGR2(10,2,5),FGR3(10,2,5),FGR4(10,2,5),FGR5(10,2,5),FER1(10,2,5)
             &,FER2(10,2,5),FER3(10,2,5),FAR1(10,2,5),FBR(10,2,5),FCR1(10,2,5),
             & FFR1(10,2,5),FFR2(10,2,5),FFR3(10,2,5),FHR1(10,2,5),FHR2(10,2,5)
             &,FHR3(10,2,5),FHR4(10,2,5),FHR5(10,2,5),FGG1(10,2,5),FGG2(10,2,5)
             &,FGG3(10,2,5),FGG4(10,2,5),FGG5(10,2,5),FEG1(10,2,5),FEG2(10,2,5)
             &,FEG3(10,2,5),FAG1(10,2,5),FBG(10,2,5),FCG1(10,2,5),FFG1(10,2,5),
             & FFG2(10,2,5),FFG3(10,2,5),FHG1(10,2,5),FHG2(10,2,5),FHG3(10,2,5)
             &,FHG4(10,2,5),FHG5(10,2,5),DFG(10,2,5)
0014          COMMON /TR1/ TGW(10,2,5),TEW(10,2,5),TAW(10,2,5),TCW(10,2,5),
             & TFW(10,2,5),THW(10,2,5),TRW(10,2,5),TUW(10,2,5),TVO(10,2,5),
             & TGO(10,2,5),TEO(10,2,5),TAO(10,2,5),TCO(10,2,5),TFO(10,2,5),
             & THO(10,2,5),TUO(10,2,5),TRO(10,2,5)
0015          COMMON /TR2/ TVG(10,2,5),TGGO(10,2,5),TEGO(10,2,5),TAGO(10,2,5),
             & TCGO(10,2,5),TFGO(10,2,5),THGO(10,2,5),TGG(10,2,5),TEG(10,2,5),
             & TAG(10,2,5),TCG(10,2,5),TFG(10,2,5),THG(10,2,5),THGO(10,2,5),
             & TRG(10,2,5)
0016          COMMON /TR3/ TFGW1(10,2,5),TFGW2(10,2,5),TFGW3(10,2,5),TFGW4(10,2
             &,5),TFGW5(10,2,5),TFEW1(10,2,5),TFEW2(10,2,5),TFEW3(10,2,5),TFAW1(
             & 10,2,5),TFCW1(10,2,5),TFFW1(10,2,5),TFFW2(10,2,5),TFFW3(10,2,5),
             & TFHW1(10,2,5),TFHW2(10,2,5),TFHW3(10,2,5),TFHW4(10,2,5),
             & TFHW5(10,2,5),TFRW(10,2,5),TFUW(10,2,5)
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0017       COMMON /TR4/ TFGO1(10,2,5),TFGO2(10,2,5),TFGO3(10,2,5),TFGO4(10,2,
          &5),TFGO5(10,2,5),TFCO1(10,2,5),TFEO2(10,2,5),TFLO3(10,2,5),TFAO1(
          & 10,2,5),TFCO1(10,2,5),TFFO1(10,2,5),TFFO2(10,2,5),TFFO3(10,2,5),
          & TFHO1(10,2,5),TFHO2(10,2,5),TFHO3(10,2,5),TFHO4(10,2,5),TFHO5(10,
          & 2,5),TFRO(10,2,5),TFUO(10,2,5),TFVO(10,2,5)
0018       COMMON /TR5/ TFGG1(10,2,5),TFGG2(10,2,5),TFGG3(10,2,5),TFGG4(10,2,
          &5),TFGG5(10,2,5),TFLG1(10,2,5),TFLG2(10,2,5),TFFG3(10,2,5),TFAG1(
          &10,2,5),TFCG1(10,2,5),TFFG1(10,2,5),TFFG2(10,2,5),TFFG3(10,2,5),
          &TFHG1(10,2,5),TFHG2(10,2,5),TFHG3(10,2,5),TFHG4(10,2,5),TFHG5(10,
          &2,5),TFGR1(10,2,5),TFGR2(10,2,5),TFGR3(10,2,5),TFGR4(10,2,5),
          & TFGR5(10,2,5),TFER1(10,2,5),TFLR2(10,2,5),TFER3(10,2,5),TFAR1(
          &10,2,5),TFCR1(10,2,5),TFFR1(10,2,5),TFFR2(10,2,5),TFFR3(10,2,5),
          & TFHR1(10,2,5),TFHR2(10,2,5),TFHR3(10,2,5),TFHR4(10,2,5),TFHR5(
          &10,2,5),TFRG(10,2,5),TFRGU(10,2,5),TFVG(10,2,5)
     C
0019       COMMON /SET2/ VB,DELX,DELY,DELZ,DELT,RH
0020       COMMON /SET3/ CON1,CON2,CON3,CON4
0021       COMMON /SET1/ RHOSO,RHOSW,RHOSG,PSC,TSC,ALPHA,BETA,GAMMA
0022       COMMON /LIMIT/ MPOT,MPWT,MPGT,MSGT,MSWT,MFSGT,MFSWT
0023       COMMON /PARM1/ CL,CF,PHI(10,2,5),FPHI(10,2,5)
0024       COMMON /PARM2/ KL(10,2,5),FKXX(10,2,5),FKXY(10,2,5),FKXZ(10,2,5),
          & FKYX(10,2,5),FKYY(10,2,5),FKYZ(10,2,5),FKZX(10,2,5),
          & FKZY(10,2,5),FKZZ(10,2,5)
0025       COMMON /PARM3/  POT(15),BOT(15),DIBOT(15),
          & RSOT(15),DRSOT(15),UOT(15),PWT(15),UWT(15),PGT(15),UGT(15),
          & DIBGT(15),UGT(15),SGT(15),KRGT(15),KROGT(15),PCGOT(15),DSGT(15),
          & SWT(15),KRWT(15),KROWT(15),PCOWT(15),DSWT(15),FSGT(15),FKRGT(15),
          & FKROGT(15),FPCGOT(15),FDSGT(15),FSWT(15),FKRWT(15),FKROWT(15),
          & FPCOWT(15),FDSWT(15),RSWT(15),RFSWT(15)
     C
0026       DIMENSION W1(10,2,5),W2(10,2,5),W3(10,2,5),W4(10,2,5),W5(10,2,5)
          &,W6(10,2,5),W7(10,2,5),W8(10,2,5),W9(10,2,5),W10(10,2,5),W11(10,
          &2,5),W12(10,2,5),W13(10,2,5),W14(10,2,5),W15(10,2,5),W16(10,2,5),
          & W17(10,2,5),W18(10,2,5),W19(10,2,5),W20(10,2,5)
     C
0027       DO 50 K=1,NZ
0028       DO 50 J=1,NY
0029       DO 50 I=1,NX
0030       CALL LINTP(MSWT,SW(I,J,K),W1(I,J,K),SWT,KRWT)
0031       CALL LINTP(MSWT,SW(I,J,K),W2(I,J,K),SWT,KROWT)
0032       CALL LINTP(MSGT,SG(I,J,K),W3(I,J,K),SGT,KRGT)
0033       CALL LINTP(MSGT,SG(I,J,K),W4(I,J,K),SGT,KROGT)
0034       CALL LINTP(MFSWT,SWF(I,J,K),W5(I,J,K),FSWT,FKRWT)
0035       CALL LINTP(MFSWT,SWF(I,J,K),W6(I,J,K),FSWT,FKROWT)
0036       CALL LINTP(MFSGT,SGF(I,J,K),W7(I,J,K),FSGT,FKROGT)
0037       CALL LINTP(MFSGT,SGF(I,J,K),W8(I,J,K),FSGT,FKRGT)
0038       CALL LINTP(MPOT,PO(I,J,K),W9(I,J,K),POT,UOT)
0039       CALL LINTP(MPWT,PW(I,J,K),W10(I,J,K),PWT,UWT)
0040       CALL LINTP(MPGT,PG(I,J,K),W11(I,J,K),PGT,UGT)
0041       CALL LINTP(MPOT,PFO(I,J,K),W12(I,J,K),POT,UOT)
0042       CALL LINTP(MPWT,PFW(I,J,K),W13(I,J,K),PWT,UWT)
0043       CALL LINTP(MPGT,PFG(I,J,K),W14(I,J,K),PGT,UGT)
0044       CALL LINTP(MPOT,PO(I,J,K),W15(I,J,K),POT,BOT)
0045       CALL LINTP(MPGT,PG(I,J,K),W16(I,J,K),PGT,BGT)
0046       CALL LINTP(MPOT,PFO(I,J,K),W17(I,J,K),POT,BOT)
0047       CALL LINTP(MPGT,PFG(I,J,K),W18(I,J,K),PGT,BGT)
0048       CALL LINTP(MPOT,PO(I,J,K),W19(I,J,K),POT,RSOT)
0049       CALL LINTP(MPGT,PFO(I,J,K),W20(I,J,K),POT,RSOT)
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0050          50 CONTINUE
0051             FACT1=CON1*VB/(DELX*144.)
0052             FACT2=CON1*CON3*VB/(2.*DELX)
0053             FACT3=CON1*VB/(DELY*144.)
0054             FACT4=CON1*CON3*VB/(2.*DELY)
0055             FACT5=CON1*VB/(DELZ*144.)
0056             FACT6=CON1*CON3*VB/(2.*DELZ)
           C
0057             DO 100 K=1,NZ
0058             DO 100 J=1,NY
0059             DO 100 I=1,NX
0060             KRW=W1(I,J,K)
0061             KROW=W2(I,J,K)
0062             KRG=W3(I,J,K)
0063             KROG=W4(I,J,K)
0064             FKRW=W5(I,J,K)
0065             FKROW=W6(I,J,K)
0066             FKROG=W7(I,J,K)
0067             FKRG=W8(I,J,K)
0068             UO=W9(I,J,K)
0069             UW=W10(I,J,K)
0070             UG=W11(I,J,K)
0071             UOF=W12(I,J,K)
0072             UWF=W13(I,J,K)
0073             UGF=W14(I,J,K)
0074             BBO=W15(I,J,K)
0075             BBG=W16(I,J,K)
0076             BFO=W17(I,J,K)
0077             BFG=W18(I,J,K)
0078             RSO=W19(I,J,K)
0079             RSF=W20(I,J,K)
0080             KRO=(KROW+KRW)*(KROG+KRG)-(KRW+KRG)
0081             FKRO=(FKROW+FKRW)*(FKROG+FKRG)-(FKRW+FKRG)
0082             IF(I.EQ.1) GO TO 11
0083             KRW1=W1(I-1,J,K)
0084             KROW1=W2(I-1,J,K)
0085             KRG1=W3(I-1,J,K)
0086             KROG1=W4(I-1,J,K)
0087             FKRW1=W5(I-1,J,K)
0088             FKROW1=W6(I-1,J,K)
0089             FKROG1=W7(I-1,J,K)
0090             FKRG1=W8(I-1,J,K)
0091             UO1=W9(I-1,J,K)
0092             UW1=W10(I-1,J,K)
0093             UG1=W11(I-1,J,K)
0094             UOF1=W12(I-1,J,K)
0095             UWF1=W13(I-1,J,K)
0096             UGF1=W14(I-1,J,K)
0097             BBO1=W15(I-1,J,K)
0098             BBG1=W16(I-1,J,K)
0099             BFO1=W17(I-1,J,K)
0100             BFG1=W18(I-1,J,K)
0101             RSO1=W19(I-1,J,K)
0102             RSF1=W20(I-1,J,K)
0103             KRO1=(KROW1+KRW1)*(KROG1+KRG1)-(KRW1+KRG1)
0104             FKRO1=(FKROW1+FKRW1)*(FKROG1+FKRG1)-(FKRW1+FKRG1)
0105          11 IF(I.EQ.NX) GO TO 12
0106             KRW2=W1(I+1,J,K)
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      KROW2=W2(I+1,J,K)
      KRG2=W3(I+1,J,K)
      KROG2=W4(I+1,J,K)
      FKRW2=W5(I+1,J,K)
      FKROW2=W6(I+1,J,K)
      FKROG2=W7(I+1,J,K)
      FKRG2=W8(I+1,J,K)
      UO2=W9(I+1,J,K)
      UW2=W10(I+1,J,K)
      UG2=W11(I+1,J,K)
      UOF2=W12(I+1,J,K)
      UWF2=W13(I+1,J,K)
      UGF2=W14(I+1,J,K)
      BBO2=W15(I+1,J,K)
      BBG2=W16(I+1,J,K)
      BFO2=W17(I+1,J,K)
      BFG2=W18(I+1,J,K)
      RSO2=W19(I+1,J,K)
      RSF2=W20(I+1,J,K)
      KRO2=(KROW2+KRW2)*(KROG2+KRG2)-(KRW2+KRG2)
      FKRO2=(FKROW2+FKRW2)*(FKROG2+FKRG2)-(FKRW2+FKRG2)
   12 IF(J.EQ.1) GO TO 13
      KRW3=W1(I,J-1,K)
      KROW3=W2(I,J-1,K)
      KRG3=W3(I,J-1,K)
      KROG3=W4(I,J-1,K)
      FKRW3=W5(I,J-1,K)
      FKROW3=W6(I,J-1,K)
      FKROG3=W7(I,J-1,K)
      FKRG3=W8(I,J-1,K)
      UO3=W9(I,J-1,K)
      UW3=W10(I,J-1,K)
      UG3=W11(I,J-1,K)
      UOF3=W12(I,J-1,K)
      UWF3=W13(I,J-1,K)
      UGF3=W14(I,J-1,K)
      BBO3=W15(I,J-1,K)
      BBG3=W16(I,J-1,K)
      BFO3=W17(I,J-1,K)
      BFG3=W18(I,J-1,K)
      RSO3=W19(I,J-1,K)
      RSF3=W20(I,J-1,K)
      KRO3=(KROW3+KRW3)*(KROG3+KRG3)-(KRW3+KRG3)
      FKRO3=(FKROW3+FKRW3)*(FKROG3+FKRG3)-(FKRW3+FKRG3)
   13 IF(J.EQ.NY) GO TO 14
      KRW4=W1(I,J+1,K)
      KROW4=W2(I,J+1,K)
      KRG4=W3(I,J+1,K)
      KROG4=W4(I,J+1,K)
      FKRW4=W5(I,J+1,K)
      FKROW4=W6(I,J+1,K)
      FKROG4=W7(I,J+1,K)
      FKRG4=W8(I,J+1,K)
      UO4=W9(I,J+1,K)
      UW4=W10(I,J+1,K)
      UG4=W11(I,J+1,K)
      UOF4=W12(I,J+1,K)
      UWF4=W13(I,J+1,K)
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      UGF4=W14(I,J+1,K)
      BBO4=W15(I,J+1,K)
      BBG4=W16(I,J+1,K)
      BFO4=W17(I,J+1,K)
      BFG4=W18(I,J+1,K)
      RSO4=W19(I,J+1,K)
      RSF4=W20(I,J+1,K)
      KRO4=(KROW4+KRW4)*(KROG4+KRG4)-(KRW4+KRG4)
      FKRO4=(FKROW4+FKRW4)*(FKROG4+FKRG4)-(FKRW4+FKRG4)
   14 IF(K.EQ.1) GO TO 15
      KRW5=W1(I,J,K-1)
      KROW5=W2(I,J,K-1)
      KRG5=W3(I,J,K-1)
      KROG5=W4(I,J,K-1)
      FKRW5=W5(I,J,K-1)
      FKROW5=W6(I,J,K-1)
      FKROG5=W7(I,J,K-1)
      FKRG5=W8(I,J,K-1)
      UO5=W9(I,J,K-1)
      UW5=W10(I,J,K-1)
      UG5=W11(I,J,K-1)
      UOF5=W12(I,J,K-1)
      UWF5=W13(I,J,K-1)
      UGF5=W14(I,J,K-1)
      BBO5=W15(I,J,K-1)
      BBG5=W16(I,J,K-1)
      BFO5=W17(I,J,K-1)
      BFG5=W18(I,J,K-1)
      RSO5=W19(I,J,K-1)
      RSF5=W20(I,J,K-1)
      KRO5=(KROW5+KRW5)*(KROG5+KRG5)-(KRW5+KRG5)
      FKRO5=(FKROW5+FKRW5)*(FKROG5+FKRG5)-(FKRW5+FKRG5)
   15 IF(K.EQ.NZ) GO TO 16
      KRW6=W1(I,J,K+1)
      KROW6=W2(I,J,K+1)
      KRG6=W3(I,J,K+1)
      KROG6=W4(I,J,K+1)
      FKRW6=W5(I,J,K+1)
      FKROW6=W6(I,J,K+1)
      FKROG6=W7(I,J,K+1)
      FKRG6=W8(I,J,K+1)
      UO6=W9(I,J,K+1)
      UW6=W10(I,J,K+1)
      UG6=W11(I,J,K+1)
      UOF6=W12(I,J,K+1)
      UWF6=W13(I,J,K+1)
      UGF6=W14(I,J,K+1)
      BBO6=W15(I,J,K+1)
      BBG6=W16(I,J,K+1)
      BFO6=W17(I,J,K+1)
      BFG6=W18(I,J,K+1)
      RSO6=W19(I,J,K+1)
      RSF6=W20(I,J,K+1)
      KRO6=(KROW6+KRW6)*(KROG6+KRG6)-(KRW6+KRG6)
      FKRO6=(FKROW6+FKRW6)*(FKROG6+FKRG6)-(FKRW6+FKRG6)
   16 CONTINUE
      CALL LINTP(BPOT,PO(I,J,K),DIBO,POT,DIBOT)
      CALL LINTP(RPOT,PO(I,J,K),DRS,POT,DRSOT)
```

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0223      CALL LINTP(MPGT,PG(I,J,K),DIBG,PGT,DIBGT)
0224      CALL LINTP(MPOT,PFO(I,J,K),DIBOF,POT,DIBOT)
0225      CALL LINTP(MPOT,PFO(I,J,K),DRSF,POT,DRSOT)
0226      CALL LINTP(MPGT,PFG(I,J,K),DIBGF,PGT,DIBGT)
0227      CALL LINTP(MSWT,SWN(I,J,K),DSWDP,SWT,DSWT)
0228      CALL LINTP(MSGT,SGN(I,J,K),DSGDP,SGT,DSGT)
0229      CALL LINTP(MFSWT,SWFN(I,J,K),DFSWDP,FSWT,FDSWT)
0230      CALL LINTP(MFSGT,SGFN(I,J,K),DFSGDP,FSGT,FDSGT)
0231      DENO=(RHOSO+RSO*RHOSG/5.615)/BBO
0232      DENOF=(RHOSO+RSF*RHOSG/5.615)/BFO
0233      DENW=RHOSW
0234      DENWF=RHOSW
0235      DENG=RHOSG/(BBG*5.615)
0236      DENGF=RHOSG/(BFG*5.615)
    C
0237      IF(I.EQ.1) GO TO 223
0238      HO1=PO(I-1,J,K)-PO(I,J,K)-DENO*DSIN(ALPHA)*DELX/144.
0239      IF(HO1.GE.0.0) TKRO=KRO1
0240      IF(HO1.LT.0.0) TKRO=KRO
0241      IF(TKRO.LT.0.0) TKRO=0.0
0242      UAVG=FAVG(UO,UO1)
0243      BAVG=FAVG(BBO,BBO1)
0244      RSAVG=FAVG(RSO,RSO1)
0245      FACT=TKRO/(BAVG*UAVG)
0246      AO(I,J,K)=TAO(I,J,K)*FACT
0247      AGO(I,J,K)=TAGO(I,J,K)*FACT*RSAVG
    C
0248      HW1=PW(I-1,J,K)-PW(I,J,K)-DENW*DSIN(ALPHA)*DELX/144.
0249      IF(HW1.GE.0.0) TKRW=KRW1
0250      IF(HW1.LT.0.0) TKRW=KRW
0251      UWAVG=FAVG(UW,UW1)
0252      AW(I,J,K)=TAW(I,J,K)*TKRW/UWAVG
    C
0253      HG1=PG(I-1,J,K)-PG(I,J,K)-DENG*DSIN(ALPHA)*DELX/144.
0254      IF(HG1.GE.0.0) TKRG=KRG1
0255      IF(HG1.LT.0.0) TKRG=KRG
0256      UGAVG=FAVG(UG,UG1)
0257      BGAVG=FAVG(BBG1,BBG)
0258      AG(I,J,K)=TAG(I,J,K)*TKRG/(BGAVG*UGAVG)
    C
0259      HOF1=PFO(I-1,J,K)-PFO(I,J,K)-DENOF*DELX*(    DSIN(ALPHA)/144.-
         & CON3*(DFLOAT(I)*DVOXDT(I,J,K)-DFLOAT(I-1)*DVOXDT(I-1,J,K) ) )
0260      IF(HOF1.GE.0.0) TKROF=FKRO1
0261      IF(HOF1.LT.0.0) TKROF=FKRO
0262      IF(TKROF.LT.0.0) TKROF=0.0
0263      BFAVG=FAVG(BFO,BFO1)
0264      UOFAV=FAVG(UOF,UOF1)
0265      RSFAV=FAVG(RSF,RSF1)
0266      FACT=TKROF/(BFAVG*UOFAV)
0267      FAO1(I,J,K)=TFAO1(I,J,K)*FACT
0268      FAR1(I,J,K)=TFAR1(I,J,K)*FACT*RSFAV
    C
0269      HWF1=PFW(I-1,J,K)-PFW(I,J,K)-DENWF*DELX*(   DSIN(ALPHA)/144.-
         & CON3*(DFLOAT(I)*DVWXDT(I,J,K)-DFLOAT(I-1)*DVWXDT(I-1,J,K) ) )
0270      IF(HWF1.GE.0.0) TKRWF=FKRW1
0271      IF(HWF1.LT.0.0) TKRWF=FKRW
0272      UWFAV=FAVG(UWF,UWF1)
0273      FAW1(I,J,K)=TFAW1(I,J,K)*TKRWF/UWFAV
```

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                 C
0274                    HGF1=PFG(I-1,J,K)-PFG(I,J,K)-DENGF*DELX*(   DSIN(ALPHA)/144.-
                      & CON3*(DFLOAT(I)*DVGXDT(I,J,K)-DFLOAT(I-1)*DVGXDT(I-1,J,K) ) )
0275                    IF(HGF1.GE.0.0) TKRGF=FKRG1
0276                    IF(HGF1.LT.0.0) TKRGF=FKRG
0277                    BFGAV=FAVG(BFG,BFG1)
0278                    UGFAV=FAVG(UGF,UGF1)
0279                    FAG1(I,J,K)=TFAG1(I,J,K)*TKRGF/(BFGAV*UGFAV)
                 C
0280              223 IF(I.EQ.NX) GO TO 230
0281                    HO2=PO(I,J,K)-PO(I+1,J,K)-DENO*DSIN(ALPHA)*DELX/144.
0282                    IF(HO2.GT.0.0) TKRO=KRO
0283                    IF(HO2.LE.0.0) TKRO=KRO2
0284                    IF(TKRO.LT.0.0) TKRO=0.0
0285                    UAVG=FAVG(UO,UO2)
0286                    BAVG=FAVG(BBO,BBO2)
0287                    RSAVG=FAVG(RSO,RSO2)
0288                    FACT=TKRO/(BAVG*UAVG)
0289                    CO(I,J,K)=TCO(I,J,K)*FACT
0290                    CGO(I,J,K)=TCGO(I,J,K)*FACT*RSAVG
                 C
0291                    HW2=PW(I,J,K)-PW(I+1,J,K)-DENW*DSIN(ALPHA)*DELX/144.
0292                    IF(HW2.GT.0.0) TKRW=KRW
0293                    IF(HW2.LE.0.0) TKRW=KRW2
0294                    UWAVG=FAVG(UW,UW2)
0295                    CW(I,J,K)=TCW(I,J,K)*TKRW/UWAVG
                 C
0296                    HG2=PG(I,J,K)-PG(I+1,J,K)-DENG*DSIN(ALPHA)*DELX/144.
0297                    IF(HG2.GT.0.0) TKRG=KRG
0298                    IF(HG2.LE.0.0) TKRG=KRG2
0299                    UGAVG=FAVG(UG,UG2)
0300                    BGAVG=FAVG(BBG2,BBG)
0301                    CG(I,J,K)=TCG(I,J,K)*TKRG/(BGAVG*UGAVG)
                 C
0302                    HOF2=PFO(I,J,K)-PFO(I+1,J,K)-DENOF*DELX*(    DSIN(ALPHA)/144.-
                      & CON3*(DFLOAT(I+1)*DVOXDT(I+1,J,K)-DFLOAT(I)*DVOXDT(I,J,K) ) )
0303                    IF(HOF2.GT.0.0) TKROF=FKRO
0304                    IF(HOF2.LE.0.0) TKROF=FKRO2
0305                    IF(TKROF.LT.0.0) TKROF=0.0
0306                    BFAVG=FAVG(BFO,BFO2)
0307                    UOFAV=FAVG(UOF,UOF2)
0308                    RSFAV=FAVG(RSF,RSF2)
0309                    FACT=TKROF/(BFAVG*UOFAV)
0310                    FCO1(I,J,K)=TFCO1(I,J,K)*FACT
0311                    FCR1(I,J,K)=TFCR1(I,J,K)*FACT*RSFAV
                 C
0312                    HWF2=PFW(I,J,K)-PFW(I+1,J,K)-DENWF*DELX*(   DSIN(ALPHA)/144.-
                      & CON3*(DFLOAT(I+1)*DVWXDT(I+1,J,K)-DFLOAT(I)*DVWXDT(I,J,K) ) )
0313                    IF(HWF2.GT.0.0) TKRWF=FKRW
0314                    IF(HWF2.LE.0.0) TKRWF=FKRW2
0315                    UWFAV=FAVG(UWF,UWF2)
0316                    FCW1(I,J,K)=TFCW1(I,J,K)*TKRWF/UWFAV
                 C
0317                    HGF2=PFG(I,J,K)-PFG(I+1,J,K)-DENGF*DELX*(   DSIN(ALPHA)/144.-
                      & CON3*(DFLOAT(I+1)*DVGXDT(I+1,J,K)-DFLOAT(I)*DVGXDT(I,J,K) ) )
0318                    IF(HGF2.GT.0.0) TKRGF=FKRG
0319                    IF(HGF2.LE.0.0) TKRGF=FKRG2
0320                    BFGAV=FAVG(BFG,BFG2)
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      UGFAV=FAVG(UGF,UGF2)
      FCG1(I,J,K)=TFCG1(I,J,K)*TKRGF/(BFGAV*UGFAV)
C
  230 IF(J.EQ.1) GO TO 238
      HO3=PO(I,J-1,K)-PO(I,J,K)-DENO*DSIN(BETA)*DELY/144.
      IF(HO3.GE.0.0) TKRO=KRO3
      IF(HO3.LT.0.0) TKRO=KRO
      IF(TKRO.LT.0.0) TKRO=0.0
      UAVG=FAVG(UO,UO3)
      BAVG=FAVG(BBO,BBO3)
      RSAVG=FAVG(RSO,RSO3)
      FACT=TKRO/(BAVG*UAVG)
      EO(I,J,K)=TEO(I,J,K)*FACT
      EGO(I,J,K)=TEGO(I,J,K)*FACT*RSAVG
C
      HW3=PW(I,J-1,K)-PW(I,J,K)-DENW*DSIN(BETA)*DELY/144.
      IF(HW3.GE.0.0) TKRW=KRW3
      IF(HW3.LT.0.0) TKRW=KRW
      UWAVG=FAVG(UW,UW3)
      EW(I,J,K)=TEW(I,J,K)*TKRW/UWAVG
C
      HG3=PG(I,J-1,K)-PG(I,J,K)-DENG*DSIN(BETA)*DELY/144.
      IF(HG3.GE.0.0) TKRG=KRG3
      IF(HG3.LT.0.0) TKRG=KRG
      UGAVG=FAVG(UG,UG3)
      BGAVG=FAVG(BBG3,BBG)
      EG(I,J,K)=TEG(I,J,K)*TKRG/(BGAVG*UGAVG)
C
      HOF3=PFO(I,J-1,K)-PFO(I,J,K)-DENOF*DELY*(    DSIN(BETA)/144.-
     & CON3*(DELOAT(J)*DVOYDT(I,J,K)-DELOAT(J-1)*DVOYDT(I,J-1,K) ) )
      IF(HOF3.GE.0.0) TKROF=FKRO3
      IF(HOF3.LT.0.0) TKROF=FKRO
      IF(TKROF.LT.0.0) TKROF=0.0
      BFAVG=FAVG(BFO,BFO3)
      UOFAV=FAVG(UOF,UOF3)
      RSFAV=FAVG(RSF,RSF3)
      FACT=TKROF/(BFAVG*UOFAV)
      FEO2(I,J,K)=TFEO2(I,J,K)*FACT
      FEP2(I,J,K)=TFEP2(I,J,K)*FACT*RSFAV
C
      HWF3=PFW(I,J-1,K)-PFW(I,J,K)-DENWF*DELY*(   DSIN(BETA)/144.-
     & CON3*(DELOAT(J)*DVWYDT(I,J,K)-DELOAT(J-1)*DVWYDT(I,J-1,K) ) )
      IF(HWF3.GE.0.0) TKRWF=FKRW3
      IF(HWF3.LT.0.0) TKRWF=FKRW
      UWFAV=FAVG(UWF,UWF3)
      FEW2(I,J,K)=TFEW2(I,J,K)*TKRWF/UWFAV
C
      HGF3=PFG(I,J-1,K)-PFG(I,J,K)-DENGF*DELY*(   DSIN(BETA)/144.-
     & CON3*(DELOAT(J)*DVGYDT(I,J,K)-DELOAT(J-1)*DVGYDT(I,J-1,K) ) )
      IF(HGF3.GE.0.0) TKRGF=FKRG3
      IF(HGF3.LT.0.0) TKRGF=FKRG
      BFGAV=FAVG(BFG,BFG3)
      UGFAV=FAVG(UGF,UGF3)
      FEG2(I,J,K)=TFEG2(I,J,K)*TKRGF/(BFGAV*UGFAV)
C
  238 IF(J.EQ.NY) GO TO 245
      HO4=PO(I,J,K)-PO(I,J+1,K)-DENO*DSIN(BETA)*DELY/144.
      IF(HO4.GT.0.0) TKRO=KRO
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0369          IF(HO4.LE.0.0) TKRO=KRO4
0370          IF(TKRO.LT.0.0) TKRO=0.0
0371          UAVG=FAVG(UO,UO4)
0372          BAVG=FAVG(BBO,BBO4)
0373          RSAVG=FAVG(RSO,RSO4)
0374          FACT=TKRO/(BAVG*UAVG)
0375          FO(I,J,K)=TFO(I,J,K)*FACT
0376          FGO(I,J,K)=TFGO(I,J,K)*FACT*RSAVG
      C
0377          HW4=PW(I,J,K)-PW(I,J+1,K)-DENW*DSIN(BETA)*DELY/144.
0378          IF(HW4.GT.0.0) TKRW=KRW
0379          IF(HW4.LE.0.0) TKRW=KRW4
0380          UWAVG=FAVG(UW,UW4)
0381          FW(I,J,K)=TFW(I,J,K)*TKRW/UWAVG
      C
0382          HG4=PG(I,J,K)-PG(I,J+1,K)-DENG*DSIN(BETA)*DELY/144.
0383          IF(HG4.GT.0.0) TKRG=KRG
0384          IF(HG4.LE.0.0) TKRG=KRG4
0385          UGAVG=FAVG(UG,UG4)
0386          BGAVG=FAVG(BBG4,BBG)
0387          FG(I,J,K)=TFG(I,J,K)*TKRG/(BGAVG*UGAVG)
      C
0388          HOF4=PFO(I,J,K)-PFO(I,J+1,K)-DENOF*DELY*(    DSIN(BETA)/144.-
             & CON3*(DFLOAT(J+1)*DVUYDT(I,J+1,K)-DFLOAT(J)*DVUYDT(I,J,K) ) )
0389          IF(HOF4.GT.0.0) TKROF=FKRO
0390          IF(HOF4.LE.0.0) TKROF=FKRO4
0391          IF(TKROF.LT.0.0) TKROF=0.0
0392          BFAVG=FAVG(BFO,BFO4)
0393          UOFAV=FAVG(UOF,UOF4)
0394          RSFAV=FAVG(RSF,RSF4)
0395          FACT=TKROF/(BFAVG*UOFAV)
0396          FFO2(I,J,K)=TFFO2(I,J,K)*FACT
0397          FFR2(I,J,K)=TFFR2(I,J,K)*FACT*RSFAV
      C
0398          HWF4=PFW(I,J,K)-PFW(I,J+1,K)-DENWF*DELY*(   DSIN(BETA)/144.-
             & CON3*(DFLOAT(J+1)*DVWYDT(I,J+1,K)-DFLOAT(J)*DVWYDT(I,J,K) ) )
0399          IF(HWF4.GT.0.0) TKRWF=FKRW
0400          IF(HWF4.LE.0.0) TKRWF=FKRW4
0401          UWFAV=FAVG(UWF,UWF4)
0402          FFW2(I,J,K)=TFFW2(I,J,K)*TKRWF/UWFAV
      C
0403          HGF4=PFG(I,J,K)-PFG(I,J+1,K)-DENGF*DELY*(   DSIN(BETA)/144.-
             & CON3*(DFLOAT(J+1)*DVGYDT(I,J+1,K)-DFLOAT(J)*DVGYDT(I,J,K) ) )
0404          IF(HGF4.GT.0.0) TKRGF=FKRG
0405          IF(HGF4.LE.0.0) TKRGF=FKRG4
0406          BFGAV=FAVG(BFG,BFG4)
0407          UGFAV=FAVG(UGF,UGF4)
0408          FFG2(I,J,K)=TFFG2(I,J,K)*TKRGF/(BFGAV*UGFAV)
      C
0409      245 IF(K.EQ.1) GO TO 252
0410          HO5=PO(I,J,K-1)-PO(I,J,K)-DENO*DCOS(GAMMA)*DELZ/144.
0411          IF(HO5.GE.0.0) TKRO=KRO5
0412          IF(HO5.LT.0.0) TKRO=KRO
0413          IF(TKRO.LT.0.0) TKRO=0.0
0414          UAVG=FAVG(UO,UO5)
0415          BAVG=FAVG(BBO,BBO5)
0416          RSAVG=FAVG(RSO,RSO5)
0417          FACT=TKRO/(BAVG*UAVG)
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0418          GO(I,J,K)=TGO(I,J,K)*FACT
0419          GGO(I,J,K)=TGGO(I,J,K)*FACT*RSAVG
        C
0420          HW5=PW(I,J,K-1)-PW(I,J,K)-DENW*DCOS(GAMMA)*DELZ/144.
0421          IF(HW5.GE.0.0) TKRW=KRW5
0422          IF(HW5.LT.0.0) TKRW=KRW
0423          UWAVG=FAVG(UW,UW5)
0424          GW(I,J,K)=TGW(I,J,K)*TKRW/UWAVG
        C
0425          HG5=PG(I,J,K-1)-PG(I,J,K)-DENG*DCOS(GAMMA)*DELZ/144.
0426          IF(HG5.GE.0.0) TKRG=KRG5
0427          IF(HG5.LT.0.0) TKRG=KRG
0428          UGAVG=FAVG(UG,UG5)
0429          BGAVG=FAVG(BBG5,BBG)
0430          GG(I,J,K)=TGG(I,J,K)*TKRG/(BGAVG*UGAVG)
        C
0431          HOF5=PFO(I,J,K-1)-PFO(I,J,K)-DENOF*DELZ*(    DCOS(GAMMA)/144.-
             & CONJ*(DFLOAT(K)*DVOZDT(I,J,K)-DFLOAT(K-1)*DVOZDT(I,J,K-1) ) )
0432          IF(HOF5.GE.0.0) TKROF=FKRO5
0433          IF(HOF5.LT.0.0) TKROF=FKRO
0434          IF(TKROF.LT.0.0) TKROF=0.0
0435          BFAVG=FAVG(BFO,BFO5)
0436          UOFAV=FAVG(UOF,UOF5)
0437          RSFAV=FAVG(RSF,RSF5)
0438          FACT=TKROF/(BFAVG*UOFAV)
0439          FGO3(I,J,K)=TFGO3(I,J,K)*FACT
0440          FGR3(I,J,K)=TFGR3(I,J,K)*FACT*RSFAV
        C
0441          HWF5=PFW(I,J,K-1)-PFW(I,J,K)-DENWF*DELZ*(   DCOS(GAMMA)/144.-
             & CONJ*(DFLOAT(K)*DVWZDT(I,J,K)-DFLOAT(K-1)*DVWZDT(I,J,K-1) ) )
0442          IF(HWF5.GE.0.0) TKRWF=FKRW5
0443          IF(HWF5.LT.0.0) TKRWF=FKRW
0444          UWFAV=FAVG(UWF,UWF5)
0445          FGW3(I,J,K)=TFGW3(I,J,K)*TKRWF/UWFAV
        C
0446          HGF5=PFG(I,J,K-1)-PFG(I,J,K)-DENGF*DELZ*(   DCOS(GAMMA)/144.-
             & CONJ*(DFLOAT(K)*DVGZDT(I,J,K)-DFLOAT(K-1)*DVGZDT(I,J,K-1) ) )
0447          IF(HGF5.GE.0.0) TKRGF=FKRG5
0448          IF(HGF5.LT.0.0) TKRGF=FKRG
0449          BFGAV=FAVG(BFG,BFG5)
0450          UGFAV=FAVG(UGF,UGF5)
0451          FGG3(I,J,K)=TFGG3(I,J,K)*TKRGF/(BFGAV*UGFAV)
        C
0452      252 IF(K.EQ.NZ) GO TO 259
0453          HO6=PO(I,J,K)-PO(I,J,K+1)-DENO*DCOS(GAMMA)*DELZ/144.
0454          IF(HO6.GT.0.0) TKRO=KRO
0455          IF(HO6.LE.0.0) TKRO=KRO6
0456          IF(TKRO.LT.0.0) TKRO=0.0
0457          UAVG=FAVG(UO,UO6)
0458          BAVG=FAVG(BBO,BBO6)
0459          RSAVG=FAVG(RSO,RSO6)
0460          FACT=TKRO/(BAVG*UAVG)
0461          HO(I,J,K)=THO(I,J,K)*FACT
0462          HGO(I,J,K)=THGO(I,J,K)*FACT*RSAVG
        C
0463          HW6=PW(I,J,K)-PW(I,J,K+1)-DENW*DCOS(GAMMA)*DELZ/144.
0464          IF(HW6.GT.0.0) TKRW=KRW
0465          IF(HW6.LE.0.0) TKRW=KRW6
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0466          UWAVG=FAVG(UW,UW6)
0467          HW(I,J,K)=THW(I,J,K)*TKRW/UWAVG
        C
0468          HG6=PG(I,J,K)-PG(I,J,K+1)-DENG*DCOS(GAMMA)*DELZ/144.
0469          IF(HG6.GT.0.0) TKRG=KRG
0470          IF(HG6.LE.0.0) TKRG=KRG6
0471          UGAVG=FAVG(UG,UG6)
0472          BGAVG=FAVG(BUG6,BUG)
0473          HG(I,J,K)=THG(I,J,K)*TKRG/(BGAVG*UGAVG)
        C
0474          HOF6=PFO(I,J,K)-PFO(I,J,K+1)-DENOF*DELZ*(    DCOS(GAMMA)/144.-
             & CON3*(DFLOAT(K+1)*DVOZDT(I,J,K+1)-DFLOAT(K)*DVOZDT(I,J,K) ) )
0475          IF(HOF6.GT.0.0) TKROF=FKRO
0476          IF(HOF6.LE.0.0) TKROF=FKRO6
0477          IF(TKROF.LT.0.0) TKROF=0.0
0478          BFAVG=FAVG(BFO,BFO6)
0479          UOFAV=FAVG(UOF,UOF6)
0480          RSFAV=FAVG(RSF,RSF6)
0481          FACT=TKROF/(BFAVG*UOFAV)
0482          FHO3(I,J,K)=TFHO3(I,J,K)*FACT
0483          FHR3(I,J,K)=TFHR3(I,J,K)*FACT*RSFAV
        C
0484          HWF6=PFW(I,J,K)-PFW(I,J,K+1)-DENWF*DELZ*(  DCOS(GAMMA)/144.-
             & CON3*(DFLOAT(K+1)*DVWZDT(I,J,K+1)-DFLOAT(K)*DVWZDT(I,J,K) ) )
0485          IF(HWF6.GT.0.0) TKRWF=FKRW
0486          IF(HWF6.LE.0.0) TKRWF=FKRW6
0487          UWFAV=FAVG(UWF,UWF6)
0488          FHW3(I,J,K)=TFHW3(I,J,K)*TKRWF/UWFAV
        C
0489          HGF6=PFG(I,J,K)-PFG(I,J,K+1)-DENGF*DELZ*(  DCOS(GAMMA)/144.-
             & CON3*(DFLOAT(K+1)*DVGZDT(I,J,K+1)-DFLOAT(K)*DVGZDT(I,J,K) ) )
0490          IF(HGF6.GT.0.0) TKRGF=FKRG
0491          IF(HGF6.LE.0.0) TKRGF=FKRG6
0492          BFGAV=FAVG(BFG,BFG6)
0493          UGFAV=FAVG(UGF,UGF6)
0494          FHG3(I,J,K)=TFHG3(I,J,K)*TKRGF/(BFGAV*UGFAV)
        C
0495      259 IF(J.EQ.1.OR.K.EQ.1) GO TO 260
0496          IF(FKYZ(I,J-1,K).EQ.0.0.AND.FKZY(I,J,K-1).EQ.0.0) GO TO 260
0497          FGW1(I,J,K)=TFGW1(I,J,K)*(FKYZ(I,J-1,K)*FKRW3/UWF3 +
             & FKZY(I,J,K-1)*FKRW5/UWF5)
0498           FT1=FKYZ(I,J-1,K)*FKRO3/(BFO3*UOF3)
0499           FT2=FKZY(I,J,K-1)*FKRO5/(BFO5*UOF5)
0500          FGO1(I,J,K)=TFGO1(I,J,K)*(FT1+FT2)
0501          FGR1(I,J,K)=TFGR1(I,J,K)*(FT1*RSF3+FT2*RSF5)
0502          FGG1(I,J,K)=TFGG1(I,J,K)*( FKYZ(I,J-1,K)*FKRG3/(BFG3*UGF3) +
             & FKZY(I,J,K-1)*FKRG5/(BFG5*UGF5) )
0503      260 IF(I.EQ.1.OR.K.EQ.1) GO TO 261
0504          IF(FKXZ(I-1,J,K).EQ.0.0.AND.FKZX(I,J,K-1).EQ.0.0) GO TO 261
0505          FGW2(I,J,K)=TFGW2(I,J,K)*( FKXZ(I-1,J,K)*FKRW1/UWF1 +
             & FKZX(I,J,K-1)*FKRW5/UWF5 )
0506          FT1=FKXZ(I-1,J,K)*FKRO1/(BFO1*UOF1)
0507          FT2=FKZX(I,J,K-1)*FKRO5/(BFO5*UOF5)
0508          FGO2(I,J,K)=TFGO2(I,J,K)*(FT1+FT2)
0509          FGR2(I,J,K)=TFGR2(I,J,K)*(FT1*RSF1+FT2*RSF5)
0510          FGG2(I,J,K)=TFGG2(I,J,K)*( FKXZ(I-1,J,K)*FKRG1/(BFG1*UGF1) +
             & FKZX(I,J,K-1)*FKRG5/(BFG5*UGF5) )
0511      261 IF(I.EQ.NX.OR.K.EQ.1) GO TO 262
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0512          IF(FKXZ(I+1,J,K).EQ.0.0.AND.FKZX(I,J,K-1).EQ.0.0) GO TO 262
0513          FGW4(I,J,K)=-TFGW4(I,J,K)*( FKXZ(I+1,J,K)*FKRW2/UWF2 +
             & FKZX(I,J,K-1)*FKRW5/UWF5 )
0514          FT1=FKXZ(I+1,J,K)*FKRO2/(UFO2*UOF2)
0515          FT2=FKZX(I,J,K-1)*FKRO5/(UFO5*UOF5)
0516          FGO4(I,J,K)=-TFGO4(I,J,K)*(FT1+FT2)
0517          FGR4(I,J,K)=-TFGR4(I,J,K)*(FT1*RSF2+FT2*RSF5)
0518          FGG4(I,J,K)=-TFGG4(I,J,K)*( FKXZ(I+1,J,K)*FKRG2/(UFG2*UGF2) +
             & FKZX(I,J,K-1)*FKRG5/(UFG5*UGF5) )
0519      262 IF(J.EQ.NY.OR.K.EQ.1) GO TO 263
0520          IF(FKYZ(I,J+1,K).EQ.0.0.AND.FKZY(I,J,K-1).EQ.0.0) GO TO 263
0521          FGW5(I,J,K)=-TFGW5(I,J,K)*( FKYZ(I,J+1,K)*FKRW4/UWF4 +
             & FKZY(I,J,K-1)*FKRW5/UWF5 )
0522          FT1=FKYZ(I,J+1,K)*FKRO4/(UFO4*UOF4)
0523          FT2=FKZY(I,J,K-1)*FKRO5/(UFO5*UOF5)
0524          FGO5(I,J,K)=-TFGO5(I,J,K)*(FT1+FT2)
0525          FGR5(I,J,K)=-TFGR5(I,J,K)*(FT1*RSF4+FT2*RSF5)
0526          FGG5(I,J,K)=-TFGG5(I,J,K)*( FKYZ(I,J+1,K)*FKRG4/(UFG4*UGF4) +
             & FKZY(I,J,K-1)*FKRG5/(UFG5*UGF5) )
0527      263 IF(I.EQ.1.OR.J.EQ.1)GO TO 264
0528          IF(FKXY(I-1,J,K).EQ.0.0.AND.FKYX(I,J-1,K).EQ.0.0) GO TO 264
0529          FEW1(I,J,K)=TFEW1(I,J,K)*( FKXY(I-1,J,K)*FKRW1/UWF1 +
             & FKYX(I,J-1,K)*FKRW3/UWF3 )
0530          FT1=FKXY(I-1,J,K)*FKRO1/(UFO1*UOF1)
0531          FT2=FKYX(I,J-1,K)*FKRO3/(UFO3*UOF3)
0532          FEO1(I,J,K)=TFEO1(I,J,K)*(FT1+FT2)
0533          FER1(I,J,K)=TFER1(I,J,K)*(FT1*RSF1+FT2*RSF3)
0534          FEG1(I,J,K)=TFEG1(I,J,K)*( FKXY(I-1,J,K)*FKRG1/(UFG1*UGF1) +
             & FKYX(I,J-1,K)*FKRG3/(UFG3*UGF3) )
0535      264 IF(I.EQ.NX.OR.J.EQ.1) GO TO 265
0536          IF(FKXY(I+1,J,K).EQ.0.0.AND.FKYX(I,J-1,K).EQ.0.0) GO TO 265
0537          FEW3(I,J,K)=-TFEW3(I,J,K)*( FKXY(I+1,J,K)*FKRW2/UWF2 +
             & FKYX(I,J-1,K)*FKRW3/UWF3 )
0538          FT1=FKXY(I+1,J,K)*FKRO2/(UFO2*UOF2)
0539          FT2=FKYX(I,J-1,K)*FKRO3/(UFO3*UOF3)
0540          FEO3(I,J,K)=-TFEO3(I,J,K)*(FT1+FT2)
0541          FER3(I,J,K)=-TFER3(I,J,K)*(FT1*RSF2+FT2*RSF3)
0542          FEG3(I,J,K)=-TFEG3(I,J,K)*( FKXY(I+1,J,K)*FKRG2/(UFG2*UGF2) +
             & FKYX(I,J-1,K)*FKRG3/(UFG3*UGF3)   )
      C
0543      265 IF(I.EQ.1.OR.J.EQ.NY) GO TO 266
0544          IF(FKXY(I-1,J,K).EQ.0.0.AND.FKYX(I,J+1,K).EQ.0.0) GO TO 266
0545          FEW1(I,J,K)=-TFEW1(I,J,K)*( FKXY(I-1,J,K)*FKRW1/UWF1 +
             & FKYX(I,J+1,K)*FKRW4/UWF4 )
0546          FT1=FKXY(I-1,J,K)*FKRO1/(UFO1*UOF1)
0547          FT2=FKYX(I,J+1,K)*FKRO4/(UFO4*UOF4)
0548          FEO1(I,J,K)=-TFEO1(I,J,K)*(FT1+FT2)
0549          FER1(I,J,K)=-TFER1(I,J,K)*(FT1*RSF1+FT2*RSF4)
0550          FEG1(I,J,K)=-TFEG1(I,J,K)*( FKXY(I-1,J,K)*FKRG1/(UFG1*UGF1) +
             & FKYX(I,J+1,K)*FKRG4/(UFG4*UGF4) )
0551      266 IF(I.EQ.NX.OR.J.EQ.NY) GO TO 267
0552          IF(FKXY(I+1,J,K).EQ.0.0.AND.FKYX(I,J+1,K).EQ.0.0) GO TO 267
0553          FEW3(I,J,K)=TFEW3(I,J,K)*( FKXY(I+1,J,K)*FKRW2/UWF2 +
             & FKYX(I,J+1,K)*FKRW4/UWF4 )
0554          FT1=FKXY(I+1,J,K)*FKRO2/(UFO2*UOF2)
0555          FT2=FKYX(I,J+1,K)*FKRO4/(UFO4*UOF4)
0556          FEO3(I,J,K)=TFEO3(I,J,K)*(FT1+FT2)
0557          FER3(I,J,K)=TFER3(I,J,K)*(FT1*RSF2+FT2*RSF4)
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0558        FFG3(I,J,K)=TFFG3(I,J,K)*( FKXY(I+1,J,K)*FKRG2/(BFG2*UGF2) +
           & FKYX(I,J+1,K)*FKRG4/(BFG4*UGF4)   )
      C
0559    267 IF(J.EQ.1.OR.K.EQ.NZ) GO TO 268
0560        IF(FKYZ(I,J-1,K).EQ.0.0.AND.FKZY(I,J,K+1).EQ.0.0) GO TO 268
0561        FHW1(I,J,K)=-TFHW1(I,J,K)*( FKYZ(I,J-1,K)*FKRW3/UWF3 +
           & FKZY(I,J,K+1)*FKRW6/UWF6)
0562         FT1=FKYZ(I,J-1,K)*FKRO3/(BFO3*UOF3)
0563         FT2=FKZY(I,J,K+1)*FKRO6/(BFO6*UOF6)
0564        FHO1(I,J,K)=-TFHO1(I,J,K)*(FT1+FT2)
0565        FHR1(I,J,K)=-TFHR1(I,J,K)*(FT1*RSF3+FT2*RSF6)
0566        FHG1(I,J,K)=-TFHG1(I,J,K)*( FKYZ(I,J-1,K)*FKRG3/(BFG3*UGF3) +
           & FKZY(I,J,K+1)*FKRG6/(BFG6*UGF6) )
0567    268 IF(I.EQ.1.OR.K.EQ.NZ) GO TO 269
0568        IF(FKXZ(I-1,J,K).EQ.0.0.AND.FKZX(I,J,K+1).EQ.0.0) GO TO 269
0569        FHW2(I,J,K)=-TFHW2(I,J,K)*( FKXZ(I-1,J,K)*FKRW1/UWF1 +
           & FKZX(I,J,K+1)*FKRW6/UWF6 )
0570        FT1=FKXZ(I-1,J,K)*FKRO1/(BFO1*UOF1)
0571        FT2=FKZX(I,J,K+1)*FKRO6/(BFO6*UOF6)
0572        FHO2(I,J,K)=-TFHO2(I,J,K)*(FT1+FT2)
0573        FHR2(I,J,K)=-TFHR2(I,J,K)*(FT1*RSF1+FT2*RSF6)
0574        FHG2(I,J,K)=-TFHG2(I,J,K)*( FKXZ(I-1,J,K)*FKRG1/(BFG1*UGF1) +
           & FKZX(I,J,K+1)*FKRG6/(BFG6*UGF6) )
0575    269 IF(I.EQ.NX.OR.K.EQ.NZ) GO TO 270
0576        IF(FKXZ(I+1,J,K).EQ.0.0.AND.FKZX(I,J,K+1).EQ.0.0) GO TO 270
0577        FHW4(I,J,K)=TFHW4(I,J,K)*( FKXZ(I+1,J,K)*FKRW2/UWF2 +
           & FKZX(I,J,K+1)*FKRW6/UWF6 )
0578        FT1=FKXZ(I+1,J,K)*FKRO2/(BFO2*UOF2)
0579        FT2=FKZX(I,J,K+1)*FKRO6/(BFO6*UOF6)
0580        FHO4(I,J,K)=TFHO4(I,J,K)*(FT1+FT2)
0581        FHR4(I,J,K)=TFHR4(I,J,K)*(FT1*RSF2+FT2*RSF6)
0582        FHG4(I,J,K)=TFHG4(I,J,K)*( FKXZ(I+1,J,K)*FKRG2/(BFG2*UGF2) +
           & FKZX(I,J,K+1)*FKRG6/(BFG6*UGF6) )
0583    270 IF(J.EQ.NY.OR.K.EQ.NZ) GO TO 271
0584        IF(FKYZ(I,J+1,K).EQ.0.0.AND.FKZY(I,J,K+1).EQ.0.0) GO TO 271
0585        FHW5(I,J,K)=TFHW5(I,J,K)*( FKYZ(I,J+1,K)*FKRW4/UWF4 +
           & FKZY(I,J,K+1)*FKRW6/UWF6 )
0586        FT1=FKYZ(I,J+1,K)*FKRO4/(BFO4*UOF4)
0587        FT2=FKZY(I,J,K+1)*FKRO6/(BFO6*UOF6)
0588        FHO5(I,J,K)=TFHO5(I,J,K)*(FT1+FT2)
0589        FHR5(I,J,K)=TFHR5(I,J,K)*(FT1*RSF4+FT2*RSF6)
0590        FHG5(I,J,K)=TFHG5(I,J,K)*( FKYZ(I,J+1,K)*FKRG4/(BFG4*UGF4) +
           & FKZY(I,J,K+1)*FKRG6/(BFG6*UGF6) )
      C
0591    271 PW(I,J,K)=TPW(I,J,K)*FPHI(I,J,K)*KRW/UW
0592        UWM(I,J,K)=-(PHI(I,J,K)/DELT)*DSWDP*TUW(I,J,K)
0593        DW(I,J,K)=-(GW(I,J,K)+EW(I,J,K)+AW(I,J,K)+CW(I,J,K)+FW(I,J,K)+
           & RW(I,J,K)+UWM(I,J,K))
0594        DW(I,J,K)=-QW(I,J,K) - (PHI(I,J,K)/DELT)*( DSWDP*(   PON(I,J,K)-
           & PWN(I,J,K)   )   )*CONP*VB
0595        IF(ALPHA.NE.0.0) DW(I,J,K)=DW(I,J,K)-DELX*DENW*DSIN(ALPHA)*(
           & CW(I,J,K)-AW(I,J,K))/144.
0596        IF(BETA.NE.0.0) DW(I,J,K)=DW(I,J,K) - DELY*DENW*DSIN(BETA)*(
           & FW(I,J,K)-EW(I,J,K))/144.
0597        DW(I,J,K)=DW(I,J,K)-DELZ*DENW*DCOS(GAMMA)*( HW(I,J,K) -
           & GW(I,J,K))/144.
      C
0598        VO(I,J,K)=-(PHI(I,J,K)/DELT)*DSWDP*TVO(I,J,K)/BBO
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0599        UOM(I,J,K)=TUO(I,J,K)*(PHI(I,J,K)/DELT)*DSGDP/BBO
0600        RO(I,J,K)=TRO(I,J,K)*FPHI(I,J,K)*KRO/(BBO*UO)
0601        BO(I,J,K)=-(GO(I,J,K)+EO(I,J,K)+AO(I,J,K)+CO(I,J,K)+FO(I,J,K)+
         &  HO(I,J,K)+RO(I,J,K)+VO(I,J,K)+UOM(I,J,K)  + (1.-SW(I,J,K)-
         &  SG(I,J,K))*(PHI(I,J,K)/DELT)*DIBO*CON2*VB  )
0602        DO(I,J,K)=-QO(I,J,K) - CON2*VB*(PHI(I,J,K)/DELT)*( ( DSGDP/BBO -
         &  DSWDP/BBO + ( 1.-SG(I,J,K)-SW(I,J,K) )*DIBO )*PON(I,J,K)  -
         &  DSGDP*PGN(I,J,K)/BBO  +  DSWDP*PWN(I,J,K)/BBO   )
0603        IF(ALPHA.NE.0.0) DO(I,J,K)=DO(I,J,K) - DENO*DSIN(ALPHA)*DELX*(
         &  CO(I,J,K)-AO(I,J,K) )/144.
0604        IF(BETA.NE.0.0) DO(I,J,K)=DO(I,J,K) -DENO*DSIN(BETA)*DELY*(
         &  FO(I,J,K)-EO(I,J,K) )/144.
0605        DO(I,J,K)=DO(I,J,K) - DENO*DCOS(GAMMA)*DELZ*(   HO(I,J,K) -
         &  GO(I,J,K)  )/144.
      C
0606        RGO(I,J,K)=FPHI(I,J,K)*TRGO(I,J,K)*KRO*RSO/(BBO*UO)
0607        VG(I,J,K)=-TVG(I,J,K)*(PHI(I,J,K)/DELT)*RSO*DSWDP/BBO
0608        BGO(I,J,K)=-(GGO(I,J,K)+EGO(I,J,K)+AGO(I,J,K)+CGO(I,J,K)+
         &  FGO(I,J,K)+HGO(I,J,K)+RGO(I,J,K)+ (PHI(I,J,K)/DELT)*CON2*VB*(
         &  -DSGDP/BBG  + DSGDP*RSO/BBO - RSO*DSWDP/BBO +RSO*(1.-SG(I,J,K)-
         &  SW(I,J,K) )*DIBO +(1.-SG(I,J,K)-SW(I,J,K) )*DRS/BBO )  )
0609        RG(I,J,K)=TRG(I,J,K)*FPHI(I,J,K)*KRG/(BBG*UG)
0610        BG(I,J,K)=-(GG(I,J,K)+EG(I,J,K)+AG(I,J,K)+CG(I,J,K)+FG(I,J,K)+
         &  HG(I,J,K)+RG(I,J,K)  +(PHI(I,J,K)/DELT)*CON2*VB*( DSGDP/BBG +
         &  SG(I,J,K)*DIBG - RSO*DSGDP/BBO )  )
0611        DG(I,J,K)=-QG(I,J,K)  -CON2*VB*(PHI(I,J,K)/DELT)*( (DSGDP/BBG+
         &  SG(I,J,K)*DIBG-RSO*DSGDP/BBO)*PGN(I,J,K)  + ( -DSGDP/BBG+
         &  RSO*DSGDP/BBO-RSO*DSWDP/BBO+RSO*(1.-SG(I,J,K)-SW(I,J,K))*DIBO+
         &  (1.-SG(I,J,K)-SW(I,J,K))*DRS/BBO )*PON(I,J,K)  +
         &  RSO*DSWDP*PWN(I,J,K)/BBO  )
0612        IF(ALPHA.NE.0.0) DG(I,J,K)=DG(I,J,K)-DENG*DSIN(ALPHA)*DELX*(
         &  CG(I,J,K)-AG(I,J,K) )/144. -DENO*DSIN(ALPHA)*DELX*( CGO(I,J,K)-
         &  AGO(I,J,K) )/144.
0613        IF(BETA.NE.0.0) DG(I,J,K)=DG(I,J,K)-DENG*DSIN(BETA)*DELY*(
         &  FG(I,J,K)-EG(I,J,K) )/144. -DENO*DSIN(BETA)*DELY*( FGO(I,J,K)-
         &  EGO(I,J,K) )/144.
0614        DG(I,J,K)=DG(I,J,K)-DENG*DCOS(GAMMA)*DELZ*( HG(I,J,K)-GG(I,J,K)
         &  )/144. -DENO*DCOS(GAMMA)*DELZ*( HGO(I,J,K)-GGO(I,J,K))/144.
      C
0615        FRW(I,J,K)=TFRW(I,J,K)*FPHI(I,J,K)*KRW/UW
0616        FUW(I,J,K)=-TFUW(I,J,K)*FPHI(I,J,K)*DFSWDP/DELT
0617        FBW(I,J,K)=-(FAW1(I,J,K)+FCW1(I,J,K)+FEW2(I,J,K)+FFW2(I,J,K)+
         &  FGW3(I,J,K)+FHW3(I,J,K)+FRW(I,J,K)+FUW(I,J,K) )
      C
      C
0618        FKXYP=FAVG(FKXY(I,J,K),FKXY(I+1,J,K))
0619        FKXYM=FAVG(FKXY(I,J,K),FKXY(I-1,J,K))
0620        FKXZP=FAVG(FKXZ(I,J,K),FKXZ(I+1,J,K))
0621        FKXZM=FAVG(FKXZ(I,J,K),FKXZ(I-1,J,K))
0622        FKYZP=FAVG(FKYZ(I,J,K),FKYZ(I,J+1,K))
0623        FKYZM=FAVG(FKYZ(I,J,K),FKYZ(I,J-1,K))
0624        FKYXP=FAVG(FKYX(I,J,K),FKYX(I,J+1,K))
0625        FKYXM=FAVG(FKYX(I,J,K),FKYX(I,J-1,K))
0626        FKZXP=FAVG(FKZX(I,J,K),FKZX(I,J,K+1))
0627        FKZXM=FAVG(FKZX(I,J,K),FKZX(I,J,K-1))
0628        FKZYP=FAVG(FKZY(I,J,K),FKZY(I,J,K+1))
0629        FKZYM=FAVG(FKZY(I,J,K),FKZY(I,J,K-1))
      C
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0630           DFW(I,J,K)=-QWF(I,J,K)-CON2*FPHI(I,J,K)*DFSWDP*(PFON(I,J,K)-
              & PFWN(I,J,K))*VB/DELT
0631           IF(I.EQ.1.OR.I.EQ.NX) GO TO 411
0632           IF(FKXX(I,J,K).NE.0.0) DFW(I,J,K)=DFW(I,J,K)-FACT2*DENWF*FKRW*
              & FKXX(I,J,K)*(DVWXDT(I+1,J,K)-DVWXDT(I-1,J,K))/UWF
0633           IF(FKXY(I,J,K).NE.0.0) DFW(I,J,K)=DFW(I,J,K)-FACT2*DENWF*FKRW*
              & FKXY(I,J,K)*(DVWYDT(I+1,J,K)-DVWYDT(I-1,J,K))/UWF
0634           IF(FKXZ(I,J,K).NE.0.0) DFW(I,J,K)=DFW(I,J,K)-FACT2*DENWF*FKRW*
              & FKXZ(I,J,K)*(DVWZDT(I+1,J,K)-DVWZDT(I-1,J,K))/UWF
0635       411 IF(J.EQ.1.OR.J.EQ.NY) GO TO 412
0636           IF(FKYX(I,J,K).NE.0.0) DFW(I,J,K)=DFW(I,J,K)-FACT4*DENWF*FKRW*
              & FKYX(I,J,K)*(DVWXDT(I,J+1,K)-DVWXDT(I,J-1,K))/UWF
0637           IF(FKYY(I,J,K).NE.0.0) DFW(I,J,K)=DFW(I,J,K)-FACT4*DENWF*FKRW*
              & FKYY(I,J,K)*(DVWYDT(I,J+1,K)-DVWYDT(I,J+1,K))/UWF
0638           IF(FKYZ(I,J,K).NE.0.0) DFW(I,J,K)=DFW(I,J,K)-FACT4*DENWF*FKRW*
              & FKYZ(I,J,K)*(DVWZDT(I,J+1,K)-DVWZDT(I,J-1,K))/UWF
0639       412 IF(K.EQ.1.OR.K.EQ.NZ) GO TO 413
0640           IF(FKZX(I,J,K).NE.0.0) DFW(I,J,K)=DFW(I,J,K)-FACT6*DENWF*FKRW*
              & FKZX(I,J,K)*(DVWXDT(I,J,K+1)-DVWXDT(I,J,K-1))/UWF
0641           IF(FKZY(I,J,K).NE.0.0) DFW(I,J,K)=DFW(I,J,K)-FACT6*DENWF*FKRW*
              & FKZY(I,J,K)*(DVWYDT(I,J,K+1)-DVWYDT(I,J,K-1))/UWF
0642           IF(FKZZ(I,J,K).NE.0.0) DFW(I,J,K)=DFW(I,J,K)-FACT6*DENWF*FKRW*
              & FKZZ(I,J,K)*(DVWZDT(I,J,K+1)-DVWZDT(I,J,K-1))/UWF
0643       413 IF(ALPHA.NE.0.0) DFW(I,J,K)=DFW(I,J,K)-DENWF*DSIN(ALPHA)*DELX*(
              & FCW1(I,J,K)-FAW1(I,J,K))/144.
0644           IF(BETA.NE.0.0) DFW(I,J,K)=DFW(I,J,K)-DENWF*DSIN(BETA)*DELY*(
              & FFW2(I,J,K)-FES2(I,J,K))/144.
0645           DFW(I,J,K)=DFW(I,J,K)-DENWF*DCOS(GAMMA)*DELZ*(FHW3(I,J,K) -
              & FGW3(I,J,K))/144.
0646           FKIP=FAVG(FKRW,FKRW2)
0647           FKIM=FAVG(FKRW,FKRW1)
0648           IF(I.EQ.NX) FKIP=0.0
0649           IF(I.EQ.1) FKIM=0.0
0650           UWFIP=FAVG(UWF,UWF2)
0651           UWFIM=FAVG(UWF,UWF1)
0652           IF(BETA.NE.0.0.AND.FKXY(I,J,K).NE.0.0) DFW(I,J,K)=DFW(I,J,K) -
              & FACT1*DENWF*DSIN(BETA)*(FKXYP*FKIP/UWFIP-FKXYM*FKIM/UWFIM)
0653           IF(FKXZ(I,J,K).NE.0.0) DFW(I,J,K)=DFW(I,J,K)-FACT1*DENWF*
              & DCOS(GAMMA)*(FKXZP*FKIP/UWFIP-FKXZM*FKIM/UWFIM)
0654           FKJP=FAVG(FKRW,FKRW4)
0655           FKJM=FAVG(FKRW,FKRW3)
0656           IF(J.EQ.NY) FKJP=0.0
0657           IF(J.EQ.1) FKJM=0.0
0658           UWFJP=FAVG(UWF,UWF4)
0659           UWFJM=FAVG(UWF,UWF3)
0660           IF(FKYX(I,J,K).NE.0.0.AND.ALPHA.NE.0.0) DFW(I,J,K)=DFW(I,J,K) -
              & FACT3*DENWF*DSIN(ALPHA)*(FKJP*FKYXP/UWFJP-FKJM*FKYXM/UWFJM)
0661           IF(FKYZ(I,J,K).NE.0.0) DFW(I,J,K)=DFW(I,J,K)-FACT3*DENWF*
              & DCOS(GAMMA)*(FKJP*FKYZP/UWFJP-FKJM*FKYZM/UWFJM)
0662           FKKP=FAVG(FKRW,FKRW6)
0663           FKKM=FAVG(FKRW,FKRW5)
0664           IF(K.EQ.NZ) FKKP=0.0
0665           IF(K.EQ.1) FKKM=0.0
0666           UWFKP=FAVG(UWF,UWF6)
0667           UWFKM=FAVG(UWF,UWF5)
0668           IF(FKZX(I,J,K).NE.0.0.AND.ALPHA.NE.0.0) DFW(I,J,K)=DFW(I,J,K) -
              & FACT5*DENWF*DSIN(ALPHA)*(FKKP*FKZXP/UWFKP-FKKM*FKZXM/UWFKM)
0669           IF(FKZY(I,J,K).NE.0.0.AND.BETA.NE.0.0) DFW(I,J,K)=DFW(I,J,K) -
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     & FACT5*DENWI*DSIN(BETA)*(FKKP*FKZYP/UWFKP-FKKM*FKZYM/UWFKM)
C
C  OIL & GAS RHS
C
      FRO(I,J,K)=TFRO(I,J,K)*KRO*FPHI(I,J,K)/(BRO*UO)
      FUO(I,J,K)=TFUO(I,J,K)*FPHI(I,J,K)*DFSGDP/(BFO*DELT)
      FVO(I,J,K)=-TFVO(I,J,K)*FPHI(I,J,K)*DFSWDP/(BFO*DELT)
      FRO(I,J,K)=-( FCO1(I,J,K)+FAO1(I,J,K)+FFO2(I,J,K)+FEO2(I,J,K)+
     & FHO3(I,J,K)+FGO3(I,J,K)+FRO(I,J,K)+FUO(I,J,K)+FVO(I,J,K)+
     & CON2*VB*FPHI(I,J,K)*DIBOF*(1.-SWF(I,J,K)-SGF(I,J,K) )/DELT )
      GFRHS=0.0
      DFO(I,J,K)=-QOF(I,J,K)-FPHI(I,J,K)*CON2*(VB/DELT)*(  (
     &(1.-SWF(I,J,K)-SGF(I,J,K))*DIBOF -(DFSWDP-DFSGDP)/BFO)*PFON(I,J,K)
     & +(DFSWDP*PFWN(I,J,K) - DFSGDP*PFGN(I,J,K))/BFO  )
      IF(I.EQ.1.OR.I.EQ.NX) GO TO 415
      IF(FKXX(I,J,K).EQ.0.0) GO TO 4141
      FF1=FACT2*DLNOF*FKRO*FKXX(I,J,K)*(DVOXDT(I+1,J,K)-DVOXDT(I-1,J,K)
     & )/(BFO*UOF)
      DFO(I,J,K)=DFO(I,J,K)-FF1
      GFRHS=GFRHS-RSF*FF1
 4141 IF(FKXY(I,J,K).EQ.0.0) GO TO 4142
      FF2=FACT2*DLNOF*FKRO*FKXY(I,J,K)*(DVOYDT(I+1,J,K)-DVOYDT(I-1,J,K)
     & )/(BFO*UOF)
      DFO(I,J,K)=DFO(I,J,K)-FF2
      GFRHS=GFRHS-RSF*FF2
 4142 IF(FKXZ(I,J,K).EQ.0.0) GO TO 415
      FF3=FACT2*DLNOF*FKRO*FKXZ(I,J,K)*(DVOZDT(I+1,J,K)-DVOZDT(I-1,J,K)
     & )/(BFO*UOF)
      DFO(I,J,K)=DFO(I,J,K)-FF3
      GFRHS=GFRHS-RSF*FF3
  415 IF(J.EQ.1.OR.J.EQ.NY) GO TO 416
      IF(FKYX(I,J,K).EQ.0.0) GO TO 4151
      FF4=FACT4*DLNOF*FKRO*FKYX(I,J,K)*(DVOXDT(I,J+1,K)-DVOXDT(I,J-1,K)
     & )/(BFO*UOF)
      DFO(I,J,K)=DFO(I,J,K)-FF4
      GFRHS=GFRHS-RSF*FF4
 4151 IF(FKYY(I,J,K).EQ.0.0) GO TO 4152
      FF5=FACT4*DLNOF*FKRO*FKYY(I,J,K)*(DVOYDT(I,J+1,K)-DVOYDT(I,J-1,K)
     & )/(BFO*UOF)
      DFO(I,J,K)=DFO(I,J,K)-FF5
      GFRHS=GFRHS-RSF*FF5
 4152 IF(FKYZ(I,J,K).EQ.0.0) GO TO 416
      FF6=FACT4*DLNOF*FKRO*FKYZ(I,J,K)*(DVOZDT(I,J+1,K)-DVOZDT(I,J-1,K)
     & )/(BFO*UOF)
      DFO(I,J,K)=DFO(I,J,K)-FF6
      GFRHS=GFRHS-RSF*FF6
  416 IF(K.EQ.1.OR.K.EQ.NZ) GO TO 417
      IF(FKZX(I,J,K).EQ.0.0) GO TO 4161
      FF7=FACT6*DLNOF*FKRO*FKZX(I,J,K)*(DVOXDT(I,J,K+1)-DVOXDT(I,J,K-1)
     & )/(BFO*UOF)
      DFO(I,J,K)=DFO(I,J,K)-FF7
      GFRHS=GFRHS-RSF*FF7
 4161 IF(FKZY(I,J,K).EQ.0.0) GO TO 4162
      FF8=FACT6*DLNOF*FKRO*FKZY(I,J,K)*(DVOYDT(I,J,K+1)-DVOYDT(I,J,K-1)
     & )/(BFO*UOF)
      DFO(I,J,K)=DFO(I,J,K)-FF8
      GFRHS=GFRHS-RSF*FF8
 4162 IF(FKZZ(I,J,K).EQ.0.0) GO TO 417
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0712          FF9=FACT6*DENOF*FKRO*FKZZ(I,J,K)*(DVUZDT(I,J,K+1)-DVUZDT(I,J,K-1)
             & )/(UFO*UOF)
0713          DFO(I,J,K)=DFO(I,J,K)-FF9
0714          GFRHS=GFRHS-RSF*FF9
0715      417 IF(ALPHA.NE.0.0) DFO(I,J,K)=DFO(I,J,K)-DENOF*DSIN(ALPHA)*DELX*(
             & FCO1(I,J,K)-FAO1(I,J,K))/144.
0716          IF(BETA.NE.0.0) DFO(I,J,K)=DFO(I,J,K)-DENOF*DSIN(BETA)*DELY*(
             & FFO2(I,J,K)-FLO2(I,J,K))/144.
0717          DFO(I,J,K)=DFO(I,J,K)-DENOF*DCOS(GAMMA)*DELZ*(FHO3(I,J,K) -
             & FGO3(I,J,K))/144.
        C
0718          FKIP=FAVG(FKRO,FKRO2)
0719          FKIM=FAVG(FKRO,FKRO1)
0720          IF(I.EQ.NX) FKIP=0.0
0721          IF(I.EQ.1) FKIM=0.0
0722          UOFIP=FAVG(UOF,UOF2)
0723          UOFIM=FAVG(UOF,UOF1)
0724          BFOIP=FAVG(BFO,BFO2)
0725          BFOIM=FAVG(BFO,BFO1)
0726          RSFIP=FAVG(RSF,RSF2)
0727          RSFIM=FAVG(RSF,RSF1)
0728          IF(BETA.NE.0.0.AND.FKXY(I,J,K).NE.0.0) DFO(I,J,K)=DFO(I,J,K) -
             & FACT1*DENOF*DSIN(BETA)*( FKXYP*FKIP/(BFOIP*UOFIP) -
             & FKXYM*FKIM/(BFOIM*UOFIM)  )
0729          IF(BETA.NE.0.0.AND.FKXY(I,J,K).NE.0.0) GFRHS=GFRHS -
             & FACT1*DENOF*DSIN(BETA)*( FKXYP*FKIP*RSFIP/(BFOIP*UOFIP) -
             & FKXYM*FKIM*RSFIM/(BFOIM*UOFIM)  )
0730          IF(FKXZ(I,J,K).NE.0.0) DFO(I,J,K)=DFO(I,J,K)-FACT1*DENOF*
             & DCOS(GAMMA)*( FKXZP*FKIP/(BFOIP*UOFIP)-FKXZM*FKIM/(BFOIM*UOFIM))
0731          IF(FKXZ(I,J,K).NE.0.0) GFRHS=GFRHS-FACT1*DENOF*DCOS(GAMMA)*(
             & FKIP*FKXZP*RSFIP/(BFOIP*UOFIP)-FKIM*FKXZM*RSFIM/(BFOIM*UOFIM) )
0732          FKJP=FAVG(FKRO,FKRO4)
0733          FKJM=FAVG(FKRO,FKRO3)
0734          IF(J.EQ.NY) FKJP=0.0
0735          IF(J.EQ.1) FKJM=0.0
0736          UOFJP=FAVG(UOF,UOF4)
0737          UOFJM=FAVG(UOF,UOF3)
0738          BFOJP=FAVG(BFO,BFO4)
0739          BFOJM=FAVG(BFO,BFO3)
0740          RSFJP=FAVG(RSF,RSF4)
0741          RSFJM=FAVG(RSF,RSF3)
0742          IF(FKYX(I,J,K).NE.0.0.AND.ALPHA.NE.0.0) DFO(I,J,K)=DFO(I,J,K) -
             & FACT3*DENOF*DSIN(ALPHA)*( FKJP*FKYXP/(BFOJP*UOFJP) -
             & FKJM*FKYXM/(BFOJM*UOFJM) )
0743          IF(FKYX(I,J,K).NE.0.0.AND.ALPHA.NE.0.0) GFRHS = GFRHS -
             & FACT3*DENOF*DSIN(ALPHA)*( FKJP*FKYXP*RSFJP/(BFOJP*UOFJP) -
             & FKJM*FKYXM*RSFJM/(BFOJM*UOFJM) )
0744          IF(FKYZ(I,J,K).NE.0.0) DFO(I,J,K)=DFO(I,J,K)-FACT3*DENOF*
             & DCOS(GAMMA)*( FKJP*FKYZP/(BFOJP*UOFJP)-FKJM*FKYZM/(BFOJM*UOFJM) )
0745          IF(FKYZ(I,J,K).NE.0.0) GFRHS=GFRHS -FACT3*DENOF*DCOS(GAMMA)*(
             & FKJP*FKYZP*RSFJP/(BFOJP*UOFJP)-FKJM*FKYZM*RSFJM/(BFOJM*UOFJM) )
0746          FKKP=FAVG(FKRO,FKRO6)
0747          FKKM=FAVG(FKRO,FKRO5)
0748          IF(K.EQ.NZ) FKKP=0.0
0749          IF(K.EQ.1) FKKM=0.0
0750          UOFKP=FAVG(UOF,UOF6)
0751          UOFKM=FAVG(UOF,UOF5)
0752          BFOKP=FAVG(BFO,BFO6)
```

```
0753        RFOKM=FAVG(BFO,BFO5)
0754        RSFKP=FAVG(RSF,RSF6)
0755        RSFKM=FAVG(RSF,RSF5)
0756        IF(FKZX(I,J,K).NE.0.0.AND.ALPHA.NE.0.0) DFO(I,J,K)=DFO(I,J,K) -
           & FACT5*DENOF*DSIN(ALPHA)*( FKKP*FKZXP/(BFOKP*UOFKP) -
           & FKKM*FKZXM/(BFOKM*UOFKM) )
0757        IF(FKZX(I,J,K).NE.0.0.AND.ALPHA.NE.0.0) GFRHS = GFRHS -
           & FACT5*DENOF*DSIN(ALPHA)*( FKKP*FKZXP*RSFKP/(BFOKP*UOFKP) -
           & FKKM*FKZXM*RSFKM/(BFOKM*UOFKM) )
0758        IF(FKZY(I,J,K).NE.0.0.AND.BETA.NE.0.0) DFO(I,J,K)=DFO(I,J,K) -
           & FACT5*DENOF*DSIN(BETA)*( FKKP*FKZYP/(BFOKP*UOFKP) -
           & FKKM*FKZYM/(BFOKM*UOFKM) )
0759        IF(FKZY(I,J,K).NE.0.0.AND.BETA.NE.0.0) GFRHS = GFRHS -
           & FACT5*DENOF*DSIN(BETA)*( FKKP*FKZYP*RSFKP/(BFOKP*UOFKP) -
           & FKKM*FKZYM*RSFKM/(BFOKM*UOFKM) )
      C
0760        FRG(I,J,K)=TFRG(I,J,K)*FPHI(I,J,K)*KRG/(BBG*UG)
0761        FVG(I,J,K)=-TFVG(I,J,K)*FPHI(I,J,K)*RSF*DFSWDP/(BFO*DELT)
0762        FBR(I,J,K)=-(FAR1(I,J,K)+FCR1(I,J,K)+FFR2(I,J,K)+FER2(I,J,K)+
           & FGR3(I,J,K)+FHR3(I,J,K)+FRGD(I,J,K)-CON2*(VB/DELT)*
           & FPHI(I,J,K)*( DFSGDP/BFG + RSF*(DFSWDP-DFSGDP)/BFO -
           & (1.-SWF(I,J,K)-SGF(I,J,K) )*(DRSF/BFO+RSF*DIBOF) ) )
0763        FBG(I,J,K)=-(FAG1(I,J,K)+FCG1(I,J,K)+FFG2(I,J,K)+FEG2(I,J,K)+
           & FGG3(I,J,K)+FHG3(I,J,K)+FRG(I,J,K)+CON2*(VB/DELT)*FPHI(I,J,K)*(
           & DFSGDP/BFG+SGF(I,J,K)*DIBGF-RSF*DFSGDP/BFO )  )
0764        DFG(I,J,K)=GFRHS - DGF(I,J,K) -CON2*FPHI(I,J,K)*(VB/DELT)*( (
           & DFSGDP/BFG + SGF(I,J,K)*DIBOF - DFSGDP*RSF/BFO )*PFGN(I,J,K) - (
           & DFSGDP/BFG + RSF*(DFSWDP-DFSGDP)/BFO - (1.-SWF(I,J,K)-SGF(I,J,K)
           &)*(DRSF/BFO+RSF*DIBOF))*PFON(I,J,K) + RSF*DFSWDP*PFWN(I,J,K)/BFO)
0765        IF(I.EQ.1.OR.I.EQ.NX) GO TO 420
0766        IF(FKXX(I,J,K).NE.0.0) DFG(I,J,K)=DFG(I,J,K)-FACT2*DENGF*FKRG*
           & FKXX(I,J,K)*(DVGXDT(I+1,J,K)-DVGXDT(I-1,J,K))/(BFG*UGF)
0767        IF(FKXY(I,J,K).NE.0.0) DFG(I,J,K)=DFG(I,J,K)-FACT2*DENGF*FKRG*
           & FKXY(I,J,K)*(DVGYDT(I+1,J,K)-DVGYDT(I-1,J,K))/(BFG*UGF)
0768        IF(FKXZ(I,J,K).NE.0.0) DFG(I,J,K)=DFG(I,J,K)-FACT2*DENGF*FKRG*
           & FKXZ(I,J,K)*(DVGZDT(I+1,J,K)-DVGZDT(I-1,J,K))/(BFG*UGF)
0769    420 IF(J.EQ.1.OR.J.EQ.NY) GO TO 421
0770        IF(FKYX(I,J,K).NE.0.0) DFG(I,J,K)=DFG(I,J,K)-FACT4*DENGF*FKRG*
           & FKYX(I,J,K)*(DVGXDT(I,J+1,K)-DVGXDT(I,J-1,K))/(BFG*UGF)
0771        IF(FKYY(I,J,K).NE.0.0) DFG(I,J,K)=DFG(I,J,K)-FACT4*DENGF*FKRG*
           & FKYY(I,J,K)*(DVGYDT(I,J+1,K)-DVGYDT(I,J+1,K))/(BFG*UGF)
0772        IF(FKYZ(I,J,K).NE.0.0) DFG(I,J,K)=DFG(I,J,K)-FACT4*DENGF*FKRG*
           & FKYZ(I,J,K)*(DVGZDT(I,J+1,K)-DVGZDT(I,J-1,K))/(BFG*UGF)
0773    421 IF(K.EQ.1.OR.K.EQ.NZ) GO TO 422
0774        IF(FKZX(I,J,K).NE.0.0) DFG(I,J,K)=DFG(I,J,K)-FACT6*DENGF*FKRG*
           & FKZX(I,J,K)*(DVGXDT(I,J,K+1)-DVGXDT(I,J,K-1))/(BFG*UGF)
0775        IF(FKZY(I,J,K).NE.0.0) DFG(I,J,K)=DFG(I,J,K)-FACT6*DENGF*FKRG*
           & FKZY(I,J,K)*(DVGYDT(I,J,K+1)-DVGYDT(I,J,K-1))/(BFG*UGF)
0776        IF(FKZZ(I,J,K).NE.0.0) DFG(I,J,K)=DFG(I,J,K)-FACT6*DENGF*FKRG*
           & FKZZ(I,J,K)*(DVGZDT(I,J,K+1)-DVGZDT(I,J,K-1))/(BFG*UGF)
0777    422 IF(ALPHA.NE.0.0) DFG(I,J,K)=DFG(I,J,K)-DENGF*DSIN(ALPHA)*DELX*(
           & FCG1(I,J,K)-FAG1(I,J,K))/144. -DENOF*DELX*DSIN(ALPHA)*(
           & FCR1(I,J,K)-FAR1(I,J,K))/144.
0778        IF(BETA.NE.0.0) DFG(I,J,K)=DFG(I,J,K)-DENGF*DSIN(BETA)*DELY*(
           & FFG2(I,J,K)-FEG2(I,J,K))/144. - DENOF*DELY*DSIN(BETA)*(
           & FFR2(I,J,K)-FER2(I,J,K))/144.
0779        DFG(I,J,K)=DFG(I,J,K)-DENGF*DCOS(GAMMA)*DELZ*(FHG3(I,J,K) -
           & FGG3(I,J,K))/144. -DENOF*DELZ*DCOS(GAMMA)*( FHR3(I,J,K) -
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                  & FGR3(I,J,K))/144.
0780               FKIP=FAVG(FKRG,FKRG2)
0781               FKIM=FAVG(FKRG,FKRG1)
0782               IF(I.EQ.NX) FKIP=0.0
0783               IF(I.EQ.1) FKIM=0.0
0784               UGFIP=FAVG(UGF,UGF2)
0785               UGFIM=FAVG(UGF,UGF1)
0786               BFGIP=FAVG(BFG,BFG2)
0787               BFGIM=FAVG(BFG,BFG1)
0788               IF(BETA.NE.0.0.AND.FKXY(I,J,K).NE.0.0) DFG(I,J,K)=DFG(I,J,K) -
                  & FACT1*DENGF*DSIN(BETA)*( FKXYP*FKIP/(BFGIP*UGFIP) -
                  & FKXYM*FKIM/(BFGIM*UGFIM))
0789               IF(FKXZ(I,J,K).NE.0.0) DFG(I,J,K)=DFG(I,J,K)-FACT1*DENGF*
                  & DCOS(GAMMA)*(FKXZP*FKIP/(BFGIP*UGFIP)-FKXZM*FKIM/(BFGIM*UGFIM))
0790               FKJP=FAVG(FKRG,FKRG4)
0791               FKJM=FAVG(FKRG,FKRG3)
0792               IF(J.EQ.NY) FKJP=0.0
0793               IF(J.EQ.1) FKJM=0.0
0794               UGFJP=FAVG(UGF,UGF4)
0795               UGFJM=FAVG(UGF,UGF3)
0796               BFGJP=FAVG(BFG,BFG4)
0797               BFGJM=FAVG(BFG,BFG3)
0798               IF(FKYX(I,J,K).NE.0.0.AND.ALPHA.NE.0.0) DFG(I,J,K)=DFG(I,J,K) -
                  & FACT3*DENGF*DSIN(ALPHA)*( FKJP*FKYXP/(BFGJP*UGFJP) -
                  & FKJM*FKYXM/(BFGJM*UGFJM) )
0799               IF(FKYZ(I,J,K).NE.0.0) DFG(I,J,K)=DFG(I,J,K)-FACT3*DENGF*
                  & DCOS(GAMMA)*(FKJP*FKYZP/(BFGJP*UGFJP)-FKJM*FKYZM/(BFGJM*UGFJM) )
0800               FKKP=FAVG(FKRG,FKRG6)
0801               FKKM=FAVG(FKRG,FKRG5)
0802               IF(K.EQ.NZ) FKKP=0.0
0803               IF(K.EQ.1) FKKM=0.0
0804               UGFKP=FAVG(UGF,UGF6)
0805               UGFKM=FAVG(UGF,UGF5)
0806               IF(FKZX(I,J,K).NE.0.0.AND.ALPHA.NE.0.0) DFG(I,J,K)=DFG(I,J,K) -
                  & FACT5*DENGF*DSIN(ALPHA)*( FKKP*FKZXP/(BFGKP*UGFKP) -
                  & FKKM*FKZXM/(BFGKM*UGFKM) )
0807               IF(FKZY(I,J,K).NE.0.0.AND.BETA.NE.0.0) DFG(I,J,K)=DFG(I,J,K) -
                  & FACT5*DENGF*DSIN(BETA)*( FKKP*FKZYP/(BFGKP*UGFKP) -
                  & FKKM*FKZYM/(BFGKM*UGFKM) )
            C
0808          100 CONTINUE
0809               RETURN
0810               END
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FORTRAN IV G1  RELEASE 2.0            FAVG            DATE = 82333         20/37/07            PAGE 0001

                  REAL FUNCTION FAVG*8(A,B)
                  IMPLICIT REAL*8(A-H,O-Z)
                  FAVG=(A+B)/2.
                  RETURN
                  END
```

```
FORTRAN IV G1  RELEASE 2.0            EXTRAP          DATE = 82333         20/37/07            PAGE 0001

                  SUBROUTINE EXTRAP(NX,NY,NZ,XN,X,DELT,DELTN)
            C
            C  SUBROUTINE TO EXTRAPOLATE VALUES AT TIME (N+1/2)
            C  AND UPDATE VALUES AT TIME STEP N
            C
                  IMPLICIT REAL*8(A-H,O-Z)
                  DIMENSION XN(NX,NY,1),X(NX,NY,1)
                  DO 100 K=1,NZ
                  DO 100 J=1,NY
                  DO 100 I=1,NX
                  TEMP=X(I,J,K)
                  XPROJ=X(I,J,K)+(DELT/DELTN)*(X(I,J,K)-XN(I,J,K))
                  X(I,J,K)=(XPROJ+X(I,J,K))/2.
                  XN(I,J,K)=TEMP
              100 CONTINUE
                  RETURN
                  END
```

```
FORTRAN IV G1  RELEASE 2.0            LINTP           DATE = 82333         20/37/07            PAGE 0001

                  SUBROUTINE LINTP(N,X0,Y0,X,Y)
            C
            C  SUBROUTINE FOR LINEAR INTERPOLATION OF Y0 AT X0
            C  (VALUES BEYOND UPPER-BOUND OF X ARE SET AT Y(N) )
            C
                  IMPLICIT REAL*8(A-H,O-Z)
                  DIMENSION X(1),Y(1)
                  IF(X0.GE.X(N)) Y0=Y(N)
                  IF(X0.GE.X(N)) RETURN
                  DO 20 I=2,N
                  IF(X0.GE.X(I)) GO TO 20
                  Y0=Y(I-1) + (X0-X(I-1))*(Y(I)-Y(I-1))/(X(I)-X(I-1))
                  RETURN
               20 CONTINUE
                  END
```

```
0001          SUBROUTINE INCON(NX,NY,NZ,NVON)
        C
        C   SUBROUTINE TO READ INITIAL PRESSURE & SATURATION DISTRIBUTIONS
        C   AND INJECTION(+)/PRODUCTION(-) INFORMATION
        C
0002          IMPLICIT REAL*8(A-H,O-Z)
0003          COMMON /FLOW/QVO(10),QVW(10),QVG(10),QVT(10),QVGF(10),QVWF(10),
             & QVGF(10),QVTF(10),TO1(10),TO2(10),TP1(10),TP2(10),PV,DP,QN1(10),
             & QN2(10),QN3(10),PN1(10),PN2(10),PN3(10)
0004          COMMON /PRESS/ PO(10,2,5),PW(10,2,5),PG(10,2,5),PFO(10,2,5),
             & PFW(10,2,5),PFG(10,2,5),PON(10,2,5),PWN(10,2,5),PGN(10,2,5),
             & PFON(10,2,5),PFWN(10,2,5),PFGN(10,2,5)
0005          COMMON /SAT/ SO(10,2,5),SW(10,2,5),SG(10,2,5),SOF(10,2,5),
             & SWF(10,2,5),SGF(10,2,5),SON(10,2,5),SWN(10,2,5),SGN(10,2,5),
             & SOFN(10,2,5),SWFN(10,2,5),SGFN(10,2,5)
0006          INTEGER*2 QN1,QN2,QN3,PN1,PN2,PN3
0007          INTEGER*2 TITLE(40)
        C
0008          READ(5,100) TITLE
0009      100 FORMAT(40A2)
0010          READ(5,101) PI,PWI,PGI,PFI,PWFI,PGFI
0011          READ(5,101) SOI,SWI,SGI,SOFI,SWFI,SGFI
0012      101 FORMAT(6F10.0)
        C
0013          DO 10 K=1,NZ
0014          DO 10 J=1,NY
0015          DO 10 I=1,NX
0016          PO(I,J,K)=PI
0017          PW(I,J,K)=PWI
0018          PG(I,J,K)=PGI
0019          PFO(I,J,K)=PFI
0020          PFW(I,J,K)=PWFI
0021          PFG(I,J,K)=PGFI
0022          PON(I,J,K)=PI
0023          PWN(I,J,K)=PWI
0024          PGN(I,J,K)=PGI
0025          PFON(I,J,K)=PFI
0026          PFWN(I,J,K)=PWFI
0027          PFGN(I,J,K)=PGFI
0028          SO(I,J,K)=SOI
0029          SW(I,J,K)=SWI
0030          SG(I,J,K)=SGI
0031          SOF(I,J,K)=SOFI
0032          SWF(I,J,K)=SWFI
0033          SGF(I,J,K)=SGFI
0034          SON(I,J,K)=SOI
0035          SWN(I,J,K)=SWI
0036          SGN(I,J,K)=SGI
0037          SOFN(I,J,K)=SOFI
0038          SWFN(I,J,K)=SWFI
0039          SGFN(I,J,K)=SGFI
0040       10 CONTINUE
0041          PRINT 102
0042      102 FORMAT('1INITIAL PRESSURE DISTRIBUTIONS IN MATRIX ROCK'///)
0043          DO 12 LK=1,NZ
0044          K=NZ-LK+1
0045          PRINT 103, K
0046      103 FORMAT('0LAYER NUMBER',I7,/' *************'//)
```

```
      J=NY
   50 PRINT 104,J
  104 FORMAT('OROW NUMBER',I7,/' -----------'//)
      PRINT 105, (PO(I,J,K),I=1,NX)
  105 FORMAT(' PO ',10F12.1)
      PRINT 106, (PW(I,J,K),I=1,NX)
  106 FORMAT(' PW ',10F12.1)
      PRINT 107, (PG(I,J,K),I=1,NX)
  107 FORMAT(' PG ',10F12.1)
      J=J-1
      IF(J.EQ.0) GO TO 12
      GO TO 50
   12 CONTINUE
C
      PRINT 108
  108 FORMAT(/////'0INITIAL PRESSURE DISTRIBUTIONS IN FRACTURE'///)
      DO 13 LK=1,NZ
      K=NZ-LK+1
      PRINT 103, K
      J=NY
   51 PRINT 104,J
      PRINT 109, (PFO(I,J,K),I=1,NX)
  109 FORMAT(' PFO',10F12.1)
      PRINT 110, (PFW(I,J,K),I=1,NX)
  110 FORMAT(' PFW',10F12.1)
      PRINT 111, (PFG(I,J,K),I=1,NX)
  111 FORMAT(' PFG',10F12.1)
      J=J-1
      IF(J.EQ.0) GO TO 13
      GO TO 51
   13 CONTINUE
C
      PRINT 112
  112 FORMAT('1INITIAL SATURATION DISTRIBUTIONS IN MATRIX ROCK'///)
      DO 14 LK=1,NZ
      K=NZ-LK+1
      PRINT 103, K
      J=NY
   52 PRINT 104,J
      PRINT 113, (SO(I,J,K),I=1,NX)
  113 FORMAT(' SO ',10F12.2)
      PRINT 114, (SW(I,J,K),I=1,NX)
  114 FORMAT(' SW ',10F12.2)
      PRINT 115, (SG(I,J,K),I=1,NX)
  115 FORMAT(' SG ',10F12.2)
      J=J-1
      IF(J.EQ.0) GO TO 14
      GO TO 52
   14 CONTINUE
C
      PRINT 116
  116 FORMAT(/////'0INITIAL SATURATION DISTRIBUTIONS IN FRACTURE'///)
      DO 15 LK=1,NZ
      K=NZ-LK+1
      PRINT 103, K
      J=NY
   53 PRINT 104,J
      PRINT 117, (SOF(I,J,K),I=1,NX)
```

```
      117 FORMAT(' SGF',10F12.2)
          PRINT 118, (SWF(I,J,K),I=1,NX)
      118 FORMAT(' SWF',10F12.2)
          PRINT 119, (SGF(I,J,K),I=1,NX)
      119 FORMAT(' SGF',10F12.2)
          J=J-1
          IF(J.EQ.0) GO TO 15
          GO TO 53
       15 CONTINUE
C
C  READ NUMBER OF VARIABLE RATE NODES AND VARIABLE PRESSURE NODES
C
          READ(5,100) TITLE
          READ(5,120) NVQN
      120 FORMAT(I5)
            IF(NVQN.EQ.0) GO TO 56
            PRINT 121,NVQN
      121 FORMAT(//////' NUMBER OF VARIABLE RATE NODES=',I5,//)
C
C  READ VARIABLE RATE NODE LOCATION AND TIME-ON AND TIME-OFF FOR
C  THOSE RATES AS WELL AS INJECTION(+)/PRODUCTION(-) RATES
C
C  MAY ADD PRODUCTIVITY INDEX AND OPTION TO CAL. BOTTOM-HOLE FLOWING P
C
          DO 16 I=1,NVQN
          READ(5,122) QN1(I),QN2(I),QN3(I),TQ1(I),TQ2(I)
      122 FORMAT(3I5,4F10.0)
          READ(5,123) QVO(I),QVW(I),QVG(I),QVT(I),QVOF(I),QVWF(I),QVGF(I),
         & QVTF(I)
      123 FORMAT(8F9.0)
          PRINT 124,QN1(I),QN2(I),QN3(I),TQ1(I),TQ2(I),QVO(I),QVW(I),QVG(I),
         & QVT(I),QVOF(I),QVWF(I),QVGF(I),QVTF(I)
      124 FORMAT('ORATE NODE LOCATION= ',3I5,/' TIME ON (DAY) =',F12.2,
         &'    TIME OFF (DAY) =',F12.2,/' QVO(STB/D)=',F10.0,'    QVW(STB/D)='
         &,F10.0,'    QVG(SCF/D)=',F10.0,'    QVT(STB/D)=',F10.0,/,
         &' QVOF(STB/D)=',F9.0,'   QVWF(STB/D)=',F10.0,'   QVGF(SCF/D)=',
         & F10.0,'    QVTF(STB/D)=',F10.0)
       16 CONTINUE
       56 RETURN
          END
```

202

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0001          SUBROUTINE MATBAL(NX,NY,NZ,STBO,STBON,STBW,STBWN,SCFT,SCFTN,MBEO,
             & MBEW,MBEG,WOR,GOR,VPM,VPF,CUMOIL,CUMWAT,CUMWI,CUMGAS,CUMGI,
             & RVOLM,RVOLF,PAVG,DELT,OILP,WATP,WATI,GASP,GASI)
        C
        C   SUBROUTINE TO CALCULATE MATERIAL BALANCE IN EACH TIME STEP
        C   AND WATER-OIL RATIO AND GAS-OIL RATIO AND AVERAGE PRESSURE
        C
0002          IMPLICIT REAL*8(A-H,O-Z)
0003          COMMON /PRESS/ PO(10,2,5),PW(10,2,5),PG(10,2,5),PFO(10,2,5),
             & PFW(10,2,5),PFG(10,2,5),PON(10,2,5),PWN(10,2,5),PGN(10,2,5),
             & PFON(10,2,5),PFWN(10,2,5),PFGN(10,2,5)
0004          COMMON /PROD/ QO(10,2,5),QW(10,2,5),QG(10,2,5),QOF(10,2,5),
             & QWF(10,2,5),QGF(10,2,5)
0005          COMMON /LIMIT/ MPOT,MPWT,MPGT,MSGT,MSWT,MFSGT,MFSWT
0006          COMMON /PARM3/  POT(15),BOT(15),DIBOT(15),
             & RSOT(15),DRSOT(15),UOT(15),PWT(15),UWT(15),PGT(15),BGT(15),
             & DIBGT(15),UGT(15),SGT(15),KRGT(15),KROGT(15),PCGOT(15),DSGT(15),
             & SWT(15),KRWT(15),KROWT(15),PCOWT(15),DSWT(15),FSGT(15),FKRGT(15),
             & FKROGT(15),FPCGOT(15),FDSGT(15),FSWT(15),FKRWT(15),FKROWT(15),
             & FPCOWT(15),FDSWT(15),RSWT(15),RFSWT(15)
0007          DIMENSION VPM(NX,NY,1),VPF(NX,NY,1)
0008          REAL*8 MBEO,MBEW,MBEG
0009          WATI=0.0
0010          WATP=0.0
0011          OILP=0.0
0012          GASP=0.0
0013          GASI=0.0
0014          PAVG=0.0
0015          PAVGF=0.0
0016          DO 15 K=1,NZ
0017          DO 15 J=1,NY
0018          DO 15 I=1,NX
0019          IF(QO(I,J,K).LT.0.0) OILP=OILP+QO(I,J,K)*DELT
0020          IF(QOF(I,J,K).LT.0.0) OILP=OILP+QOF(I,J,K)*DELT
0021          IF(QW(I,J,K).LT.0.0) WATP=WATP+QW(I,J,K)*DELT
0022          IF(QWF(I,J,K).LT.0.0) WATP=WATP+QWF(I,J,K)*DELT
0023          IF(QW(I,J,K).GT.0.0) WATI=WATI+QW(I,J,K)*DELT
0024          IF(QWF(I,J,K).GT.0.0) WATI=WATI+QWF(I,J,K)*DELT
0025          IF(QG(I,J,K).LT.0.0) GASP=GASP+QG(I,J,K)*DELT
0026          IF(QGF(I,J,K).LT.0.0) GASP=GASP+QGF(I,J,K)*DELT
0027          IF(QG(I,J,K).GT.0.0) GASI=GASI+QG(I,J,K)*DELT
0028          IF(QGF(I,J,K).GT.0.0) GASI=GASI+QGF(I,J,K)*DELT
0029          PAVG=PAVG+PO(I,J,K)*VPM(I,J,K)
0030          PAVGF=PAVGF+PFO(I,J,K)*VPF(I,J,K)
0031       15 CONTINUE
0032          CUMOIL=CUMOIL+DABS(OILP)
0033          CUMWAT=CUMWAT+DABS(WATP)
0034          CUMWI=CUMWI+WATI
0035          CUMGAS=CUMGAS+DABS(GASP)
0036          CUMGI=CUMGI+GASI
0037          MBEO=(1.-STBO/(STBON-CUMOIL))*100.
0038          MBEW=(1.-STBW/(STBWN-CUMWAT+CUMWI))*100.
0039          MBEG=(1.-SCFT/(SCFTN-CUMGAS+CUMGI))*100.
        C
0040          PAVG=PAVG/RVOLM
0041          PAVGF=PAVGF/RVOLF
0042          CALL LINTP(MPOT,PAVG,RSO,POT,RSOT)
        C
```

```
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0043                  GOR=121.0
0044                  WOR=120001.0
0045                  IF(OILP.NE.0.0) GOR=GASP/OILP + RSO
0046                  IF(OILP.NE.0.0) WOR=WATP/OILP
0047                  RETURN
0048                  END
```

```
FORTRAN IV G1  RELEASE 2.0            PORUSY           DATE = 82333          20/37/07               PAGE 0001

0001                  SUBROUTINE PORUSY(NX,NY,NZ,RVOLM,RVOLF,VB,VPM,VPF)
                C
                C  SUBROUTINE TO UPDATE POROSITY AT NEW VALUES OF PRESSURE
                C  (USE OIL PRESSURE AS RLING FLUID PORE PRESSURE)
                C
0002                  IMPLICIT REAL*8(A-H,O-Z)
0003                  COMMON /PRESS/ PO(10,2,5),PW(10,2,5),PG(10,2,5),PFO(10,2,5),
                     & PFW(10,2,5),PFG(10,2,5),PON(10,2,5),PWN(10,2,5),PGN(10,2,5),
                     & PFON(10,2,5),PFWN(10,2,5),PFGN(10,2,5)
0004                  COMMON /PARM1/ CL,CF,PHI(10,2,5),FPHI(10,2,5)
0005                  DIMENSION VPM(NX,NY,1),VPF(NX,NY,1)
0006                  RVOLM=0.0
0007                  RVOLF=0.0
0008                  L=0
0009                  DO 100 K=1,NZ
0010                  DO 100 J=1,NY
0011                  DO 100 I=1,NX
0012                  PHIN=PHI(I,J,K)
0013                  FPHIN=FPHI(I,J,K)
0014                  PHI(I,J,K)=PHIN*(1.+(1.-PHIN)*CL*(PO(I,J,K)-PON(I,J,K)) -
                     & FPHIN*CF*(PFO(I,J,K)-PFON(I,J,K))   )
0015                  FPHI(I,J,K)=FPHIN*(1.+(1.-FPHIN)*CF*(PFO(I,J,K)-PFON(I,J,K)) -
                     & PHIN*CL*(PO(I,J,K)-PON(I,J,K))   )
0016                  VPM(I,J,K)=VB*PHI(I,J,K)
0017                  VPF(I,J,K)=VB*FPHI(I,J,K)
0018                  RVOLM=RVOLM+VPM(I,J,K)
0019                  RVOLF=RVOLF+VPF(I,J,K)
0020                  IF(PHI(I,J,K).LT.0.0.OR.FPHI(I,J,K).LT.0.0) L=1
0021              100 CONTINUE
0022                  IF(L.EQ.1) PRINT 101
0023              101 FORMAT('0WARNING:  NEGATIVE POROSITY ENCOUNTERED')
0024                  RETURN
0025                  END
```

```
0001          SUBROUTINE PSOR(NX,NY,NZ,MITER,TOL,OMEGA,NITER)
        C
        C    SUBROUTINE TO SOLVE PRESSURE EQUATIONS BY
        C    POINT-SUCCESSIVE-OVER-RELAXATION METHOD
        C
0002          IMPLICIT REAL*8(A-H,O-Z)
0003          COMMON /PRESS/ PO(10,2,5),PW(10,2,5),PG(10,2,5),PFO(10,2,5),
             & PFW(10,2,5),PFG(10,2,5),PON(10,2,5),PWN(10,2,5),PGN(10,2,5),
             & PFON(10,2,5),PFWN(10,2,5),PFGN(10,2,5)
0004          COMMON /CMTX1/ GW(10,2,5),EW(10,2,5),AW(10,2,5),BW(10,2,5),
             &CW(10,2,5),FW(10,2,5),HW(10,2,5),RW(10,2,5),UWM(10,2,5),DW(10,2,5)
0005          COMMON /CMTX2/ VO(10,2,5),GO(10,2,5),EO(10,2,5),AO(10,2,5),
             & BO(10,2,5),CO(10,2,5),FO(10,2,5),HO(10,2,5),UOM(10,2,5),
             & RO(10,2,5),DO(10,2,5)
0006          COMMON /CMTX3/ VG(10,2,5),GGO(10,2,5),EGO(10,2,5),AGO(10,2,5),
             & BGO(10,2,5),CGO(10,2,5),FGO(10,2,5),HGO(10,2,5),GG(10,2,5),
             & EG(10,2,5),AG(10,2,5),BG(10,2,5),CG(10,2,5),FG(10,2,5),
             & HG(10,2,5),RGO(10,2,5),RG(10,2,5),DG(10,2,5)
0007          COMMON /CMTX4/ FRW(10,2,5),FGW1(10,2,5),FGW2(10,2,5),FGW3(10,2,5)
             &,FGW4(10,2,5),FGW5(10,2,5),FEW1(10,2,5),FEW2(10,2,5),FEW3(10,2,5)
             &,FAW1(10,2,5),FBW(10,2,5),FCW1(10,2,5),FFW1(10,2,5),FFW2(10,2,5)
             &,FFW3(10,2,5),FHW1(10,2,5),FHW2(10,2,5),FHW3(10,2,5),FHW4(10,2,5)
             &,FHW5(10,2,5),FJW(10,2,5),DFW(10,2,5)
0008          COMMON /CMTX5/ FRO(10,2,5),FVO(10,2,5),FGO1(10,2,5),FGO2(10,2,5),
             & FGO3(10,2,5),FGO4(10,2,5),FGO5(10,2,5),FEO1(10,2,5),FEO2(10,2,5)
             &,FEO3(10,2,5),FAO1(10,2,5),FBO(10,2,5),FCO1(10,2,5),FFO1(10,2,5),
             & FFO2(10,2,5),FFO3(10,2,5),FHO1(10,2,5),FHO2(10,2,5),FHO3(10,2,5)
             &,FHO4(10,2,5),FHO5(10,2,5),FUO(10,2,5),DFO(10,2,5)
0009          COMMON /CMTX6/ FRGO(10,2,5),FRG(10,2,5),FVG(10,2,5),FGR1(10,2,5),
             & FGR2(10,2,5),FGR3(10,2,5),FGR4(10,2,5),FGR5(10,2,5),FER1(10,2,5)
             &,FER2(10,2,5),FER3(10,2,5),FAR1(10,2,5),FBR(10,2,5),FCR1(10,2,5),
             & FFR1(10,2,5),FFR2(10,2,5),FFR3(10,2,5),FHR1(10,2,5),FHR2(10,2,5)
             &,FHR3(10,2,5),FHR4(10,2,5),FHR5(10,2,5),FGG1(10,2,5),FGG2(10,2,5)
             &,FGG3(10,2,5),FGG4(10,2,5),FGG5(10,2,5),FEG1(10,2,5),FEG2(10,2,5)
             &,FEG3(10,2,5),FAG1(10,2,5),FBG(10,2,5),FCG1(10,2,5),FFG1(10,2,5),
             & FFG2(10,2,5),FFG3(10,2,5),FHG1(10,2,5),FHG2(10,2,5),FHG3(10,2,5)
             &,FHG4(10,2,5),FHG5(10,2,5),DFG(10,2,5)
        C
0010          NITER=0
0011       11 NITER=NITER+1
0012          RMAX=0.0
0013          DO 15 K=1,NZ
0014          DO 15 J=1,NY
0015          DO 15 I=1,NX
0016          PKW=PW(I,J,K)
0017          PW(I,J,K)=(DW(I,J,K) -GW(I,J,K)*PW(I,J,K-1) -EW(I,J,K)*PW(I,J-1,K)
             & -AW(I,J,K)*PW(I-1,J,K) -CW(I,J,K)*PW(I+1,J,K) -FW(I,J,K)*PW(I,
             &J+1,K) -HW(I,J,K)*PW(I,J,K+1) -RW(I,J,K)*PFW(I,J,K)
             & -UWM(I,J,K)*PO(I,J,K) )/BW(I,J,K)
0018          PW(I,J,K)=PKW+OMEGA*(PW(I,J,K)-PKW)
        C
0019          PKO=PO(I,J,K)
0020          PO(I,J,K)=(DO(I,J,K) -VO(I,J,K)*PW(I,J,K) -GO(I,J,K)*PO(I,J,K-1)
             & -EO(I,J,K)*PO(I,J-1,K) -AO(I,J,K)*PO(I-1,J,K) -CO(I,J,K)*PO(
             &I+1,J,K) -FO(I,J,K)*PO(I,J+1,K) -HO(I,J,K)*PO(I,J,K+1)
             & -UOM(I,J,K)*PG(I,J,K) -RO(I,J,K)*PFO(I,J,K) )/BO(I,J,K)
0021          PO(I,J,K)=PKO+OMEGA*(PO(I,J,K)-PKO)
        C
```

205

```
0022             PKG=PG(I,J,K)
0023             PG(I,J,K)=(DG(I,J,K) -VG(I,J,K)*PW(I,J,K) -GGO(I,J,K)*PO(I,J,
                &K-1) -EGO(I,J,K)*PO(I,J-1,K) -AGO(I,J,K)*PO(I-1,J,K)
                & -CGO(I,J,K)*PO(I+1,J,K) -FGO(I,J,K)*PO(I,J+1,K) -HGO(I,J,K)*PO(
                &I,J,K+1) -GG(I,J,K)*PG(I,J,K-1) -BGO(I,J,K)*PO(I,J,K) -EG(I,J,K)*
                &PG(I,J-1,K) -AG(I,J,K)*PG(I-1,J,K) -CG(I,J,K)*PG(I+1,J,K)
                & -FG(I,J,K)*PG(I,J+1,K) -HG(I,J,K)*PG(I,J,K+1) -RGO(I,J,K)*PFO(I,
                &J,K) -RG(I,J,K)*PFG(I,J,K) )/BG(I,J,K)
0024             PG(I,J,K)=PKG+OMEGA*(PG(I,J,K)-PKG)
           C
0025             PKWF=PFW(I,J,K)
0026             PFW(I,J,K)=(DFW(I,J,K) -FRW(I,J,K)*PW(I,J,K) -FGW1(I,J,K)*PFW(I,
                &J-1,K-1) -FGW2(I,J,K)*PFW(I-1,J,K-1) -FGW3(I,J,K)*PFW(I,J,K-1)
                & -FGW4(I,J,K)*PFW(I+1,J,K-1) -FGW5(I,J,K)*PFW(I,J+1,K-1)
                & -FEW1(I,J,K)*PFW(I-1,J-1,K) -FEW2(I,J,K)*PFW(I,J-1,K) -FEW3(I,J,K
                &)*PFW(I+1,J-1,K) -FAW1(I,J,K)*PFW(I-1,J,K) -FCW1(I,J,K)*PFW(I+1,J,
                &K) -FFW1(I,J,K)*PFW(I-1,J+1,K) -FFW2(I,J,K)*PFW(I,J+1,K) -FFW3(I,
                &J,K)*PFW(I+1,J+1,K) -FHW1(I,J,K)*PFW(I,J-1,K+1) -FHW2(I,J,K)*PFW(
                &I-1,J,K+1) -FHW3(I,J,K)*PFW(I,J,K+1) -FHW4(I,J,K)*PFW(I+1,J,K+1)
                & -FHW5(I,J,K)*PFW(I,J+1,K+1) -FUW(I,J,K)*PFO(I,J,K) )/FBW(I,J,K)
0027             PFW(I,J,K)=PKWF+OMEGA*(PFW(I,J,K)-PKWF)
           C
0028             PKOF=PFO(I,J,K)
0029             PFO(I,J,K)=(DFO(I,J,K) -FRO(I,J,K)*PO(I,J,K) -FVO(I,J,K)*PFW(I,J,K
                &) -FGO1(I,J,K)*PFO(I,J-1,K-1) -FGO2(I,J,K)*PFO(I-1,J,K-1) -FGO3(I,
                &J,K)*PFO(I,J,K-1) -FGO4(I,J,K)*PFO(I+1,J,K-1) -FGO5(I,J,K)*PFO(I,
                &J+1,K-1) -FEO1(I,J,K)*PFO(I-1,J-1,K) -FEO2(I,J,K)*PFO(I,J-1,K)
                & -FEO3(I,J,K)*PFO(I+1,J-1,K) -FAO1(I,J,K)*PFO(I-1,J,K) -FCO1(I,J,
                &K)*PFO(I+1,J,K) -FFO1(I,J,K)*PFO(I-1,J+1,K) -FFO2(I,J,K)*PFO(I,
                &J+1,K) -FFO3(I,J,K)*PFO(I+1,J+1,K) -FHO1(I,J,K)*PFO(I,J-1,K+1)
                &-FHO2(I,J,K)*PFO(I-1,J,K+1) -FHO3(I,J,K)*PFO(I,J,K+1) -FHO4(I,J,
                &K)*PFO(I+1,J,K+1) -FHO5(I,J,K)*PFO(I,J+1,K+1) -FUO(I,J,K)*PFG(I,J,
                &K)  )/FBO(I,J,K)
0030             PFO(I,J,K)=PKOF+OMEGA*(PFO(I,J,K)-PKOF)
           C
0031             PKGF=PFG(I,J,K)
0032             TEM=DFG(I,J,K) -FRGO(I,J,K)*PO(I,J,K) -FRG(I,J,K)*PG(I,J,K)
                & -FVG(I,J,K)*PFW(I,J,K) -FGR1(I,J,K)*PFO(I,J-1,K) -FGR2(I,J,K)*
                &PFO(I-1,J,K-1) -FGR3(I,J,K)*PFO(I,J,K-1) -FGR4(I,J,K)*PFO(I+1,J,
                &K-1) -FGR5(I,J,K)*PFO(I,J+1,K-1) -FER1(I,J,K)*PFO(I-1,J-1,K)
                & -FER2(I,J,K)*PFO(I,J-1,K) -FER3(I,J,K)*PFO(I+1,J-1,K) -FAR1(I,J,
                &K)*PFO(I-1,J,K) -FBP(I,J,K)*PFO(I,J,K) -FCR1(I,J,K)*PFO(I+1,J,K)
                & -FFR1(I,J,K)*PFO(I-1,J+1,K) -FFR2(I,J,K)*PFO(I,J+1,K)
                & -FFR3(I,J,K)*PFO(I+1,J+1,K) -FHR1(I,J,K)*PFO(I,J-1,K+1) -FHR2(I,
                &J,K)*PFO(I-1,J,K+1) -FHR3(I,J,K)*PFO(I,J,K+1) -FHR4(I,J,K)*PFO(
                &I+1,J,K+1) -FHR5(I,J,K)*PFO(I,J+1,K+1)
0033             TEM1=-FGG1(I,J,K)*PFG(I,J-1,K-1) -FGG2(I,J,K)*PFG(I-1,J,K-1)
                & -FGG3(I,J,K)*PFG(I,J,K-1) -FGG4(I,J,K)*PFG(I+1,J,K-1) -FGG5(I,J,K
                &)*PFG(I,J+1,K-1) -FEG1(I,J,K)*PFG(I-1,J-1,K) -FEG2(I,J,K)*PFG(I,
                &J-1,K) -FEG3(I,J,K)*PFG(I+1,J-1,K) -FAG1(I,J,K)*PFG(I-1,J,K)
                & -FCG1(I,J,K)*PFG(I+1,J,K) -FFG1(I,J,K)*PFG(I-1,J+1,K) -FFG2(I,J,K
                &)*PFG(I,J+1,K) -FFG3(I,J,K)*PFG(I+1,J+1,K) -FHG1(I,J,K)*PFG(I,J-1,
                &K+1) -FHG2(I,J,K)*PFG(I-1,J,K+1) -FHG3(I,J,K)*PFG(I,J,K+1)
                & -FHG4(I,J,K)*PFG(I+1,J,K+1) -FHG5(I,J,K)*PFG(I,J+1,K+1)
0034             PFG(I,J,K)=(TEM+TEM1)/FBG(I,J,K)
0035             PFG(I,J,K)=PKGF+OMEGA*(PFG(I,J,K)-PKGF)
           C
0036             R1=DABS(PG(I,J,K)-PKG)
```

```
            IF(R1.GT.RMAX) RMAX=R1
            R2=DABS(PW(I,J,K)-PKW)
            IF(R2.GT.RMAX) RMAX=R2
            R3=DABS(PG(I,J,K)-PKG)
            IF(R3.GT.RMAX) RMAX=R3
            R4=DABS(PFO(I,J,K)-PKOF)
            IF(R4.GT.RMAX) RMAX=R4
            R5=DABS(PFW(I,J,K)-PKWF)
            IF(R5.GT.RMAX) RMAX=R5
            R6=DABS(PFG(I,J,K)-PKGF)
            IF(R6.GT.RMAX) RMAX=R6
         15 CONTINUE
            IF(RMAX.LT.TOL) GO TO 20
            IF(NITER.GE.MITER) GO TO 30
            GO TO 11
         20 PRINT 95,NITER
         95 FORMAT('0CONVERGENCE AFTER',I7,'   ITERATIONS')
            RETURN
         30 PRINT 96,NITER
         96 FORMAT('0CONVERGENCE NOT ACHIEVED AFTER',I7,'   ITERATIONS')
            RETURN
            END
```

```
      SUBROUTINE PTPRES(NX,NY,NZ,N,PAVG,MBEO,MBEW,MBEG,CUMOIL,CUMWAT,
     & CUMWI,CUMGAS,CUMGI,OILP,WATP,WATI,GASP,GASI,WOR,GOR,ETIME,DELTN)
C
C  SUBROUTINE TO PRINT OUT PRESSURE DISTRIBUTIONS AND OTHER RESERVOIR
C  PARAMETERS
C
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 MBEO,MBEW,MBEG
      COMMON /PRESS/ PO(10,2,5),PW(10,2,5),PG(10,2,5),PFO(10,2,5),
     & PFW(10,2,5),PFG(10,2,5),PON(10,2,5),PWN(10,2,5),PGN(10,2,5),
     & PFON(10,2,5),PFWN(10,2,5),PFGN(10,2,5)
C
      PRINT 100,N,ETIME,DELTN
  100 FORMAT('1SIMULATION RESULTS AFTER TIME STEP ',I5,/,'0ELAPSED TIME
     & =',F10.2,' DAYS',/'0TIME STEP SIZE (DAY)    =',F10.2,///)
      PRINT 101,PAVG,MBEO,MBEW,MBEG,CUMOIL,CUMWAT,CUMWI
  101 FORMAT('0AVERAGE RESERVOIR (MATRIX) PRESSURE (PSIA)  =',F12.2,//,
     &        ' OIL MATERIAL BALANCE THIS STEP (PERCENT)    =',F12.4,/,
     &        ' WATER MATERIAL BALANCE THIS STEP (PERCENT)  =',F12.4,/,
     &        ' GAS MATERIAL BALANCE THIS STEP (PERCENT)    =',F12.4,//,
     &        ' CUMULATIVE OIL PRODUCED (STB)               =',F12.0,/,
     &        ' CUMULATIVE WATER PRODUCED (STB)             =',F12.0,/,
     &        ' CUMULATIVE WATER INJECTED (STB)             =',F12.0)
      PRINT 102,CUMGAS,CUMGI,WOR,GOR
  102 FORMAT(' CUMULATIVE GAS PRODUCED (SCF)               =',F12.0,/,
     &        ' CUMULATIVE GAS INJECTED (SCF)               =',F12.0,//,
     &        ' WATER-OIL RATIO                             =',F12.1,/,
     &        ' GAS-OIL RATIO                               =',F12.1,//)
      PRINT 103,OILP,WATP,WATI,GASP,GASI
  103 FORMAT(' OIL PRODUCTION THIS STEP (STB)              =',F12.2,/,
     &        ' WATER PRODUCTION THIS STEP (STB)            =',F12.2,/,
     &        ' WATER INJECTION THIS STEP (STB)             =',F12.2,/,
     &        ' GAS PRODUCTION THIS STEP (SCF)              =',F12.2,/,
     &     ' GAS INJECTION THIS STEP (SCF)               =',F12.2,////)
      PRINT 104
  104 FORMAT('1 PRESSURE DISTRIBUTIONS IN MATRIX ROCK',/,
     &        '  ***************************************'//)
      DO 12 LK=1,NZ
      K=NZ-LK+1
      PRINT 105, K
  105 FORMAT('0LAYER NUMBER',I7,/' ************'/)
      J=NY
   50 PRINT 106,J
  106 FORMAT('0ROW NUMBER',I7,/' ----------'/)
      PRINT 107, (PO(I,J,K),I=1,NX)
  107 FORMAT(' PO ',10F12.1)
      PRINT 108, (PW(I,J,K),I=1,NX)
  108 FORMAT(' PW ',10F12.1)
      PRINT 109, (PG(I,J,K),I=1,NX)
  109 FORMAT(' PG ',10F12.1)
      J=J-1
      IF(J.EQ.0) GO TO 12
      GO TO 50
   12 CONTINUE
C
      PRINT 110
  110 FORMAT(/////'0 PRESSURE DISTRIBUTIONS IN FRACTURE',/,
     &             ' ************************************'//)
```

```
      DO 13 LK=1,NZ
      K=NZ-LK+1
      PRINT 105, K
      J=NY
   51 PRINT 106,J
      PRINT 111, (PFU(I,J,K),I=1,NX)
  111 FORMAT(' PFU',10F12.1)
      PRINT 112, (PFW(I,J,K),I=1,NX)
  112 FORMAT(' PFW',10F12.1)
      PRINT 113, (PFG(I,J,K),I=1,NX)
  113 FORMAT(' PFG',10F12.1)
      J=J-1
      IF(J.EQ.0) GO TO 13
      GO TO 51
   13 CONTINUE
      RETURN
      END
```

```
0001            SUBROUTINE PTSAT(NX,NY,NZ,N,ETIME)
          C
          C  SUBROUTINE TO PRINT SATURATION DISTRIBUTIONS
          C
0002            IMPLICIT REAL*8(A-H,O-Z)
0003            COMMON /SAT/ SO(10,2,5),SW(10,2,5),SG(10,2,5),SOF(10,2,5),
               & SWF(10,2,5),SGF(10,2,5),SON(10,2,5),SWN(10,2,5),SGN(10,2,5),
               & SOFN(10,2,5),SWFN(10,2,5),SGFN(10,2,5)
          C
0004            PRINT 112,N,ETIME
0005        112 FORMAT(/////'0FOR TIME STEP',I5,'  ELAPSED TIME (DAYS)=',F12.2,//
               & ,'0 SATURATION DISTRIBUTIONS IN MATRIX ROCK',/,
               & '  ****************************************'//)
0006            DO 14 LK=1,NZ
0007            K=NZ-LK+1
0008            PRINT 103, K
0009            J=NY
0010         52 PRINT 104,J
0011            PRINT 113, (SO(I,J,K),I=1,NX)
0012        113 FORMAT(' SO ',10F12.2)
0013            PRINT 114, (SW(I,J,K),I=1,NX)
0014        114 FORMAT(' SW ',10F12.2)
0015            PRINT 115, (SG(I,J,K),I=1,NX)
0016        115 FORMAT(' SG ',10F12.2)
0017            J=J-1
0018            IF(J.EQ.0) GO TO 14
0019            GO TO 52
0020         14 CONTINUE
          C
0021            PRINT 116
0022        116 FORMAT(/////'0 SATURATION DISTRIBUTIONS IN FRACTURE',/,
               &           '  **************************************'//)
0023            DO 15 LK=1,NZ
0024            K=NZ-LK+1
0025            PRINT 103, K
0026            J=NY
0027         53 PRINT 104,J
0028            PRINT 117, (SOF(I,J,K),I=1,NX)
0029        117 FORMAT(' SOF',10F12.2)
0030            PRINT 118, (SWF(I,J,K),I=1,NX)
0031        118 FORMAT(' SWF',10F12.2)
0032            PRINT 119, (SGF(I,J,K),I=1,NX)
0033        119 FORMAT(' SGF',10F12.2)
0034            J=J-1
0035            IF(J.EQ.0) GO TO 15
0036            GO TO 53
0037         15 CONTINUE
0038        103 FORMAT('0LAYER NUMBER ',I5,/' *************'/)
0039        104 FORMAT('0ROW NUMBER',I5,/' ----------'/)
          C
0040            RETURN
0041            END
```

```
      SUBROUTINE PTPOR(NX,NY,NZ,N,ETIME)
C
C  SUBROUTINE TO PRINT POROSITY DISTRIBUTIONS
C
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON /PARM1/ CL,CF,PHI(10,2,5),FPHI(10,2,5)
C
      PRINT 112,N,ETIME
  112 FORMAT(/////'0FOR TIME STEP',I5,'  ELAPSED TIME (DAYS)=',F12.2,//
     & ,'0 POROSITY DISTRIBUTIONS IN MATRIX ROCK',/,
     & '  ****************************************'//)
      DO 12 LK=1,NZ
      K=NZ-LK+1
      PRINT 103, K
      J=NY
   23 PRINT 104,J
      PRINT 189, (PHI(I,J,K),I=1,NX)
      J=J-1
      IF(J.EQ.0) GO TO 12
      GO TO 23
   12 CONTINUE
      PRINT 152
  152 FORMAT(///' *** POROSITY DISTRIBUTION IN FRACTURE ***',/,
     &       '      ***********************************'//)
      DO 18 LK=1,NZ
      K=NZ-LK+1
      PRINT 103,K
      J=NY
   31 PRINT 104,J
      PRINT 189,(FPHI(I,J,K),I=1,NX)
      J=J-1
      IF(J.EQ.0) GO TO 18
      GO TO 31
   18 CONTINUE
  103 FORMAT('0LAYER NUMBER ',I5,/' ************'/)
  104 FORMAT('0ROW NUMBER',I5,/' ----------'/)
  189 FORMAT(('0',10F12.4))
C
      RETURN
      END
```

```
0001            SUBROUTINE PTVELO(NX,NY,NZ,N,ETIME,DELT)
          C
          C  SUBROUTINE TO PRINT VELOCITY DISTRIBUTIONS OF FLUIDS IN FRACTURE
          C
0002            IMPLICIT REAL*8(A-H,O-Z)
0003            COMMON /VELO/ VOX(10,2,5),VOY(10,2,5),VOZ(10,2,5),VWX(10,2,5),
               &VWY(10,2,5),VWZ(10,2,5),VGX(10,2,5),VGY(10,2,5),VGZ(10,2,5)
          C
0004            PRINT 100,N,ETIME,DELT
0005        100 FORMAT('1SIMULATION RESULTS AFTER TIME STEP ',I5,/,'0ELAPSED TIME
               & =',F10.2,' DAYS',/'0TIME STEP SIZE (DAY)    =',F10.2,///)
0006            PRINT 114
0007        114 FORMAT(//' FLUID VELOCITY DISTRIBUTIONS IN FRACTURES',/,
               &          ' ******************************************'//)
0008            DO 14 LK=1,NZ
0009            K=NZ-LK+1
0010            PRINT 105,K
0011        105 FORMAT('0LAYER NUMBER',I7,/' ************'/)
0012            J=NY
0013         52 PRINT 106,J
0014        106 FORMAT('0ROW NUMBER',I7,/' ----------'/)
0015            PRINT 115, (VOX(I,J,K),I=1,NX)
0016        115 FORMAT(' VOX',10D12.4)
0017            PRINT 116, (VOY(I,J,K),I=1,NX)
0018        116 FORMAT(' VOY',10D12.4)
0019            PRINT 117, (VOZ(I,J,K),I=1,NX)
0020        117 FORMAT(' VOZ',10D12.4)
0021            PRINT 118, (VWX(I,J,K),I=1,NX)
0022        118 FORMAT(' VWX',10D12.4)
0023            PRINT 119, (VWY(I,J,K),I=1,NX)
0024        119 FORMAT(' VWY',10D12.4)
0025            PRINT 120, (VWZ(I,J,K),I=1,NX)
0026        120 FORMAT(' VWZ',10D12.4)
0027            PRINT 121, (VGX(I,J,K),I=1,NX)
0028        121 FORMAT(' VGX',10D12.4)
0029            PRINT 122, (VGY(I,J,K),I=1,NX)
0030        122 FORMAT(' VGY',10D12.4)
0031            PRINT 123, (VGZ(I,J,K),I=1,NX)
0032        123 FORMAT(' VGZ',10D12.4)
0033            J=J-1
0034            IF(J.EQ.0) GO TO 14
0035            GO TO 52
0036         14 CONTINUE
0037            RETURN
0038            END
```

```
      SUBROUTINE RESDAT(NX,NY,NZ)
C
C  SUBROUTINE TO READ IN RESERVOIR AND FLUID DATA
C
      IMPLICIT REAL*8(A-H,K,O-Z)
      INTEGER K,KPHIL,KPERL,KPHIF
      COMMON /SET1/ RHOSO,RHOSW,RHOSG,PSC,TSC,ALPHA,BETA,GAMMA
      COMMON /LIMIT/ MPOT,MPWT,MPGT,MSGT,MSWT,MFSGT,MFSWT
      COMMON /PARM1/ CL,CF,PHI(10,2,5),FPHI(10,2,5)
      COMMON /PARM2/ KL(10,2,5),FKXX(10,2,5),FKXY(10,2,5),FKXZ(10,2,5),
     & FKYX(10,2,5),FKYY(10,2,5),FKYZ(10,2,5),FKZX(10,2,5),
     & FKZY(10,2,5),FKZZ(10,2,5)
      COMMON /PARM3/  POT(15),BOT(15),DIBOT(15),
     & RSOT(15),DRSOT(15),UOT(15),PWT(15),UWT(15),PGT(15),BGT(15),
     & DIBGT(15),UGT(15),SGT(15),KRGT(15),KROGT(15),PCGOT(15),DSGT(15),
     & SWT(15),KRWT(15),KROWT(15),PCOWT(15),DSWT(15),FSGT(15),FKRGT(15),
     & FKROGT(15),FPCGOT(15),FDSGT(15),FSWT(15),FKRWT(15),FKROWT(15),
     & FPCOWT(15),FDSWT(15),RSWT(15),RFSWT(15)
      INTEGER*2 TITLE(40)
C
C  READ CODE NUMBER FOR ROCK-MATRIX POROSITY AND PERMEABILITY
C  (FOR UNIFORM DISTRIBUTION:  KPHIL=0, KPERL=0)
C
      READ(5,112) TITLE
      READ(5,100) KPHIL,KPERL
      IF(KPHIL.NE.0) GO TO 20
      READ(5,112) TITLE
      READ(5,101) PHIL
      DO 10 K=1,NZ
      DO 10 J=1,NY
      DO 10 I=1,NX
      PHI(I,J,K)=PHIL
   10 CONTINUE
      GO TO 21
C
C  READ NODES' POROSITY STARTING FROM LAYER  NZ, NZ-1, ...., 3, 2, 1.
C  FOR EACH LAYER THE ROW ORDER IS: NY, NY-1, NY-2, ....., 3, 2, 1.
C
   20 READ(5,112) TITLE
      DO 11 LK=1,NZ
      K=NZ-LK+1
      J=NY
   22 READ(5,102) (PHI(I,J,K), I=1,NX)
      J=J-1
      IF(J.EQ.0) GO TO 11
      GO TO 22
   11 CONTINUE
   21 PRINT 50
   50 FORMAT(//' *** POROSITY DISTRIBUTION IN ROCK MATRIX ***'//)
      DO 12 LK=1,NZ
      K=NZ-LK+1
      PRINT 103, K
      J=NY
   23 PRINT 104, (PHI(I,J,K),I=1,NX)
      J=J-1
      IF(J.EQ.0) GO TO 12
      GO TO 23
   12 CONTINUE
```

```
            IF(KPERL.NE.0) GO TO 25
            READ(5,112) TITLE
            READ(5,101) PERL
            DO 13 K=1,NZ
            DO 13 J=1,NY
            DO 13 I=1,NX
            KL(I,J,K)=PERL
         13 CONTINUE
            GO TO 24
      C
      C  READ NODES' PERMEABILITY STARTING FROM LAYER NZ,NZ-1,.....,2,1.
      C  FOR EACH LAYER, THE ROW ORDER IS: NY,NY-1,NY-2,.....,3,2,1.
      C
         25 READ(5,112) TITLE
            DO 14 LK=1,NZ
            K=NZ-LK+1
            J=NY
         26 READ(5,102) (KL(I,J,K),I=1,NX)
            J=J-1
            IF(J.EQ.0) GO TO 14
            GO TO 26
         14 CONTINUE
         24 PRINT 151
        151 FORMAT(//' *** ISOTROPIC PERMEABILITY DISTRIBUTION IN ROCK MATRIX
           &***'//)
            DO 15 LK=1,NZ
            K=NZ-LK+1
            PRINT 103,K
            J=NY
         27 PRINT 107, (KL(I,J,K),I=1,NX)
            J=J-1
            IF(J.EQ.0) GO TO 15
            GO TO 27
         15 CONTINUE
      C
      C  READ CODE NUMBERS FOR FRACTURE POROSITY AND PERMEABILITY
      C  (FOR UNIFORM DISTRIBUTION: KPHIF=0, NUMKF=0)
      C  AS FOR PERMEABILITY TENSOR, IF NOT UNIFORM(NUMKF.NE.0), ONE SET OF
      C  TENSOR VALUES WILL BE ASSIGNED TO ALL NODES; THEN NUMKF SETS OF
      C  PERMEABILITY TENSOR WILL BE READ IN FOR NODES THAT ARE DIFFERENT
      C
            READ(5,112) TITLE
            READ(5,100) KPHIF,NUMKF
            IF(KPHIF.NE.0) GO TO 28
            READ(5,112) TITLE
            READ(5,101) PHIF
            DO 16 K=1,NZ
            DO 16 J=1,NY
            DO 16 I=1,NX
            FPHI(I,J,K)=PHIF
         16 CONTINUE
            GO TO 29
         28 READ(5,112) TITLE
            DO 17 LK=1,NZ
            K=NZ-LK+1
            J=NY
         30 READ(5,102) (FPHI(I,J,K),I=1,NX)
            J=J-1
```

```
          IF(J.EQ.0) GO TO 17
          GO TO 30
       17 CONTINUE
       29 PRINT 152
      152 FORMAT(///' *** POROSITY DISTRIBUTION IN FRACTURE ***'//)
          DO 18 LK=1,NZ
          K=NZ-LK+1
          PRINT 103,K
          J=NY
       31 PRINT 104,(FPHI(I,J,K),I=1,NX)
          J=J-1
          IF(J.EQ.0) GO TO 18
          GO TO 31
       18 CONTINUE
          READ(5,112) TITLE
          READ(5,108) CFKXX,CFKXY,CFKXZ,CFKYX,CFKYY,CFKYZ,CFKZX,CFKZY,CFKZZ
          DO 19 K=1,NZ
          DO 19 J=1,NY
          DO 19 I=1,NX
          FKXX(I,J,K)=CFKXX
          FKXY(I,J,K)=CFKXY
          FKXZ(I,J,K)=CFKXZ
          FKYX(I,J,K)=CFKYX
          FKYY(I,J,K)=CFKYY
          FKYZ(I,J,K)=CFKYZ
          FKZX(I,J,K)=CFKZX
          FKZY(I,J,K)=CFKZY
          FKZZ(I,J,K)=CFKZZ
       19 CONTINUE
          IF(NUMKF.EQ.0) GO TO 32
          READ(5,112) TITLE
          DO 80 L=1,NUMKF
          READ(5,109)I,J,K,FKXX(I,J,K),FKXY(I,J,K),FKXZ(I,J,K),FKYX(I,J,K),
         & FKYY(I,J,K),FKYZ(I,J,K),FKZX(I,J,K),FKZY(I,J,K),FKZZ(I,J,K)
       80 CONTINUE
      100 FORMAT(2I5)
      101 FORMAT(F10.0)
      102 FORMAT(10F6.0)
      103 FORMAT('0LAYER NUMBER ',I5,/' ************'/)
      104 FORMAT('0',12F10.2)
      106 FORMAT(8F10.0)
      107 FORMAT('0',12F11.4)
      108 FORMAT(9F8.0)
      109 FORMAT(3I5,9F6.0)
      110 FORMAT('0ROW NUMBER',I5,/' ----------'/)
      111 FORMAT(4(3X,3F9.1,3X))
      112 FORMAT(40A2)
      115 FORMAT(//'0PMAXO =',F10.1,' PSI'/,'0PMAXW =',F10.1,' PSI',/,
         & '0PMAXG =',F10.1,' PSI',/,'0SGMAX =',F11.2,/,'0SWMAX =',F11.2)
      114 FORMAT(///'0OIL PVT DATA TABLE',/' ******************'//,T9,
         &'PO',T18,'BO',T27,'D(1/BO)/DP',T43,'RSO',T56,'DRSO/DP',T68,
         &'UO'/,T6,'(PSI)',T15,'(BBL/STB)',T25,'(STB/BBL/PSI)',T40,
         &'(SCF/STB)',T52,'(SCF/STB/PSI)',T67,'(CP)',/,
         &' ------------------------------------------------------------
         &----------'/)
      117 FORMAT('0',F10.1,F10.4,D15.5,F10.1,F15.4,F10.4)
      116 FORMAT(6F12.0)
     1131 FORMAT(///'0WATER PVT DATA TABLE',/,' ********************',//,
```

```
                 & T9,'PW',T18,'UW',/,T7,'(PSI)',T17,
                 &'(CP)',/' ----------------------------------',/)
0138         1171 FORMAT('0',F10.1,2F10.4)
0139         1172 FORMAT('0',F10.1,D15.5,F10.5,F10.4)
0140         1132 FORMAT(///'0GAS PVT DATA TABLE',/,' ******************',//,T9,
                 &'PG',T18,'BG',T29,'D(1/BG)/DP',T42,'UG',/,T7,'(PSI)',T16,
                 &'(BBL/SCF)',T27,'(SCF/BBL/PSI)',T41,'(CP)',/,
                 &' --------------------------------------------------',/)
0141          119 FORMAT(//'0STANDARD PRESSURE =',F16.4,' PSIA',/'0STANDARD TEMPERAT
                 &URE =',F10.1,' DEG. F',/,'0OIL DENSITY =',F12.4,' LBM/CU FT',/,
                 &'0WATER DENSITY =',F10.4,' LBM/CU FT',/,'0GAS DENSITY =',F12.4,
                 &' LBM/CU FT'/)
0142         1191 FORMAT(//' TILTING ANGLES OF RESERVOIR FORMATION:',//,
                 &'0ALPHA =',F10.2,' DEG.'/,'0BETA  =',F10.2,' DEG.',/,
                 &'0GAMMA =',F10.2,' DEG.'//)
0143          120 FORMAT(2D12.4)
0144          121 FORMAT(//'0FRACTURE COMPRESSIBILITY =',D15.4,' PSI-1'/,
                 &          '0MATRIX ROCK COMPRESSIBILITY =',D12.4,' PSI-1'/)
0145         1173 FORMAT('0',F10.2,3F10.3,F10.5)
0146         1134 FORMAT(  ///'0GAS-OIL RELATIVE PERMEABILITY & CAPILLARY PRESSURE
                 &DATA FOR MATRIX ROCK'/,' ******************************************
                 &*******************************',//,T7,'SG',T17,'KRG',T26,
                 &'KROG',T37,'PCGO',T44,'DSG/DPC'/,
                 & T36,'(PSI)',T44,'(PSI-1)',/,
                 &' -------------------------------------------------------',//)
0147         1135 FORMAT(///'0WATER-OIL RELATIVE PERMEABILITY & CAPILLARY PRESSURE
                 &DATA FOR MATRIX ROCK',/,' *****************************************
                 &***********************************',//,T7,'SW',T17,'KRW',T26,
                 &'KROW',T38,'PCOW',T45,'DSW/DPC',/,
                 & T37,'(PSI)',T45,'(PSI-1)',/,
                 &' ----------------------------------------------------'//)
0148         1136 FORMAT(  ///'0GAS-OIL RELATIVE PERMEABILITY & CAPILLARY PRESSURE
                 &DATA FOR FRACTURE'/,    ' ****************************************
                 &*****************************',//,T7,'SG',T17,'KRG',T26,
                 &'KROG',T37,'PCGO',T44,'DSG/DPC'/,
                 & T36,'(PSI)',T44,'(PSI-1)',/,
                 &' -------------------------------------------------------',//)
0149         1137 FORMAT(///'0WATER-OIL RELATIVE PERMEABILITY & CAPILLARY PRESSURE
                 &DATA FOR FRACTURE',/,    ' ***************************************
                 &*********************************',//,T7,'SW',T17,'KRW',T26,
                 &'KROW',T38,'PCOW',T45,'DSW/DPC',/,
                 & T37,'(PSI)',T45,'(PSI-1)',/,
                 &' ----------------------------------------------------'//)
            C
            C  PRINT PERMEABILITY TENSOR
            C
0150           32 PRINT 153
0151          153 FORMAT(///' *** ANISOTROPIC PERMEABILITY DISTRIBUTION IN FRACTURE
                 &***'//)
0152              DO 81 LK=1,NZ
0153              K=NZ-LK+1
0154              PRINT 103,K
0155              J=NY
0156           33 PRINT 110,J
0157              DO 82 II=1,NX,4
0158              IEND=II+3
0159              IF(IEND.GT.NX) IEND=NX
0160              PRINT 111, (FKXX(I,J,K),FKXY(I,J,K),FKXZ(I,J,K),I=II,IEND)
```

```
                PRINT 111, (FKYX(I,J,K),FKYY(I,J,K),FKYZ(I,J,K),I=II,IEND)
                PRINT 111, (FKZX(I,J,K),FKZY(I,J,K),FKZZ(I,J,K),I=II,IEND)
                PRINT 135
            135 FORMAT('0')
             82 CONTINUE
                J=J-1
                IF(J.EQ.0) GO TO 81
                GO TO 33
             81 CONTINUE
          C
          C  READ MAXIMUM PRESSURES AND SATURATIONS FOR VALUES IN TABLES
          C
                READ(5,112) TITLE
                READ(5,106) PMAXO,PMAXW,PMAXG,SGMAX,SWMAX
                PRINT 115,PMAXO,PMAXW,PMAXG,SGMAX,SWMAX
          C
          C  READ OIL PVT DATA
          C
                READ(5,112) TITLE
                PRINT 114
                DO 105 I=1,500
                READ(5,116) POT(I),BOT(I),DIBOT(I),RSOT(I),DRSOT(I),UOT(I)
                PRINT 117, POT(I),BOT(I),DIBOT(I),RSOT(I),DRSOT(I),UOT(I)
                MPOT=I
                IF(POT(I).GE.PMAXO) GO TO 51
            105 CONTINUE
          C
          C  READ WATER PVT DATA
          C
             51 READ(5,112) TITLE
                PRINT 1131
                DO 53 I=1,500
                MPWT=I
                READ(5,116) PWT(I),UWT(I)
                PRINT 1171,PWT(I),UWT(I)
                IF(PWT(I).GE.PMAXW) GO TO 54
             53 CONTINUE
          C
          C  READ GAS PVT DATA
          C
             54 READ(5,112) TITLE
                PRINT 1132
                DO 55 I=1,500
                MPGT=I
                READ(5,116) PGT(I),BGT(I),DIBGT(I),UGT(I)
                PRINT 1172, PGT(I),BGT(I),DIBGT(I),UGT(I)
                IF(PGT(I).GE.PMAXG) GO TO 56
             55 CONTINUE
          C
          C  READ OIL, WATER, GAS DENSITIES IN LBM/CU FT AT STANDARD CONDITIONS
          C
             56 READ(5,112) TITLE
                READ(5,116) RHOSO,RHOSW,RHOSG,PSC,TSC
                PRINT 119,PSC,TSC,RHOSO,RHOSW,RHOSG
          C
          C  READ FRACTURE AND MATRIX COMPRESSIBILITY
          C
                READ(5,112) TITLE
```

```
            READ(5,120) CF,CL
            PRINT 121,CF,CL
C
C     READ TILTING ANGLES OF THE FORMATION (IN DEGREES)
C
            READ(5,112) TITLE
            READ(5,116)  ALPHA,BETA,GAMMA
            PRINT 1191, ALPHA,BETA,GAMMA
            CONV=3.141593/180.
            ALPHA=ALPHA*CONV
            BETA=BETA*CONV
            GAMMA=GAMMA*CONV
C
C     READ GAS-OIL RELATIVE PERMEABILITY & CAPILLARY PRESSURE FOR MATRIX
C     ROCK
C
            READ(5,112) TITLE
            PRINT 1134
            DO 57 I=1,500
            MSGT=I
            READ(5,116) SGT(I),KRGT(I),KROGT(I),PCGOT(I),DSGT(I)
            PRINT 1173, SGT(I),KRGT(I),KROGT(I),PCGOT(I),DSGT(I)
            IF(SGT(I).GE.SGMAX) GO TO 58
         57 CONTINUE
C
C     READ WATER-OIL RELATIVE PERMEABILITY & CAPILLARY PRESSURE FOR
C     MATRIX ROCK
C
         58 READ(5,112) TITLE
            PRINT 1135
            DO 59 I=1,500
            MSWT=I
            READ(5,116) SWT(I),KRWT(I),KROWT(I),PCOWT(I),DSWT(I)
            PRINT 1173, SWT(I),KRWT(I),KROWT(I),PCOWT(I),DSWT(I)
            IF(SWT(I).GE.SWMAX) GO TO 60
         59 CONTINUE
C
C     REARRANGE PCOWT VERSUS SWT SO THAT PCOWT IS INCREASING
C
         60 MHALF=(MSWT+1)/2
            DO 70 I=1,MHALF
            TMP=PCOWT(MSWT-I+1)
            PCOWT(MSWT-I+1)=PCOWT(I)
            PCOWT(I)=TMP
         70 CONTINUE
            DO 71 I=1,MSWT
            RSWT(I)=SWT(MSWT-I+1)
         71 CONTINUE
C
C     READ GAS-OIL RELATIVE PERMEABILITY & CAPILLARY PRESSURE FOR FRACTURE
C
            READ(5,112) TITLE
            PRINT 1136
            DO 61 I=1,500
            MFSGT=I
            READ(5,116) FSGT(I),FKRGT(I),FKROGT(I),FPCGOT(I),FDSGT(I)
            PRINT 1173, FSGT(I),FKRGT(I),FKROGT(I),FPCGOT(I),FDSGT(I)
            IF(FSGT(I).GE.SGMAX) GO TO 62
```

```
0242        61 CONTINUE
      C
      C  READ WATER-OIL RELATIVE PERMEABILITY & CAPILLARY PRESSURE FOR
      C  FRACTURE
      C
0243        62 READ(5,112) TITLE
0244           PRINT 1137
0245           DO 63 I=1,500
0246           MFSWT=I
0247           READ(5,116) FSWT(I),FKRWT(I),FKROWT(I),FPCOWT(I),FDSWT(I)
0248           PRINT 1173, FSWT(I),FKRWT(I),FKROWT(I),FPCOWT(I),FDSWT(I)
0249           IF(FSWT(I).GE.SWMAX) GO TO 64
0250        63 CONTINUE
      C
      C   REARRANGE FPCOWT VERSUS FSWT SO THAT FPCOWT IS INCREASING
      C
0251        64 MHALF=(MFSWT+1)/2
0252           DO 72 I=1,MHALF
0253           TMP=FPCOWT(MFSWT-I+1)
0254           FPCOWT(MFSWT-I+1)=FPCOWT(I)
0255           FPCOWT(I)=TMP
0256        72 CONTINUE
0257           DO 73 I=1,MFSWT
0258           RFSWT(I)=FSWT(MFSWT-I+1)
0259        73 CONTINUE
0260           RETURN
0261           END
```

```
      SUBROUTINE RESDIM(NX,NY,NZ,XL,YL,ZL,DELX,DELY,DELZ,RH)
C
C  SUBROUTINE TO READ RESERVOIR AND GRID DIMENSIONS
C  AND CALCULATE FRACTURE HYDRAULIC RADIUS
C
      IMPLICIT REAL*8(A-H,O-Z)
      INTEGER TITLE(40)
      READ(5,100) TITLE
  100 FORMAT(40A2)
      READ(5,101) NX,NY,NZ,XL,YL,ZL
  101 FORMAT(3I5,3F10.0)
      DELX=XL/DFLOAT(NX)
      DELY=YL/DFLOAT(NY)
      DELZ=ZL/DFLOAT(NZ)
      PRINT 102,XL,YL,ZL,NX,NY,NZ,DELX,DELY,DELZ
  102 FORMAT('1RESERVOIR AND GRID DIMENSIONS'//'0LENGTH =',F12.1,' FEET'
     &,/'0WIDTH = ',F12.1,' FEET',/'0THICKNESS =',F9.1,' FEET',//,
     &'0NUMBER OF GRID POINTS IN X-DIRECTION =',I7,/,
     &'0NUMBER OF GRID POINTS IN Y-DIRECTION =',I7,/,
     &'0NUMBER OF GRID POINTS IN Z-DIRECTION =',I7,///,
     &'0DELTA-X (FT) =',F10.2,'   DELTA-Y (FT) =',F10.2,
     &'    DELTA-Z (FT) =',F10.2,///)
C
C   READ FRACTURE HALF-WIDTH AND CALCULATE HYDRAULIC RADIUS
C
      READ(5,100) TITLE
      READ(5,103) WF
  103 FORMAT(F10.0)
      RH=3.141593*WF/4.
      PRINT 104,WF,RH
  104 FORMAT('0NATURAL FRACTURE HALF-WIDTH =',F12.6,' FEET',/,
     &'0HYDRAULIC RADIUS =',F12.6,' FEET'///)
      RETURN
      END
```

```
0001          SUBROUTINE TRAN(NX,NY,NZ,KL,FKXX,FKYY,FKZZ)
        C
        C  SUBROUTINE TO CALCULATE TRANSMISCIBILITY
        C
0002          IMPLICIT REAL*8(A-H,K,O-Z)
0003          INTEGER K
0004          COMMON /TR1/ TGW(10,2,5),TEW(10,2,5),TAW(10,2,5),TCW(10,2,5),
             & TFW(10,2,5),THW(10,2,5),TRW(10,2,5),TUW(10,2,5),TVD(10,2,5),
             & TGO(10,2,5),TEO(10,2,5),TAO(10,2,5),TCO(10,2,5),TFO(10,2,5),
             & THO(10,2,5),TUO(10,2,5),TRO(10,2,5)
0005          COMMON /TR2/ TVG(10,2,5),TGGO(10,2,5),TEGO(10,2,5),TAGO(10,2,5),
             & TCGO(10,2,5),TFGO(10,2,5),THGO(10,2,5),TGG(10,2,5),TEG(10,2,5),
             & TAG(10,2,5),TCG(10,2,5),TFG(10,2,5),THG(10,2,5),TRGO(10,2,5),
             & TRG(10,2,5)
0006          COMMON /TR3/ TFGW1(10,2,5),TFGW2(10,2,5),TFGW3(10,2,5),TFGW4(10,2
             &,5),TFGW5(10,2,5),TFEW1(10,2,5),TFEW2(10,2,5),TFEW3(10,2,5),TFAW1(
             & 10,2,5),TFCW1(10,2,5),TFFW1(10,2,5),TFFW2(10,2,5),TFFW3(10,2,5),
             & TFHW1(10,2,5),TFHW2(10,2,5),TFHW3(10,2,5),TFHW4(10,2,5),
             & TFHW5(10,2,5),TFRW(10,2,5),TFUW(10,2,5)
0007          COMMON /TR4/ TFGO1(10,2,5),TFGO2(10,2,5),TFGO3(10,2,5),TFGO4(10,2,
             &5),TFGO5(10,2,5),TFEO1(10,2,5),TFEO2(10,2,5),TFEO3(10,2,5),TFAO1(
             & 10,2,5),TFCO1(10,2,5),TFFO1(10,2,5),TFFO2(10,2,5),TFFO3(10,2,5),
             & TFHO1(10,2,5),TFHO2(10,2,5),TFHO3(10,2,5),TFHO4(10,2,5),TFHO5(10,
             & 2,5),TFRO(10,2,5),TFUO(10,2,5),TFVO(10,2,5)
0008          COMMON /TR5/ TFGG1(10,2,5),TFGG2(10,2,5),TFGG3(10,2,5),TFGG4(10,2,
             &5),TFGG5(10,2,5),TFEG1(10,2,5),TFEG2(10,2,5),TFEG3(10,2,5),TFAG1(
             &10,2,5),TFCG1(10,2,5),TFFG1(10,2,5),TFFG2(10,2,5),TFFG3(10,2,5),
             &TFHG1(10,2,5),TFHG2(10,2,5),TFHG3(10,2,5),TFHG4(10,2,5),TFHG5(10,
             &2,5),TFGR1(10,2,5),TFGR2(10,2,5),TFGR3(10,2,5),TFGR4(10,2,5),
             & TFGR5(10,2,5),TFER1(10,2,5),TFER2(10,2,5),TFER3(10,2,5),TFAR1(
             &10,2,5),TFCR1(10,2,5),TFFR1(10,2,5),TFFR2(10,2,5),TFFR3(10,2,5),
             & TFHR1(10,2,5),TFHR2(10,2,5),TFHR3(10,2,5),TFHR4(10,2,5),TFHR5(
             &10,2,5),TFRG(10,2,5),TFRGO(10,2,5),TFVG(10,2,5)
0009          COMMON /SET2/ VB,DELX,DELY,DELZ,DELT,RH
0010          COMMON /SET3/ CON1,CON2,CON3,CON4
0011          DIMENSION KL(NX,NY,1),FKXX(NX,NY,1),FKYY(NX,NY,1),FKZZ(NX,NY,1)
0012          DXSQ=DELX*DELX
0013          DYSQ=DELY*DELY
0014          DZSQ=DELZ*DELZ
0015          FACT1=VB*CON1
0016          FACT2=FACT1/4.
0017          FACT3=VB*CON2
0018          FACT4=FACT1/(RH*DELX/2.)
0019          FACT5=FACT2/(DELY*DELZ)
0020          FACT6=FACT2/(DELX*DELZ)
0021          FACT7=FACT2/(DELX*DELY)
0022          FACT8=FACT1/DXSQ
0023          FACT9=FACT1/DYSQ
0024          FACT10=FACT1/DZSQ
        C
0025          DO 100 K=1,NZ
0026          DO 100 J=1,NY
0027          DO 100 I=1,NX
0028          TGW(I,J,K)=FAVG(KL(I,J,K-1),KL(I,J,K))
0029          TGW(I,J,K)=TGW(I,J,K)*FACT10
0030          TEW(I,J,K)=FAVG(KL(I,J-1,K),KL(I,J,K))
0031          TEW(I,J,K)=TEW(I,J,K)*FACT9
0032          TAW(I,J,K)=FAVG(KL(I-1,J,K),KL(I,J,K))
```

```
0033          TAW(I,J,K)=TAW(I,J,K)*FACT8
0034          TCW(I,J,K)=FAVG(KL(I+1,J,K),KL(I,J,K))
0035          TCW(I,J,K)=TCW(I,J,K)*FACT8
0036          TFW(I,J,K)=FAVG(KL(I,J+1,K),KL(I,J,K))
0037          TFW(I,J,K)=TFW(I,J,K)*FACT9
0038          THW(I,J,K)=FAVG(KL(I,J,K+1),KL(I,J,K))
0039          THW(I,J,K)=THW(I,J,K)*FACT10
0040          TRW(I,J,K)=KL(I,J,K)*FACT4
0041          TUW(I,J,K)=FACT3
      C
0042          TVO(I,J,K)=FACT3
0043          TGO(I,J,K)=TGW(I,J,K)
0044          TEO(I,J,K)=TEW(I,J,K)
0045          TAO(I,J,K)=TAW(I,J,K)
0046          TCO(I,J,K)=TCW(I,J,K)
0047          TFO(I,J,K)=TFW(I,J,K)
0048          THO(I,J,K)=THW(I,J,K)
0049          TUO(I,J,K)=FACT3
0050          TRO(I,J,K)=TRW(I,J,K)
      C
0051          TVG(I,J,K)=FACT3
0052          TGGO(I,J,K)=TGW(I,J,K)
0053          TEGO(I,J,K)=TEW(I,J,K)
0054          TAGO(I,J,K)=TAW(I,J,K)
0055          TCGO(I,J,K)=TCW(I,J,K)
0056          TFGO(I,J,K)=TFW(I,J,K)
0057          THGO(I,J,K)=THW(I,J,K)
0058          TGG(I,J,K)=TGW(I,J,K)
0059          TEG(I,J,K)=TEW(I,J,K)
0060          TAG(I,J,K)=TAW(I,J,K)
0061          TCG(I,J,K)=TCW(I,J,K)
0062          TFG(I,J,K)=TFW(I,J,K)
0063          THG(I,J,K)=THW(I,J,K)
0064          TRGO(I,J,K)=TRW(I,J,K)
0065          TRG(I,J,K)=TRW(I,J,K)
      C
0066          TFGW1(I,J,K)=FACT5
0067          TFGW2(I,J,K)=FACT6
0068          TFGW3(I,J,K)=FAVG(FKZZ(I,J,K),FKZZ(I,J,K-1))
0069          TFGW3(I,J,K)=TFGW3(I,J,K)*FACT10
0070          TFGW4(I,J,K)=FACT6
0071          TFGW5(I,J,K)=FACT5
0072          TFEW1(I,J,K)=FACT7
0073          TFEW2(I,J,K)=FAVG(FKYY(I,J,K),FKYY(I,J-1,K))
0074          TFEW2(I,J,K)=TFEW2(I,J,K)*FACT9
0075          TFEW3(I,J,K)=FACT7
0076          TFAW1(I,J,K)=FAVG(FKXX(I,J,K),FKXX(I-1,J,K))
0077          TFAW1(I,J,K)=TFAW1(I,J,K)*FACT8
0078          TFCW1(I,J,K)=FAVG(FKXX(I,J,K),FKXX(I+1,J,K))
0079          TFCW1(I,J,K)=TFCW1(I,J,K)*FACT8
0080          TFFW1(I,J,K)=FACT7
0081          TFFW2(I,J,K)=FAVG(FKYY(I,J,K),FKYY(I,J+1,K))
0082          TFFW2(I,J,K)=TFFW2(I,J,K)*FACT9
0083          TFFW3(I,J,K)=FACT7
0084          TFHW1(I,J,K)=FACT5
0085          TFHW2(I,J,K)=FACT6
0086          TFHW3(I,J,K)=FAVG(FKZZ(I,J,K),FKZZ(I,J,K+1))
0087          TFHW3(I,J,K)=TFHW3(I,J,K)*FACT10
```

```
      TFHW4(I,J,K)=FACT6
      TFHW5(I,J,K)=FACT5
      TFRW(I,J,K)=KL(I,J,K)*FACT4
      TFUW(I,J,K)=FACT3
C
      TFGO1(I,J,K)=TFGW1(I,J,K)
      TFGO2(I,J,K)=TFGW2(I,J,K)
      TFGO3(I,J,K)=TFGW3(I,J,K)
      TFGO4(I,J,K)=TFGW4(I,J,K)
      TFGO5(I,J,K)=TFGW5(I,J,K)
      TFEO1(I,J,K)=TFEW1(I,J,K)
      TFEO2(I,J,K)=TFEW2(I,J,K)
      TFEO3(I,J,K)=TFEW3(I,J,K)
      TFAO1(I,J,K)=TFAW1(I,J,K)
      TFCO1(I,J,K)=TFCW1(I,J,K)
      TFFO1(I,J,K)=TFFW1(I,J,K)
      TFFO2(I,J,K)=TFFW2(I,J,K)
      TFFO3(I,J,K)=TFFW3(I,J,K)
      TFHO1(I,J,K)=TFHW1(I,J,K)
      TFHO2(I,J,K)=TFHW2(I,J,K)
      TFHO3(I,J,K)=TFHW3(I,J,K)
      TFHO4(I,J,K)=TFHW4(I,J,K)
      TFHO5(I,J,K)=TFHW5(I,J,K)
      TFRO(I,J,K)=TFRW(I,J,K)
      TFUO(I,J,K)=FACT3
      TFVO(I,J,K)=FACT3
C
      TFGG1(I,J,K)=TFGW1(I,J,K)
      TFGG2(I,J,K)=TFGW2(I,J,K)
      TFGG3(I,J,K)=TFGW3(I,J,K)
      TFGG4(I,J,K)=TFGW4(I,J,K)
      TFGG5(I,J,K)=TFGW5(I,J,K)
      TFEG1(I,J,K)=TFEW1(I,J,K)
      TFEG2(I,J,K)=TFEW2(I,J,K)
      TFEG3(I,J,K)=TFEW3(I,J,K)
      TFAG1(I,J,K)=TFAW1(I,J,K)
      TFCG1(I,J,K)=TFCW1(I,J,K)
      TFFG1(I,J,K)=TFFW1(I,J,K)
      TFFG2(I,J,K)=TFFW2(I,J,K)
      TFFG3(I,J,K)=TFFW3(I,J,K)
      TFHG1(I,J,K)=TFHW1(I,J,K)
      TFHG2(I,J,K)=TFHW2(I,J,K)
      TFHG3(I,J,K)=TFHW3(I,J,K)
      TFHG4(I,J,K)=TFHW4(I,J,K)
      TFHG5(I,J,K)=TFHW5(I,J,K)
      TFGR1(I,J,K)=TFGW1(I,J,K)
      TFGR2(I,J,K)=TFGW2(I,J,K)
      TFGR3(I,J,K)=TFGW3(I,J,K)
      TFGR4(I,J,K)=TFGW4(I,J,K)
      TFGR5(I,J,K)=TFGW5(I,J,K)
      TFER1(I,J,K)=TFEW1(I,J,K)
      TFER2(I,J,K)=TFEW2(I,J,K)
      TFER3(I,J,K)=TFEW3(I,J,K)
      TFAR1(I,J,K)=TFAW1(I,J,K)
      TFCR1(I,J,K)=TFCW1(I,J,K)
      TFFR1(I,J,K)=TFFW1(I,J,K)
      TFFR2(I,J,K)=TFFW2(I,J,K)
      TFFR3(I,J,K)=TFFW3(I,J,K)
```

```
      TFHR1(I,J,K)=TFHW1(I,J,K)
      TFHR2(I,J,K)=TFHW2(I,J,K)
      TFHR3(I,J,K)=TFHW3(I,J,K)
      TFHR4(I,J,K)=TFHW4(I,J,K)
      TFHR5(I,J,K)=TFHW5(I,J,K)
      TFRG(I,J,K)=TFRW(I,J,K)
      TFRGU(I,J,K)=TFRW(I,J,K)
      TFVG(I,J,K)=FACT3
  100 CONTINUE
      RETURN
      END
```

```
0001            SUBROUTINE VELOCY(NX,NY,NZ)
          C
          C  SUBROUTINE TO CALCULATE VELOCITY AND ACCELERATION OF FLUIDS IN
          C  FRACTURE
          C
0002            IMPLICIT REAL*8(A-H,K,O-Z)
0003            INTEGER K
0004            COMMON /VELO/ VOX(10,2,5),VOY(10,2,5),VOZ(10,2,5),VWX(10,2,5),
               &VWY(10,2,5),VWZ(10,2,5),VGX(10,2,5),VGY(10,2,5),VGZ(10,2,5)
0005            COMMON /ACCL/ DVOXDT(10,2,5),DVOYDT(10,2,5),DVOZDT(10,2,5),
               & DVWXDT(10,2,5),DVWYDT(10,2,5),DVWZDT(10,2,5),DVGXDT(10,2,5),
               & DVGYDT(10,2,5),DVGZDT(10,2,5)
0006            COMMON /PRESS/ PO(10,2,5),PW(10,2,5),PG(10,2,5),PFO(10,2,5),
               & PFW(10,2,5),PFG(10,2,5),PON(10,2,5),PWN(10,2,5),PGN(10,2,5),
               & PFON(10,2,5),PFWN(10,2,5),PFGN(10,2,5)
0007            COMMON /SAT/ SO(10,2,5),SW(10,2,5),SG(10,2,5),SOF(10,2,5),
               & SWF(10,2,5),SGF(10,2,5),SON(10,2,5),SWN(10,2,5),SGN(10,2,5),
               & SOFN(10,2,5),SWFN(10,2,5),SGFN(10,2,5)
0008            COMMON /SLT2/ VB,DELX,DELY,DELZ,DELT,RH
0009            COMMON /SET3/ CON1,CON2,CON3,CON4
0010            COMMON /LIMIT/ MPOT,MPWT,MPGT,MSGT,MSWT,MFSGT,MFSWT
0011            COMMON /SET1/ RHOSO,RHOSW,RHOSG,PSC,TSC,ALPHA,BETA,GAMMA
0012            COMMON /PARM1/ CL,CF,PHI(10,2,5),FPHI(10,2,5)
0013            COMMON /PARM2/ KL(10,2,5),FKXX(10,2,5),FKXY(10,2,5),FKXZ(10,2,5),
               & FKYX(10,2,5),FKYY(10,2,5),FKYZ(10,2,5),FKZX(10,2,5),
               & FKZY(10,2,5),FKZZ(10,2,5)
0014            COMMON /PARM3/  POT(15),BOT(15),DIBOT(15),
               & RSOT(15),DPSOT(15),UOT(15),PWT(15),UWT(15),PGT(15),BGT(15),
               & DIBGT(15),UGT(15),SGT(15),KRGT(15),KROGT(15),PCGOT(15),DSGT(15),
               & SWT(15),KRWT(15),KROWT(15),PCOWT(15),DSWT(15),FSGT(15),FKRGT(15),
               & FKROGT(15),FPCGOT(15),FDSGT(15),FSWT(15),FKRWT(15),FKROWT(15),
               & FPCOWT(15),FDSWT(15),RSWT(15),RFSWT(15)
          C
0015            CON5=CON4*CON3
0016            CON6=CON4/144.
0017            DO 100 K=1,NZ
0018            DO 100 J=1,NY
0019            DO 100 I=1,NX
0020            CALL LINTP(MFSWT,SWF(I,J,K),FKRW,FSWT,FKRWT)
0021            CALL LINTP(MFSWT,SWF(I,J,K),FKROW,FSWT,FKROWT)
0022            CALL LINTP(MFSGT,SGF(I,J,K),FKRG,FSGT,FKRGT)
0023            CALL LINTP(MFSGT,SGF(I,J,K),FKROG,FSGT,FKROGT)
0024            FKRO=(FKROW+FKRW)*(FKROG+FKRG)-(FKRW+FKRG)
0025            IF(FKRO.LT.0.0) FKRO=0.0
0026            CALL LINTP(MPOT,PFO(I,J,K),UOF,POT,UOT)
0027            CALL LINTP(MPGT,PFG(I,J,K),UGF,PGT,UGT)
0028            CALL LINTP(MPWT,PFW(I,J,K),UWF,PWT,UWT)
0029            CALL LINTP(MPOT,PFO(I,J,K),BFO,POT,BOT)
0030            CALL LINTP(MPGT,PFG(I,J,K),BFG,PGT,BGT)
0031            CALL LINTP(MPOT,PFO(I,J,K),RSF,POT,RSOT)
0032            DENOF=(RHOSO+RHOSG*RSF/5.615)/BFO
0033            DENGF=RHOSG/(BFG*5.615)
0034            DENWF=RHOSW
0035            IF(FKRG.LE.0.0) GO TO 301
          C
0036            IF(I.EQ.1.OR.I.EQ.NX) DPD2X=0.0
0037            IF(I.GT.1.AND.I.LT.NX) DPD2X=CON4*(PFG(I+1,J,K)-PFG(I-1,J,K))/(
               & 2.*DELX)
```

```
0038          IF(J.EQ.1.OR.J.EQ.NY) DPD2Y=0.0
0039          IF(J.GT.1.AND.J.LT.NY) DPD2Y=CON4*(PFG(I,J+1,K)-PFG(I,J-1,K))/(
             & 2.*DELY)
0040          IF(K.EQ.1.OR.K.EQ.NZ) DPD2Z=0.0
0041          IF(K.GT.1.AND.K.LT.NZ) DPD2Z=CON4*(PFG(I,J,K+1)-PFG(I,J,K-1))/(
             & 2.*DELZ)
0042          VGXN=VGX(I,J,K)
0043          FKUG=-FKRG/UGF
0044          FF=FKUG*CON5*DENGF/DELT
0045          FACT=1.-FF*FKXX(I,J,K)
0046          VGX(I,J,K)=FKXX(I,J,K)*(DPD2X-CON5*DENGF*VGXN/DELT+
             & DENGF*CON6*DSIN(ALPHA))
0047          IF(FKXY(I,J,K).NE.0.0) VGX(I,J,K)=VGX(I,J,K) + FKXY(I,J,K)*(
             & DPD2Y+CON5*DENGF*DVGYDT(I,J,K)+CON6*DENGF*DSIN(BETA)   )
0048          IF(FKXZ(I,J,K).NE.0.0) VGX(I,J,K)=VGX(I,J,K) + FKXZ(I,J,K)*(
             & DPD2Z+CON5*DENGF*DVGZDT(I,J,K)+CON6*DENGF*DCOS(GAMMA)  )
0049          VGX(I,J,K)=VGX(I,J,K)*FKUG/FACT
0050          VGYN=VGY(I,J,K)
0051          FACT=1.-FF*FKYY(I,J,K)
0052          VGY(I,J,K)=FKYY(I,J,K)*(DPD2Y-CON5*DENGF*VGYN/DELT+
             & CON6*DENGF*DSIN(BETA))
0053          IF(FKYX(I,J,K).NE.0.0) VGY(I,J,K)=VGY(I,J,K) + FKYX(I,J,K)*(
             & DPD2X+CON5*DENGF*DVGXDT(I,J,K)+CON6*DENGF*DSIN(ALPHA)   )
0054          IF(FKYZ(I,J,K).NE.0.0) VGY(I,J,K)=VGY(I,J,K) + FKYZ(I,J,K)*(
             & DPD2Z+CON5*DENGF*DVGZDT(I,J,K)+CON6*DENGF*DCOS(GAMMA)   )
0055          VGY(I,J,K)=VGY(I,J,K)*FKUG/FACT
0056          VGZN=VGZ(I,J,K)
0057          FACT=1.-FF*FKZZ(I,J,K)
0058          VGZ(I,J,K)=FKZZ(I,J,K)*(DPD2Z-CON5*DENGF*VGZN/DELT+
             & CON6*DENGF*DCOS(GAMMA))
0059          IF(FKZX(I,J,K).NE.0.0) VGZ(I,J,K)=VGZ(I,J,K) + FKZX(I,J,K)*(
             & DPD2X+CON5*DENGF*DVGXDT(I,J,K)+CON6*DENGF*DSIN(ALPHA)   )
0060          IF(FKZY(I,J,K).NE.0.0) VGZ(I,J,K)=VGZ(I,J,K) + FKZY(I,J,K)*(
             & DPD2Y+CON5*DENGF*DVGYDT(I,J,K)+CON6*DENGF*DSIN(BETA)   )
0061          VGZ(I,J,K)=VGZ(I,J,K)*FKUG/FACT
0062          DVGXDT(I,J,K)=(VGX(I,J,K)-VGXN)/DELT
0063          DVGYDT(I,J,K)=(VGY(I,J,K)-VGYN)/DELT
0064          DVGZDT(I,J,K)=(VGZ(I,J,K)-VGZN)/DELT
        C
0065      301 IF(I.EQ.1.OR.I.EQ.NX) DPD2X=0.0
0066          IF(I.GT.1.AND.I.LT.NX) DPD2X=CON4*(PFO(I+1,J,K)-PFO(I-1,J,K))/(
             & 2.*DELX)
0067          IF(J.EQ.1.OR.J.EQ.NY) DPD2Y=0.0
0068          IF(J.GT.1.AND.J.LT.NY) DPD2Y=CON4*(PFO(I,J+1,K)-PFO(I,J-1,K))/(
             & 2.*DELY)
0069          IF(K.EQ.1.OR.K.EQ.NZ) DPD2Z=0.0
0070          IF(K.GT.1.AND.K.LT.NZ) DPD2Z=CON4*(PFO(I,J,K+1)-PFO(I,J,K-1))/(
             & 2.*DELZ)
0071          VOXN=VOX(I,J,K)
0072          FKUO=-FKRO/UOF
0073          FF=FKUO*CON5*DENOF/DELT
0074          FACT=1.-FF*FKXX(I,J,K)
0075          VOX(I,J,K)=FKXX(I,J,K)*(DPD2X-CON5*DENOF*VOXN/DELT+
             & DENOF*CON6*DSIN(ALPHA))
0076          IF(FKXY(I,J,K).NE.0.0) VOX(I,J,K)=VOX(I,J,K) + FKXY(I,J,K)*(
             & DPD2Y+CON5*DENOF*DVOYDT(I,J,K)+CON6*DENOF*DSIN(BETA)   )
0077          IF(FKXZ(I,J,K).NE.0.0) VOX(I,J,K)=VOX(I,J,K) + FKXZ(I,J,K)*(
             & DPD2Z+CON5*DENOF*DVOZDT(I,J,K)+CON6*DENOF*DCOS(GAMMA)  )
```

```
0078                  VOX(I,J,K)=VOX(I,J,K)*FKUO/FACT
0079                  VOYN=VOY(I,J,K)
0080                  FACT=1.-FF*FKYY(I,J,K)
0081                  VOY(I,J,K)=FKYY(I,J,K)*(DPD2Y-CON5*DENOF*VOYN/DELT+
                     & CON6*DENOF*DSIN(BETA))
0082                  IF(FKYX(I,J,K).NE.0.0) VOY(I,J,K)=VOY(I,J,K) + FKYX(I,J,K)*(
                     & DPD2X+CON5*DENOF*DVOXDT(I,J,K)+CON6*DENOF*DSIN(ALPHA)   )
0083                  IF(FKYZ(I,J,K).NE.0.0) VOY(I,J,K)=VOY(I,J,K) + FKYZ(I,J,K)*(
                     & DPD2Z+CON5*DENOF*DVOZDT(I,J,K)+CON6*DENOF*DCOS(GAMMA)   )
0084                  VOY(I,J,K)=VOY(I,J,K)*FKUO/FACT
0085                  VOZN=VOZ(I,J,K)
0086                  FACT=1.-FF*FKZZ(I,J,K)
0087                  VOZ(I,J,K)=FKZZ(I,J,K)*(DPD2Z-CON5*DENOF*VOZN/DELT+
                     & CON6*DENOF*DCOS(GAMMA))
0088                  IF(FKZX(I,J,K).NE.0.0) VOZ(I,J,K)=VOZ(I,J,K) + FKZX(I,J,K)*(
                     & DPD2X+CON5*DENOF*DVOXDT(I,J,K)+CON6*DENOF*DSIN(ALPHA)   )
0089                  IF(FKZY(I,J,K).NE.0.0) VOZ(I,J,K)=VOZ(I,J,K) + FKZY(I,J,K)*(
                     & DPD2Y+CON5*DENOF*DVOYDT(I,J,K)+CON6*DENOF*DSIN(BETA)   )
0090                  VOZ(I,J,K)=VOZ(I,J,K)*FKUO/FACT
0091                  DVOXDT(I,J,K)=(VOX(I,J,K)-VOXN)/DELT
0092                  DVOYDT(I,J,K)=(VOY(I,J,K)-VOYN)/DELT
0093                  DVOZDT(I,J,K)=(VOZ(I,J,K)-VOZN)/DELT
            C
0094                  IF(I.EQ.1.OR.I.EQ.NX) DPD2X=0.0
0095                  IF(I.GT.1.AND.I.LT.NX) DPD2X=CON4*(PFW(I+1,J,K)-PFW(I-1,J,K))/(
                     & 2.*DELX)
0096                  IF(J.EQ.1.OR.J.EQ.NY) DPD2Y=0.0
0097                  IF(J.GT.1.AND.J.LT.NY) DPD2Y=CON4*(PFW(I,J+1,K)-PFW(I,J-1,K))/(
                     & 2.*DELY)
0098                  IF(K.EQ.1.OR.K.EQ.NZ) DPD2Z=0.0
0099                  IF(K.GT.1.AND.K.LT.NZ) DPD2Z=CON4*(PFW(I,J,K+1)-PFW(I,J,K-1))/(
                     & 2.*DELZ)
0100                  VWXN=VWX(I,J,K)
0101                  FKUW=-FKRW/UW
0102                  FF=FKUW*CON5*DENWF/DELT
0103                  FACT=1.-FF*FKXX(I,J,K)
0104                  VWX(I,J,K)=FKXX(I,J,K)*(DPD2X-CON5*DENWF*VWXN/DELT+
                     & DENWF*CON6*DSIN(ALPHA))
0105                  IF(FKXY(I,J,K).NE.0.0) VWX(I,J,K)=VWX(I,J,K) + FKXY(I,J,K)*(
                     & DPD2Y+CON5*DENWF*DVWYDT(I,J,K)+CON6*DENWF*DSIN(BETA)   )
0106                  IF(FKXZ(I,J,K).NE.0.0) VWX(I,J,K)=VWX(I,J,K) + FKXZ(I,J,K)*(
                     & DPD2Z+CON5*DENWF*DVWZDT(I,J,K)+CON6*DENWF*DCOS(GAMMA)  )
0107                  VWX(I,J,K)=VWX(I,J,K)*FKUW/FACT
0108                  VWYN=VWY(I,J,K)
0109                  FACT=1.-FF*FKYY(I,J,K)
0110                  VWY(I,J,K)=FKYY(I,J,K)*(DPD2Y-CON5*DENWF*VWYN/DELT+
                     & CON6*DENWF*DSIN(BETA))
0111                  IF(FKYX(I,J,K).NE.0.0) VWY(I,J,K)=VWY(I,J,K) + FKYX(I,J,K)*(
                     & DPD2X+CON5*DENWF*DVWXDT(I,J,K)+CON6*DENWF*DSIN(ALPHA)   )
0112                  IF(FKYZ(I,J,K).NE.0.0) VWY(I,J,K)=VWY(I,J,K) + FKYZ(I,J,K)*(
                     & DPD2Z+CON5*DENWF*DVWZDT(I,J,K)+CON6*DENWF*DCOS(GAMMA)   )
0113                  VWY(I,J,K)=VWY(I,J,K)*FKUW/FACT
0114                  VWZN=VWZ(I,J,K)
0115                  FACT=1.-FF*FKZZ(I,J,K)
0116                  VWZ(I,J,K)=FKZZ(I,J,K)*(DPD2Z-CON5*DENWF*VWZN/DELT+
                     & CON6*DENWF*DCOS(GAMMA))
0117                  IF(FKZX(I,J,K).NE.0.0) VWZ(I,J,K)=VWZ(I,J,K) + FKZX(I,J,K)*(
                     & DPD2X+CON5*DENWF*DVWXDT(I,J,K)+CON6*DENWF*DSIN(ALPHA)   )
```

```
0118            IF(FKZY(I,J,K).NE.0.0) VWZ(I,J,K)=VWZ(I,J,K) + FKZY(I,J,K)*(
               & DPD2Y+CON5*DENWF*DVWYDT(I,J,K)+CON6*DENWF*DSIN(BETA)  )
0119            VWZ(I,J,K)=VWZ(I,J,K)*FKUW/FACT
0120            DVWXDT(I,J,K)=(VWX(I,J,K)-VWXN)/DELT
0121            DVWYDT(I,J,K)=(VWY(I,J,K)-VWYN)/DELT
0122            DVWZDT(I,J,K)=(VWZ(I,J,K)-VWZN)/DELT
          C
0123        100 CONTINUE
          C
0124            DO 815 K=1,NZ
0125            DO 815 J=1,NY
0126            DO 815 I=1,NX
0127            IF(DABS(VOX(I,J,K)).LT.1.0D-20) VOX(I,J,K)=0.0
0128            IF(DABS(VOY(I,J,K)).LT.1.0D-20) VOY(I,J,K)=0.0
0129            IF(DABS(VOZ(I,J,K)).LT.1.0D-20) VOZ(I,J,K)=0.0
0130            IF(DABS(VWX(I,J,K)).LT.1.0D-20) VWX(I,J,K)=0.0
0131            IF(DABS(VWY(I,J,K)).LT.1.0D-20) VWY(I,J,K)=0.0
0132            IF(DABS(VWZ(I,J,K)).LT.1.0D-20) VWZ(I,J,K)=0.0
0133            IF(DABS(VGX(I,J,K)).LT.1.0D-20) VGX(I,J,K)=0.0
0134            IF(DABS(VGY(I,J,K)).LT.1.0D-20) VGY(I,J,K)=0.0
0135            IF(DABS(VGZ(I,J,K)).LT.1.0D-20) VGZ(I,J,K)=0.0
0136        815 CONTINUE
0137            RETURN
0138            END
```

APPENDIX G

Monte Carlo Program for Generating Fractured Nodes

```
G1  RELEASE 2.0                 MAIN                 DATE = 82339

      C
      C    MONTE CARLO METHOD FOR GENERATING FRACTURE CELLS
      C    THIS PROGRAM IS FOR 2-DIMENSIONAL RESERVOIR AREA
      C    GAUSS CELL ORDERING SCHEME IS USED IN NUMBERING THE NODES
      C     E.G. FOR A 10 * 7 GRID SYSTEM, THE ORDER IS AS FOLLOWS.
      C
      C          61  62  63  64  65  66  67  68  69  70
      C          51  52  53  54  55  56  57  58  59  60
      C          41  42  43  44  45  46  47  48  49  50
      C          31  32  33  34  35  36  37  38  39  40
      C          21  22  23  24  25  26  27  28  29  30
      C          11  12  13  14  15  16  17  18  19  20
      C           1   2   3   4   5   6   7   8   9  10
      C
      C     NX = NUMBER OF NODES IN X-DIRECTION
      C     NY = NUMBER OF NODES IN Y-DIRECTION
      C     NPERCT = PERCENTAGE OF FRACTURED NODES
      C     N1     = INITIAL RANDOM NUMBER
      C
            DIMENSION NFCELL(10,10),NF(100)
            DATA NFCELL/100*0/
            DATA NX,NY,NPERCT,N1/10,7,35,2498/
            NTAL=0
            MTAL=0
            NTOTAL=NX*NY
            TOTAL=NTOTAL
            MM=NPERCT*NTOTAL/100
            MT=NPERCT*NTOTAL-MM*100
            IF(MT.GE.50) MM=MM+1
          1 NTAL=NTAL+1
            CALL RANDU(N1,N2,RN)
            RNF=1.+RN*(TOTAL-1.)
            NF(NTAL)=RNF
            NROWM1=(NF(NTAL)-1)/NX
            NROW=NROWM1+1
            NCOL=NF(NTAL)-NX*NROWM1
            IF(NFCELL(NCOL,NROW).EQ.0) MTAL=MTAL+1
            NFCELL(NCOL,NROW)=1
            PRINT 103,NTAL,N1,RN,RNF,NF(NTAL),NROW,NCOL
        103 FORMAT('0',I5,I10,2F10.4,3I10)
            N1=N2
            IF(MTAL.LT.MM) GO TO 1
            DO 12 J=1,NY
            KJ=NY-J+1
            PRINT 101,(NFCELL(I,KJ),I=1,NX)
        101 FORMAT('0',20I5)
         12 CONTINUE
            PRINT 90
         90 FORMAT(/////' FRACTURED NODES       = 1',/,
           &            ' NON-FRACTURED NODES = 0'/)
            STOP
            END
```

APPENDIX H

Estimation of Hydraulic Radius from Thomas et al Example

In Evans' model, the fluid interaction terms are written in the oilfield unit as:

$$[\Gamma_j]_i = 0.001127 \frac{K_1 k_{r1j} \phi_f C_{ij1} \rho_{j1}}{r_H{}^1 \mu_{j1}} (P_{1j} - P_{fj}) \qquad \text{(H-1)}$$

For example, the water component in water phase has:

$C_{Ww1} = 1$, and $\rho_{w1} = \frac{\rho_{ws}}{B_{w1}}$

Hence,

$$[\Gamma_w]_W = 0.001127 \frac{K_1 k_{r1w} \phi_f \rho_{Ws}}{r_H{}^1 \mu_{w1} B_{w1}} (P_{1w} - P_{fw}) \qquad \text{(H-2)}$$

Note: The dimensions of $[\Gamma_w]_W$ above are $\frac{M}{L^3 t}$.

In Thomas et al model[22], the matrix-fracture flow equations are given as illustrated below for the water phase. (written in this study's notation).

$$\frac{V_B}{\Delta t} \bar{\delta}\left(\frac{\phi_1 S_{w1}}{B_{w1}}\right) = -0.001127\sigma \frac{K_1 k_{r1w} V_B}{\mu_{w1} B_{w1}} (P_{1w} - P_{fw}) \qquad \text{(H-3)}$$

The left-hand-side of the above equation represents the water flow rate from the rock matrix to the fractures. Before comparison between the two models can be made, the equations must have the same dimensions. Therefore, the dimensions of Thomas et al equation are converted from $(\frac{L^3}{t})$

to $\left(\frac{M}{L^3 t}\right)$ as shown below. Multiply the equation by $\frac{\rho_{ws}}{V_B}$.

$$\therefore \quad \frac{\rho_{ws}}{V_B \Delta t}\,\overline{\delta}\left(\frac{V_B \phi_1 S_{w1}}{B_{w1}}\right) = -0.001127\,\sigma\,\frac{\rho_{ws}}{V_B}\,\frac{K_1 k_{r1w}}{\mu_{w1} B_{w1}}\,V_B (P_{1w} - P_{fw}) \tag{H-4}$$

The left-hand-side now represents the mass flow rate per unit volume and has dimensions of $\left(\frac{M}{L^3 t}\right)$. Note that $\overline{\delta}$ signifies time step difference

$(\overline{\delta} = \delta^{n+1} - \delta^{n})$.

Consequently, comparison between the two models results in the following relationship.

$$\sigma = \frac{\phi_f}{r_H l} \tag{H-5}$$

$$r_H = \frac{\phi_f}{\sigma l} \tag{H-6}$$

In this study, $l = \frac{\Delta x}{2} = 100$ ft, $\phi_f = 0.01$. From Thomas et al example, the matrix shape factor (σ) equals 0.25 ft^{-2}. Thus,

$$r_H = \frac{0.01}{0.25 \times 100} = 0.0004 \text{ ft.}$$

From section 4.6, the fracture half-width is related to the hydraulic radius by:

$$d = \frac{4 r_H}{\pi} \tag{H-7}$$

Hence, in this study:

$$d = \frac{4 \times 0.0004}{\pi} \approx 0.0005 \text{ ft.}$$

APPENDIX I

Effect of Decreasing the Fracture Hydraulic Radius

The effect of decreasing the fracture hydraulic radius was investigated by reducing the value of the fracture half-width from 0.0005 to 0.0001 ft (i.e. decrease r_H from 0.0004 to 0.00008 ft). Water breakthrough of this run occured at approximately the same time as the Original results (255 days). However, it was observed that the water saturation profiles of this differed slightly from those of the original run in Figure 10 and 11 (indicated by dash lines in Figures I-1 and I-2). As the fracture half width decreases, the water fronts tend to move slower in the fractures while the water fronts in the rock matrix tend to move faster. This implies that as the fracture half-width approaches zero, the water fronts in the fractures and the rock matrix converge become identical when no fracture exists (i.e. $d = 0$).

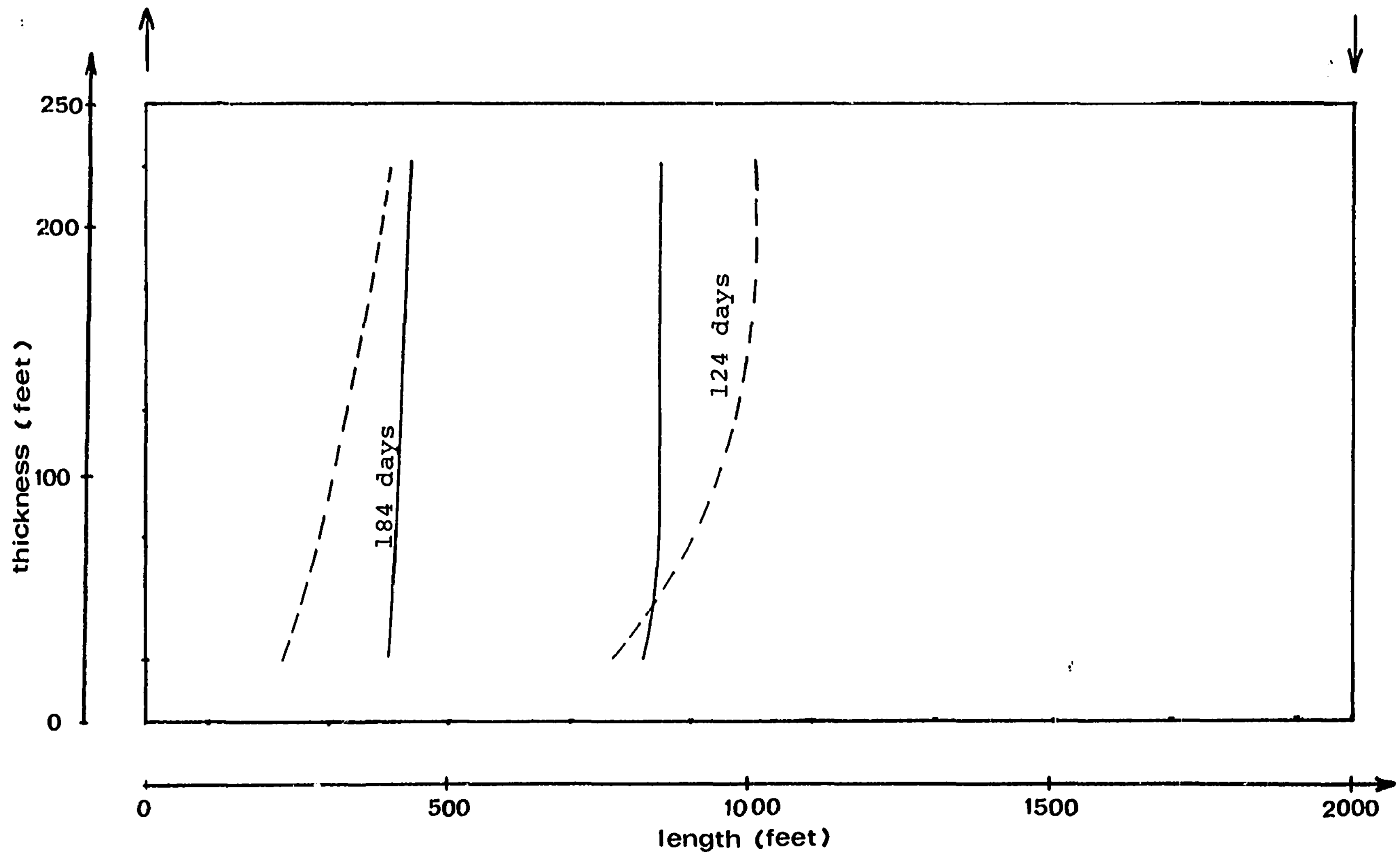

Figure I-1 Fracture 50% Water Saturation Profile (center cross-section).

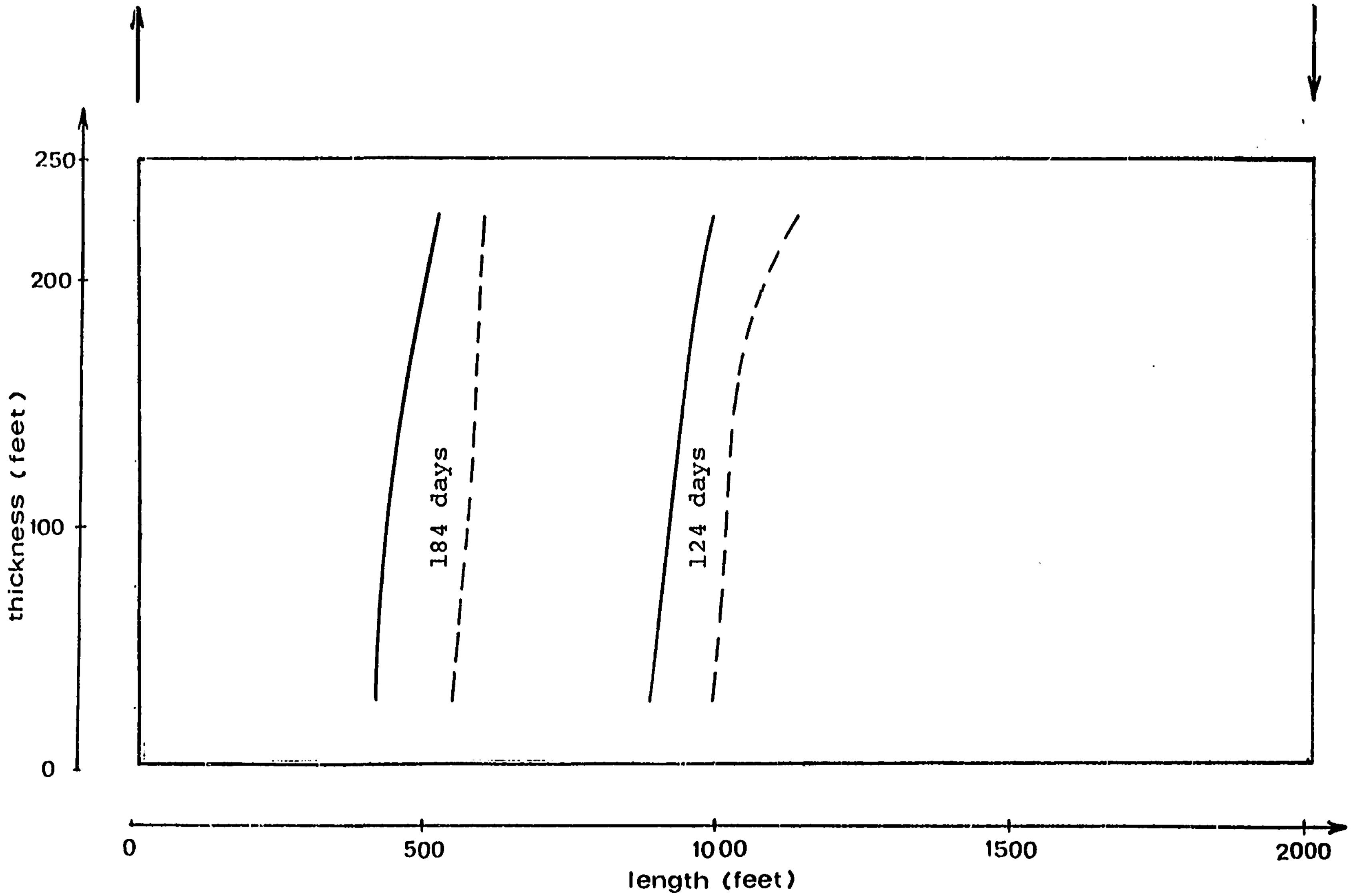

Figure I-2 Matrix 50% Water Saturation Profile (Center cross-section)

APPENDIX J

Effect of Smaller Grid Sizes

For comparative study the grid sizes used in this study were the same as those used in Thomas et al[22] paper (i.e. $\Delta X = \Delta Y = 200$ ft and $\Delta Z = 50$ ft). To investigate the level of truncation errors caused by replacing derivatives in the partial differential equation with the finite difference formulae, the grid sizes ΔX and ΔY were decreased from 200 ft to 100 ft. Hence, the reservoir system consisted of 20x4x5 = 400 grid points (or 6x400 = 2400 simultaneous linear equations). As the grid sizes decreased, the fracture characteristics half width ($\ell = \Delta X/2$) decreased as well. In order to preserve the same valve of geometrical factor used by Thomas et al, the fracture half width (thus, the hydraulic radius) had to be proportionally increased according to equation H-5. Thus, the fracture half width used in this run was increased from 0.0005 to 0.001 ft.

The results of this run are shown in Figures J-1 and J-2 (original results of Figures 10 and 11 are shown by dash lines). It is noted that the water fronts from the two runs have similar profiles although the water fronts of this run move at slightly slower pace than those of the original run. Water breakthrough occurred at approximately 290 days (or 33 days later than the original results). The difference between the two results, however, may be considered small and constitutes an acceptable level of truncation errors.

It should be pointed out that as the grid sizes decreases, the number of equations to be solved and the computing time increases considerably. Therefore, one should carefully weigh between the accuracy desired and the time and cost of computation involved.

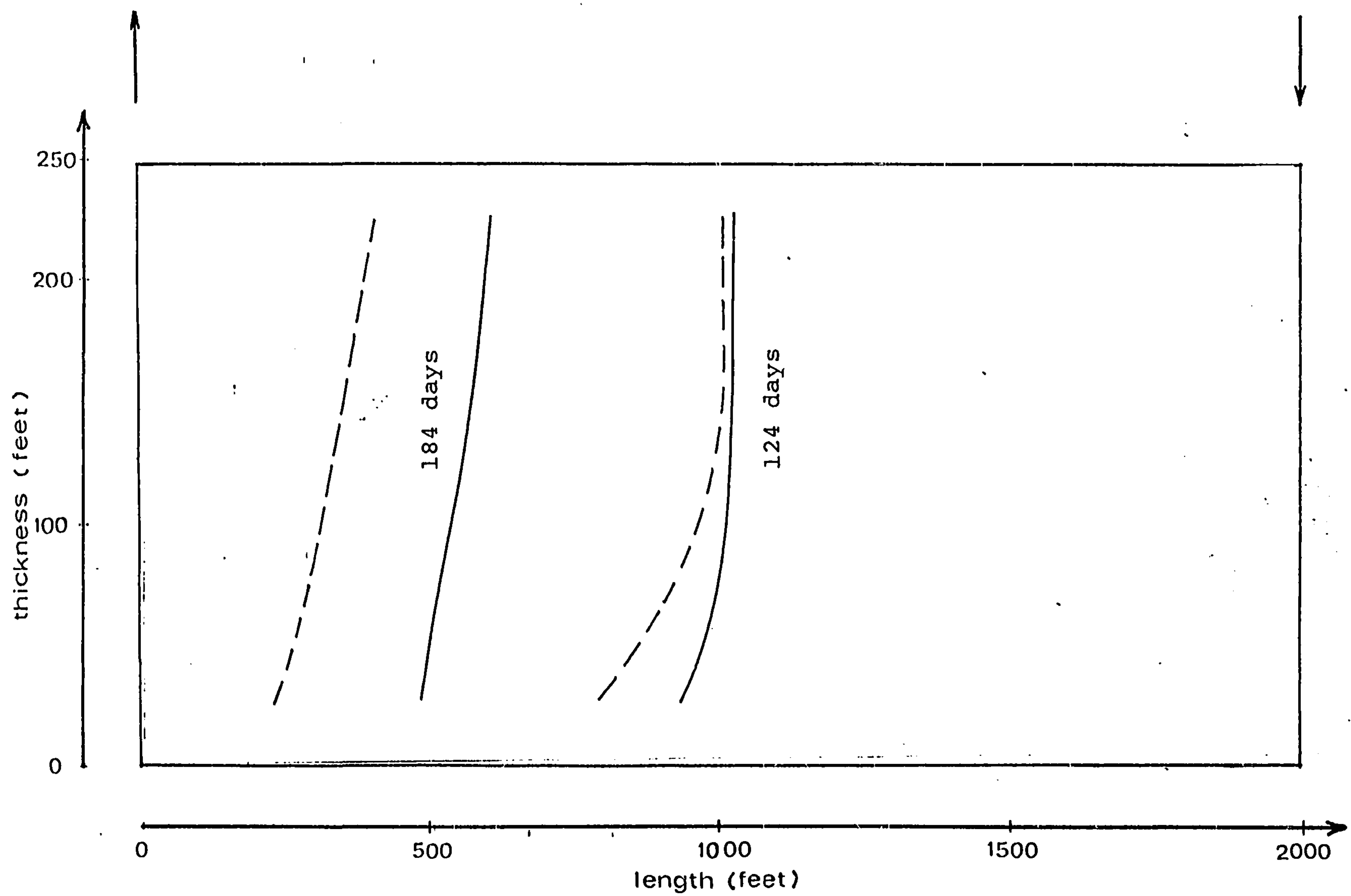

Figure J.1 Fracture 50% Water Saturation Profile (Center cross-section)

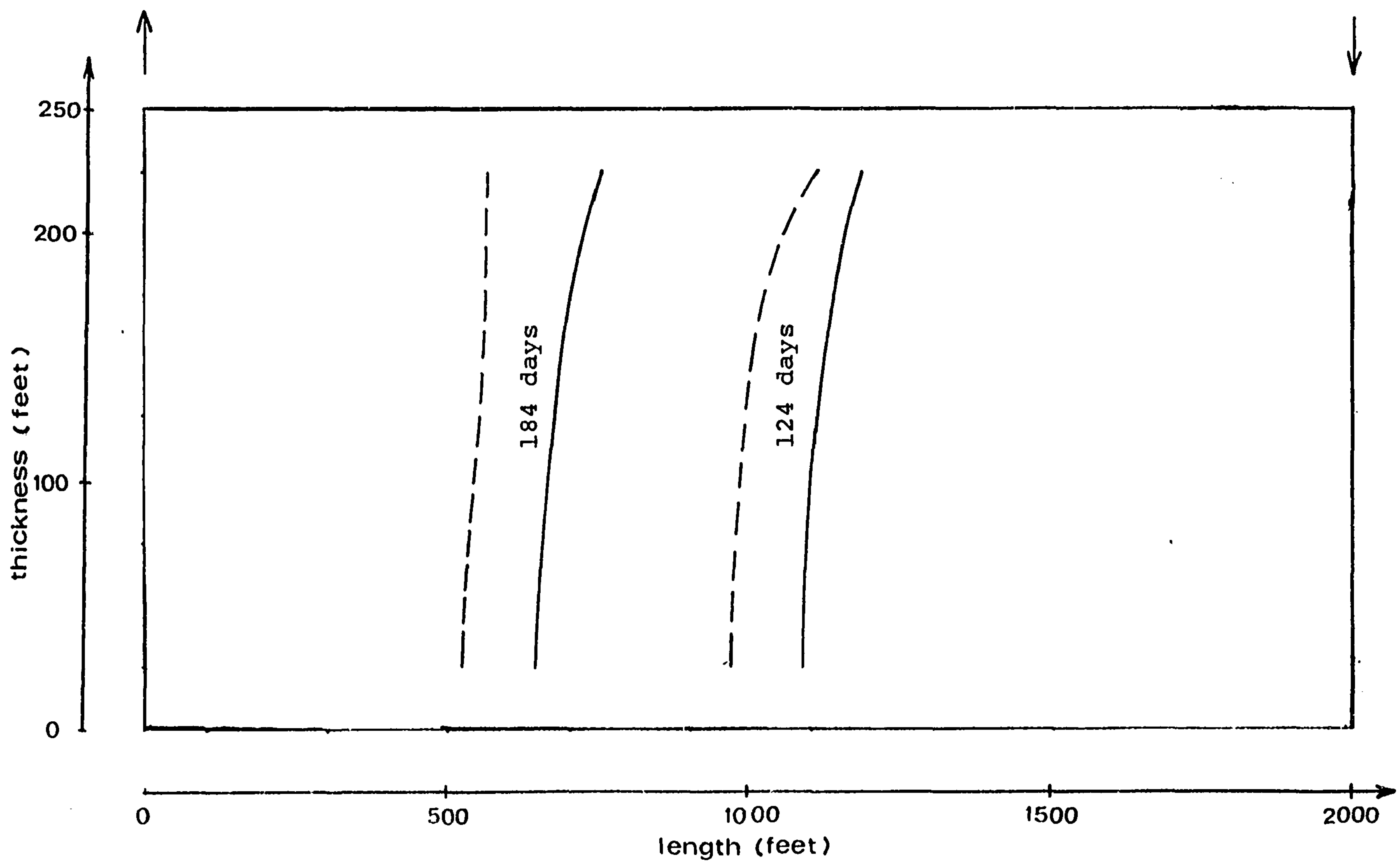

Figure J.2 Matrix 50% Water Saturation Profile (center cross-section)