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# NUMERICAL SIMULATION OF MULTIPHASE FLUID FLOW IN NATURALLY FRACTURED RESERVOIRS

*The University of Oklahoma* PH.D. 1983

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# 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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## ACKNOWLEDGMENTS

The author is deeply grateful to Dr. R. D. Evans, Professor of Petroleum and Geological Engineering and chairman of his dissertation committee, for his guidance, support, encouragement and valuable suggestions. His philosophy, his standard of excellence, and most of all, his trust in the author's ability have been inspirational as well as motivational throughout this research.

The author also wishes to express his sincere appreciation to Professors Dr. D. E. Menzie, Dr. D. Tiab, Dr. E. F. Blick of the School of Petroleum and Geological Engineering, and Dr. A. A. Aly of the School of Industrial Engineering for serving as members of his dissertation committee.

Financial support throughout this academic endeavor by the Department of Mineral Resources of Thailand is gratefully acknowledged. Appreciation is also extended to the Energy Resource Center and the Oklahoma Mining and Mineral Resources Research Institute of the University of Oklahoma for their financial assistance.

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],

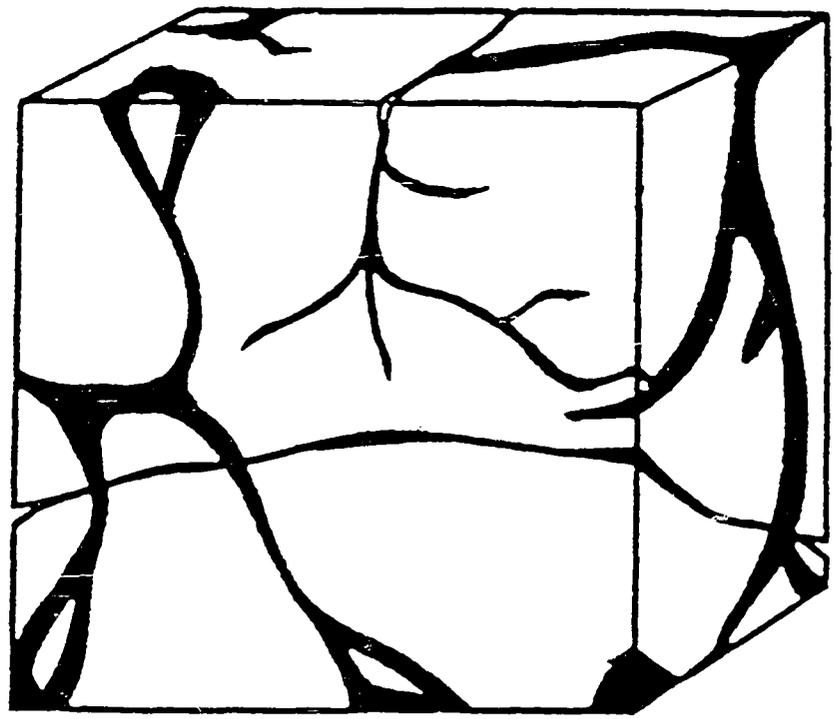

Figure 1. Actual naturally fractured reservoir.

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

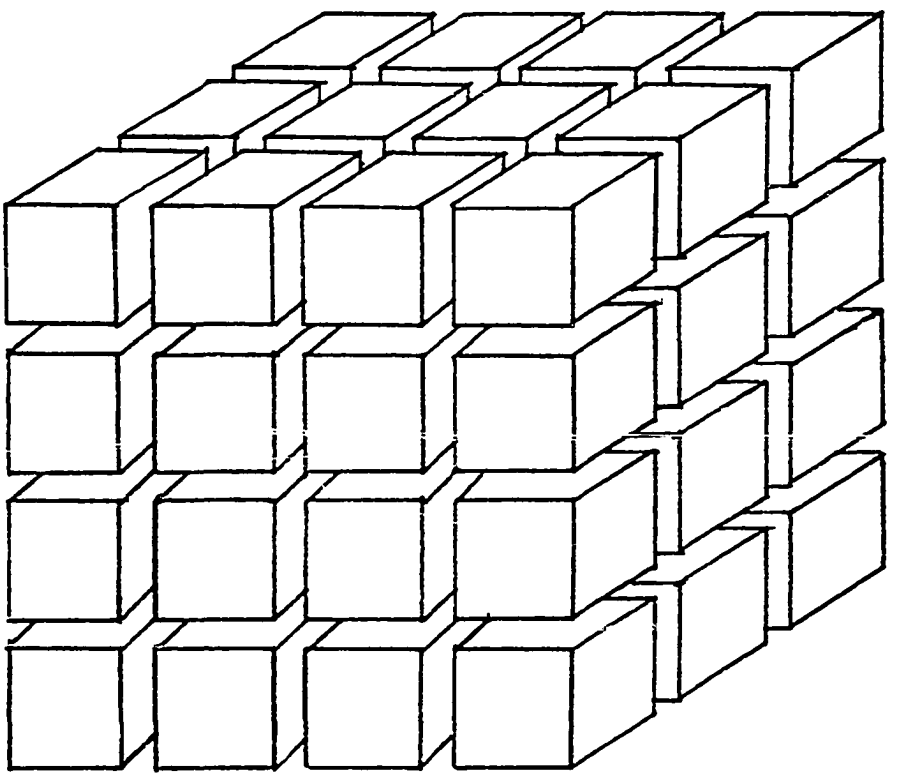

Figure 2. Idealization of a naturally fractured porous medium (Warren and Root model).

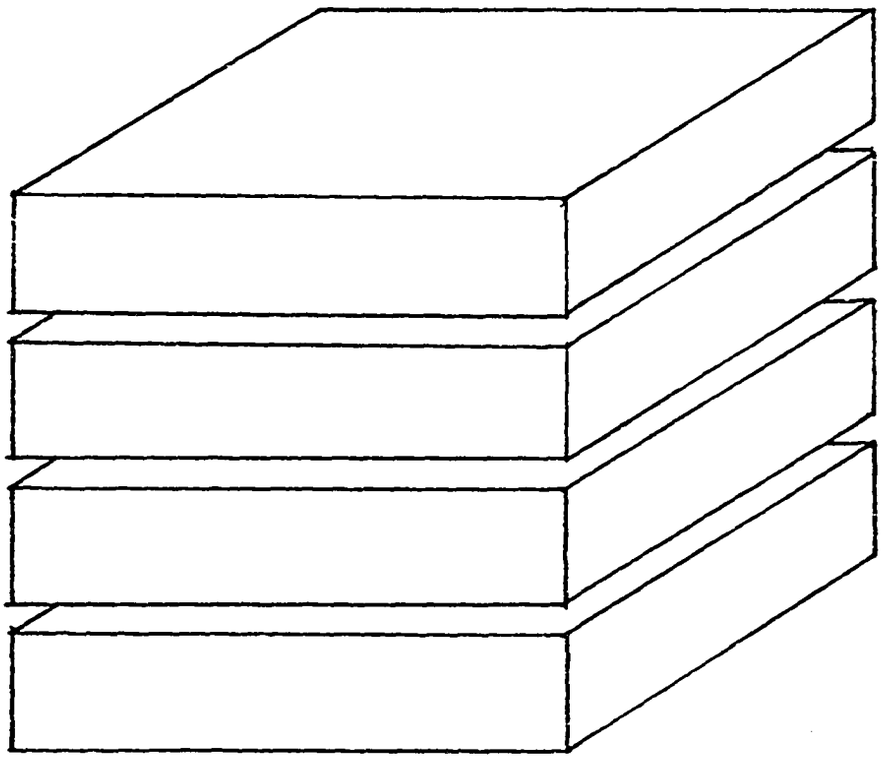

Figure 3. Idealization of a naturally fractured porous medium (Kazemi model).

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 $f(\bar{r},\Omega)$ to represent the distribution of fractures throughout the reservoir system. Furthermore, he shows that the intrinsic permeability tensor for the fracture ($\bar{\bar{K}}_f$) 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:

$$\nabla\cdot[\sum_j C_{ijl}\rho_{jl}\vec{V}_{lj}] + \sum_j \Gamma_j - \frac{\rho_{is}q_{isl}}{\Delta x\cdot\Delta y\cdot\Delta z}$$

$$+ \frac{\partial}{\partial t}[\phi_l \sum_j C_{ijl}\rho_{jl}S_{jl}] = 0$$

3.2.2 Equations of Motion:

Fracture:

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

Rock Matrix:

$$\vec{V}_{lj} = - \frac{K_l k_{rlj}}{\mu_{jl}}\left[\nabla P_{lj} - \rho_{jl}\frac{g}{g_c}\nabla D\right]$$

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:

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

or the steady state condition:

$$\Gamma_j = \frac{\beta_j}{\mu_{jl}}\left[P_{lj} - P_{fj}\right]$$

where

$$\beta_j = \frac{K_l k_{rlj}\phi_f C_{ijl}\rho_{jl}}{r_H^{\ell}}$$

$$B_j = \frac{K_l k_{rlj} n^2 \Pi^2 t}{2\ell^2 \mu_{jl}\phi_l c_l}$$

3.2.4 Porosity Equations:

Fracture:

$$\frac{\partial \phi_f}{\partial t} = \phi_f(1-\phi_f)C_f\frac{\partial P_f}{\partial t} - \phi_l\phi_f C_l\frac{\partial P_l}{\partial t}$$

Rock Matrix:

$$\frac{\partial \phi_l}{\partial t} = \Phi_l(1 - \Phi_l)C_l \frac{\partial P_l}{\partial t} - \phi_l \phi_f C_f \frac{\partial P_f}{\partial t}$$

3.2.5 Required Auxillary Equations:

Saturations:

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

$$S_{gl} + S_{wl} + S_{ol} = 1 \qquad \text{(rock matrix)}$$

Capillary Pressures:

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

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

$$P_{cgol} = P_{lg} - P_{lo} \qquad \text{(rock matrix)}$$

$$P_{cowl} = P_{lo} - P_{lw} \qquad \text{(rock matrix)}$$

Conservation of mass of each fluid phase:

$$\sum_i C_{igl} = 1 \qquad \text{(rock matrix)}$$

$$\sum_i C_{iol} = 1 \qquad \text{(rock matrix)}$$

$$\sum_i C_{iwl} = 1 \qquad \text{(rock matrix)}$$

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

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

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

## 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 $\rho_{OS}$ be the density of the oil component, and $\rho_{GS}$ 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 $\nabla D$ 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)

$\alpha$ = angle of the x axis with the horizontal plane

$\beta$ = angle of the y axis with the horizontal plane

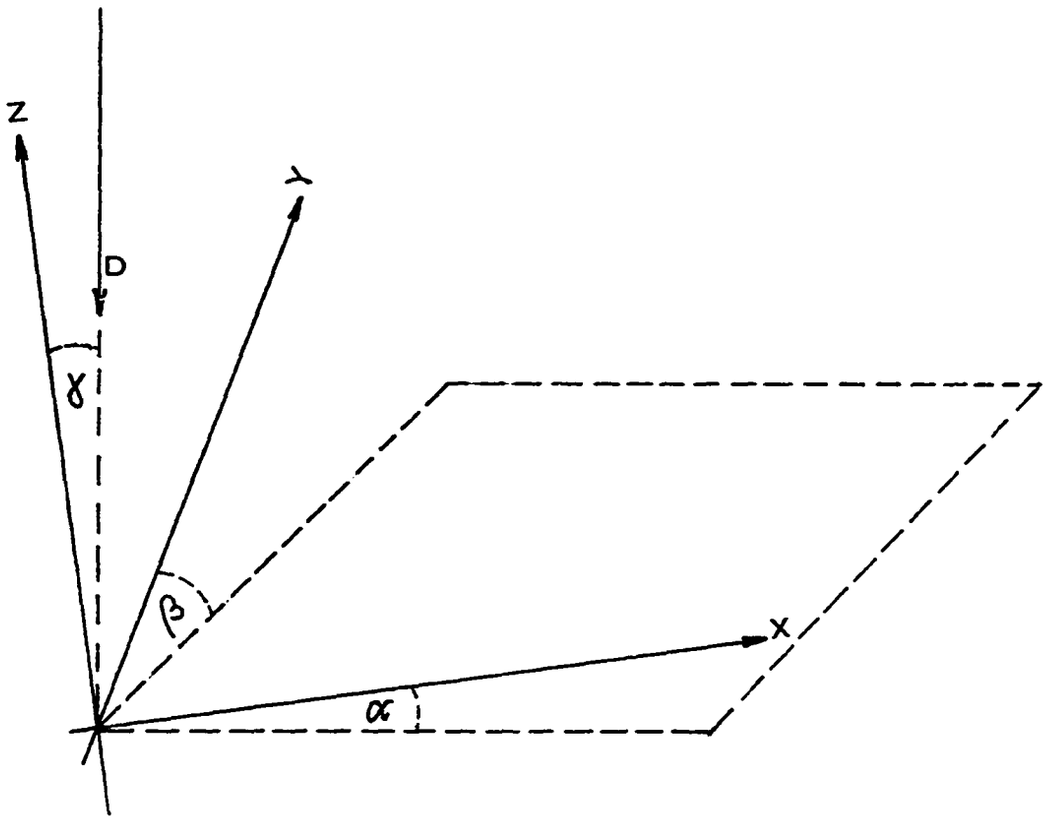


Figure 4. Coordinate convention.

$\gamma$ = 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:

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

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

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

$$\nabla\cdot[C_{igl}\rho_{gl}\vec{V}_{lg} + C_{iol}\rho_{ol}\vec{V}_{lo} + C_{iwl}\rho_{wl}\vec{V}_{lw}] + [\Gamma_g + \Gamma_o + \Gamma_w]_i$$

$$- \frac{\rho_{is}q_{isl}}{\Delta x\cdot\Delta y\cdot\Delta z} + \frac{\partial}{\partial t}[\phi_l(C_{igl}\rho_{gl}S_{gl} + C_{iol}\rho_{ol}S_{ol} + C_{iwl}\rho_{wl}S_{wl})] = 0 \qquad (2)$$

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

For Water Component

$$\nabla\cdot[\frac{\rho_{WS}\vec{V}_{lw}}{B_{wl}}] + [\Gamma_g + \Gamma_o + \Gamma_w]_W - \frac{\rho_{WS}q_{WSl}}{\Delta x\cdot\Delta y\cdot\Delta z}$$

$$+ \frac{\partial}{\partial t}[\phi_l\rho_{WS}\ S_{wl}/B_{wl}] = 0 \qquad (3)$$

For Oil Component

$$\nabla\cdot[\frac{\rho_{OS}}{B_{ol}}\vec{V}_{lo}] + [\Gamma_g + \Gamma_o + \Gamma_w]_O - \frac{\rho_{OS}q_{OSl}}{\Delta x\cdot\Delta y\cdot\Delta z}$$

$$+ \frac{\partial}{\partial t}[\frac{\phi_l\rho\ S_{ol}}{B_{ol}}] = 0 \qquad (4)$$

For Gas Component

$$\nabla\cdot[\frac{\rho_{GS}}{B_{gl}}\vec{V}_{lg} + \frac{R_{sol}\rho_{GS}}{B_{ol}}\vec{V}_{lo}] + [\Gamma_g+\Gamma_o+\Gamma_w]_G - \frac{\rho_{GS}q_{GSl}}{\Delta x\cdot\Delta y\cdot\Delta z}$$

$$+ \frac{\partial}{\partial t}[\phi_l(\frac{\rho_{GS}S_{gl}}{B_{gl}} + \frac{R_{sol}\rho_{GS}\ S_{ol}}{B_{ol}})] = 0 \qquad (5)$$

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

$$[\Gamma_j]_i = \frac{\beta_j}{\mu_{jl}} [P_{lj} - P_{fj}] \tag{6}$$

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:

For Water Component

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

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

$$[\Gamma_w]_W = \frac{K_l k_{rlw} \phi_f \rho_{WS}}{r_H{}^l \mu_{wl} B_{wl}} (P_{lw} - P_{fw}) \tag{9}$$

For Oil Component

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

$$[\Gamma_o]_O = \frac{K_l k_{rlo} \phi_f \rho_{OS}}{r_H{}^l \mu_{ol} B_{ol}} (P_{lo} - P_{fo}) \tag{11}$$

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

For Gas Component

$$[\Gamma_g]_G = \frac{K_l k_{rlg} \phi_f \rho_{GS}}{r_H{}^l \mu_{gl} B_{gl}} (P_{lg} - P_{fg}) \tag{13}$$

$$[\Gamma_o]_G = \frac{K_l k_{rlo} \phi_f R_{sol} \rho_{GS}}{r_h{}^l \mu_{ol} B_{ol}} (P_{lo} - P_{fo}) \tag{14}$$

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

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

respective continuity equations.

For Water Component

$$\nabla\cdot\left[\frac{K_l k_{rlw}}{B_{wl}\mu_{wl}}\{\nabla P_{lw} - \rho_{wl}\frac{g}{g_c}\nabla D\}\right] - \left[\frac{K_l k_{rlw}\phi_f}{r_{Hl}\mu_{wl}B_{wl}}(P_{lw} - P_{fw})\right] + \frac{q_{WSl}}{\Delta x\cdot\Delta y\cdot\Delta z} = \phi_l\frac{\partial(S_{wl}/B_{wl})}{\partial t} \quad (16)$$

For Oil Component

$$\nabla\cdot\left[\frac{K_l k_{rlo}}{B_{ol}\mu_{ol}}\{\nabla P_{lo} - \rho_{ol}\frac{g}{g_c}\nabla D\}\right] - \left[\frac{K_l k_{rlo}\phi_f}{r_{Hl}\mu_{ol}B_{ol}}(P_{lo} - P_{fo})\right] + \frac{q_{OSl}}{\Delta x\cdot\Delta y\cdot\Delta z} = \phi_l\frac{\partial(S_{ol}/B_{ol})}{\partial t} \quad (17)$$

For Gas Component

$$\nabla\cdot\left[\frac{K_l k_{rlg}}{B_{gl}\mu_{gl}}\{\nabla P_{lg} - \rho_{gl}\frac{g}{g_c}\nabla D\}\right] + \nabla\cdot\left[\frac{R_{sol}K_l k_{rlo}}{B_{ol}\mu_{ol}}\{\nabla P_{lo} - \rho_{ol}\frac{g}{g_c}\nabla D\}\right] - \left[\frac{K_l k_{rlg}\phi_f}{r_{Hl}\mu_{gl}B_{gl}}(P_{lg} - P_{fg}) + \frac{K_l k_{rlo}\phi_f R_{sol}}{r_{Hl}\mu_{ol}B_{ol}}(P_{lo} - P_{fo})\right] + \frac{q_{GSl}}{\Delta x\cdot\Delta y\cdot\Delta z} = \phi_l\frac{\partial}{\partial t}(S_{gl}/B_{gl} + R_{sol}S_{ol}/B_{ol}) \quad (18)$$

3.5.2 Fracture

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

$$\nabla\cdot\left[\sum_j C_{ijf}\rho_{jf}\vec{V}_{fj}\right] - \sum_j \Gamma_j - \frac{\rho_{jsf}q_{isf}}{\Delta x\cdot\Delta y\cdot\Delta z} + \frac{\partial}{\partial t}\left[\phi_f\sum_j C_{ijf}\rho_{jf}S_{jf}\right] = 0 \quad (19)$$

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

For Water Component

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

$$+ \frac{\partial}{\partial t}\left[\phi_f \rho_{WS} S_{wf}/B_{wf}\right] = 0 \qquad (20)$$

For Oil Component

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

$$+ \frac{\partial}{\partial t}\left[\phi_f \rho_{OS} S_{of}/B_{of}\right] = 0 \qquad (21)$$

For Gas Component

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

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

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

For Water Component

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

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

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

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

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

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

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

$$+ \left[\frac{K_1 k_{rlw}\phi_f}{r_H{}^2\mu_{wl}B_{wl}}(P_{lw} - P_{fw})\right] + \frac{q_{WSf}}{\Delta x \cdot \Delta y \cdot \Delta z} = \phi_f \frac{\partial}{\partial t}\left[S_{wf}/B_{wf}\right] \quad (24)$$

For Oil Component

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

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

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

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

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

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

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

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

$$+\left[\frac{K_l k_{rlo}\phi_f}{r_H{}^l\mu_{ol}B_{ol}}(P_{lo}-P_{fo})\right]+\frac{q_{osf}}{\Delta x\cdot\Delta y\cdot\Delta z}=\phi_f\frac{\partial}{\partial t}\left[S_{of}/B_{of}\right] \quad (25)$$

For Gas Component

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

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

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

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

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

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

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

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

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

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

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

$$-\rho_{of}\frac{g}{g_c}\frac{\partial D}{\partial z}\Big)\Big\}\Big]\Big]+\Big[\frac{K_l K_{rlg}\phi_f}{r_H{}^l\mu_{gl}B_{gl}}(P_{lg}-P_{fg})+\frac{K_l k_{rlo}\phi_f R_{sol}}{r_H{}^l\mu_{ol}B_{ol}}(P_{lo}$$

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

## 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

$$\frac{\partial}{\partial x}\left[\frac{K_l k_{rlw}}{B_{wl}\mu_{wl}}\left\{\frac{\partial P_{lw}}{\partial x}+\frac{\rho_{WS}}{B_{wl}}\frac{g}{g_c}\sin\alpha\right\}\right]+\frac{\partial}{\partial y}\left[\frac{K_l k_{rlw}}{B_{wl}\mu_{wl}}\left\{\frac{\partial P_{lw}}{\partial y}+\frac{\rho_{WS}}{B_{wl}}\frac{g}{g_c}\sin\beta\right\}\right]$$

$$+\frac{\partial}{\partial z}\left[\frac{K_l k_{rlw}}{B_{wl}\mu_{wl}}\left\{\frac{\partial P_{lw}}{\partial z}+\frac{\rho_{WS}}{B_{wl}}\frac{g}{g_c}\cos\gamma\right\}\right]-\left[\frac{K_l k_{rlw}\phi_f}{r_{Hl}\mu_{wl}B_{wl}}(P_{lw}-P_{fw})\right]+\frac{q_{WSl}}{\Delta x\Delta y\Delta z}$$

$$=\phi_l\left[\frac{1}{B_{wl}}\frac{\partial S_{wl}}{\partial P_{cowl}}\left(\frac{\partial P_{lo}}{\partial t}-\frac{\partial P_{lw}}{\partial t}\right)+S_{wl}\frac{\partial\left(\frac{1}{B_{wl}}\right)}{\partial P_{lw}}\frac{\partial P_{lw}}{\partial t}\right]^{*} \qquad (27)$$

### 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 $\left(\frac{\partial(1/B_{wl})}{\partial P_{lw}}=0\right)$.

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

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

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

3.6.3 The Gas Diffusivity Equation in the Matrix Rock

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

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

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

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

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

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

3.6.4 The Water Diffusivity Equation in the Fractures

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

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

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

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

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

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

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

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

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

$$+ \left[\frac{K_l k_{rlw}\phi_f}{r_{Hl}B_{wl}\mu_{wl}}(P_{lw} - P_{fw})\right] + \frac{q_{WSf}}{\Delta x\cdot\Delta y\cdot\Delta z}$$

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

3.6.5 The Oil Diffusivity Equation in the Fractures

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

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

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

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

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

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

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

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

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

$$+ \left[\frac{K_l k_{rlo}\phi_f}{r_H{}^l B_{ol}\mu_{ol}}(P_{lo} - P_{fo})\right] + \frac{q_{osf}}{\Delta x\Delta y\Delta z}$$

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

### 3.6.6 The Gas Diffusivity Equation in the Fractures

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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.

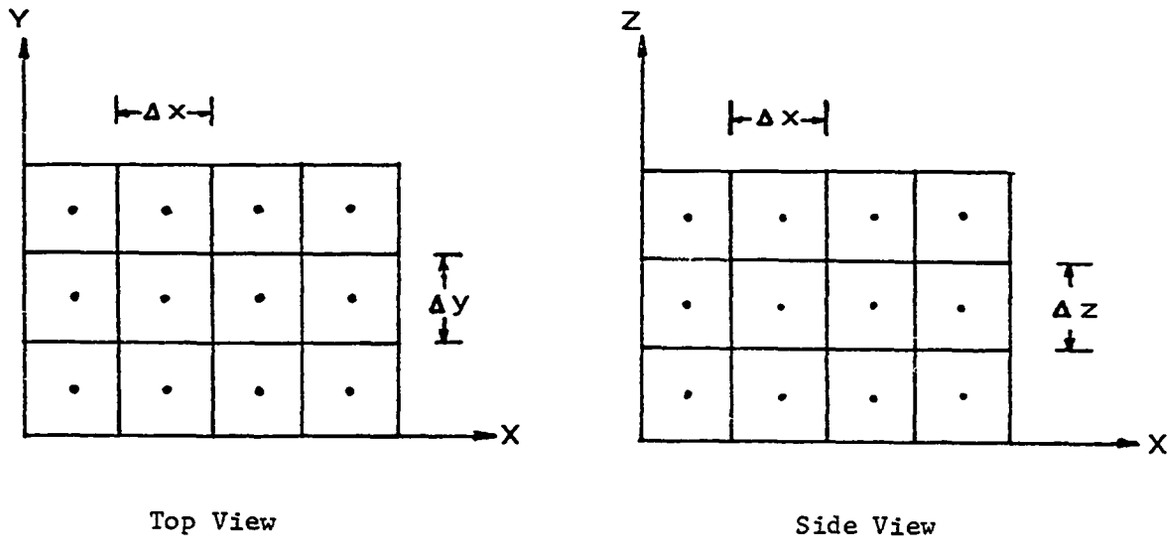
# CHAPTER IV

# 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



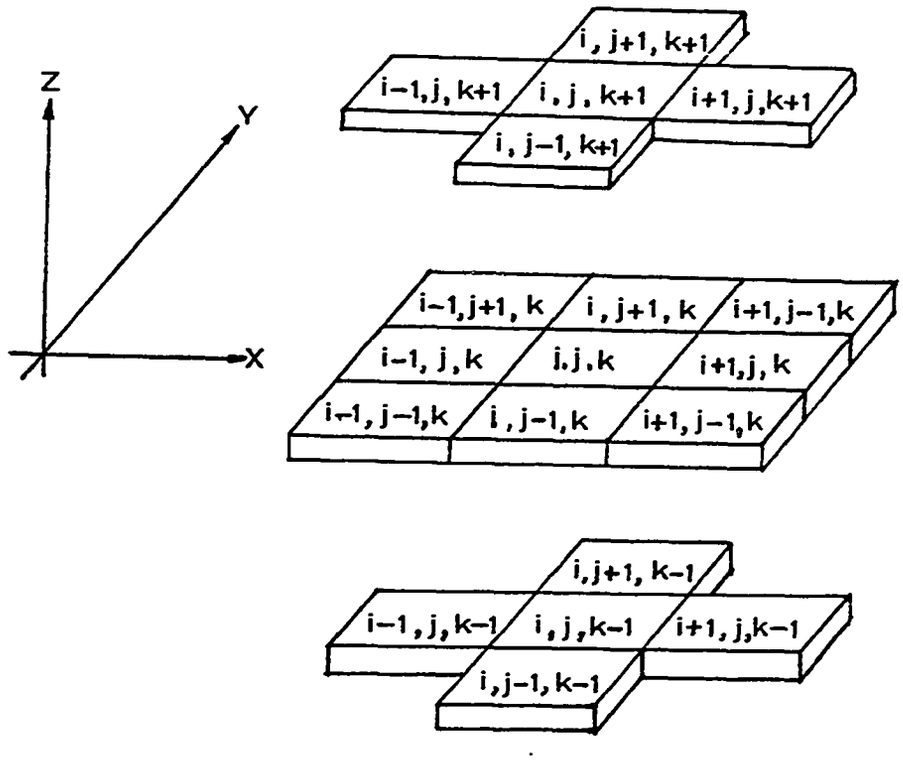




Figure 5. Block-centered grid system

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

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

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

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

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

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

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

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.

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

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

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

---

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

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

$$+ (FO)_{i,j,k}\, P^{n+1}_{lo}{}_{i,j+1,k} + (HO)_{i,j,k}\, P^{n+1}_{lo}{}_{i,j,k+1} + (UO)_{i,j,k}\, P^{n+1}_{lg}{}_{i,j,k}$$

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

---

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

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

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

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

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

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

---

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

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

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

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

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

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

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

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

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

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

---

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

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

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

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

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

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

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

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

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

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

---

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

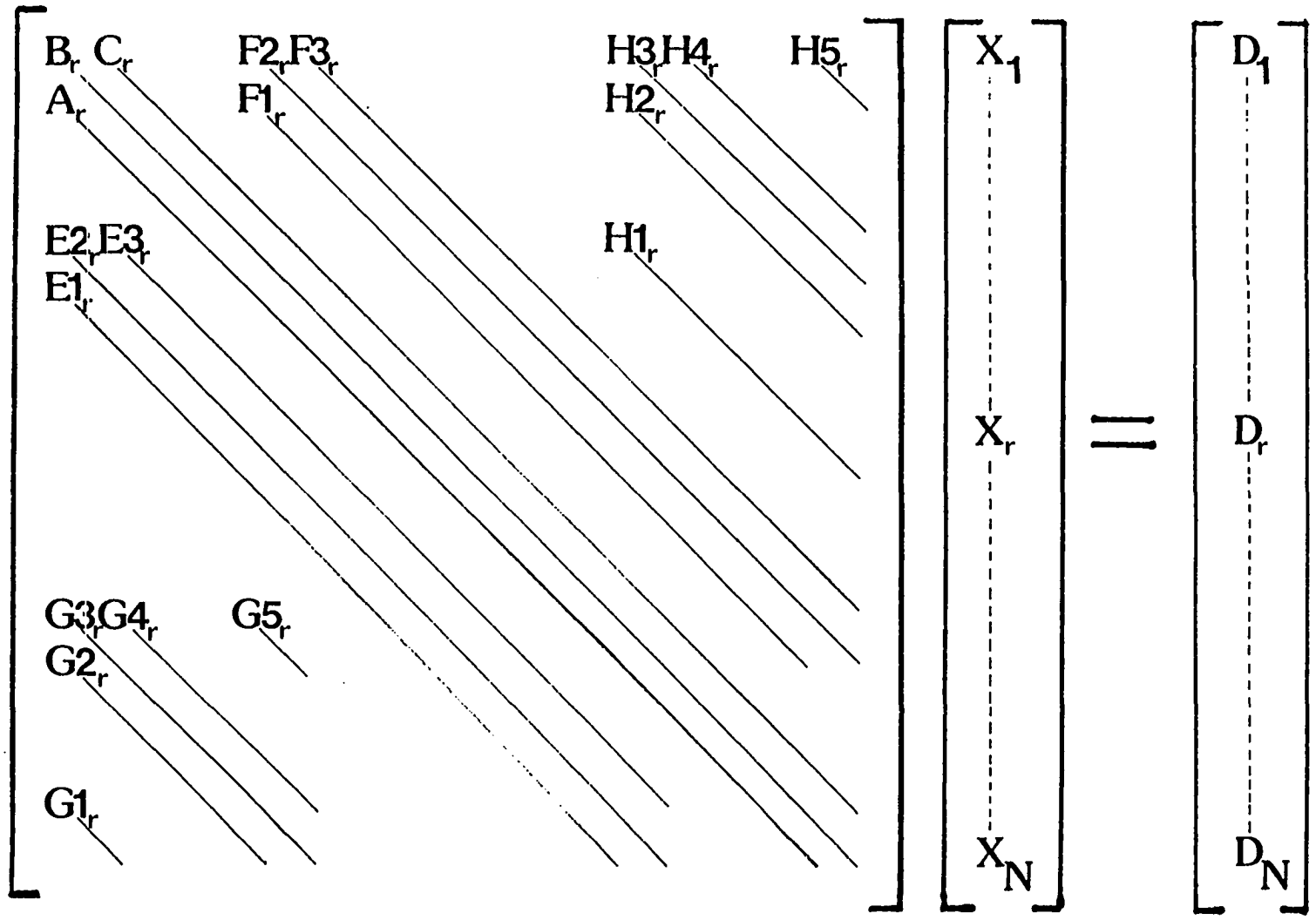



Figure 6. Block matrix form of the pressure equations (19-band diagonal matrix)

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

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

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

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

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

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

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

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

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

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

$$E2_r = E2_{i,j,k} = \begin{bmatrix} EW_{i,j,k} & & & & & \\ & EO_{i,j,k} & & & & \\ & EGO_{i,j,k} & EG_{i,j,k} & & & \\ & & & FEW2_{i,j,k} & & \\ & & & & FEO2_{i,j,k} & \\ & & & & FER2_{i,j,k} & FEG2_{i,j,k} \\ 0 & & & & & \end{bmatrix}$$

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

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

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

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

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

$$H2_r = H2_{,i,j,k} = \begin{bmatrix} 0 & & & \\ & 0 & & \\ & & 0 & \\ & & & FHW2_{i,j,k} \\ & & & FHO2_{i,j,k} \\ & & & FHR2_{i,j,k}FHG2_{i,j,k} \end{bmatrix}$$

$$H3_r = H3_{,i,j,k} = \begin{bmatrix} HW_{i,j,k} & & & \\ & HO_{i,j,k} & & \\ & & HGO_{i,j,k}HG_{i,j,k} & \\ & & & FHW3_{i,j,k} \\ & & & FHO3_{i,j,k} \\ & & & FHR3_{i,j,k}FHG3_{i,j,k} \end{bmatrix}$$

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

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

## 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 $B_o$, $B_g$, $R_{so}$, $d(1/B_o)dP_o$, $d(1/B_g)/dP_g$, $dR_{so}/dP_o$, $\mu_o$, $\mu_w$ and $\mu_g$ 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

$$U_{i+\frac{1}{2},j,k} = \frac{U_{i,j,k} + U_{i+1,j,k}}{2} \tag{41}$$

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

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

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

where

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

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

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

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

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

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

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.

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

where $\partial R$ 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 $\partial R$ can be as well accomplished by setting coefficient $K = 0$ on $\partial R$.

## 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

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

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

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

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

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

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 $\ell$ 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:

$$\phi_{l\ i,j,k}^{n+1} = \phi_{l\ i,j,k}^{n}(1-\phi_{l\ i,j,k}^{n})c_l(P_{lo\ i,j,k}^{n+1}-P_{lo\ i,j,k}^{n}) - \phi_{l\ i,j,k}^{n}\,\phi_{f\ i,j,k}^{n}\,c_f\,(P_{fo\ i,j,k}^{n+1}-P_{fo\ i,j,k}^{n}) + \phi_{l\ i,j,k}^{n} \tag{49}$$

For the fractures:

$$\phi_{f\ i,j,k}^{n+1} = \phi_{f\ i,j,k}^{n}(1-\phi_{f\ i,j,k}^{n})c_f(P_{fo\ i,j,k}^{n+1}-P_{fo\ i,j,k}^{n}) -\phi_{l\ i,j,k}^{n}\,\phi_{f\ i,j,k}^{n})c_l\,(P_{lo\ i,j,k}^{n+1}-P_{lo\ i,j,k}^{n}) +\phi_{f\ i,j,k}^{n} \tag{50}$$

## 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:

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

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

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

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:

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

Thus,

$$\begin{aligned} V^{n+1}_{fjx\ i,j,k} = {} & \frac{1}{1+\left(\frac{k_{rjf}}{\mu_{jf}}\frac{\rho_{jf}}{g_c}\frac{K_{xx}}{\Delta t}\right)^{n+1}_{i,j,k}}\left(-\frac{k_{rjf}}{\mu_{jf}}\right)^{n+1}_{i,j,k} \\ & \left[K_{xx\ i,j,k}\left(\frac{P^{n+1}_{fj\ i+1,j,k} - P^{n+1}_{fj\ i-1,j,k}}{2\Delta x}\right) - \frac{\rho^{n+1}_{jf\ i,j,k}}{g_c\Delta t}\right. \end{aligned}$$

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

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

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

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

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:

$$\tilde{P}^{k+1}_{lw\ i,j,k}{}^{n+1} = \frac{1}{(BW)_{i,j,k}} [(DW)_{i,j,k} - (GW)_{i,j,k} P^{k+1}_{lw\ i,j,k-1}{}^{n+1}$$

$$- (EW)_{i,j,k} P^{k+1}_{lw\ i,j-1,k}{}^{n+1} - (AW)_{i,j,k} P^{k+1}_{lw\ i-1,j,k}{}^{n+1}$$

$$- (CW)_{i,j,k} P^{k}_{lw\ i+1,j,k}{}^{n+1} - (FW)_{i,j,k} P^{k}_{lw\ i,j+1,k}{}^{n+1}$$

$$- (HW)_{i,j,k} P^{k}_{lw\ i,j,k+1}{}^{n+1} - (RW)_{i,j,k} P^{k}_{fw\ i,j,k}{}^{n+1}$$

$$- (UW)_{i,j,k} P^{k}_{lo\ i,j,k}{}^{n+1}] \qquad (55)$$

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

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

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

where $\omega$ is a relaxation parameter.

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

$$\left| P^{n+1}_{lw\ i,j,k}{}^{k+1} - P^{n+1}_{lw\ i,j,k}{}^{k} \right| \leq \varepsilon \quad (57)$$

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

With regard to the relaxation parameter $\omega$, its function is to speed up the convergence rate. The selection of the optimum value of $\omega$ usually requires some trial-and-error simulation runs with varying $\omega$. The optimum $\omega$ is the one that produces the minimum number of iteration per time step. Generally, the more homogeneous the system, the closer the value of $\omega$ is to 1.0, and as the degree of anisotropy increases, the more $\omega$ approaches 2. And in practice, an overestimation of $\omega$ 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

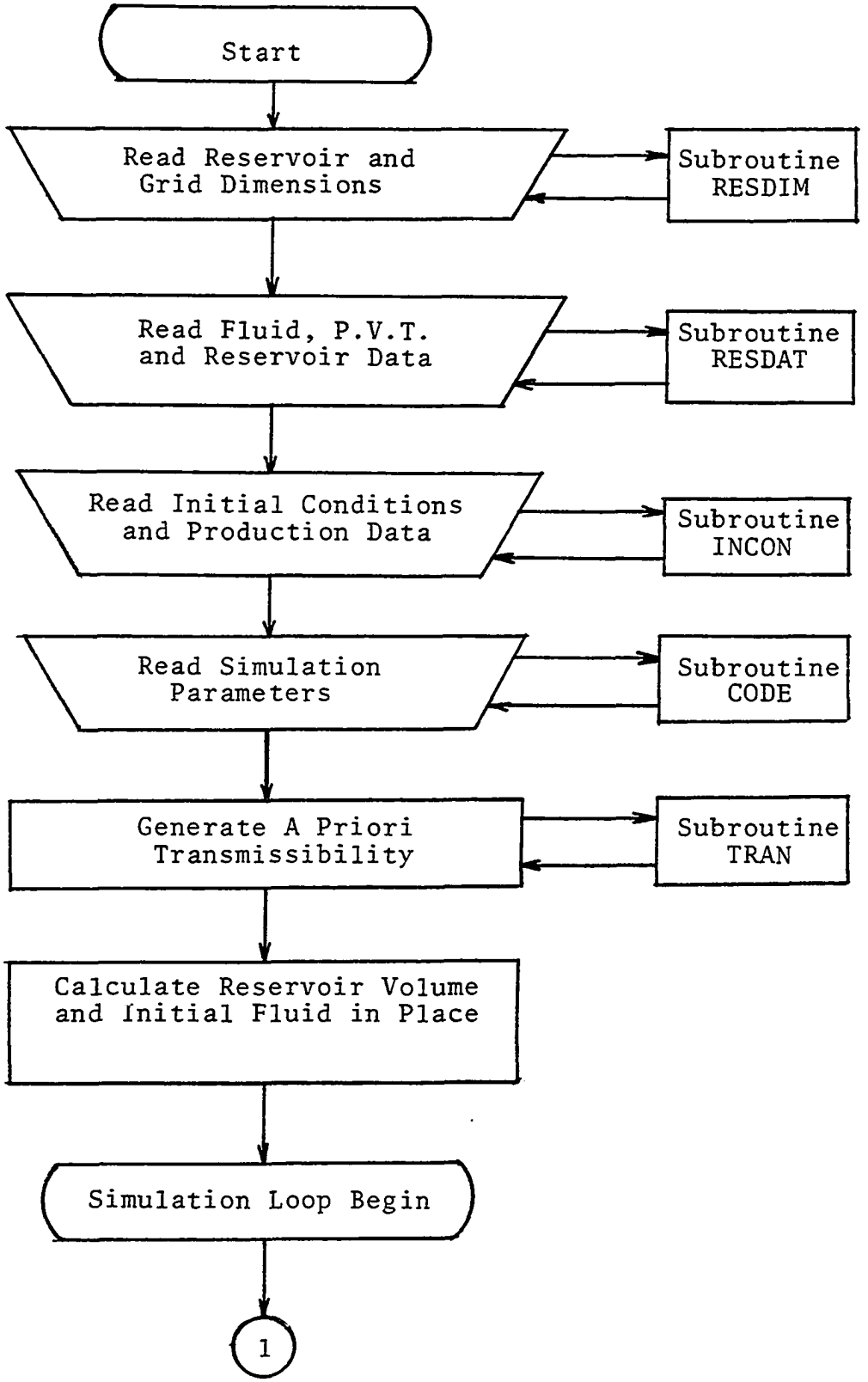



Figure 7. Flow chart of the simulation program.

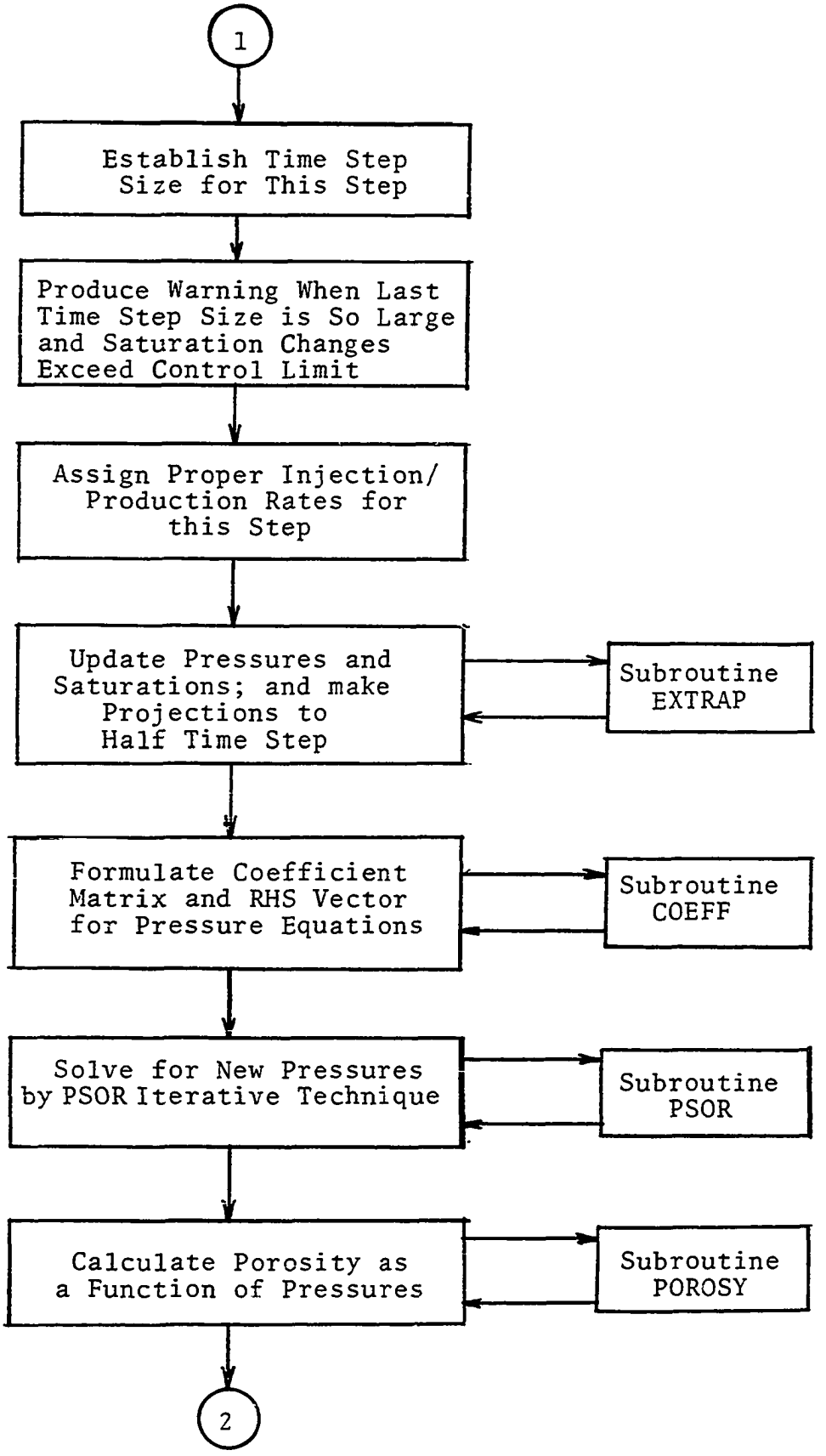

1
Establish Time Step Size for This Step
Produce Warning When Last Time Step Size is So Large and Saturation Changes Exceed Control Limit
Assign Proper Injection/ Production Rates for this Step
Update Pressures and Saturations; and make Projections to Half Time Step
Subroutine EXTRAP
Formulate Coefficient 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)

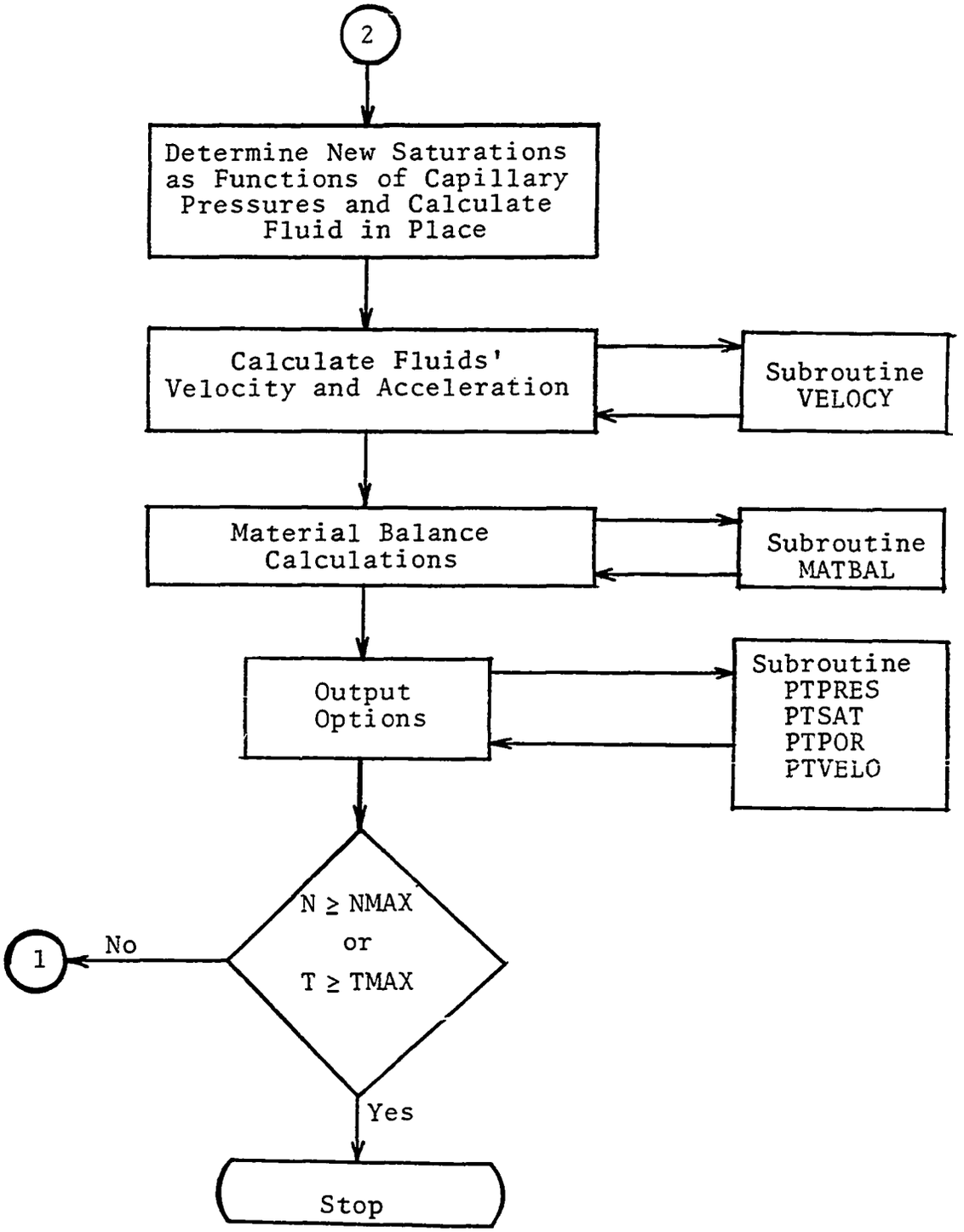

2
Determine New Saturations as Functions of Capillary Pressures and Calculate Fluid in Place
Calculate Fluids' Velocity and Acceleration
Subroutine VELOCY
Material Balance Calculations
Subroutine MATBAL
Output Options
Subroutine PTPRES PTSAT PTPOR PTVELO
N ≥ NMAX or T ≥ TMAX
No
1
Yes
Stop

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

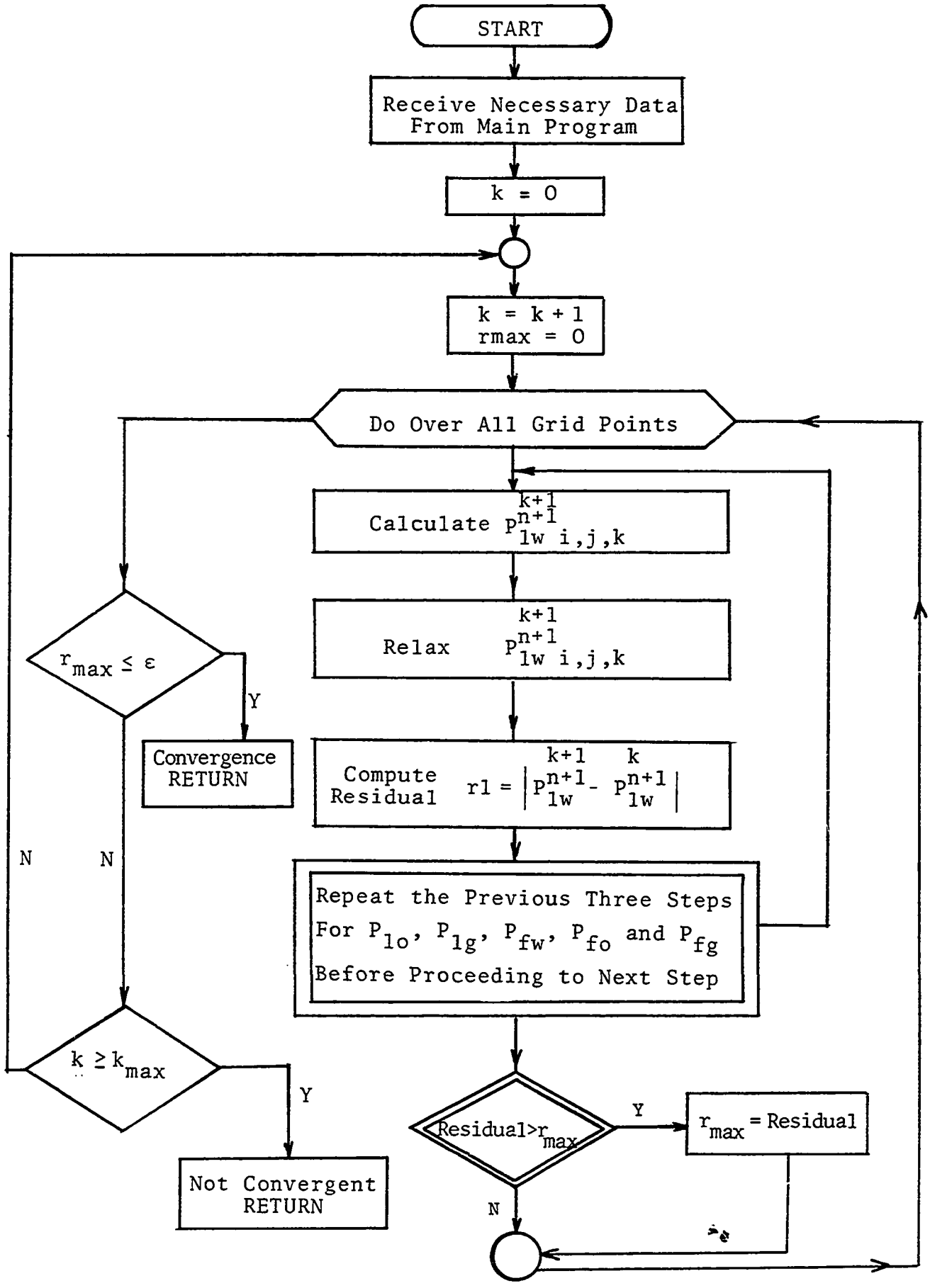



Figure 8. Flow Chart of PSOR subroutine.

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 ( $\sigma$ ) 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 | 0.29835 | 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 | 0.78540D-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 | 6214.8 | 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 | 6164.8 | 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-08 | -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 NUMBER 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 |

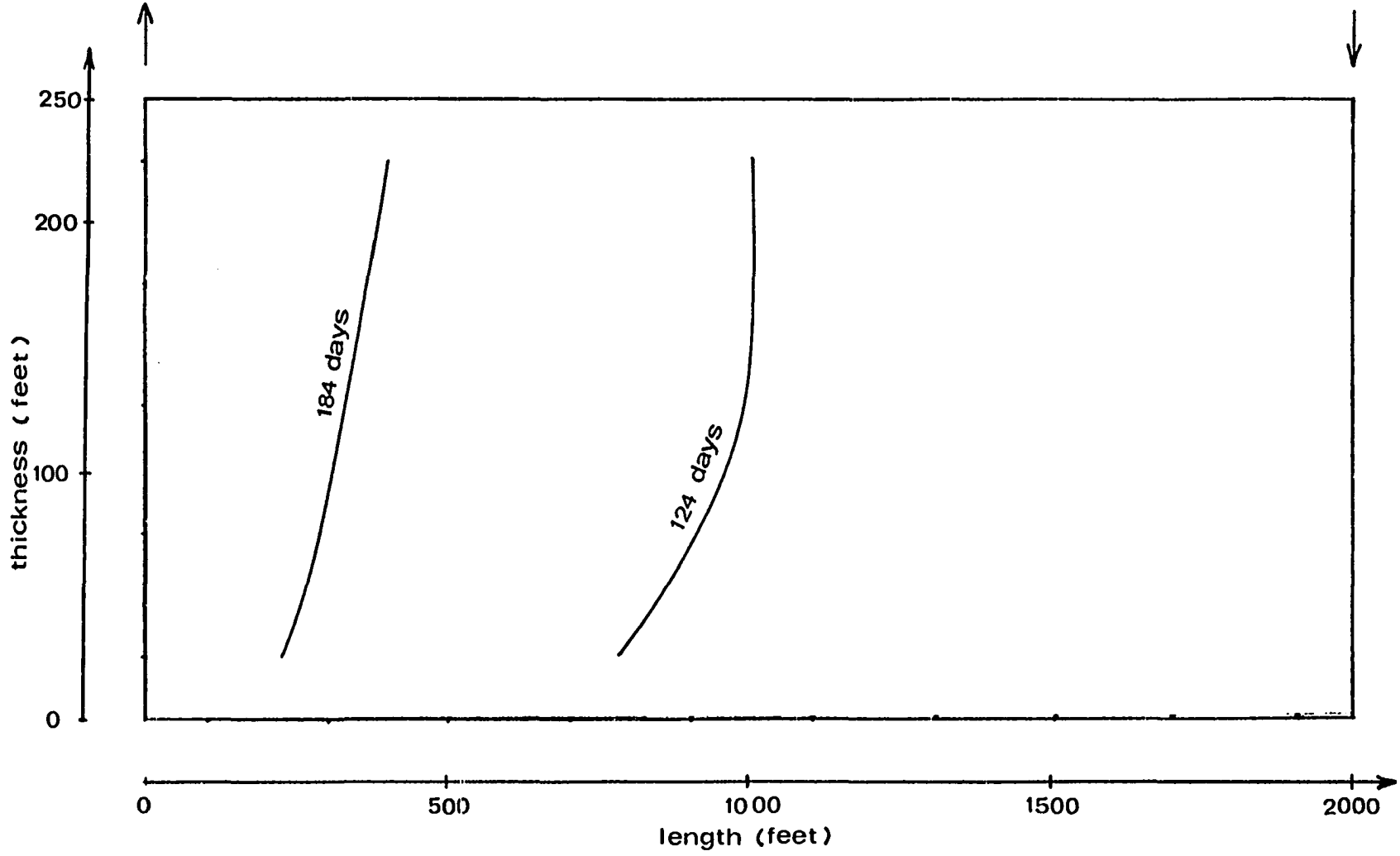



Figure 10. Fracture 50% Water Saturation Profile (center cross-section).

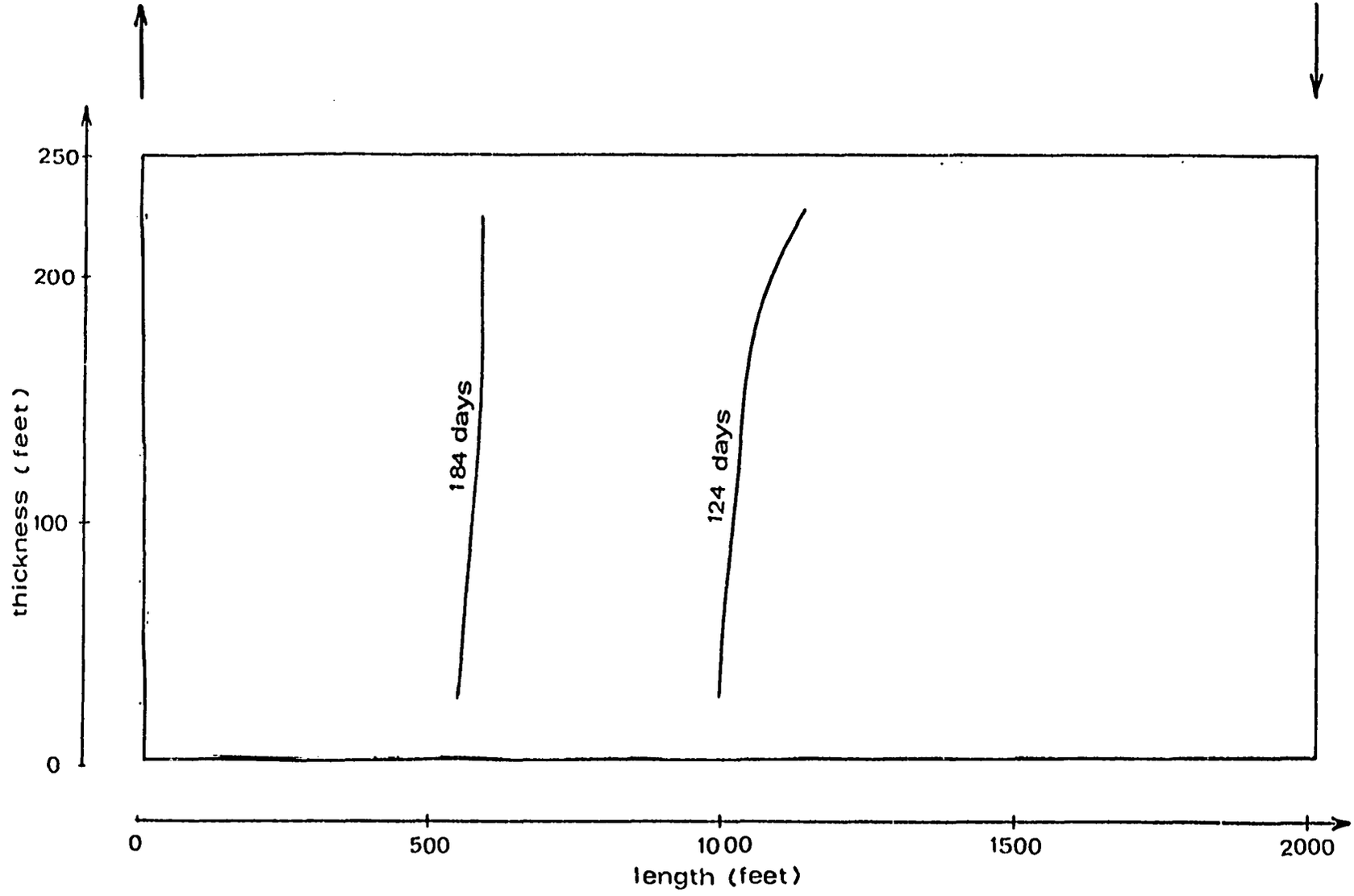



Figure 11. Matrix 50% Water Saturation Profile (Center cross-section)

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.

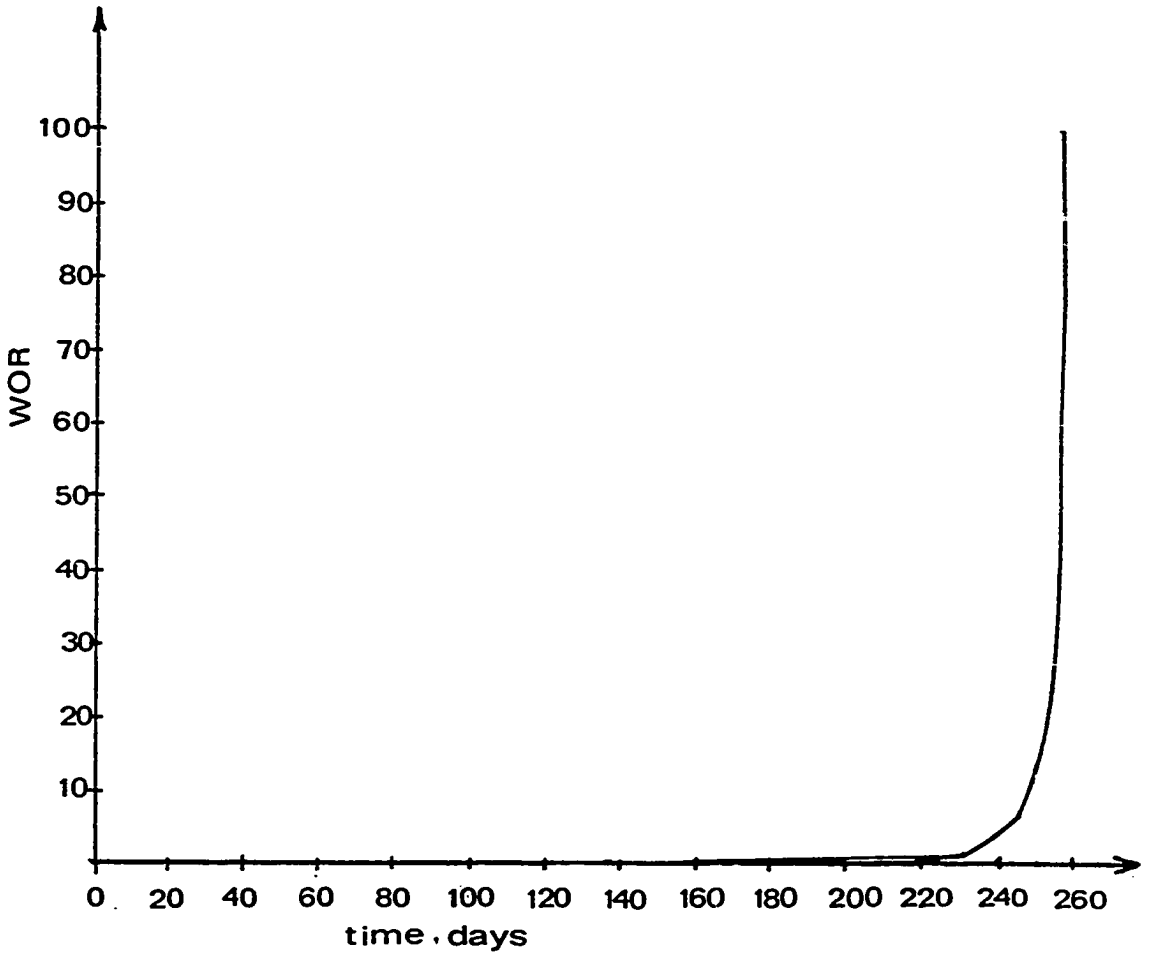
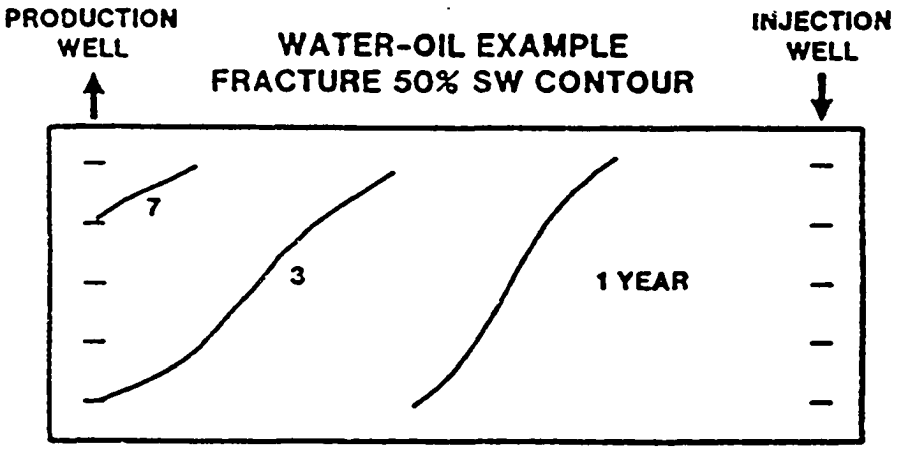



Figure 12 Water-Oil Ratio versus time.



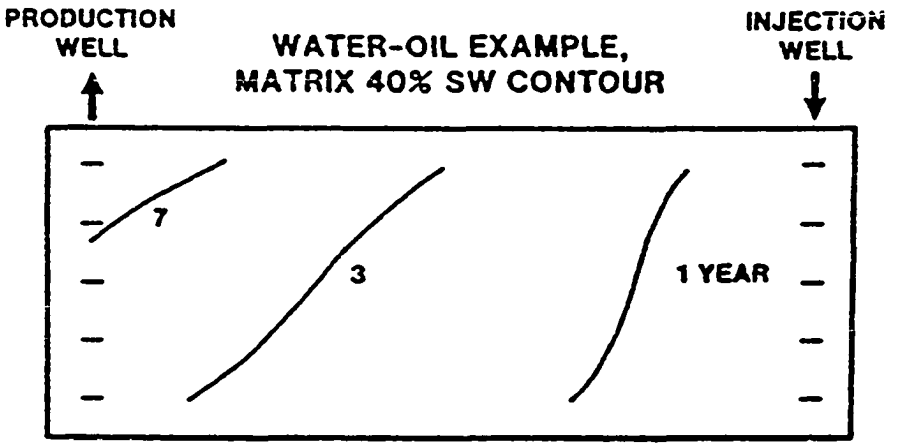




Figure 13. Fracture 50% Water Saturation Profile and Matrix 40% Water Saturation Profile (after Thomas et al. example).

### 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

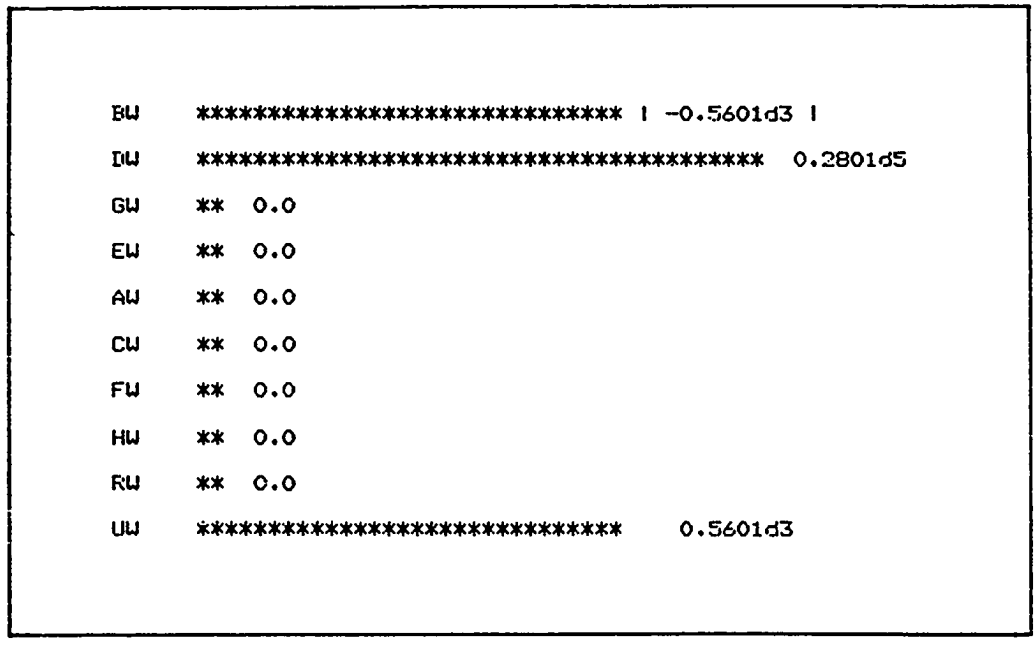
among variables and how much impact a certain variable has on the final solution.

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




$$P^{n+1}_{lw\ i,j,k} = \frac{1}{BW_{i,j,k}} \left( DW_{i,j,k} - GW_{i,j,k} P^{n+1}_{lw\ i,j,k-1} - EW_{i,j,k} P^{n+1}_{lw\ i,j-1,k} - AW_{i,j,k} P^{n+1}_{lw\ i-1,j,k} \right.$$

$$- CW_{i,j,k} P^{n+1}_{lw\ i+1,j,k} - FW_{i,j,k} P^{n+1}_{lw\ i,j+1,k} - HW_{i,j,k} P^{n+1}_{lw\ i,j,k+1}$$

$$\left. - RW_{i,j,k} P^{n+1}_{fw\ i,j,k} - UW_{i,j,k} P^{n+1}_{lo\ i,j,k} \right)$$

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
```

$$P^{n+1}_{lo\ i,j,k} = \frac{1}{BO_{i,j,k}} \Big( DO_{i,j,k} - VO_{i,j,k} P^{n+1}_{lw\ i,j,k} - GO_{i,j,k} P^{n+1}_{lo\ i,j,k-1} - EO_{i,j,k} P^{n+1}_{lo\ i,j-1,k}$$

$$- AO_{i,j,k} P^{n+1}_{lo\ i-1,j,k} - CO_{i,j,k} P^{n+1}_{lo\ i+1,j,k} - FO_{i,j,k} P^{n+1}_{lo\ i,j+1,k}$$

$$- HO_{i,j,k} P^{n+1}_{lo\ i,j,k+1} - UO_{i,j,k} P^{n+1}_{lg\ i,j,k} - RO_{i,j,k} P^{n+1}_{fo\ i,j,k} \Big)$$

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 |
| FGO1 | ** | 0.0 |
| FGO2 | ** | 0.0 |
| FGO3 | ** | 0.0 |
| FGO4 | ** | 0.0 |
| FGO5 | ** | 0.0 |
| FEO1 | ** | 0.0 |
| FEO2 | ** | 0.0 |
| FEO3 | ** | 0.0 |
| FAO1 | ********** | 0.1707d1 |
| FCO1 | ********** | 0.1707d1 |
| FFO1 | ** | 0.0 |
| FFO2 | ********** | 0.1707d1 |
| FFO3 | ** | 0.0 |
| FHO1 | ** | 0.0 |
| FHO2 | ** | 0.0 |
| FHO3 | ********** | 0.2731d2 |
| FHO4 | ** | 0.0 |
| FHO5 | ** | 0.0 |
| FUO | ********** | 0.7885d5 |

$$P^{n+1}_{fo\ i,j,k} = \frac{1}{FBO_{i,j,k}} \Big( DFO_{i,j,k} - FRO_{i,j,k} P^{n+1}_{lo\ i,j,k} - FVO_{i,j,k} P^{n+1}_{fw\ i,j,k}$$

$$- FGO1_{i,j,k} P^{n+1}_{fo\ i,j-1,k-1} - FGO2_{i,j,k} P^{n+1}_{fo\ i-1,j,k-1} - FGO3_{i,j,k} P^{n+1}_{fo\ i,j,k-1}$$

$$- FGO4_{i,j,k} P^{n+1}_{fo\ i+1,j,k-1} - FGO5_{i,j,k} P_{fo\ i,j+1,k-1} - FEO1_{i,j,k} P^{n+1}_{fo\ i-1,j-1,k}$$

$$- FEO2_{i,j,k} P^{n+1}_{fo\ i,j-1,k} - FEO3_{i,j,k} P_{fo\ i+1,j-1,k} - FAO1_{i,j,k} P^{n+1}_{fo\ i-1,j.k}$$

$$- FCO1_{i,j,k} P^{n+1}_{fo\ i+1,j,k} - FFO1_{i,j,k} P^{n+1}_{fo\ i-1,j+1,k} - FFO2_{i,j,k} P^{n+1}_{fo\ i,j+1,k}$$

$$- FFO3_{i,j,k} P^{n+1}_{fo\ i+1,j+1,k} - FHO1_{i,j,k} P^{n+1}_{fo\ i,j-1,k+1} - FHO2_{i,j,k} P^{n+1}_{fo\ i-1,j,k+1}$$

$$- FHO3_{i,j,k} P^{n+1}_{fo\ i,j,k+1} - FHO4_{i,j,k} P^{n+1}_{fo\ i+1,j,k+1} - FHO5_{i,j,k} P^{n+1}_{fo\ i,j+1,k+1}$$

$$- FUO_{i,j,k} P^{n+1}_{fg\ i,j,k} \Big)$$

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).

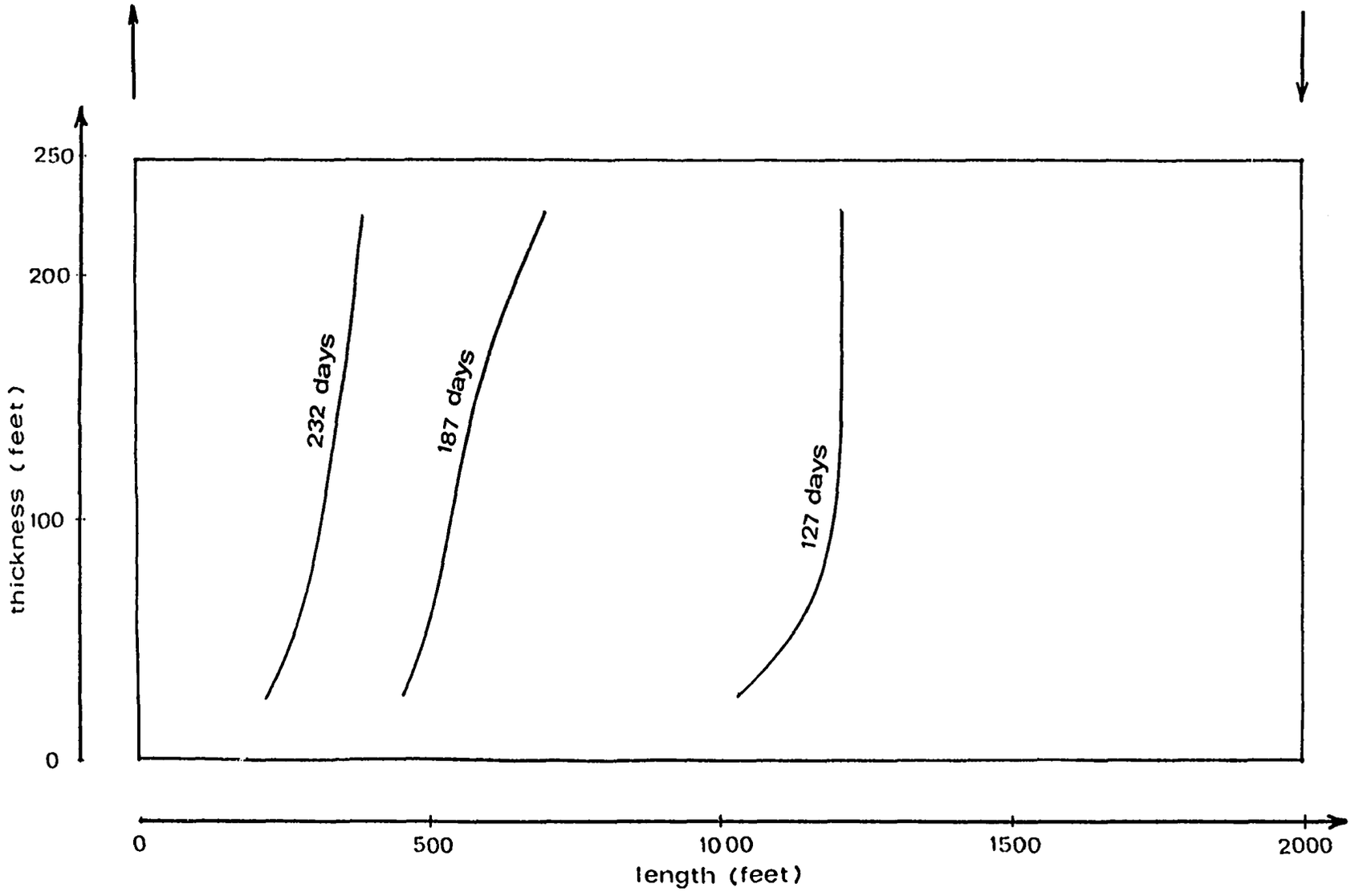



Figure 18. Fracture 50% Water Saturation Profile (Center cross-section; water injection rate = 4000 STB/day)

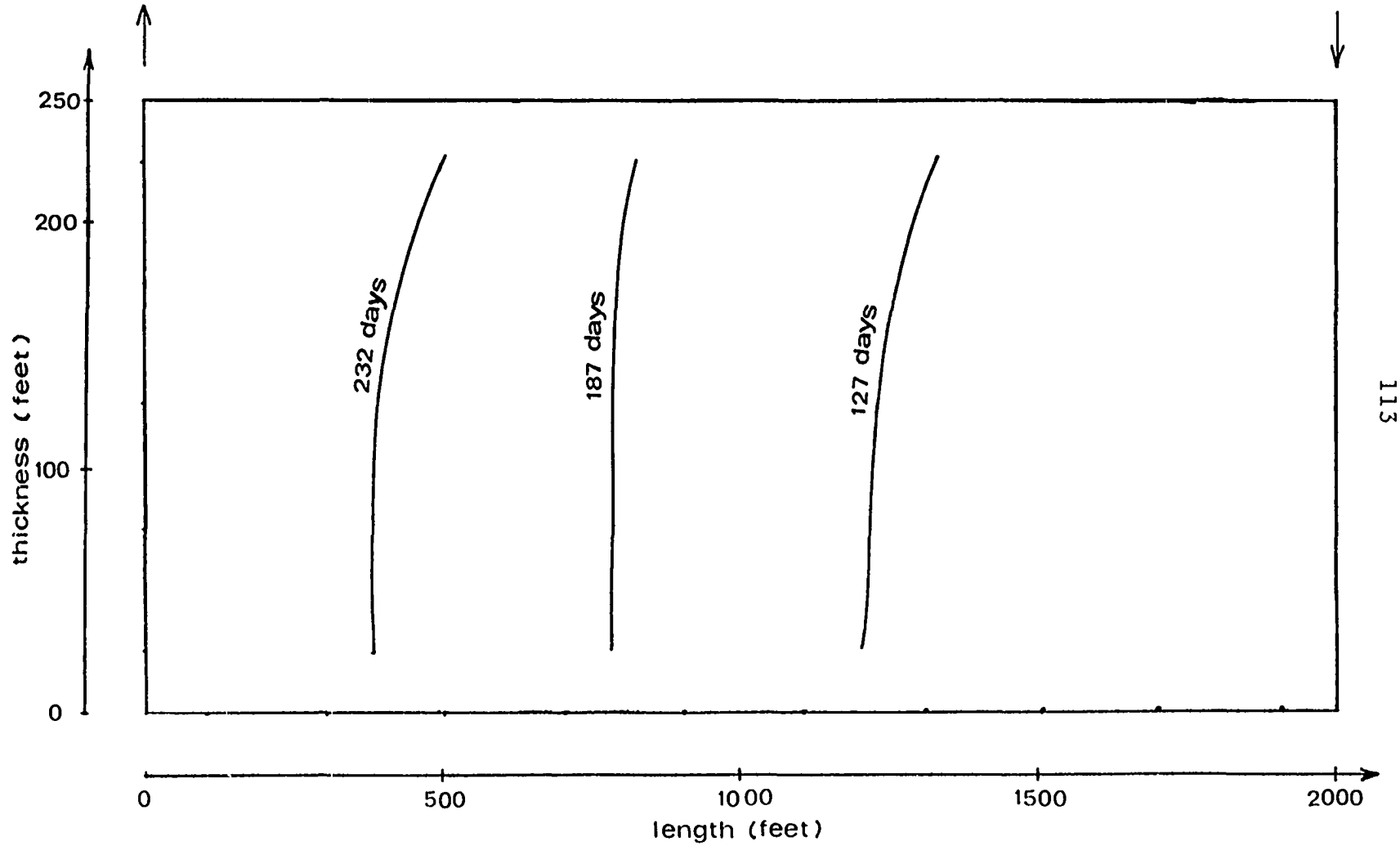



Figure 19. Matrix 50% Water Saturation Profile (center cross-section, water injection rate = 4000 STB/day).

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) |
| $f(\bar{r},\bar{\Omega})$ | = | Fracture distribution function |
| $g$ | = | Acceleration of gravity |
| $g_c$ | = | Unit conversion factor (32.174 lbm-ft/lbf $sec^2$) |
| $K$ | = | Absolute permeability (md) |
| $\bar{\bar{K}}_f$ | = | Fracture permeability tensor (md) |
| $k_{rj}$ | = | Relative permeability of phase j |
| $\ell$ or 1 | = | 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

$\alpha$ = Angle of the x-axis to the horizontal plane

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

$\Gamma$ = Fluid interaction term between the fracture and the rock matrix

$\gamma$ = Angle of the z-axis to the vertical plane

$\varepsilon$ = Tolerance limit

$\lambda$ = Fluid mobility

$\mu$ = Fluid viscosity (cp)

$\rho$ = Fluid density ($lbm/ft^3$)

$\Phi$ = Flow potential (psi)

$\phi$ = Porosity

$\omega$ = 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

$\vec{\ }$ = Vector

$\overline{\overline{\ }}$ = Tensor

$\nabla$ = Nabla differential operator

$\Delta$ = 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 | $5.434396 \times 10^5$ |
| $q_g$ | Gas Flow Rate | $m^3/S$ | $cm^3/S$ | SFC/day | $3.051187 \times 10^6$ |
| k | Permeability | $m^2$ | darcy | md | $1.01325 \times 10^{15}$ |
| $\mu$ | Viscosity | Pa.S | cp | cp | $1 \times 10^3$ |
| P | Pressure | Pa | atm | psi | $1.450377 \times 10^{-4}$ |
| x,y,z | Distances | m | cm | ft | 3.28084 |
| t | Time | S | S | day | $\frac{1}{86400}$ |
| c | Compressibility | $Pa^{-1}$ | $atm^{-1}$ | $psi^{-1}$ | $6.894757 \times 10^3$ |
| T | Temperature | K | K | R | 1.8 |
| $\rho$ | Density | $kg/m^3$ | $gm/cm^3$ | $lb_m/ft^3$ | $6.242797 \times 10^{-2}$ |
| 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 | $2.834646 \times 10^5$ |

* 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: $1 \text{ acre} = 43560 \text{ ft}^2$

Permeability: $1 \text{ darcy} = 1000 \text{ md}$

$= 9.86923 \times 10^{-13} \text{ m}^2$

$= 9.86923 \times 10^{-9} \text{ cm}^2$

Viscosity: $1 \text{ poise} = 1 \frac{\text{gm}}{\text{cm} \cdot \text{s}}$

$= 100 \text{ cp}$

$= 0.1 \text{ Pa} \cdot \text{S}$

$= 6.719689 \times 10^{-2} \frac{\text{lb}_m}{\text{ft} \cdot \text{S}}$

$= 2.088543 \times 10^{-3} \frac{\text{lb}_f \cdot \text{S}}{\text{ft}^2}$

Volume: $1 \text{ bbl} = 5.614583 \text{ ft}^3$

$= 42 \text{ gal}$

$1 \text{ gal} = 3785.43 \text{ cm}^3$

$= 231 \text{ in}^3$

$1 \text{ ft}^3 = 7.4805 \text{ gal}$

$= 28.317 \text{ liter}$

$1 \text{ m}^3 = 6.2898 \text{ bbl}$

Pressure: $1 \text{ atm} = 760 \text{ mm Hg. } (0°\text{c})$

$= 33.8995 \text{ ft water } (4°\text{c})$

$= 14.696 \text{ psi}$

$= 1.01325 \text{ bar}$

$= 1.01325 \times 10^5 \text{ Pa (pascal or N/m}^2\text{)}$

Mass: $1 \text{ lb}_m = 453.59243 \text{ gm.}$

# APPENDIX B

## COMPARISON OF EQUATIONS UNDER SI UNITS AND OILFIELD UNITS

| SI UNITS | OILFIELD UNITS |
|---|---|
| **Darcy's Law For Flow in Rock Matrix** | |
| $\vec{V}_{lj} = - \frac{K_l k_{rlj}}{\mu_{jl}} [\nabla P_{lj} - \rho_{jl} \frac{g}{g_c} \nabla D]$ | $\vec{V}_{lj} = -0.0063283 \frac{K_l k_{rlj}}{\mu_{jl}} [\nabla P_{lj} - \frac{1}{144} \rho_{jl} \nabla D]$ |
| **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** | |
| $\nabla \cdot [\frac{K_l k_{rlw}}{B_{wl} \mu_{wl}} \{\nabla P_{lw} - \frac{\rho_{ws}}{B_{wl}} \nabla D\}] - [\frac{K_l k_{rlw} \phi_f}{r_H^l \mu_{wl} B_{wl}} (P_{lw} - P_{fw})] + \frac{q_{ws}}{\Delta x \cdot \Delta y \cdot \Delta z} = \phi_l \frac{\partial}{\partial t} (S_{wl}/B_{wl})$ | $0.001127 \nabla \cdot [\frac{K_l k_{rlw}}{B_{wl} \mu_{wl}} \{\nabla P_{lw} - \frac{1}{144} \frac{\rho_{ws}}{B_{wl}} \nabla D\}] - 0.001127 [\frac{K_l k_{rlw} \phi_f}{r_H^l \mu_{wl} B_{wl}} (P_{lw} - P_{fw})] + \frac{q_{ws}}{\Delta x \cdot \Delta y \cdot \Delta z} = \frac{1}{5.615} \phi_l \frac{\partial}{\partial t} (S_{wl}/B_{wl})$ |

| SI UNITS | OILFIELD UNITS |
|---|---|

## Oil Equation for Flow in Rock Matrix

$$\nabla\cdot\left[\frac{K_l k_{rlo}}{B_{ol}\mu_o}\{\nabla P_{lo} - \rho_{ol}\frac{g}{g_c}\nabla D\}\right] - \left[\frac{K_l k_{rlo}\phi_f}{r_{Hl}\mu_{ol}B_{ol}}(P_{lo}-P_{fo})\right] + \frac{q_{os}}{\Delta x\cdot\Delta y\cdot\Delta z} = \phi_l\frac{\partial}{\partial t}(S_{ol}/B_{ol})$$

$$0.001127\,\nabla\cdot\left[\frac{K_l k_{rlo}}{B_{ol}\mu_o}\{\nabla P_{lo} - \frac{1}{144}\rho_{ol}\nabla D\}\right] - 0.001127\left[\frac{K_l k_{rlo}\Phi f}{r_{Hl}\mu_{ol}B_{ol}}(P_{lo} - P_{fo})\right] + \frac{q_{os}}{\Delta x\cdot\Delta y\cdot\Delta z} = \frac{1}{5.615}\phi_l\frac{\partial}{\partial t}(S_{ol}/B_{ol})$$

## Gas Equation for Flow in Rock Matrix

$$\nabla\cdot\left[\frac{K_l k_{rlg}}{B_{gl}\mu_{gl}}\{\nabla P_{lg} - \rho_{gl}\frac{g}{g_c}\nabla D\}\right] + \nabla\cdot\left[\frac{R_{sol}K_l k_{rlo}}{B_{ol}\mu_{ol}}\{\Delta P_{lo} - \rho_{ol}\frac{g}{g_c}\nabla D\}\right] - \left[\frac{K_l k_{rlg}\phi_f}{r_{Hl}\mu_{gl}B_{gl}}(P_{lg}-P_{fg})\right] - \left[\frac{K_l k_{rlo}\phi_f R_{sol}}{r_{Hl}\mu_{ol}B_{ol}}(P_{lo}-P_{fo})\right] + \frac{q_{gs}}{\Delta x\cdot\Delta y\cdot\Delta z} = \phi_l\frac{\partial}{\partial t}\left[\frac{S_{gl}}{B_{gl}} + \frac{R_{sol}S_{ol}}{B_{ol}}\right]$$

$$0.001127\nabla\cdot\left[\frac{K_l k_{rlg}}{B_{gl}\mu_{gl}}\{\nabla P_{lg} - \frac{1}{144}\rho_{gl}\nabla D\}\right] + 0.001127\,\nabla\cdot\left[\frac{R_{sol}K_l k_{rlo}}{B_{ol}\mu_{ol}}\{\Delta P_{lo} - \frac{1}{144}\rho_{ol}\nabla D\}\right] - 0.001127\left[\frac{K_l k_{rlg}\phi_f}{r_{Hl}\mu_{gl}B_{gl}}(P_{lg}-P_{fg})\right] - 0.001127\left[\frac{K_l k_{rlo}\phi_f R_{sol}}{r_{Hl}\mu_{ol}B_{ol}}(P_{lo}-P_{fo})\right] + \frac{q_{gs}}{\Delta x\cdot\Delta y\cdot\Delta z} = \frac{1}{5.615}\phi_l\frac{\partial}{\partial t}\left[\frac{S_{gl}}{B_{gl}} + \frac{R_{sol}S_{ol}}{B_{ol}}\right]$$

SI UNITS

OILFIELD UNITS

## Water Equation for Flow in Fracture

$$\nabla\cdot\left[\frac{k_{rwf}\bar{\bar{K}}_f}{B_{wf}\,\mu_{wf}}\cdot\left\{\nabla P_{fw}+\frac{\rho_{ws}}{B_{wf}}\frac{1}{g_c}\frac{\partial \bar{V}_{fw}}{\partial t}-\frac{\rho_{ws}}{B_{wf}}\frac{g}{g_c}\nabla D\right\}\right]+\left[\frac{K_l k_{rlw}\phi_f}{r_{Hl}\,B_{wl}\mu_{wl}}(P_{lw}-P_{fw})\right]+\frac{q_{wsf}}{\Delta x\cdot\Delta y\cdot\Delta z}=\phi_f\frac{\partial}{\partial t}\left[\frac{S_{wf}}{B_{wf}}\right]$$

$$0.001127\,\Delta\cdot\left[\frac{k_{rwf}\bar{\bar{K}}_f}{B_{wf}\mu_{wf}}\cdot\left\{\nabla P_{fw}+2.891738\times10^{-14}\frac{\rho_{ws}}{B_{wf}}\frac{\partial \bar{V}_{fw}}{\partial t}-\frac{1}{144}\frac{\rho_{ws}}{B_{wf}}\nabla D\right\}\right]+0.001127\left[\frac{K_l k_{rlw}\phi_f}{r_{Hl}\mu_{wl}B_{wl}}(P_{lw}-P_{fw})\right]+\frac{q_{wsf}}{\Delta x\cdot\Delta y\cdot\Delta z}=\frac{1}{5.615}\phi_f\frac{\partial}{\partial t}\left[\frac{S_{wf}}{B_{wf}}\right]$$

## Oil Equation for Flow in Fracture

$$\nabla\cdot\left[\frac{k_{rof}\bar{\bar{K}}_f}{B_{of}\mu_{of}}\cdot\left\{\nabla P_{fo}+\rho_{ol}\frac{g}{g_c}\frac{\partial \bar{V}_{fo}}{\partial t}-\rho_{ol}\frac{g}{g_c}\nabla D\right\}\right]+\left[\frac{K_l k_{rlo}\phi_f}{r_{Hl}\,B_{ol}\mu_{ol}}(P_{lo}-P_{fo})\right]+\frac{q_{osf}}{\Delta x\cdot\Delta y\cdot\Delta z}=\phi_f\frac{\partial}{\partial t}\left[\frac{S_{of}}{B_{of}}\right]$$

$$0.001127\nabla\cdot\left[\frac{k_{rof}\bar{\bar{K}}_f}{B_{of}\mu_{of}}\cdot\left\{\nabla P_{fo}+2.891738\times10^{-14}\rho_{ol}\frac{\partial \bar{V}_{fo}}{\partial t}-\frac{1}{144}\rho_{ol}\nabla D\right\}\right]+0.001127\left[\frac{K_l k_{rlo}\phi_f}{r_{Hl}\,B_{ol}\mu_{ol}}(P_{lo}-P_{fo})\right]+\frac{q_{osf}}{\Delta x\cdot\Delta y\cdot\Delta z}=\frac{1}{5.615}\phi_f\frac{\partial}{\partial t}\left[\frac{S_{of}}{B_{of}}\right]$$

## Gas Equation for Flow in Fracture

**SI UNITS**

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

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

$$+\left[\frac{K_1k_{rlg}\phi_f}{r_H{}^1\mu_{gl}B_{gl}}(P_{lg}-P_{fg})\right]$$

$$+\left[\frac{K_1k_{rlo}\phi_fR_{sol}}{r_H{}^1\mu_{ol}B_{ol}}(P_{lo}-P_{fo})\right]$$

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

**OILFIELD UNITS**

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

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

$$+0.001127\left[\frac{K_1k_{rlg}\phi_f}{r_H{}^1\mu_{gl}B_{gl}}(P_{lg}-P_{fg})\right]$$

$$+0.001127\left[\frac{K_1k_{rlo}\phi_fR_{sol}}{r_H{}^1\mu_{ol}B_{ol}}(P_{lo}-P_{fo})\right]$$

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

## APPENDIX C

## EXPRESSIONS FOR THE COEFFICIENTS

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

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

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

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

$$\begin{aligned} BW_{i,j,k} = -V_B \Bigg[ & \frac{1}{\Delta z^2} \left( \frac{K_l k_{rlw}}{B_{wl}\mu_{wl}} \right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}} + \frac{1}{\Delta z^2} \left( \frac{K_l k_{rlw}}{B_{wl}\mu_{wl}} \right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} \\ & + \frac{1}{\Delta y^2} \left( \frac{K_l k_{rlw}}{B_{wl}\mu_{wl}} \right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k} + \frac{1}{\Delta y^2} \left( \frac{K_l k_{rlw}}{B_{wl}\mu_{wl}} \right)_{i,j+\frac{1}{2},k} \\ & + \frac{1}{\Delta x^2} \left( \frac{K_l k_{rlw}}{B_{wl}\mu_{wl}} \right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k} + \frac{1}{\Delta x^2} \left( \frac{K_l k_{rlw}}{B_{wl}\mu_{wl}} \right)_{i+\frac{1}{2},j,k} \\ & + \frac{\phi^n_{f_{i,j,k}}}{r_{H^l}} \left( \frac{K_l k_{rlw}}{B_{wl}\mu_{wl}} \right)^{n+\frac{1}{2}}_{i,j,k} - \frac{(\phi_l)^n_{i,j,k}}{\Delta t} \frac{1}{B^{n+\frac{1}{2}}_{wl_{i,j,k}}} (S'_{wl})^n_{i,j,k} \\ & + \frac{\phi^n_{l_{i,j,k}}}{\Delta t} S^{n+\frac{1}{2}}_{wl_{i,j,k}} \left( \frac{1}{B_{wl}} \right)'^{n+\frac{1}{2}}_{i,j,k} \Bigg]^* \end{aligned}$$

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

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

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

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

$$RW_{i,j,k} = \frac{V_B (\phi_f)^n_{i,j,k}}{r_{H1}} \left( \frac{K_1 k_{rlw}}{B_{wl}\mu_{wl}} \right)^{n+\frac{1}{2}}_{i,j,k}$$

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

$$DW_{i,j,k} = -(q_{wsl})_{i,j,k} - \frac{(\phi_1)^n_{i,j,k} V_B}{\Delta t} \left[ \frac{(S_{wl})^n_{i,j,k}}{B^{n+\frac{1}{2}}_{wl_{i,j,k}}} \left( P^n_{lo} - P^n_{lw_{i,j,k}} \right) + S^{n+\frac{1}{2}}_{wl_{i,j,k}} \left( \frac{1}{B_{wl}} \right)'^{n+\frac{1}{2}}_{i,j,k} P^n_{lw_{i,j,k}} \right]^*$$

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

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

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

*This term is zero when water is assumed incompressible.

Oil Equation in Matrix Rock

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Gas Equation in Matrix Rock

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$DG_{i,j,k} = -(q_{Gsl})_{i,j,k} - \frac{V_B(\phi_1)^n_{i,j,k}}{\Delta t} \left[ \left\{ \frac{(S'_{gl})^n_{i,j,k}}{B^{n+\frac{1}{2}}_{gl_{i,j,k}}} \right.\right.$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\begin{aligned} FBW_{i,j,k} = -V_B\Bigg[&\frac{1}{\Delta x^2}\left(\frac{K_{xx}k_{rwf}}{B_{wf}\mu_{wf}}\right)^{n+\frac{1}{2}}_{i+\frac{1}{2},j,k} + \frac{1}{\Delta x^2}\left(\frac{K_{xx}k_{rwf}}{B_{wf}\mu_{wf}}\right)^{n+\frac{1}{2}}_{i-\frac{1}{2},j,k} \\ &+ \frac{1}{\Delta y^2}\left(\frac{K_{yy}k_{rwf}}{B_{wf}\mu_{wf}}\right)^{n+\frac{1}{2}}_{i,j+\frac{1}{2},k} + \frac{1}{\Delta y^2}\left(\frac{K_{yy}k_{rwf}}{B_{wf}\mu_{wf}}\right)^{n+\frac{1}{2}}_{i,j-\frac{1}{2},k} \\ &+ \frac{1}{\Delta z^2}\left(\frac{K_{zz}k_{rwf}}{B_{wf}\mu_{wf}}\right)^{n+\frac{1}{2}}_{i,j,k+\frac{1}{2}} + \frac{1}{\Delta z^2}\left(\frac{K_{zz}k_{rwf}}{B_{wf}\mu_{wf}}\right)^{n+\frac{1}{2}}_{i,j,k-\frac{1}{2}} \\ &+ \frac{(\phi_f)^n_{i,j,k}}{r_{H^1}}\left(\frac{K_1k_{rlw}}{B_{wl}\mu_{wl}}\right)^{n+\frac{1}{2}}_{i,j,k} - \frac{(\phi_f)^n_{i,j,k}}{\Delta t\, B^{n+\frac{1}{2}}_{wf_{i,j,k}}}(S'_{wf})^n_{i,j,k} \\ &+ \frac{(\phi_f)^n_{i,j,k}}{\Delta t} S^{n+\frac{1}{2}}_{wf\,i,j,k}\left(\frac{1}{B_{wf}}\right)'^{n+\frac{1}{2}}_{i,j,k}\Bigg]^* \end{aligned}$$

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

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

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

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*This term is zero when water is incompressible.

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

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

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

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

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

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

$$FRW_{i,j,k} = \frac{V_B(\phi_f)^n_{i,j,k}}{r_{H1}}\left(\frac{K_1k_{r1w}}{B_{w1}\mu_{w1}}\right)^{n+\frac{1}{2}}_{i,j,k}$$

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

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

$$- P^n_{fw\ i,j,k} - \frac{V_B(\phi_f)^n_{i,j,k}}{\Delta t}S^{n+\frac{1}{2}}_{wf\ i,j,k}\left(\frac{1}{B_{wf}}\right)'^{n+\frac{1}{2}}_{i,j,k}P^n_{fw_{i,j,k}}\ *$$

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

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

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*This term is zero when water is assumed incompressible.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Oil Equation in Fracture

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Gas Equation in fracture

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\left.\left. - R^{n+\frac{1}{2}}_{sof_{i,j,k}}\frac{1}{B^{n+\frac{1}{2}}_{of_{i,j,k}}}(S'_{gf})^n_{i,j,k}\right\} + \frac{(\phi_f)^n_{i,j,k}}{r_H{}^1}\left(\frac{K_1 k_{rlg}}{B_{gl}\mu_{gl}}\right)^{n+\frac{1}{2}}_{i,j,k}\right]$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\left. + \frac{(\phi_f)^n_{i,j,k}}{r_{H1}}\left(\frac{K_1 k_{rlo} R_{sol}}{B_{ol}\mu_{ol}}\right)^{n+\frac{1}{2}}_{i,j,k}\right]$$

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

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

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

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

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

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

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

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

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

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

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

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

$$DFG_{i,j,k} = -(q_{Gsf}) - \frac{(\phi_f)^n_{i,j,k} V_B}{\Delta t} \left[ \left\{ \frac{(S'_{gf})^n_{i,j,k}}{B^{n+\frac{1}{2}}_{gf\ i,j,k}} \right.\right.$$

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

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

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

$$P^n_{fo\ i,j,k} + \frac{R^{n+\frac{1}{2}}_{sof\ i,j,k}}{B^{n+\frac{1}{2}}_{of\ i,j,k}} (S'_{wf})^n_{i,j,k} P^n_{fw\ i,j,k} \Big]$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

# 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 ≠ 0)

19. Fracture permeability tensor and grid point locations (if NUMKF ≠ 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    581.5        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       -0.0000605    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       0.43545      0.226
 5614.7        1.8649       -0.0000580    1557.6       0.50122      0.206
 7014.7        2.1978       -0.0000579    2259.0       0.50111      0.109
WATER PVT TABLE
 14.7          0.35
 7014.7        0.35
GAS PVT TABLES
 14.7          0.17809      0.29835      0.01205
 1714.7        0.0019485    0.31458      0.0163
 2114.7        0.0015567    0.30453      0.0173
 2614.7        0.0012671    0.23563      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 | 0.380 | 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 | 0.180 | 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 | 0.180 | 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)                                        00000010
0002                  INTEGER K                                                         00000020
                C                                                                       00000021
                C                                                                       00000030
                C  ***********************************************************************00000040
                C  *                                                                 *  00000050
                C  *  THREE-DIMENSIONAL, THREE-PHASE, BLACK OIL RESERVOIR SIMULATOR *  00000060
                C  *  FOR FLUID FLOW IN NATURALLY FRACTURED RESERVOIR               *  00000070
                C  *                                                                 *  00000080
                C  *        AUTHOR:  KURUJIT NAKORNTHAP                              *  00000090
                C  *        ADVISOR: DR. RONALD D. EVANS                             *  00000100
                C  *                                                                 *  00000110
                C  *        SCHOOL OF PETROLEUM AND GEOLOGICAL ENGINELRING           *  00000120
                C  *        UNIVERSITY OF OKLAHOMA                                   *  00000130
                C  *        NOVEMBER 1982                                            *  00000140
                C  *                                                                 *  00000150
                C  ***********************************************************************00000160
                C                                                                       00000170
                C                                                                       00000180
0003                   COMMON /PRESS/ PO(10,2,5),PW(10,2,5),PG(10,2,5),PFO(10,2,5),     00000190
                      & PFW(10,2,5),PFG(10,2,5),PON(10,2,5),PWN(10,2,5),PGN(10,2,5),    00000200
                      & PFON(10,2,5),PFWN(10,2,5),PFGN(10,2,5)                          00000210
0004                   COMMON /SAT/ SO(10,2,5),SW(10,2,5),SG(10,2,5),SOF(10,2,5),       00000220
                      & SWF(10,2,5),SGF(10,2,5),SON(10,2,5),SWN(10,2,5),SGN(10,2,5),    00000230
                      & SOFN(10,2,5),SWFN(10,2,5),SGFN(10,2,5)                          00000240
0005                   COMMON /PROD/ QO(10,2,5),QW(10,2,5),QG(10,2,5),QOF(10,2,5),      00000250
                      & QWF(10,2,5),QGF(10,2,5)                                         00000260
0006                   COMMON /VELU/ VOX(10,2,5),VOY(10,2,5),VOZ(10,2,5),VWX(10,2,5),   00000270
                      &VWY(10,2,5),VWZ(10,2,5),VGX(10,2,5),VGY(10,2,5),VGZ(10,2,5)      00000280
0007                   COMMON /ACCL/ DVOXDT(10,2,5),DVOYDT(10,2,5),DVOZDT(10,2,5),      00000290
                      & DVWXDT(10,2,5),DVWYDT(10,2,5),DVWZDT(10,2,5),DVGXDT(10,2,5),    00000300
                      & DVGYDT(10,2,5),DVGZDT(10,2,5)                                   00000310
0008                   COMMON /CMTX1/ GW(10,2,5),EW(10,2,5),AW(10,2,5),BW(10,2,5),      00000320
                      &CW(10,2,5),FW(10,2,5),HW(10,2,5),RW(10,2,5),UWM(10,2,5),DW(10,2,5)00000330
0009                   COMMON /CMTX2/ VO(10,2,5),GO(10,2,5),EO(10,2,5),AO(10,2,5),      00000340
                      & BO(10,2,5),CO(10,2,5),FO(10,2,5),HO(10,2,5),UOM(10,2,5),        00000350
                      & RO(10,2,5),DO(10,2,5)                                           00000360
0010                   COMMON /CMTX3/ VG(10,2,5),GGO(10,2,5),EGO(10,2,5),AGO(10,2,5),   00000370
                      & BGO(10,2,5),CGO(10,2,5),FGO(10,2,5),HGO(10,2,5),GG(10,2,5),     00000380
                      & EG(10,2,5),AG(10,2,5),BG(10,2,5),CG(10,2,5),FG(10,2,5),         00000390
                      & HG(10,2,5),RGO(10,2,5),RG(10,2,5),DG(10,2,5)                    00000400
0011                   COMMON /CMTX4/ FRW(10,2,5),FGW1(10,2,5),FGW2(10,2,5),FGW3(10,2,5) 00000410
                      &,FGW4(10,2,5),FGW5(10,2,5),FEW1(10,2,5),FEW2(10,2,5),FEW3(10,2,5) 00000420
                      &,FAW1(10,2,5),FBW(10,2,5),FCW1(10,2,5),FFW1(10,2,5),FFW2(10,2,5)  00000430
                      &,FFW3(10,2,5),FHW1(10,2,5),FHW2(10,2,5),FHW3(10,2,5),FHW4(10,2,5) 00000440
                      &,FHW5(10,2,5),FOW(10,2,5),DFW(10,2,5)                            00000450
0012                   COMMON /CMTX5/ FRO(10,2,5),FVO(10,2,5),FGO1(10,2,5),FGO2(10,2,5), 00000460
                      & FGO3(10,2,5),FGO4(10,2,5),FGO5(10,2,5),FEO1(10,2,5),FEO2(10,2,5) 00000470
                      &,FEO3(10,2,5),FAO1(10,2,5),FBO(10,2,5),FCO1(10,2,5),FFO1(10,2,5), 00000480
                      & FFO2(10,2,5),FFO3(10,2,5),FHO1(10,2,5),FHO2(10,2,5),FHO3(10,2,5) 00000490
                      &,FHO4(10,2,5),FHO5(10,2,5),FOO(10,2,5),DFO(10,2,5)               00000500
0013                   COMMON /CMTX6/ FRGO(10,2,5),FRG(10,2,5),FVG(10,2,5),FGR1(10,2,5), 00000510
                      & FGR2(10,2,5),FGR3(10,2,5),FGR4(10,2,5),FGR5(10,2,5),FER1(10,2,5) 00000520
                      &,FER2(10,2,5),FER3(10,2,5),FAR1(10,2,5),FBR(10,2,5),FCR1(10,2,5), 00000530
                      & FFR1(10,2,5),FFR2(10,2,5),FFR3(10,2,5),FHR1(10,2,5),FHR2(10,2,5) 00000540
                      &,FHR3(10,2,5),FHR4(10,2,5),FHR5(10,2,5),FGG1(10,2,5),FGG2(10,2,5) 00000550
                      &,FGG3(10,2,5),FGG4(10,2,5),FGG5(10,2,5),FEG1(10,2,5),FEG2(10,2,5) 00000560
                      &,FEG3(10,2,5),FAG1(10,2,5),FBG(10,2,5),FCG1(10,2,5),FFG1(10,2,5), 00000570
```

```
     &  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 /SLT2/ 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/ MPUT,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/  PUT(15),BUT(15),DIBUT(15),                         00000950
     &  RSUT(15),DRSUT(15),UUT(15),PWT(15),UWT(15),PGT(15),BGT(15),       00000960
     &  DIBGT(15),UGT(15),SGT(15),KRGT(15),KROGT(15),PCGUT(15),DSGT(15),  00000970
     &  SWT(15),KRWT(15),KROWT(15),PCUWT(15),DSWT(15),FSGT(15),FKRGT(15), 00000980
     &  FKROGT(15),FPCGUT(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 MDEO,MDEW,MDEG                                               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
```

```
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,PBP,PMIN,WORMAX,
             & GORMAX,LPOR,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(MPOT,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(MPOT,PO(I,J,K),RSO,POT,RSOT)
0056          CALL LINTP(MPOT,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          ETIME=0.0
0068          STIME=0.0
0069          LPN=LPT
0070          LSN=LST
0071          LPORN=LPOR
0072          LVELON=LVELO
```

```
0072          LVELON=LVELO
0073          NITER=0
        C
0074          DO 9000 N=1,NMAX
0075          IF(N.GT.1) DELTN=DELT
0076          IF(N.GT.1) ETIME=ETIME+DELT
0077          IF(ID.EQ.0) READ(5,2009,END=777) DELT
0078      778 STIME=STIME+DELT
0079          IF(ETIME.GE.TMAX) GO TO 9999
0080          IF(NITER.GE.25) DELT=DELT*0.5
0081          IF(NITER.LE.5.AND.N.GT.30)  DELT=DELT*2.0
0082          IF(DELT.LE.0.001) PRINT 2333
0083          IF(DELT.LE.0.001) STOP
        C
        C   CHECK MAXIMUM SATURATION CHANGE FOR LAST TIME STEP
        C
0084          IF(N.EQ.1) GO TO 302
0085          DSMAX=0.0
0086          DSFMAX=0.0
0087          DO 800 K=1,NZ
0088          DO 800 J=1,NY
0089          DO 800 I=1,NX
0090          DSO=SO(I,J,K)-SON(I,J,K)
0091          DSW=SW(I,J,K)-SWN(I,J,K)
0092          DSG=SG(I,J,K)-SGN(I,J,K)
0093          DSOF=SOF(I,J,K)-SOFN(I,J,K)
0094          DSWF=SWF(I,J,K)-SWFN(I,J,K)
0095          DSGF=SGF(I,J,K)-SGFN(I,J,K)
0096          IF(DABS(DSO).GT.DSMAX) DSMAX=DABS(DSO)
0097          IF(DABS(DSW).GT.DSMAX) DSMAX=DABS(DSW)
0098          IF(DABS(DSG).GT.DSMAX) DSMAX=DABS(DSG)
0099          IF(DABS(DSOF).GT.DSFMAX) DSFMAX=DABS(DSOF)
0100          IF(DABS(DSWF).GT.DSFMAX) DSFMAX=DABS(DSWF)
0101          IF(DABS(DSGF).GT.DSFMAX) DSFMAX=DABS(DSGF)
0102      800 CONTINUE
0103          IF(DSMAX.GT.0.30) PRINT 2002
0104          IF(DSFMAX.GT.0.30) PRINT 2003
0105      302 CONTINUE
        C
        C   DETERMINE FLOW RATES FOR ALL NODES
        C
0106          DO 807 K=1,NZ
0107          DO 807 J=1,NY
0108          DO 807 I=1,NX
0109          QO(I,J,K)=0.0
0110          QW(I,J,K)=0.0
0111          QG(I,J,K)=0.0
0112          QOF(I,J,K)=0.0
0113          QWF(I,J,K)=0.0
0114          QGF(I,J,K)=0.0
0115      807 CONTINUE
0116          IF(NVQN.EQ.0) GO TO 315
0117          DO 802 I=1,NVQN
0118          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,BOO,POT,BOT)                                00002630
0134                  CALL LINTP(MPGT,PPG,BOG,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                  UMOBF=AKROF/UOF                                                  00003070
0173                  TMOBF=UMOBW+WMOBF+GMOBF                                          00003080
0174                  QOF(QN1(I),QN2(I),QN3(I))=QVTF(I)*GMOBF/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)-PFU(I,J,K)                                       00004140
0206                IF(PCWU.LT.PCUWT(1)) PCWU=PCUWT(1)                                00004181
0207                IF(PCWUF.LT.FPCUWT(1)) PCWUF=FPCUWT(1)                            00004182
0208                IF(PCGU.LT.PCGUT(1)) PCGU=PCGUT(1)                                00004190
0209                IF(PCGUF.LT.FPCGUT(1)) PCGUF=FPCGUT(1)                            00004200
0210                CALL LINTP(MSWT,PCWU,SW(I,J,K),PCUWT,RSWT)                        00004210
0211                CALL LINTP(MFSWT,PCWUF,SWF(I,J,K),FPCUWT,RFSWT)                   00004220
0212                CALL LINTP(MSGT,PCGU,SG(I,J,K),PCGUT,SGT)                         00004230
0213                CALL LINTP(MFSGT,PCGUF,SGF(I,J,K),FPCGUT,SGT)                     00004240
0214                IF(PU(I,J,K).GT.PBP) SG(I,J,K)=0.0                                00004250
0215                IF(PFU(I,J,K).GT.PHP) SGF(I,J,K)=0.0                              00004260
0216                SU(I,J,K)=1.0-SW(I,J,K)-SG(I,J,K)                                 00004270
0217                SUF(I,J,K)=1.0-SWF(I,J,K)-SGF(I,J,K)                              00004280
0218                CALL LINTP(MPOT,PU(I,J,K),BBU,POT,BUT)                            00004290
0219                CALL LINTP(MPOT,PFU(I,J,K),BFU,POT,BUT)                           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,PU(I,J,K),RSU,POT,RSUT)                           00004330
0223                CALL LINTP(MPOT,PFU(I,J,K),RSF,POT,RSUT)                          00004340
0224                SCFU=SCFU+VPM(I,J,K)*SU(I,J,K)/BBU+VPF(I,J,K)*SUF(I,J,K)/BFU      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)*SU(I,J,K)*RSU/(BBU*5.615) +                00004390
                   &           VPF(I,J,K)*SUF(I,J,K)*RSF/(BFU*5.615)                 00004400
0228              303 CONTINUE                                                        00004410
0229                STBU=SCFU/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 BALANCE ERRORS 00004535
                  C   FOR THE PREVIOUS TIME STEP                                   00004536
                  C                                                                 00004537
0233                CALL MATBAL(NX,NY,NZ,STBU,STBUN,STBW,STBWN,SCFT,SCFTN,MBED,MBEW, 00004538
                   & MBEG,WUR,GUR,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(WUR.GT.WURMAX) GO TO 9005                                    00004542
0236                IF(GUR.GT.GURMAX) 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 PTPRLS(NX,NY,NZ,N,PAVG,MBEU,MBEW,MBEG,CUMOIL,CUMWAT,CUMWI, 00004548
                   & CUMGAS,CUMGI,OILP,WATP,WATI,GASP,GASI,WUR,GUR,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.LPURN) GO TO 372                           00004552
0242                CALL PTPUR(NX,NY,NZ,N,STIME)                                    00004553
0243              372 IF(N.NE.0.AND.N.NE.LVELUN) GO TO 373                          00004554
0244                CALL PTVELU(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.LPURN) LPURN=LPURN+LPUR                                 00004558
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0248                IF(N.EQ.LVELON) LVELON=LVELON+LVELO                                 00004559
                  C                                                                     00004560
                  C                                                                     00004561
0249               9000 CONTINUE                                                        00004562
0250                    GO TO 9999                                                      00004563
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
                     &LXCEED 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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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/ FRG0(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),FRG1(10,2,5),FHG2(10,2,5),FHG3(10,2,5)                      00005120
     &,FHG4(10,2,5),FHG5(10,2,5),UFG(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/,CON3/2.89170-14/,CON4/0.00632883/         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/,FRG0/100*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
```

```
0001                  SUBROUTINE CODE(NMAX,TMAX,TOL,LPT,LST,MITER,OMEGA,PBP,PMIN,
                     & WORMAX,GORMAX,LPOR,LVELO)
                      C
                      C   SUBROUTINE TO SIMULATION PARAMETERS
                      C
0002                        IMPLICIT REAL*8(A-H,O-Z)
0003                        INTEGER*2 TITLE(40)
0004                        READ(5,100) TITLE
0005                  100 FORMAT(40A2)
                      C
                      C  RUN TIME PARAMLTERS
                      C
0006                        READ(5,101) NMAX,TMAX,WORMAX,GORMAX,PBP,PMIN
0007                  101 FORMAT(I5,5F10.0)
0008                        PRINT 102,NMAX,TMAX,WORMAX,GORMAX,PBP,PMIN
0009                  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
0010                        READ(5,103) MITER,LPT,LST,LPOR,LVELO,OMEGA,TOL
0011                  103 FORMAT(5I5,2F10.0)
0012                        PRINT 104,MITER,LPT,LST,LPOR,LVELO,OMEGA,TOL
0013                  104 FORMAT('0MAXIMUM ALLOWABLE ITERATIONS FOR PSOR =',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 PSOR =',F15.6,//)
0014                        RETURN
0015                        END
```

```
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),QWM(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),QOM(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),QG(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),FQW(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),TQW(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),TQO(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),TRGO(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),TFQW(10,2,5),TFOW(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),TFVO(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),TFFR1(10,2,5),TFLR2(10,2,5),TFFR3(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)
               C
0019          COMMON /SLT2/ VB,DELX,DELY,DELZ,DELT,RH
0020          COMMON /SLT3/ CON1,CON2,CON3,CON4
0021          COMMON /SLT1/ 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),BOF(15),DIBOT(15),
             & RSOT(15),ORSOT(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),KPWT(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(RSWT,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(RSGT,SG(I,J,K),W4(I,J,K),SGT,KROGT)
0034          CALL LINTP(MFSWT,SW(I,J,K),W5(I,J,K),FSWT,FKRWT)
0035          CALL LINTP(RFSWT,SW(I,J,K),W6(I,J,K),FSWT,FKROWT)
0036          CALL LINTP(MFSGT,SG(I,J,K),W7(I,J,K),FSGT,FKRGT)
0037          CALL LINTP(RFSGT,SG(I,J,K),W8(I,J,K),FSGT,FKROGT)
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(RPOT,PO(I,J,K),W12(I,J,K),POT,UOT)
0042          CALL LINTP(RPWT,PW(I,J,K),W13(I,J,K),PWT,UWT)
0043          CALL LINTP(RPGT,PG(I,J,K),W14(I,J,K),PGT,UGT)
0044          CALL LINTP(MPOT,PO(I,J,K),W15(I,J,K),POT,UOT)
0045          CALL LINTP(MPGT,PG(I,J,K),W16(I,J,K),PGT,UGT)
0046          CALL LINTP(RPOT,PO(I,J,K),W17(I,J,K),POT,UOT)
0047          CALL LINTP(RPGT,PG(I,J,K),W18(I,J,K),PGT,UGT)
0048          CALL LINTP(RPOT,PO(I,J,K),W19(I,J,K),POT,RSOT)
0049          CALL LINTP(MPGT,PO(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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```
0107                KROW2=W2(I+1,J,K)
0108                KRG2=W3(I+1,J,K)
0109                KROG2=W4(I+1,J,K)
0110                FKRW2=W5(I+1,J,K)
0111                FKROW2=W6(I+1,J,K)
0112                FKROG2=W7(I+1,J,K)
0113                FKRG2=W8(I+1,J,K)
0114                UO2=W9(I+1,J,K)
0115                UW2=W10(I+1,J,K)
0116                UG2=W11(I+1,J,K)
0117                UOF2=W12(I+1,J,K)
0118                UWF2=W13(I+1,J,K)
0119                UGF2=W14(I+1,J,K)
0120                BBO2=W15(I+1,J,K)
0121                BBG2=W16(I+1,J,K)
0122                BFO2=W17(I+1,J,K)
0123                BFG2=W18(I+1,J,K)
0124                RSO2=W19(I+1,J,K)
0125                RSF2=W20(I+1,J,K)
0126                KRO2=(KROW2+KRW2)*(KROG2+KRG2)-(KRW2+KRG2)
0127                FKRO2=(FKROW2+FKRW2)*(FKROG2+FKRG2)-(FKRW2+FKRG2)
0128             12 IF(J.EQ.1) GO TO 13
0129                KRW3=W1(I,J-1,K)
0130                KROW3=W2(I,J-1,K)
0131                KRG3=W3(I,J-1,K)
0132                KROG3=W4(I,J-1,K)
0133                FKRW3=W5(I,J-1,K)
0134                FKROW3=W6(I,J-1,K)
0135                FKROG3=W7(I,J-1,K)
0136                FKRG3=W8(I,J-1,K)
0137                UO3=W9(I,J-1,K)
0138                UW3=W10(I,J-1,K)
0139                UG3=W11(I,J-1,K)
0140                UOF3=W12(I,J-1,K)
0141                UWF3=W13(I,J-1,K)
0142                UGF3=W14(I,J-1,K)
0143                BBO3=W15(I,J-1,K)
0144                BBG3=W16(I,J-1,K)
0145                BFO3=W17(I,J-1,K)
0146                BFG3=W18(I,J-1,K)
0147                RSO3=W19(I,J-1,K)
0148                RSF3=W20(I,J-1,K)
0149                KRO3=(KROW3+KRW3)*(KROG3+KRG3)-(KRW3+KRG3)
0150                FKRO3=(FKROW3+FKRW3)*(FKROG3+FKRG3)-(FKRW3+FKRG3)
0151             13 IF(J.EQ.NY) GO TO 14
0152                KRW4=W1(I,J+1,K)
0153                KROW4=W2(I,J+1,K)
0154                KRG4=W3(I,J+1,K)
0155                KROG4=W4(I,J+1,K)
0156                FKRW4=W5(I,J+1,K)
0157                FKROW4=W6(I,J+1,K)
0158                FKROG4=W7(I,J+1,K)
0159                FKRG4=W8(I,J+1,K)
0160                UO4=W9(I,J+1,K)
0161                UW4=W10(I,J+1,K)
0162                UG4=W11(I,J+1,K)
0163                UOF4=W12(I,J+1,K)
0164                UWF4=W13(I,J+1,K)
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0165                  UGF4=W14(I,J+1,K)
0166                  UUU4=W15(I,J+1,K)
0167                  UUG4=W16(I,J+1,K)
0168                  UFU4=W17(I,J+1,K)
0169                  UFG4=W18(I,J+1,K)
0170                  RSU4=W19(I,J+1,K)
0171                  RSF4=W20(I,J+1,K)
0172                  KRU4=(KROW4+KRW4)*(KROG4+KRG4)-(KRW4+KRG4)
0173                  FKRU4=(FKROW4+FKRW4)*(FKROG4+FKRG4)-(FKRW4+FKRG4)
0174               14 IF(K.EQ.1) GO TO 15
0175                  KRW5=W1(I,J,K-1)
0176                  KROW5=W2(I,J,K-1)
0177                  KRG5=W3(I,J,K-1)
0178                  KROG5=W4(I,J,K-1)
0179                  FKRW5=W5(I,J,K-1)
0180                  FKROW5=W6(I,J,K-1)
0181                  FKROG5=W7(I,J,K-1)
0182                  FKRG5=W8(I,J,K-1)
0183                  UU5=W9(I,J,K-1)
0184                  UW5=W10(I,J,K-1)
0185                  UG5=W11(I,J,K-1)
0186                  UUF5=W12(I,J,K-1)
0187                  UWF5=W13(I,J,K-1)
0188                  UGF5=W14(I,J,K-1)
0189                  UUU5=W15(I,J,K-1)
0190                  UUG5=W16(I,J,K-1)
0191                  UFU5=W17(I,J,K-1)
0192                  UFG5=W18(I,J,K-1)
0193                  RSU5=W19(I,J,K-1)
0194                  RSF5=W20(I,J,K-1)
0195                  KRU5=(KROW5+KRW5)*(KROG5+KRG5)-(KRW5+KRG5)
0196                  FKRU5=(FKROW5+FKRW5)*(FKROG5+FKRG5)-(FKRW5+FKRG5)
0197               15 IF(K.EQ.NZ) GO TO 16
0198                  KRW6=W1(I,J,K+1)
0199                  KROW6=W2(I,J,K+1)
0200                  KRG6=W3(I,J,K+1)
0201                  KROG6=W4(I,J,K+1)
0202                  FKRW6=W5(I,J,K+1)
0203                  FKROW6=W6(I,J,K+1)
0204                  FKROG6=W7(I,J,K+1)
0205                  FKRG6=W8(I,J,K+1)
0206                  UU6=W9(I,J,K+1)
0207                  UW6=W10(I,J,K+1)
0208                  UG6=W11(I,J,K+1)
0209                  UUF6=W12(I,J,K+1)
0210                  UWF6=W13(I,J,K+1)
0211                  UGF6=W14(I,J,K+1)
0212                  UUU6=W15(I,J,K+1)
0213                  UUG6=W16(I,J,K+1)
0214                  UFU6=W17(I,J,K+1)
0215                  UFG6=W18(I,J,K+1)
0216                  RSU6=W19(I,J,K+1)
0217                  RSF6=W20(I,J,K+1)
0218                  KRU6=(KROW6+KRW6)*(KROG6+KRG6)-(KRW6+KRG6)
0219                  FKRU6=(FKROW6+FKRW6)*(FKROG6+FKRG6)-(FKRW6+FKRG6)
0220               16 CONTINUE
0221                  CALL LINTP(3,POT,PU(I,J,K),D110,POT,D110UT)
0222                  CALL LINTP(2,POT,PU(I,J,K),DRS,POT,DRSUT)
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0223                CALL LINTP(MPGT,PG(I,J,K),DIRG,PGT,DIDGT)
0224                CALL LINTP(MPOT,PFO(I,J,K),DIDOF,POT,DIDOT)
0225                CALL LINTP(MPOT,PFO(I,J,K),DRSF,POT,DRSOT)
0226                CALL LINTP(MPGT,PFG(I,J,K),DIDGF,PGT,DIDGT)
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)/BO
0232                DENOF=(RHOSO+RSF*RHOSG/5.615)/BFO
0233                DENW=RHOSW
0234                DENWF=RHOSW
0235                DENG=RHOSG/(BRG*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(BO,BO1)
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(BGG1,BG)
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)=TFW1(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                 UFGAV=FAVG(UFG,UFG1)
0278                 UGFAV=FAVG(UGF,UGF1)
0279                 FAG1(I,J,K)=TFAG1(I,J,K)*TKRGF/(UFGAV*UGFAV)
                C
0280              223 IF(I.EQ.NX) GO TO 230
0281                 HU2=PU(I,J,K)-PU(I+1,J,K)-DENU*DSIN(ALPHA)*DELX/144.
0282                 IF(HU2.GT.0.0) TKRU=KRU
0283                 IF(HU2.LE.0.0) TKRU=KRU2
0284                 IF(TKRU.LT.0.0) TKRU=0.0
0285                 UAVG=FAVG(UU,UU2)
0286                 UAVG=FAVG(PPU,UUU2)
0287                 RSAVG=FAVG(RSU,RSU2)
0288                 FACT=TKRU/(UAVG*UAVG)
0289                 CU(I,J,K)=TCU(I,J,K)*FACT
0290                 CGU(I,J,K)=TCGU(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                 UGAVG=FAVG(PRG2,UUG)
0301                 CG(I,J,K)=TCG(I,J,K)*TKRG/(UGAVG*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                 OFAVG=FAVG(OFO,OFO2)
0307                 UOFAV=FAVG(UOF,UOF2)
0308                 RSFAV=FAVG(RSF,RSF2)
0309                 FACT=TKROF/(OFAVG*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                 PFGAV=FAVG(PFG,PFG2)
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0321                  UGFAV=FAVG(UGF,UGF3)
0322                  FCG1(I,J,K)=FCG1(I,J,K)*TKRGF/(DFGAV*UGFAV)
                C
0323                230 IF(J.EQ.1) GO TO 230
0324                  HO3=PO(I,J-1,K)-PO(I,J,K)-DENO*DSIN(BETA)*DELY/144.
0325                  IF(HO3.GE.0.0) TKRO=KRO3
0326                  IF(HO3.LT.0.0) TKRO=KRO
0327                  IF(TKRO.LT.0.0) TKRO=0.0
0328                  UAVG=FAVG(UO,UO3)
0329                  UAVG=FAVG(UOO,UPO3)
0330                  RSAVG=FAVG(RSO,RSO3)
0331                  FACT=TKRO/(UAVG*UAVG)
0332                  EO(I,J,K)=TEO(I,J,K)*FACT
0333                  EGO(I,J,K)=TEGO(I,J,K)*FACT*RSAVG
                C
0334                  HW3=PW(I,J-1,K)-PW(I,J,K)-DLNW*DSIN(BETA)*DELY/144.
0335                  IF(HW3.GE.0.0) TKRW=KRW3
0336                  IF(HW3.LT.0.0) TKRW=KRW
0337                  UWAVG=FAVG(UW,UW3)
0338                  EW(I,J,K)=TEW(I,J,K)*TKRW/UWAVG
                C
0339                  HG3=PG(I,J-1,K)-PG(I,J,K)-DENG*DSIN(BETA)*DELY/144.
0340                  IF(HG3.GE.0.0) TKRG=KRG3
0341                  IF(HG3.LT.0.0) TKRG=KRG
0342                  UGAVG=FAVG(UG,UG3)
0343                  DGAVG=FAVG(DBG3,DBG)
0344                  EG(I,J,K)=TEG(I,J,K)*TKRG/(DGAVG*UGAVG)
                C
0345                  HOF3=PFO(I,J-1,K)-PFO(I,J,K)-DENOF*DELY*(   DSIN(BETA)/144.-
                     & CON3*(DFLOAT(J)*DVOYDT(I,J,K)-DFLOAT(J-1)*DVOYDT(I,J-1,K) ) )
0346                  IF(HOF3.GE.0.0) TKROF=TKRO3
0347                  IF(HOF3.LT.0.0) TKROF=TKRO
0348                  IF(TKROF.LT.0.0) TKROF=0.0
0349                  DFAVG=FAVG(DFO,DFO3)
0350                  UOFAV=FAVG(UOF,UOF3)
0351                  RSFAV=FAVG(RSF,RSF3)
0352                  FACT=TKROF/(DFAVG*UOFAV)
0353                  FEO2(I,J,K)=TFEO2(I,J,K)*FACT
0354                  FEP2(I,J,K)=TFEP2(I,J,K)*FACT*RSFAV
                C
0355                  HWF3=PFW(I,J-1,K)-PFW(I,J,K)-DLNWF*DELY*(   DSIN(BETA)/144.-
                     & CON3*(DFLOAT(J)*DVWYDT(I,J,K)-DFLOAT(J-1)*DVWYDT(I,J-1,K) ) )
0356                  IF(HWF3.GE.0.0) TKRWF=TKRW3
0357                  IF(HWF3.LT.0.0) TKRWF=TKRW
0358                  UWFAV=FAVG(UWF,UWF3)
0359                  FEW2(I,J,K)=TFEW2(I,J,K)*TKRWF/UWFAV
                C
0360                  HGF3=PFG(I,J-1,K)-PFG(I,J,K)-DLNGF*DELY*(   DSIN(BETA)/144.-
                     & CON3*(DFLOAT(J)*DVGYDT(I,J,K)-DFLOAT(J-1)*DVGYDT(I,J-1,K) ) )
0361                  IF(HGF3.GE.0.0) TKRGF=TKRG3
0362                  IF(HGF3.LT.0.0) TKRGF=TKRG
0363                  DFGAV=FAVG(DFG,DFG3)
0364                  UGFAV=FAVG(UGF,UGF3)
0365                  FEG2(I,J,K)=TFEG2(I,J,K)*TKRGF/(DFGAV*UGFAV)
                C
0366                240 IF(J.EQ.NY) GO TO 245
0367                  HO4=PO(I,J,K)-PO(I,J+1,K)-DENO*DSIN(BETA)*DELY/144.
0368                  IF(HO4.GT.0.0) TKRO=KRO
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0369                  IF(HD4.LE.0.0) TKRO=KRO4
0370                  IF(TKRO.LT.0.0) TKRO=0.0
0371                  UAVG=FAVG(UO,UO4)
0372                  DAVG=FAVG(DDO,DDO4)
0373                  RSAVG=FAVG(RSO,RSO4)
0374                  FACT=TKRO/(DAVG*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)*DVOYDT(I,J+1,K)-DFLOAT(J)*DVOYDT(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)-DLHW*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(BG5,BG)
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(BO,BO6)
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)-DLHW*DCOS(GAMMA)*DELZ/144.
0464                    IF(HW6.GT.0.0) TKRW=KRW
0465                    IF(HW6.LE.0.0) TKRW=KRW6
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                      UWAVG=FAVG(UW,UW6)
                      HW(I,J,K)=THW(I,J,K)*TKRW/UWAVG
                C
                      HG6=PG(I,J,K)-PG(I,J,K+1)-DENG*DCOS(GAMMA)*DELZ/144.
                      IF(HG6.GT.0.0) TKRG=KRG
                      IF(HG6.LE.0.0) TKRG=KRG6
                      UGAVG=FAVG(UG,UG6)
                      BGAVG=FAVG(BBG6,BBG)
                      HG(I,J,K)=THG(I,J,K)*TKRG/(BGAVG*UGAVG)
                C
                      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) ) )
                      IF(HOF6.GT.0.0) TKROF=FKRO
                      IF(HOF6.LE.0.0) TKROF=FKRO6
                      IF(TKROF.LT.0.0) TKROF=0.0
                      BOFAVG=FAVG(BFO,BFO6)
                      UOFAV=FAVG(UOF,UOF6)
                      RSFAV=FAVG(RSF,RSF6)
                      FACT=TKROF/(BOFAVG*UOFAV)
                      FHO3(I,J,K)=THO3(I,J,K)*FACT
                      FHR3(I,J,K)=THR3(I,J,K)*FACT*RSFAV
                C
                      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) ) )
                      IF(HWF6.GT.0.0) TKRWF=FKRW
                      IF(HWF6.LE.0.0) TKRWF=FKRW6
                      UWFAV=FAVG(UWF,UWF6)
                      FHW3(I,J,K)=THW3(I,J,K)*TKRWF/UWFAV
                C
                      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) ) )
                      IF(HGF6.GT.0.0) TKRGF=FKRG
                      IF(HGF6.LE.0.0) TKRGF=FKRG6
                      BFGAV=FAVG(BFG,BFG6)
                      UGFAV=FAVG(UGF,UGF6)
                      FHG3(I,J,K)=THG3(I,J,K)*TKRGF/(BFGAV*UGFAV)
                C
                  259 IF(J.EQ.1.OR.K.EQ.1) GO TO 260
                      IF(FKYZ(I,J-1,K).EQ.0.0.AND.FKZY(I,J,K-1).EQ.0.0) GO TO 260
                      FGW1(I,J,K)=TFGW1(I,J,K)*(FKYZ(I,J-1,K)*FKRW3/UWF3 +
                     & FKZY(I,J,K-1)*FKRW5/UWF5)
                        FT1=FKYZ(I,J-1,K)*FKRO3/(BFO3*UOF3)
                        FT2=FKZY(I,J,K-1)*FKRO5/(BFO5*UOF5)
                      FGO1(I,J,K)=TFGO1(I,J,K)*(FT1+FT2)
                      FGR1(I,J,K)=TFGR1(I,J,K)*(FT1*RSF3+FT2*RSF5)
                      FGG1(I,J,K)=TFGG1(I,J,K)*( FKYZ(I,J-1,K)*FKRG3/(BFG3*UGF3) +
                     & FKZY(I,J,K-1)*FKRG5/(BFG5*UGF5) )
                  260 IF(I.EQ.1.OR.K.EQ.1) GO TO 261
                      IF(FKXZ(I-1,J,K).EQ.0.0.AND.FKZX(I,J,K-1).EQ.0.0) GO TO 261
                      FGW2(I,J,K)=TFGW2(I,J,K)*( FKXZ(I-1,J,K)*FKRW1/UWF1 +
                     & FKZX(I,J,K-1)*FKRW5/UWF5 )
                      FT1=FKXZ(I-1,J,K)*FKRO1/(BFO1*UOF1)
                      FT2=FKZX(I,J,K-1)*FKRO5/(BFO5*UOF5)
                      FGO2(I,J,K)=TFGO2(I,J,K)*(FT1+FT2)
                      FGR2(I,J,K)=TFGR2(I,J,K)*(FT1*RSF1+FT2*RSF5)
                      FGG2(I,J,K)=TFGG2(I,J,K)*( FKXZ(I-1,J,K)*FKRG1/(BFG1*UGF1) +
                     & FKZX(I,J,K-1)*FKRG5/(BFG5*UGF5) )
                  261 IF(I.EQ.NX.OR.K.EQ.1) GO TO 262
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                      IF(FKXZ(I+1,J,K).EQ.0.0.AND.FKZX(I,J,K-1).LQ.0.0) GO TO 262
                      FGW4(I,J,K)=-TFGW4(I,J,K)*( FKXZ(I+1,J,K)*FKRW2/UWF2 +
                     & FKZX(I,J,K-1)*FKRW5/UWF5 )
                      FT1=FKXZ(I+1,J,K)*FKRU2/(UFU2*UUF2)
                      FT2=FKZX(I,J,K-1)*FKRU5/(UFU5*UUF5)
                      FGU4(I,J,K)=-TFGU4(I,J,K)*(FT1+FT2)
                      FGR4(I,J,K)=-TFGR4(I,J,K)*(FT1*RSF2+FT2*RSF5)
                      FGG4(I,J,K)=-TFGG4(I,J,K)*( FKXZ(I+1,J,K)*FKRG2/(UFG2*UGF2) +
                     & FKZX(I,J,K-1)*FKRG5/(UFG5*UGF5) )
  262               IF(J.EQ.NY.OR.K.EQ.1) GO TO 263
                      IF(FKYZ(I,J+1,K).LQ.0.0.AND.FKZY(I,J,K-1).LQ.0.0) GO TO 263
                      FGW5(I,J,K)=-TFGW5(I,J,K)*( FKYZ(I,J+1,K)*FKRW4/UWF4 +
                     & FKZY(I,J,K-1)*FKRW5/UWF5 )
                      FT1=FKYZ(I,J+1,K)*FKRU4/(UFU4*UUF4)
                      FT2=FKZY(I,J,K-1)*FKRU5/(UFU5*UUF5)
                      FGU5(I,J,K)=-TFGU5(I,J,K)*(FT1+FT2)
                      FGR5(I,J,K)=-TFGR5(I,J,K)*(FT1*RSF4+FT2*RSF5)
                      FGG5(I,J,K)=-TFGG5(I,J,K)*( FKYZ(I,J+1,K)*FKRG4/(UFG4*UGF4) +
                     & FKZY(I,J,K-1)*FKRG5/(UFG5*UGF5) )
  263               IF(I.EQ.1.OR.J.LQ.1)GO TO 264
                      IF(FKXY(I-1,J,K).LQ.0.0.AND.FKYX(I,J-1,K).EQ.0.0) GO TO 264
                      FFW1(I,J,K)=TFFW1(I,J,K)*( FKXY(I-1,J,K)*FKRW1/UWF1 +
                     & FKYX(I,J-1,K)*FKRW3/UWF3 )
                      FT1=FKXY(I-1,J,K)*FKRU1/(UFU1*UUF1)
                      FT2=FKYX(I,J-1,K)*FKRU3/(UFU3*UUF3)
                      FFU1(I,J,K)=TFFU1(I,J,K)*(FT1+FT2)
                      FFR1(I,J,K)=TFFR1(I,J,K)*(FT1*RSF1+FT2*RSF3)
                      FFG1(I,J,K)=TFFG1(I,J,K)*( FKXY(I-1,J,K)*FKRG1/(UFG1*UGF1) +
                     & FKYX(I,J-1,K)*FKRG3/(UFG3*UGF3) )
  264               IF(I.EQ.NX.OR.J.EQ.1) GO TO 265
                      IF(FKXY(I+1,J,K).LQ.0.0.AND.FKYX(I,J-1,K).LQ.0.0) GO TO 265
                      FFW3(I,J,K)=-TFFW3(I,J,K)*( FKXY(I+1,J,K)*FKRW2/UWF2 +
                     & FKYX(I,J-1,K)*FKRW3/UWF3 )
                      FT1=FKXY(I+1,J,K)*FKRU2/(UFU2*UUF2)
                      FT2=FKYX(I,J-1,K)*FKRU3/(UFU3*UUF3)
                      FFU3(I,J,K)=-TFFU3(I,J,K)*(FT1+FT2)
                      FFR3(I,J,K)=-TFFR3(I,J,K)*(FT1*RSF2+FT2*RSF3)
                      FFG3(I,J,K)=-TFFG3(I,J,K)*( FKXY(I+1,J,K)*FKRG2/(UFG2*UGF2) +
                     & FKYX(I,J-1,K)*FKRG3/(UFG3*UGF3) )
C
  265               IF(I.EQ.1.OR.J.EQ.NY) GO TO 266
                      IF(FKXY(I-1,J,K).EQ.0.0.AND.FKYX(I,J+1,K).LQ.0.0) GO TO 266
                      FFW1(I,J,K)=-TFFW1(I,J,K)*( FKXY(I-1,J,K)*FKRW1/UWF1 +
                     & FKYX(I,J+1,K)*FKRW4/UWF4 )
                      FT1=FKXY(I-1,J,K)*FKRU1/(UFU1*UUF1)
                      FT2=FKYX(I,J+1,K)*FKRU4/(UFU4*UUF4)
                      FFU1(I,J,K)=-TFFU1(I,J,K)*(FT1+FT2)
                      FFR1(I,J,K)=-TFFR1(I,J,K)*(FT1*RSF1+FT2*RSF4)
                      FFG1(I,J,K)=-TFFG1(I,J,K)*( FKXY(I-1,J,K)*FKRG1/(UFG1*UGF1) +
                     & FKYX(I,J+1,K)*FKRG4/(UFG4*UGF4) )
  266               IF(I.EQ.NX.OR.J.EQ.NY) GO TO 267
                      IF(FKXY(I+1,J,K).LQ.0.0.AND.FKYX(I,J+1,K).EQ.0.0) GO TO 267
                      FFW3(I,J,K)=TFFW3(I,J,K)*( FKXY(I+1,J,K)*FKRW2/UWF2 +
                     & FKYX(I,J+1,K)*FKRW4/UWF4 )
                      FT1=FKXY(I+1,J,K)*FKRU2/(UFU2*UUF2)
                      FT2=FKYX(I,J+1,K)*FKRU4/(UFU4*UUF4)
                      FFU3(I,J,K)=TFFU3(I,J,K)*(FT1+FT2)
                      FFR3(I,J,K)=TFFR3(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/(DFG2*UGF2) +
                     & FKYX(I,J+1,K)*FKRG4/(DFG4*UGF4)  )
                C
0559                267 IF(J.EQ.1.OR.K.LO.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)*FKRG3/(DFG3*UGF3)
0563                     FT2=FKZY(I,J,K+1)*FKRG6/(DFG6*UGF6)
0564                    FHG1(I,J,K)=-TFHG1(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/(DFG3*UGF3) +
                     & FKZY(I,J,K+1)*FKRG6/(DFG6*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)*FKRG1/(DFG1*UGF1)
0571                     FT2=FKZX(I,J,K+1)*FKRG6/(DFG6*UGF6)
0572                    FHG2(I,J,K)=-TFHG2(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/(DFG1*UGF1) +
                     & FKZX(I,J,K+1)*FKRG6/(DFG6*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)*FKRG2/(DFG2*UGF2)
0579                     FT2=FKZX(I,J,K+1)*FKRG6/(DFG6*UGF6)
0580                    FHG4(I,J,K)=TFHG4(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/(DFG2*UGF2) +
                     & FKZX(I,J,K+1)*FKRG6/(DFG6*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)*FKRG4/(DFG4*UGF4)
0587                     FT2=FKZY(I,J,K+1)*FKRG6/(DFG6*UGF6)
0588                    FHG5(I,J,K)=TFHG5(I,J,K)*(FT1+FT2)
0589                    FHR5(I,J,K)=TFHR5(I,J,K)*(FT1*RSF4+FT2*RSF5)
0590                    FHG5(I,J,K)=TFHG5(I,J,K)*( FKYZ(I,J+1,K)*FKRG4/(DFG4*UGF4) +
                     & FKZY(I,J,K+1)*FKRG6/(DFG6*UGF6) )
                C
0591                271 PW(I,J,K)=TRW(I,J,K)*PHI(I,J,K)*KRW/UW
0592                    UWN(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)+UW1(I,J,K))
0594                     DW(I,J,K)=-DW(I,J,K) - (PHI(I,J,K)/DELT)*( DSWDP*(   PUN(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) DS(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)*( BW(I,J,K) -
                     & GW(I,J,K))/144.
                C
0598                     VO(I,J,K)=-(PHI(I,J,K)/DELT)*DSWDP*TVO(I,J,K)/1000
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0598                  UOM(I,J,K)=TUO(I,J,K)*(PHI(I,J,K)/DELT)*DSGDP/DBO
0600                  PO(I,J,K)=TRO(I,J,K)*(PHI(I,J,K)*KRO/(BBO*UO)
0601                  HO(I,J,K)=-(GO(I,J,K)+FO(I,J,K)+AO(I,J,K)+CO(I,J,K)+FO(I,J,K)+
     &  HO(I,J,K)+RSO(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)=-OO(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)=-1VG(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)+PG(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)=-OG(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. -DLNO*DSIN(ALPHA)*DLLX*( 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. -DLNO*DSIN(BETA)*DELY*( FGO(I,J,K)-
     &  EGO(I,J,K) )/144.
0614                  DG(I,J,K)=DG(I,J,K)-DLNG*DCOS(GAMMA)*DELZ*( HG(I,J,K)-GG(I,J,K)
     &  )/144. -DENO*DCOS(GAMMA)*DLLZ*( 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                  FRW(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))*VOLUMT
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(DETA.NE.0.0) DFW(I,J,K)=DFW(I,J,K)-DENWF*DSIN(DETA)*DELY*(
                   & FFW2(I,J,K)-FE%2(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(DETA.NE.0.0.AND.FKXY(I,J,K).NE.0.0) DFW(I,J,K)=DFW(I,J,K) -
                   & FACT1*DENWF*DSIN(DETA)*(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,FKRW1)
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.DETA.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
0679        FRO(I,J,K)=TFRO(I,J,K)*KRO*FPHI(I,J,K)/(BBO*UO)
0680        FUO(I,J,K)=TFUO(I,J,K)*FPHI(I,J,K)*DFSGDP/(BFO*DELT)
0681        FVO(I,J,K)=-TFVO(I,J,K)*FPHI(I,J,K)*DFSWDP/(BFO*DELT)
0682        FRO(I,J,K)=-( FCOI(I,J,K)*FADI(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)*DTHOF*(1.-SWF(I,J,K)-SGF(I,J,K) )/DELT )
0683        GFRHS=0.0
0684        DFO(I,J,K)=-UOF(I,J,K)-FPHI(I,J,K)*CON2*(VB/DELT)*(   (
     &(1.-SWF(I,J,K)-SGF(I,J,K))*DTHOF -(DFSWDP-DFSGDP)/BFO)*PFUN(I,J,K)
     &  +(DFSWDP*PFWN(I,J,K) - DFSGDP*PFGN(I,J,K))/BFO   )
0685        IF(I.EQ.1.OR.I.EQ.NX) GO TO 415
0686        IF(FKXX(I,J,K).EQ.0.0) GO TO 4141
0687        FF1=FACT2*DLNOF*FKRO*FKXX(I,J,K)*(DVOXDT(I+1,J,K)-DVOXDT(I-1,J,K)
     &  )/(BFO*UOF)
0688        DFO(I,J,K)=DFO(I,J,K)-FF1
0689        GFRHS=GFRHS-RSF*FF1
0690   4141 IF(FKXY(I,J,K).EQ.0.0) GO TO 4142
0691        FF2=FACT2*DLNOF*FKRO*FKXY(I,J,K)*(DVOYDT(I+1,J,K)-DVOYDT(I-1,J,K)
     &  )/(BFO*UOF)
0692        DFO(I,J,K)=DFO(I,J,K)-FF2
0693        GFRHS=GFRHS-RSF*FF2
0694   4142 IF(FKXZ(I,J,K).EQ.0.0) GO TO 415
0695        FF3=FACT2*DLNOF*FKRO*FKXZ(I,J,K)*(DVOZDT(I+1,J,K)-DVOZDT(I-1,J,K)
     &  )/(BFO*UOF)
0696        DFO(I,J,K)=DFO(I,J,K)-FF3
0697        GFRHS=GFRHS-RSF*FF3
0698    415 IF(J.EQ.1.OR.J.EQ.NY) GO TO 416
0699        IF(FKYX(I,J,K).EQ.0.0) GO TO 4151
0700        FF4=FACT4*DLNOF*FKRO*FKYX(I,J,K)*(DVOXDT(I,J+1,K)-DVOXDT(I,J-1,K)
     &  )/(BFO*UOF)
0701        DFO(I,J,K)=DFO(I,J,K)-FF4
0702        GFRHS=GFRHS-RSF*FF4
0703   4151 IF(FKYY(I,J,K).EQ.0.0) GO TO 4152
0704        FF5=FACT4*DLNOF*FKRO*FKYY(I,J,K)*(DVOYDT(I,J+1,K)-DVOYDT(I,J-1,K)
     &  )/(BFO*UOF)
0705        DFO(I,J,K)=DFO(I,J,K)-FF5
0706        GFRHS=GFRHS-RSF*FF5
0707   4152 IF(FKYZ(I,J,K).EQ.0.0) GO TO 416
0708        FF6=FACT4*DLNOF*FKRO*FKYZ(I,J,K)*(DVOZDT(I,J+1,K)-DVOZDT(I,J-1,K)
     &  )/(BFO*UOF)
0709        DFO(I,J,K)=DFO(I,J,K)-FF6
0710        GFRHS=GFRHS-RSF*FF6
0711    416 IF(K.EQ.1.OR.K.EQ.NZ) GO TO 417
0712        IF(FKZX(I,J,K).EQ.0.0) GO TO 4161
0713        FF7=FACT6*DLNOF*FKRO*FKZX(I,J,K)*(DVOXDT(I,J,K+1)-DVOXDT(I,J,K-1)
     &  )/(BFO*UOF)
0714        DFO(I,J,K)=DFO(I,J,K)-FF7
0715        GFRHS=GFRHS-RSF*FF7
0716   4161 IF(FKZY(I,J,K).EQ.0.0) GO TO 4162
0717        FF8=FACT6*DLNOF*FKRO*FKZY(I,J,K)*(DVOYDT(I,J,K+1)-DVOYDT(I,J,K-1)
     &  )/(BFO*UOF)
0718        DFO(I,J,K)=DFO(I,J,K)-FF8
0719        GFRHS=GFRHS-RSF*FF8
0720   4162 IF(FKZZ(I,J,K).EQ.0.0) GO TO 417
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0712                  TF9=FACT6*DENOF*FKRO*FKZZ(I,J,K)*(DVUZDT(I,J,K+1)-DVOZDT(I,J,K-1)
                     &  )/(DFO*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*(
                     & FGU1(I,J,K)-FAU1(I,J,K))/144.
0716                  IF(BETA.NE.0.0) DFO(I,J,K)=DFO(I,J,K)-DENOF*DSIN(BETA)*DELY*(
                     & FFU2(I,J,K)-FLU2(I,J,K))/144.
0717                  DFO(I,J,K)=DFO(I,J,K)-DENOF*DCOS(GAMMA)*DELZ*(FHOJ(I,J,K) -
                     & FGU3(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)
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0753                  DFOKM=FAVG(DFO,DFOS)
0754                  RSFKP=FAVG(RSF,RSFS)
0755                  RSFKM=FAVG(RSF,RSFS)
0756                  IF(FKZX(I,J,K).NE.0.0.AND.ALPHA.NE.0.0) DFO(I,J,K)=DFO(I,J,K) -
                     & FACTS*DENOF*DSIN(ALPHA)*( FKKP*FKZXP/(DFOKP*UOFKP) -
                     & FKKM*FKZXM/(DFOKM*UOFKM) )
0757                  IF(FKZX(I,J,K).NE.0.0.AND.ALPHA.NE.0.0) GFRHS = GFRHS -
                     & FACTS*DENOF*DSIN(ALPHA)*( FKKP*FKZXP*RSFKP/(DFOKP*UOFKP) -
                     & FKKM*FKZXM*RSFKM/(DFOKM*UOFKM) )
0758                  IF(FKZY(I,J,K).NE.0.0.AND.DLTA.NE.0.0) DFO(I,J,K)=DFO(I,J,K) -
                     & FACTS*DENOF*DSIN(DLTA)*( FKKP*FKZYP/(DFOKP*UOFKP) -
                     & FKKM*FKZYM/(DFOKM*UOFKM) )
0759                  IF(FKZY(I,J,K).NE.0.0.AND.DLTA.NE.0.0) GFRHS = GFRHS -
                     & FACTS*DLNOF*DSIN(DLTA)*( FKKP*FKZYP*RSFKP/(DFOKP*UOFKP) -
                     & FKKM*FKZYM*RSFKM/(DFOKM*UOFKM) )
                C
0760                  FRG(I,J,K)=TFRG(I,J,K)*FPHI(I,J,K)*KRG/(BIG*UG)
0761                  FVG(I,J,K)=-TFVG(I,J,K)*FPHI(I,J,K)*RSF*DFSWDP/(DFO*DELT)
0762                  FBR(I,J,K)=-(FAR1(I,J,K)+FCR1(I,J,K)+FFR2(I,J,K)+FLR2(I,J,K)+
                     & FGR3(I,J,K)+FHR3(I,J,K)+FRGD(I,J,K)-CON2*(VH/DLLT)*
                     & FPHI(I,J,K)*( DFSGDP/DFG + RSF*(DFSWDP-DFSGDP)/DFO -
                     & (1.-SWF(I,J,K)-SGF(I,J,K) )*(DRSF/DFO+RSF*DIDOF) ) )
0763                  FDG(I,J,K)=-(FAG1(I,J,K)+FCG1(I,J,K)+FFG2(I,J,K)+FLG2(I,J,K)+
                     & FGG3(I,J,K)+FHG3(I,J,K)+FRG(I,J,K)+CON2*(VD/DELT)*FPHI(I,J,K)*(
                     & DFSGDP/DFG*SGF(I,J,K)*DIDOF-RSF*DFSGDP/DFO )  )
0764                  DFG(I,J,K)=GFRHS - QGF(I,J,K) -CON2*FPHI(I,J,K)*(VD/DLLT)*( (
                     & DFSGDP/DFG + SGF(I,J,K)*DIDOF - DFSGDP*RSF/DFO )*PFGN(I,J,K) - (
                     & DFSGDP/DFG + RSF*(DFSWDP-DFSGDP)/DFO - (1.-SWF(I,J,K)-SGF(I,J,K)
                     &)*(DRSF/DFO+RSF*DIDOF))*PFON(I,J,K) + RSF*DFSWDP*PFWN(I,J,K)/DFO)
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))/(DFG*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))/(DFG*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))/(DFG*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))/(DFG*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))/(DFG*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))/(DFG*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))/(DFG*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))/(DFG*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))/(DFG*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(DLTA.NE.0.0) DFG(I,J,K)=DFG(I,J,K)-DENGF*DSIN(DLTA)*DELY*(
                     & FFG2(I,J,K)-FLG2(I,J,K))/144. - DENOF*DELY*DSIN(DLTA)*(
                     & FFR2(I,J,K)-FLR2(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                DFGIP=FAVG(DFG,DFG2)
0787                DFGIM=FAVG(DFG,DFG1)
0788                IF(DELTA.NE.0.0.AND.FKXY(I,J,K).NE.0.0) DFG(I,J,K)=DFG(I,J,K) -
     &  FACT1*DENGF*DSIN(DELTA)*( FKXYP*FKIP/(DFGIP*UGFIP) -
     &  FKXYM*FKIM/(DFGIM*UGFIM))
0789                IF(FKXZ(I,J,K).NE.0.0) DFG(I,J,K)=DFG(I,J,K)-FACT1*DENGF*
     &  DCOS(GAMMA)*(FKXZP*FKIP/(DFGIP*UGFIP)-FKXZM*FKIM/(DFGIM*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                DFGJP=FAVG(DFG,DFG4)
0797                DFGJM=FAVG(DFG,DFG3)
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/(DFGJP*UGFJP) -
     &  FKJM*FKYXM/(DFGJM*UGFJM) )
0799                IF(FKYZ(I,J,K).NE.0.0) DFG(I,J,K)=DFG(I,J,K)-FACT3*DENGF*
     &  DCOS(GAMMA)*(FKJP*FKYZP/(DFGJP*UGFJP)-FKJM*FKYZM/(DFGJM*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/(DFGKP*UGFKP) -
     &  FKKM*FKZXM/(DFGKM*UGFKM) )
0807                IF(FKZY(I,J,K).NE.0.0.AND.DELTA.NE.0.0) DFG(I,J,K)=DFG(I,J,K) -
     &  FACT5*DENGF*DSIN(DELTA)*( FKKP*FKZYP/(DFGKP*UGFKP) -
     &  FKKM*FKZYM/(DFGKM*UGFKM) )
               C
0808             100 CONTINUE
0809                RETURN
0810                END
```

```
FORTRAN IV G1  RELEASE 2.0            FAVG              DATE = 82333        20/37/07          PAGE 0001

0001                  REAL FUNCTION FAVG*8(A,B)
0002                  IMPLICIT REAL*8(A-H,O-Z)
0003                  FAVG=(A+B)/2.
0004                  RETURN
0005                  END
```

```
FORTRAN IV G1  RELEASE 2.0            EXTRAP            DATE = 82333        20/37/07          PAGE 0001

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
0002                  IMPLICIT REAL*8(A-H,O-Z)
0003                  DIMENSION XN(NX,NY,1),X(NX,NY,1)
0004                  DO 100 K=1,NZ
0005                  DO 100 J=1,NY
0006                  DO 100 I=1,NX
0007                  TEMP=X(I,J,K)
0008                  XPROJ=X(I,J,K)+(DELT/DELTN)*(X(I,J,K)-XN(I,J,K))
0009                  X(I,J,K)=(XPROJ+X(I,J,K))/2.
0010                  XN(I,J,K)=TEMP
0011              100 CONTINUE
0012                  RETURN
0013                  END
```

```
FORTRAN IV G1  RELEASE 2.0            LINTP             DATE = 82333        20/37/07          PAGE 0001

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
0002                  IMPLICIT REAL*8(A-H,O-Z)
0003                  DIMENSION X(1),Y(1)
0004                  IF(X0.GE.X(N)) Y0=Y(N)
0005                  IF(X0.GE.X(N)) RETURN
0006                  DO 20 I=2,N
0007                  IF(X0.GE.X(I)) GO TO 20
0008                  Y0=Y(I-1) + (X0-X(I-1))*(Y(I)-Y(I-1))/(X(I)-X(I-1))
0009                  RETURN
0010               20 CONTINUE
0011                  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),QVOF(10),QVWF(10),
                     & QVGF(10),QVTF(10),TQ1(10),TQ2(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 BLOCK'///)
0043                  DO 12 LK=1,NZ
0044                  K=NZ-LK+1
0045                  PRINT 103, K
0046                103 FORMAT('0LAYER NUMBER',I7,/' **************'//)
```

```
0047                  J=NY
0048                50 PRINT 104,J
0049               104 FORMAT('0ROW NUMBER',I7,/' ----------'//)
0050                  PRINT 105, (PO(I,J,K),I=1,NX)
0051               105 FORMAT(' PO ',10F12.1)
0052                  PRINT 106, (PW(I,J,K),I=1,NX)
0053               106 FORMAT(' PW ',10F12.1)
0054                  PRINT 107, (PG(I,J,K),I=1,NX)
0055               107 FORMAT(' PG ',10F12.1)
0056                  J=J-1
0057                  IF(J.EQ.0) GO TO 12
0058                  GO TO 50
0059                12 CONTINUE
                  C
0060                  PRINT 108
0061               108 FORMAT(/////'0INITIAL PRESSURE DISTRIBUTIONS IN FRACTURE'///)
0062                  DO 13 LK=1,NZ
0063                  K=NZ-LK+1
0064                  PRINT 103, K
0065                  J=NY
0066                51 PRINT 104,J
0067                  PRINT 109, (PFO(I,J,K),I=1,NX)
0068               109 FORMAT(' PFO',10F12.1)
0069                  PRINT 110, (PFW(I,J,K),I=1,NX)
0070               110 FORMAT(' PFW',10F12.1)
0071                  PRINT 111, (PFG(I,J,K),I=1,NX)
0072               111 FORMAT(' PFG',10F12.1)
0073                  J=J-1
0074                  IF(J.EQ.0) GO TO 13
0075                  GO TO 51
0076                13 CONTINUE
                  C
0077                  PRINT 112
0078               112 FORMAT('1INITIAL SATURATION DISTRIBUTIONS IN MATRIX ROCK'///)
0079                  DO 14 LK=1,NZ
0080                  K=NZ-LK+1
0081                  PRINT 103, K
0082                  J=NY
0083                52 PRINT 104,J
0084                  PRINT 113, (SO(I,J,K),I=1,NX)
0085               113 FORMAT(' SO ',10F12.2)
0086                  PRINT 114, (SW(I,J,K),I=1,NX)
0087               114 FORMAT(' SW ',10F12.2)
0088                  PRINT 115, (SG(I,J,K),I=1,NX)
0089               115 FORMAT(' SG ',10F12.2)
0090                  J=J-1
0091                  IF(J.EQ.0) GO TO 14
0092                  GO TO 52
0093                14 CONTINUE
                  C
0094                  PRINT 116
0095               116 FORMAT(/////'0INITIAL SATURATION DISTRIBUTIONS IN FRACTURE'///)
0096                  DO 15 LK=1,NZ
0097                  K=NZ-LK+1
0098                  PRINT 103, K
0099                  J=NY
0100                53 PRINT 104,J
0101                  PRINT 117, (SOF(I,J,K),I=1,NX)
```

```
0102              117 FORMAT(' SGF',10F12.2)
0103                  PRINT 118, (SWF(I,J,K),I=1,NX)
0104              118 FORMAT(' SWF',10F12.2)
0105                  PRINT 119, (SGF(I,J,K),I=1,NX)
0106              119 FORMAT(' SGF',10F12.2)
0107                  J=J-1
0108                  IF(J.EQ.0) GO TO 15
0109                  GO TO 53
0110               15 CONTINUE
                C
                C  READ NUMBER OF VARIABLE RATE NODES AND VARIABLE PRESSURE NODES
                C
0111                  READ(5,100) TITLE
0112                  READ(5,120) NVQN
0113              120 FORMAT(I5)
0114                   IF(NVQN.EQ.0) GO TO 56
0115                   PRINT 121,NVQN
0116              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
0117                  DO 16 I=1,NVQN
0118                  READ(5,122) QN1(I),QN2(I),QN3(I),TQ1(I),TQ2(I)
0119              122 FORMAT(3I5,4F10.0)
0120                  READ(5,123) QVO(I),QVW(I),QVG(I),QVT(I),QVOF(I),QVWF(I),QVGF(I),
                     & QVTF(I)
0121              123 FORMAT(8F9.0)
0122                  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)
0123              124 FORMAT('0RATE 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)=',F0.0,'  QVWF(STB/D)=',F10.0,'  QVGF(SCF/D)=',
                     & F10.0,'   QVTF(STB/D)=',F10.0)
0124               16 CONTINUE
0125               56 RETURN
0126                  END
```

```
0001                  SUBROUTINE MATBAL(NX,NY,NZ,STBO,STBON,STBW,STBWN,SCFT,SCFTN,MBEO,
                     & MBEW,MBEG,POR,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
```

```
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
```



```
0001                SUBROUTINE POROSY(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),
                     & DO(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),
                     & FG(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),FUW(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) )/DO(I,J,K)
0021                   PO(I,J,K)=PKO+OMEGA*(PO(I,J,K)-PKO)
                C
```

```
0022                  RKG=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) -LG(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) )/FDW(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)  )/FDO(I,J,K)
0030                  PFO(I,J,K)=PKOF+OMEGA*(PFO(I,J,K)-PKOF)
                    C
0031                  PKGF=PFG(I,J,K)
0032                  TEH=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) -FFR1(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) -FCR1(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                  TEH1=-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)=(TEH+TEH1)/FDG(I,J,K)
0035                  PFG(I,J,K)=PKGF+OMEGA*(PFG(I,J,K)-PKGF)
                    C
0036                  R1=DABS(PO(I,J,K)-PKO)
```

```
0037                IF(R1.GT.RMAX) RMAX=R1
0038                P2=DABS(PW(I,J,K)-PKW)
0039                IF(R2.GT.RMAX) RMAX=R2
0040                R3=DABS(PG(I,J,K)-PKG)
0041                IF(R3.GT.RMAX) RMAX=R3
0042                R4=DABS(PFO(I,J,K)-PKOF)
0043                IF(R4.GT.RMAX) RMAX=R4
0044                R5=DABS(PFW(I,J,K)-PKWF)
0045                IF(R5.GT.RMAX) RMAX=R5
0046                R6=DABS(PFG(I,J,K)-PKGF)
0047                IF(R6.GT.RMAX) RMAX=R6
0048             15 CONTINUE
0049                IF(RMAX.LT.TOL) GO TO 20
0050                IF(NITER.GE.MITER) GO TO 30
0051                GO TO 11
0052             20 PRINT 95,NITER
0053             95 FORMAT('0CONVERGENCE AFTER',I7,'  ITERATIONS')
0054                RETURN
0055             30 PRINT 96,NITER
0056             96 FORMAT('0CONVERGENCE NOT ACHIEVED AFTER',I7,'  ITERATIONS')
0057                RETURN
0058                END
```

```
0001                  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
0002                  IMPLICIT REAL*8(A-H,O-Z)
0003                  REAL*8 MBEO,MBEW,MBEG
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)
                     C
0005                  PRINT 100,N,ETIME,DELTN
0006                100 FORMAT('1SIMULATION RESULTS AFTER TIME STEP ',I5,/,'0ELAPSED TIME
                     & =',F10.2,' DAYS',/'0TIME STEP SIZE (DAY)   =',F10.2,///)
0007                  PRINT 101,PAVG,MBEO,MBEW,MBEG,CUMOIL,CUMWAT,CUMWI
0008                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)
0009                  PRINT 102,CUMGAS,CUMGI,WOR,GOR
0010                102 FORMAT(' CUMULATIVE GAS PRODUCED (SCF)                =',F12.0,/,
                     &       ' CUMULATIVE GAS INJECTED (SCF)               =',F12.0,//,
                     &       ' WATER-OIL RATIO                             =',F12.1,/,
                     &       ' GAS-OIL RATIO                               =',F12.1,//)
0011                  PRINT 103,OILP,WATP,WATI,GASP,GASI
0012                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,////)
0013                  PRINT 104
0014                104 FORMAT('1 PRESSURE DISTRIBUTIONS IN MATRIX ROCK',/,
                     &       '  ************************************'//)
0015                  DO 12 LK=1,NZ
0016                  K=NZ-LK+1
0017                  PRINT 105, K
0018                105 FORMAT('0LAYER NUMBER',I7,/' ************'/)
0019                  J=NY
0020                 50 PRINT 106,J
0021                106 FORMAT('0ROW NUMBER',I7,/' ----------'/)
0022                  PRINT 107, (PO(I,J,K),I=1,NX)
0023                107 FORMAT(' PO ',10F12.1)
0024                  PRINT 108, (PW(I,J,K),I=1,NX)
0025                108 FORMAT(' PW ',10F12.1)
0026                  PRINT 10?, (PG(I,J,K),I=1,NX)
0027                109 FORMAT(' PG ',10F12.1)
0028                  J=J-1
0029                  IF(J.EQ.0) GO TO 12
0030                  GO TO 50
0031                 12 CONTINUE
                     C
0032                  PRINT 110
0033                110 FORMAT(//////'0 PRESSURE DISTRIBUTIONS IN FRACTURE',/,
                     &             '  ************************************'//)
```

```
0034                  DO 13 LK=1,NZ
0035                  K=NZ-LK+1
0036                  PRINT 105, K
0037                  J=NY
0038                51 PRINT 106,J
0039                  PRINT 111, (PFU(I,J,K),I=1,NX)
0040               111 FORMAT(' PFU',10F12.1)
0041                  PRINT 112, (PFW(I,J,K),I=1,NX)
0042               112 FORMAT(' PFW',10F12.1)
0043                  PRINT 113, (PFG(I,J,K),I=1,NX)
0044               113 FORMAT(' PFG',10F12.1)
0045                  J=J-1
0046                  IF(J.EQ.0) GO TO 13
0047                  GO TO 51
0048                13 CONTINUE
0049                  RETURN
0050                  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('OLAYER NUMBER ',I5,/' ************'/)
0039                104 FORMAT('OROW NUMBER',I5,/' ----------'/)
                      C
0040                  RETURN
0041                  END
```

```
0001                  SUBROUTINE PTPOR(NX,NY,NZ,N,ETIME)
                C
                C  SUBROUTINE TO PRINT POROSITY DISTRIBUTIONS
                C
0002                  IMPLICIT REAL*8(A-H,O-Z)
0003                  COMMON /PARM1/ CL,CF,PHI(10,2,5),FPHI(10,2,5)
                C
0004                  PRINT 112,N,ETIME
0005                112 FORMAT(//////'0FOR TIME STEP',I5,'  ELAPSED TIME (DAYS)=',F12.2,//
                     &  ,'0 POROSITY DISTRIBUTIONS IN MATRIX ROCK',/,
                     &   '  ************************************'//)
0006                  DO 12 LK=1,NZ
0007                  K=NZ-LK+1
0008                  PRINT 103, K
0009                  J=NY
0010                 23 PRINT 104,J
0011                  PRINT 189, (PHI(I,J,K),I=1,NX)
0012                  J=J-1
0013                  IF(J.EQ.0) GO TO 12
0014                  GO TO 23
0015                 12 CONTINUE
0016                  PRINT 152
0017                152 FORMAT(///' *** POROSITY DISTRIBUTION IN FRACTURE ***',/,
                     &           '     **********************************'//)
0018                  DO 18 LK=1,NZ
0019                  K=NZ-LK+1
0020                  PRINT 103,K
0021                  J=NY
0022                 31 PRINT 104,J
0023                  PRINT 189,(FPHI(I,J,K),I=1,NX)
0024                  J=J-1
0025                  IF(J.EQ.0) GO TO 18
0026                  GO TO 31
0027                 18 CONTINUE
0028                103 FORMAT('0LAYER NUMBER ',I5,/' ************'/)
0029                104 FORMAT('0ROW NUMBER',I5,/' ----------'/)
0030                189 FORMAT(('0',10F12.4))
                C
0031                  RETURN
0032                  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
```

```
0001                  SUBROUTINE RESDAT(NX,NY,NZ)
                C
                C  SUBROUTINE TO READ IN RESERVOIR AND FLUID DATA
                C
0002                  IMPLICIT REAL*8(A-H,K,O-Z)
0003                  INTEGER K,KPHIL,KPERL,KPHIF
0004                  COMMON /SET1/ RHOSO,RHOSW,RHOSG,PSC,TSC,ALPHA,BETA,GAMMA
0005                  COMMON /LIMIT/ MPOT,MPWT,MPGT,MSGT,MSWT,MFSGT,MFSWT
0006                  COMMON /PARM1/ CL,CF,PHI(10,2,5),FPHI(10,2,5)
0007                  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)
0008                  COMMON /PARM3/  P01(15),BOT(15),DIBOT(15),
                     & RSOT(15),DRSOT(15),VOT(15),PWT(15),VWT(15),PGT(15),BGT(15),
                     & DIBGT(15),VGT(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)
0009                  INTEGER*2 TITLL(40)
                C
                C  READ CODE NUMBER FOR ROCK-MATRIX POROSITY AND PERMEABILITY
                C  (FOR UNIFORM DISTRIBUTION:  KPHIL=0, KPERL=0)
                C
0010                  READ(5,112) TITLE
0011                  READ(5,100) KPHIL,KPERL
0012                  IF(KPHIL.NE.0) GO TO 20
0013                  READ(5,112) TITLE
0014                  READ(5,101) PHIL
0015                  DO 10 K=1,NZ
0016                  DO 10 J=1,NY
0017                  DO 10 I=1,NX
0018                  PHI(I,J,K)=PHIL
0019               10 CONTINUE
0020                  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
0021               20 READ(5,112) TITLE
0022                  DO 11 LK=1,NZ
0023                  K=NZ-LK+1
0024                  J=NY
0025               22 READ(5,102) (PHI(I,J,K), I=1,NX)
0026                  J=J-1
0027                  IF(J.EQ.0) GO TO 11
0028                  GO TO 22
0029               11 CONTINUE
0030               21 PRINT 50
0031               50 FORMAT(//' *** POROSITY DISTRIBUTION IN ROCK MATRIX ***'//)
0032                  DO 12 LK=1,NZ
0033                  K=NZ-LK+1
0034                  PRINT 103, K
0035                  J=NY
0036               23 PRINT 104, (PHI(I,J,K),I=1,NX)
0037                  J=J-1
0038                  IF(J.EQ.0) GO TO 12
0039                  GO TO 23
0040               12 CONTINUE
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0041                  IF(KPERL.NE.0) GO TO 25
0042                  READ(5,112) TITLE
0043                  READ(5,101) PERL
0044                  DO 13 K=1,NZ
0045                  DO 13 J=1,NY
0046                  DO 13 I=1,NX
0047                  KL(I,J,K)=PERL
0048                13 CONTINUE
0049                  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
0050                25 READ(5,112) TITLE
0051                  DO 14 LK=1,NZ
0052                  K=NZ-LK+1
0053                  J=NY
0054                26 READ(5,102) (KL(I,J,K),I=1,NX)
0055                  J=J-1
0056                  IF(J.EQ.0) GO TO 14
0057                  GO TO 26
0058                14 CONTINUE
0059                24 PRINT 151
0060               151 FORMAT(//' *** ISOTROPIC PERMEABILITY DISTRIBUTION IN ROCK MATRIX
                      C***'//)
0061                  DO 15 LK=1,NZ
0062                  K=NZ-LK+1
0063                  PRINT 103,K
0064                  J=NY
0065                27 PRINT 107, (KL(I,J,K),I=1,NX)
0066                  J=J-1
0067                  IF(J.EQ.0) GO TO 15
0068                  GO TO 27
0069                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
0070                  READ(5,112) TITLE
0071                  READ(5,100) KPHIF,NUMKF
0072                  IF(KPHIF.NE.0) GO TO 28
0073                  READ(5,112) TITLE
0074                  READ(5,101) PHIF
0075                  DO 16 K=1,NZ
0076                  DO 16 J=1,NY
0077                  DO 16 I=1,NX
0078                  FPHI(I,J,K)=PHIF
0079                16 CONTINUE
0080                  GO TO 29
0081                28 READ(5,112) TITLE
0082                  DO 17 LK=1,NZ
0083                  K=NZ-LK+1
0084                  J=NY
0085                30 READ(5,102) (FPHI(I,J,K),I=1,NX)
0086                  J=J-1
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0087                  IF(J.EQ.0) GO TO 17
0088                  GO TO 30
0089                17 CONTINUE
0090                29 PRINT 152
0091               152 FORMAT(///' *** POROSITY DISTRIBUTION IN FRACTURE ***'//)
0092                  DO 18 LK=1,NZ
0093                  K=NZ-LK+1
0094                  PRINT 103,K
0095                  J=NY
0096                31 PRINT 104,(FPHI(I,J,K),I=1,NX)
0097                  J=J-1
0098                  IF(J.EQ.0) GO TO 18
0099                  GO TO 31
0100                18 CONTINUE
0101                  READ(5,112) TITLE
0102                  READ(5,108) CFKXX,CFKXY,CFKXZ,CFKYX,CFKYY,CFKYZ,CFKZX,CFKZY,CFKZZ
0103                  DO 19 K=1,NZ
0104                  DO 19 J=1,NY
0105                  DO 19 I=1,NX
0106                  FKXX(I,J,K)=CFKXX
0107                  FKXY(I,J,K)=CFKXY
0108                  FKXZ(I,J,K)=CFKXZ
0109                  FKYX(I,J,K)=CFKYX
0110                  FKYY(I,J,K)=CFKYY
0111                  FKYZ(I,J,K)=CFKYZ
0112                  FKZX(I,J,K)=CFKZX
0113                  FKZY(I,J,K)=CFKZY
0114                  FKZZ(I,J,K)=CFKZZ
0115                19 CONTINUE
0116                  IF(NUMKF.LQ.0) GO TO 32
0117                  READ(5,112) TITLE
0118                  DO 80 L=1,NUMKF
0119                  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)
0120                80 CONTINUE
0121               100 FORMAT(2I5)
0122               101 FORMAT(F10.0)
0123               102 FORMAT(10F6.0)
0124               103 FORMAT('0LAYER NUMBER ',I5,/' ************'/)
0125               104 FORMAT('0',12F10.2)
0126               106 FORMAT(8F10.0)
0127               107 FORMAT('0',12F11.4)
0128               108 FORMAT(9F8.0)
0129               109 FORMAT(3I5,9F6.0)
0130               110 FORMAT('0ROW NUMBER',I5,/' ----------'/)
0131               111 FORMAT(4(3X,3F9.1,3X))
0132               112 FORMAT(40A2)
0133               115 FORMAT(//'0PMAXO =',F10.1,' PSI'/,'0PMAXW =',F10.1,' PSI',/,
                     & '0PMAXG =',F10.1,' PSI',/,'0SGMAX =',F11.2,/,'0SWMAX =',F11.2)
0134               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)',/,
                     &' ------------------------------------------------------------
                     &----------'/)
0135               117 FORMAT('0',F10.1,F10.4,D15.5,F10.1,F15.4,F10.4)
0136               116 FORMAT(6F12.0)
0137              1131 FORMAT(///'0WATER PVT DATA TABLE',/,' ********************',//,
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     &  T9,'PW',T16,'OW',/,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)
```

```
0161                  PRINT 111, (FKYX(I,J,K),FKYY(I,J,K),FKYZ(I,J,K),I=II,IEND)
0162                  PRINT 111, (FKZX(I,J,K),FKZY(I,J,K),FKZZ(I,J,K),I=II,IEND)
0163                  PRINT 135
0164                135 FORMAT('0')
0165                 82 CONTINUE
0166                  J=J-1
0167                  IF(J.EQ.0) GO TO 81
0168                  GO TO 33
0169                 81 CONTINUE
                    C
                    C  READ MAXIMUM PRESSURES AND SATURATIONS FOR VALUES IN TABLES
                    C
0170                  READ(5,112) TITLE
0171                  READ(5,106) PMAXO,PMAXW,PMAXG,SGMAX,SWMAX
0172                  PRINT 115,PMAXO,PMAXW,PMAXG,SGMAX,SWMAX
                    C
                    C  READ OIL PVT DATA
                    C
0173                  READ(5,112) TITLE
0174                  PRINT 114
0175                  DO 105 I=1,500
0176                  READ(5,116) POT(I),BOT(I),DIBOT(I),RSOT(I),DRSOT(I),UOT(I)
0177                  PRINT 117, POT(I),BOT(I),DIBOT(I),RSOT(I),DRSOT(I),UOT(I)
0178                  MPOT=I
0179                  IF(POT(I).GE.PMAXO) GO TO 51
0180                105 CONTINUE
                    C
                    C  READ WATER PVT DATA
                    C
0181                 51 READ(5,112) TITLE
0182                  PRINT 1131
0183                  DO 53 I=1,500
0184                  MPWT=I
0185                  READ(5,116) PWT(I),UWT(I)
0186                  PRINT 1171,PWT(I),UWT(I)
0187                  IF(PWT(I).GE.PMAXW) GO TO 54
0188                 53 CONTINUE
                    C
                    C  READ GAS PVT DATA
                    C
0189                 54 READ(5,112) TITLE
0190                  PRINT 1132
0191                  DO 55 I=1,500
0192                  MPGT=I
0193                  READ(5,116) PGT(I),BGT(I),DIBGT(I),UGT(I)
0194                  PRINT 1172, PGT(I),BGT(I),DIBGT(I),UGT(I)
0195                  IF(PGT(I).GE.PMAXG) GO TO 56
0196                 55 CONTINUE
                    C
                    C  READ OIL, WATER, GAS DENSITIES IN LBM/CU FT AT STANDARD CONDITIONS
                    C
0197                 56 READ(5,112) TITLE
0198                  READ(5,116) RHOSO,RHOSW,RHOSG,PSC,TSC
0199                  PRINT 119,PSC,TSC,RHOSO,RHOSW,RHOSG
                    C
                    C  READ FRACTURE AND MATRIX COMPRESSIBILITY
                    C
0200                  READ(5,112) TITLE
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0201                READ(5,120) CF,CL
0202                PRINT 121,CF,CL
                C
                C  READ TILTING ANGLES OF THE FORMATION (IN DEGREES)
                C
0203                READ(5,112) TITLE
0204                READ(5,116)  ALPHA,BETA,GAMMA
0205                PRINT 1191, ALPHA,BETA,GAMMA
0206                CONV=3.141593/180.
0207                ALPHA=ALPHA*CONV
0208                BETA=BETA*CONV
0209                GAMMA=GAMMA*CONV
                C
                C  READ GAS-OIL RELATIVE PERMEABILITY & CAPILLARY PRESSURE FOR MATRIX
                C  ROCK
                C
0210                READ(5,112) TITLE
0211                PRINT 1134
0212                DO 57 I=1,500
0213                MSGT=I
0214                READ(5,116) SGT(I),KRGT(I),KROGT(I),PCGOT(I),DSGT(I)
0215                PRINT 1173, SGT(I),KRGT(I),KROGT(I),PCGOT(I),DSGT(I)
0216                IF(SGT(I).GE.SGMAX) GO TO 58
0217             57 CONTINUE
                C
                C  READ WATER-OIL RELATIVE PERMEABILITY & CAPILLARY PRESSURE FOR
                C  MATRIX ROCK
                C
0218             58 READ(5,112) TITLE
0219                PRINT 1135
0220                DO 59 I=1,500
0221                MSWT=I
0222                READ(5,116) SWT(I),KRWT(I),KROWT(I),PCOWT(I),DSWT(I)
0223                PRINT 1173, SWT(I),KRWT(I),KROWT(I),PCOWT(I),DSWT(I)
0224                IF(SWT(I).GE.SWMAX) GO TO 60
0225             59 CONTINUE
                C
                C  REARRANGE PCOWT VERSUS SWT SO THAT PCOWT IS INCREASING
                C
0226             60 MHALF=(MSWT+1)/2
0227                DO 70 I=1,MHALF
0228                TMP=PCOWT(MSWT-I+1)
0229                PCOWT(MSWT-I+1)=PCOWT(I)
0230                PCOWT(I)=TMP
0231             70 CONTINUE
0232                DO 71 I=1,MSWT
0233                RSWT(I)=SWT(MSWT-I+1)
0234             71 CONTINUE
                C
                C  READ GAS-OIL RELATIVE PERMEABILITY & CAPILLARY PRESSURE FOR FRACTURE
                C
0235                READ(5,112) TITLE
0236                PRINT 1136
0237                DO 61 I=1,500
0238                MFSGT=I
0239                READ(5,116) FSGT(I),FKRGT(I),FKROGT(I),FPCGOT(I),FDSGT(I)
0240                PRINT 1173, FSGT(I),FKRGT(I),FKROGT(I),FPCGOT(I),FDSGT(I)
0241                IF(FSGT(I).GE.SGMAX) GO TO 62
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```
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
```

```
0001                  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
0002                  IMPLICIT REAL*8(A-H,O-Z)
0003                  INTEGER TITLE(40)
0004                  READ(5,100) TITLE
0005                100 FORMAT(40A2)
0006                  READ(5,101) NX,NY,NZ,XL,YL,ZL
0007                101 FORMAT(3I5,3F10.0)
0008                  DELX=XL/DFLOAT(NX)
0009                  DELY=YL/DFLOAT(NY)
0010                  DELZ=ZL/DFLOAT(NZ)
0011                  PRINT 102,XL,YL,ZL,NX,NY,NZ,DELX,DELY,DELZ
0012                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
0013                  READ(5,100) TITLE
0014                  READ(5,103) WF
0015                103 FORMAT(F10.6)
0016                  RH=3.141593*WF/4.
0017                  PRINT 104,WF,RH
0018                104 FORMAT('0NATURAL FRACTURE HALF-WIDTH =',F12.6,' FEET',/,
                       &'0HYDRAULIC RADIUS =',F12.6,' FEET'///)
0019                  RETURN
0020                  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),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)
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=FACT1/0.250
                      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                  TCW(I,J,K)=FAVG(KL(I,J-1,K),KL(I,J,K))
0031                  TCW(I,J,K)=TCW(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
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0088                TFHW4(I,J,K)=FACT6
0089                TFHW5(I,J,K)=FACT5
0090                TFRW(I,J,K)=KL(I,J,K)*FACT4
0091                TFUW(I,J,K)=FACT3
                C
0092                TFGO1(I,J,K)=TFGW1(I,J,K)
0093                TFGO2(I,J,K)=TFGW2(I,J,K)
0094                TFGO3(I,J,K)=TFGW3(I,J,K)
0095                TFGO4(I,J,K)=TFGW4(I,J,K)
0096                TFGO5(I,J,K)=TFGW5(I,J,K)
0097                TFEO1(I,J,K)=TFEW1(I,J,K)
0098                TFEO2(I,J,K)=TFEW2(I,J,K)
0099                TFEO3(I,J,K)=TFEW3(I,J,K)
0100                TFAO1(I,J,K)=TFAW1(I,J,K)
0101                TFCO1(I,J,K)=TFCW1(I,J,K)
0102                TFFO1(I,J,K)=TFFW1(I,J,K)
0103                TFFO2(I,J,K)=TFFW2(I,J,K)
0104                TFFO3(I,J,K)=TFFW3(I,J,K)
0105                TFHO1(I,J,K)=TFHW1(I,J,K)
0106                TFHO2(I,J,K)=TFHW2(I,J,K)
0107                TFHO3(I,J,K)=TFHW3(I,J,K)
0108                TFHO4(I,J,K)=TFHW4(I,J,K)
0109                TFHO5(I,J,K)=TFHW5(I,J,K)
0110                TFRO(I,J,K)=TFRW(I,J,K)
0111                TFUO(I,J,K)=FACT3
0112                TFVO(I,J,K)=FACT3
                C
0113                TFGG1(I,J,K)=TFGW1(I,J,K)
0114                TFGG2(I,J,K)=TFGW2(I,J,K)
0115                TFGG3(I,J,K)=TFGW3(I,J,K)
0116                TFGG4(I,J,K)=TFGW4(I,J,K)
0117                TFGG5(I,J,K)=TFGW5(I,J,K)
0118                TFEG1(I,J,K)=TFEW1(I,J,K)
0119                TFEG2(I,J,K)=TFEW2(I,J,K)
0120                TFEG3(I,J,K)=TFEW3(I,J,K)
0121                TFAG1(I,J,K)=TFAW1(I,J,K)
0122                TFCG1(I,J,K)=TFCW1(I,J,K)
0123                TFFG1(I,J,K)=TFFW1(I,J,K)
0124                TFFG2(I,J,K)=TFFW2(I,J,K)
0125                TFFG3(I,J,K)=TFFW3(I,J,K)
0126                TFHG1(I,J,K)=TFHW1(I,J,K)
0127                TFHG2(I,J,K)=TFHW2(I,J,K)
0128                TFHG3(I,J,K)=TFHW3(I,J,K)
0129                TFHG4(I,J,K)=TFHW4(I,J,K)
0130                TFHG5(I,J,K)=TFHW5(I,J,K)
0131                TFGR1(I,J,K)=TFGW1(I,J,K)
0132                TFGR2(I,J,K)=TFGW2(I,J,K)
0133                TFGR3(I,J,K)=TFGW3(I,J,K)
0134                TFGR4(I,J,K)=TFGW4(I,J,K)
0135                TFGR5(I,J,K)=TFGW5(I,J,K)
0136                TFER1(I,J,K)=TFEW1(I,J,K)
0137                TFER2(I,J,K)=TFEW2(I,J,K)
0138                TFER3(I,J,K)=TFEW3(I,J,K)
0139                TFAR1(I,J,K)=TFAW1(I,J,K)
0140                TFCR1(I,J,K)=TFCW1(I,J,K)
0141                TFFR1(I,J,K)=TFFW1(I,J,K)
0142                TFFR2(I,J,K)=TFFW2(I,J,K)
0143                TFFR3(I,J,K)=TFFW3(I,J,K)
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0144                TFHR1(I,J,K)=TFHW1(I,J,K)
0145                TFHR2(I,J,K)=TFHW2(I,J,K)
0146                TFHR3(I,J,K)=TFHW3(I,J,K)
0147                TFHR4(I,J,K)=TFHW4(I,J,K)
0148                TFHR5(I,J,K)=TFHW5(I,J,K)
0149                TFRG(I,J,K)=TFRW(I,J,K)
0150                TFRGG(I,J,K)=TFRW(I,J,K)
0151                TFVG(I,J,K)=FACT3
0152              100 CONTINUE
0153                RETURN
0154                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,DLLY,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)
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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) )
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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/DWI
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',2015)
         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:

$$[\Gamma_j]_i = 0.001127 \frac{K_1 k_{r1j} \phi_f C_{ij1} \rho_{j1}}{r_H{}^1 \mu_{j1}} (P_{1j} - P_{fj}) \qquad (H\text{-}1)$$

For example, the water component in water phase has:

$C_{Ww1} = 1$, and $\rho_{w1} = \frac{\rho_{ws}}{B_{w1}}$

Hence,

$$[\Gamma_w]_W = 0.001127 \frac{K_1 k_{r1w} \phi_f \rho_{Ws}}{r_H{}^1 \mu_{w1} B_{w1}} (P_{1w} - P_{fw}) \qquad (H\text{-}2)$$

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).

$$\frac{V_B}{\Delta t} \bar{\delta}\left(\frac{\phi_1 S_{w1}}{B_{w1}}\right) = -0.001127\sigma \frac{K_1 k_{r1w} V_B}{\mu_{w1} B_{w1}} (P_{1w} - P_{fw}) \qquad (H\text{-}3)$$

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 $(\frac{M}{L^3t})$ as shown below. Multiply the equation by $\frac{\rho_{ws}}{V_B}$.

$$\therefore \quad \frac{\rho_{ws}}{V_B \Delta t}\bar{\delta}\left(\frac{V_B \phi_1 S_{w1}}{B_{w1}}\right) = -0.001127\,\sigma \frac{\rho_{ws}}{V_B}\frac{K_1 k_{r1w}}{\mu_{w1} B_{w1}} V_B (P_{1w} - P_{fw}) \tag{H-4}$$

The left-hand-side now represents the mass flow rate per unit volume and has dimensions of $(\frac{M}{L^3t})$. Note that $\bar{\delta}$ signifies time step difference

$$(\bar{\delta} = \delta^{n+1} - \delta^{n}).$$

Consequently, comparison between the two models results in the following relationship.

$$\sigma = \frac{\phi_f}{r_H 1} \tag{H-5}$$

$$r_H = \frac{\phi_f}{\sigma 1} \tag{H-6}$$

In this study, $1 = \frac{\Delta x}{2} = 100$ ft, $\phi_f = 0.01$. From Thomas et al example, the matrix shape factor ($\sigma$) 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).

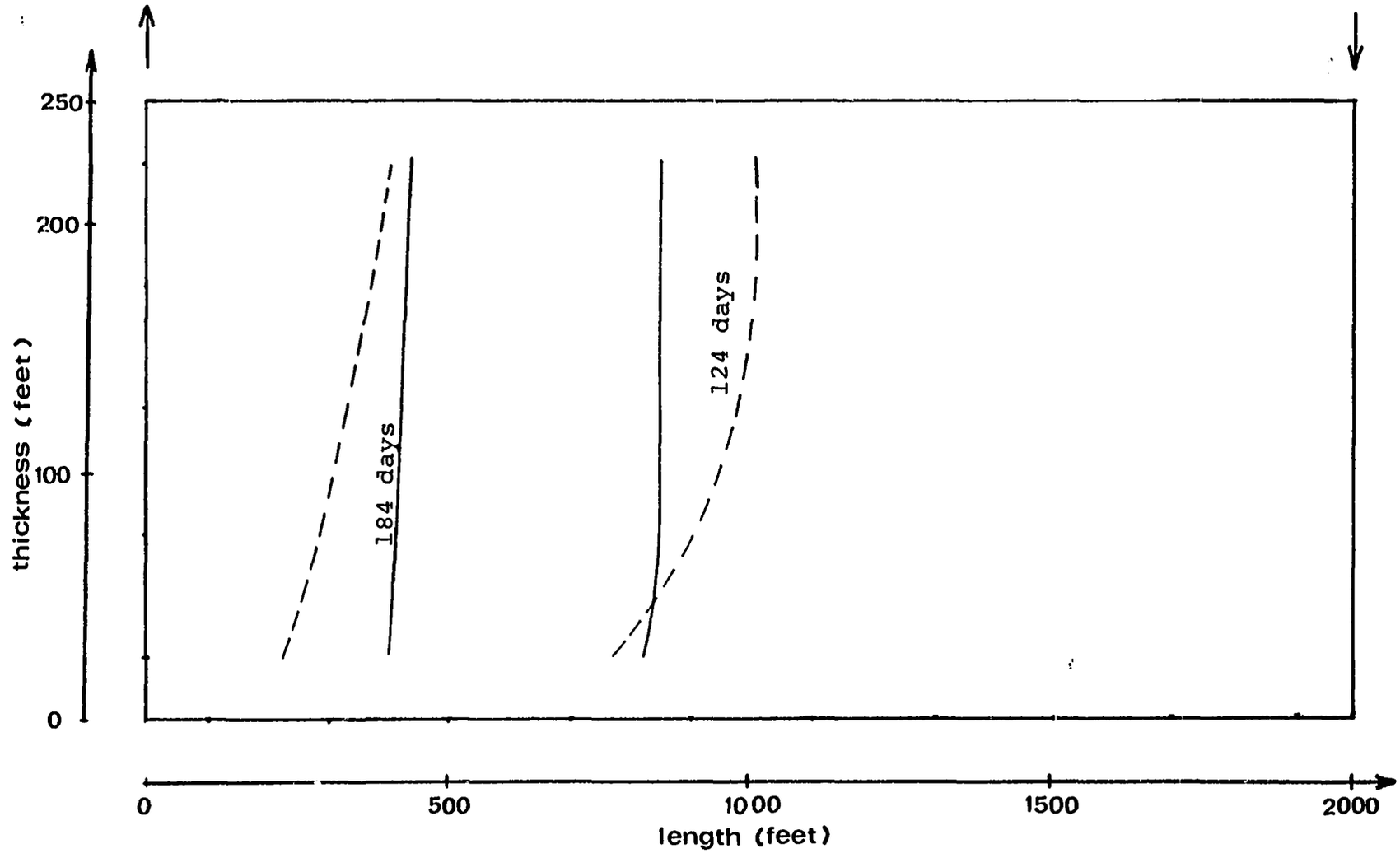


Figure I-1 Fracture 50% Water Saturation Profile (center cross-section).

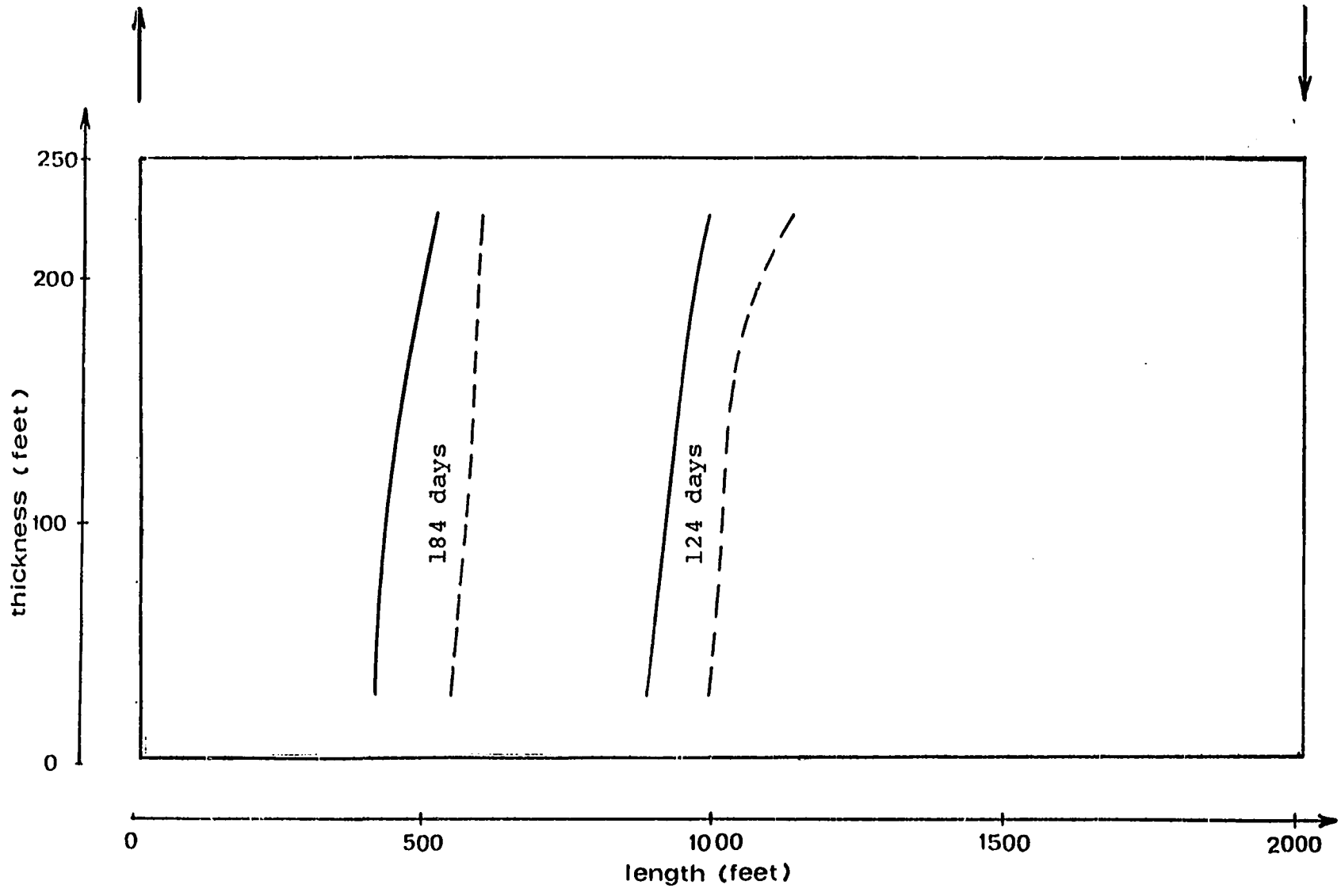


Figure I-2 Matrix 50% Water Saturation Profile (Center cross-section)

## 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 $\Delta X$ and $\Delta Y$ 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 be-

tween 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.

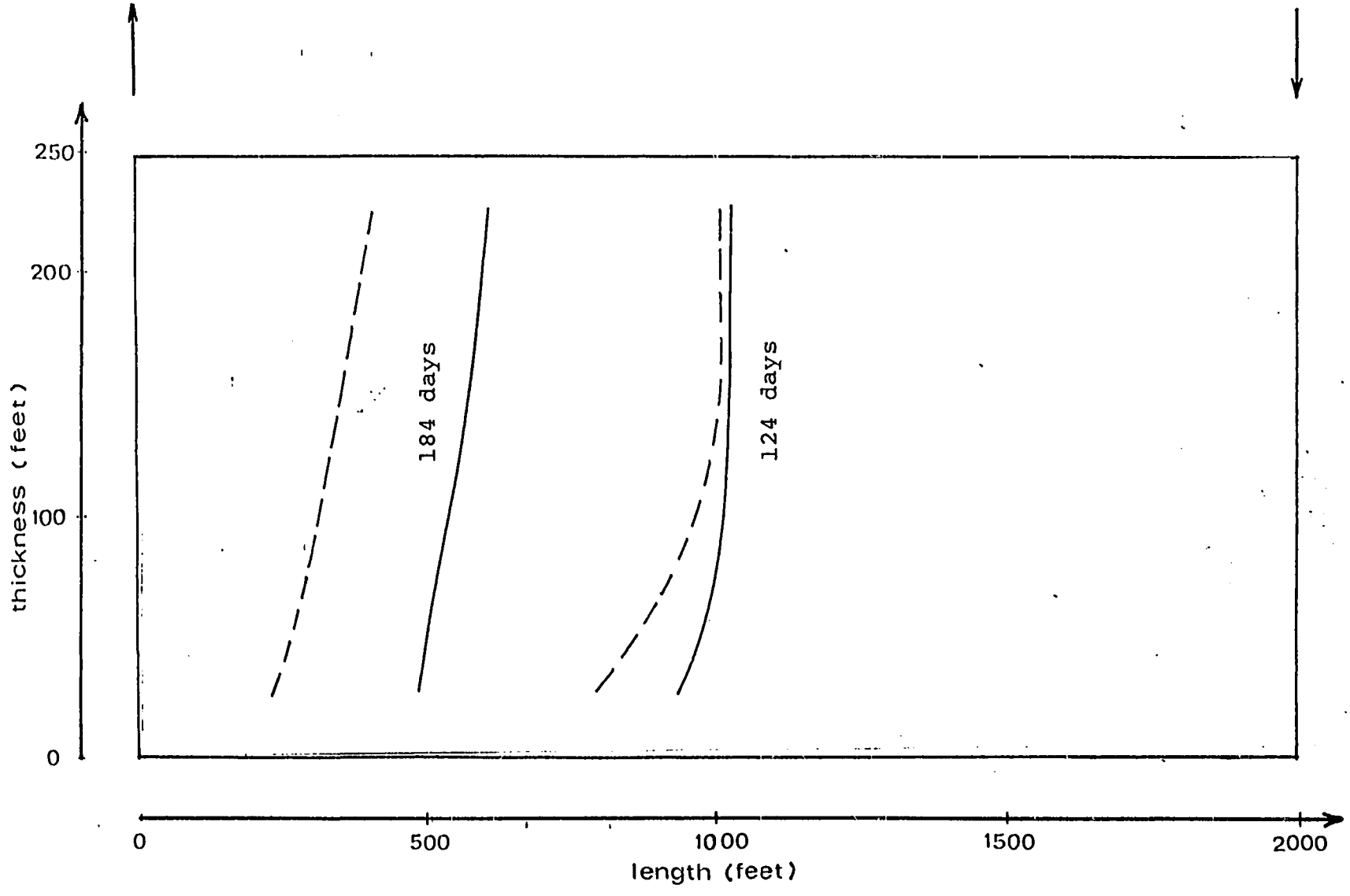


Figure J.1 Fracture 50% Water Saturation Profile (Center cross-section)

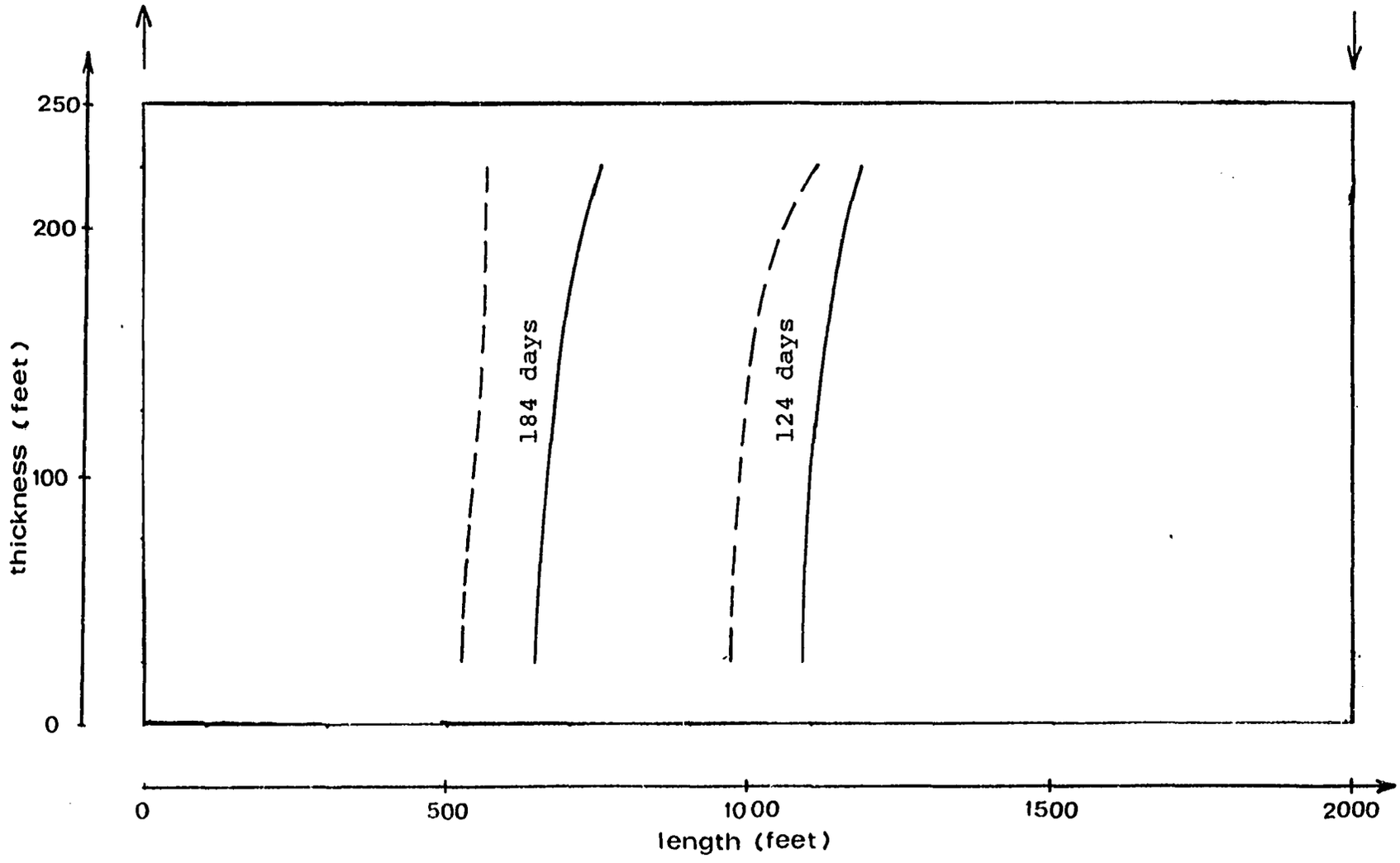


Figure J.2 Matrix 50% Water Saturation Profile (center cross-section)