Special Requirements for Computer Simulation of Injection Projects

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SIMULATION CONCEPT

The simulation of reservoir performance using grid-type mathematical models first involves gridding the reservoir as shown in Fig. 1. Each of the areas formed by the grid lines can be viewed as a block of reservoir whose properties can be different from any other block in the field. This permits handling of heterogeneous situations involving variations in net pay, saturations, pressures, etc. Included in the concept, however, is the fact that within each block homogeneous conditions prevail. That is, the saturation is uniform throughout each of the small blocks, the pressure is even, etc.

The difficulty in developing a computer program which will simulate performance of a gridded reservoir is to develop efficient and stable mathematical relationships that will permit the determination of the action and interaction of each of the blocks in the reservoir on each other. Basically, these calculations involve writing equations for fluid flow across the faces of the blocks and devising material balance procedures for keeping track of the reservoir flux into and out of each block. Referring to Fig. 2, the basis of the typical model is the development of equations for relating the flow of fluids into and out of each of the blocks across the four faces as shown.

Most of the procedures currently used involve finite difference equations wherein it is considered that all pertinent relationships can be differentiated with sufficient accuracy over small periods of time.

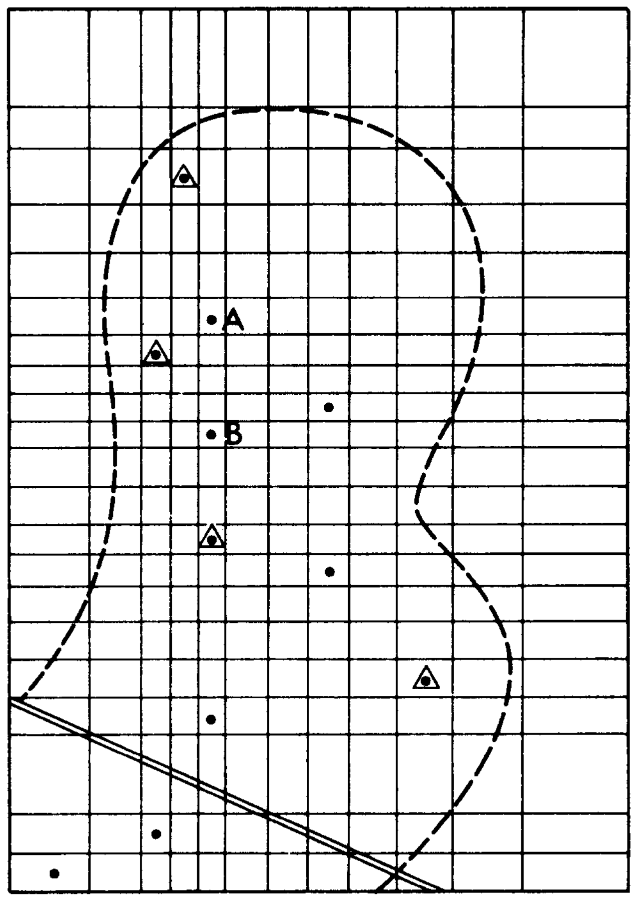

FIGURE 1

Typical Grid System for Reservoir Simulation Study.

BUBBLE POINT PROBLEM

One of the mathematical difficulties that arises in the simulation of oil reservoirs involved in water or gas injection projects is illustrated in Fig. 3. Here a typical oil formation volume factor curve and a gas solubility curve are shown. The solid lines show these conventional curves, wherein the initial saturation pressure is shown as P_1. As the reservoir undergoes depletion and drops below the original bubble point, a substantial portion of the evolved gas may be produced as casinghead gas prior to the time that a waterflood is commenced. Accordingly, when the waterflood is undertaken and the pressure is restored, the point at which no free gas is left is no longer the same as original saturation

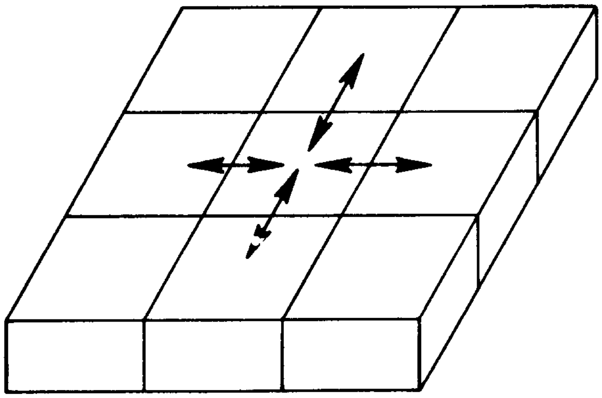

FIGURE 2

Matrix Model Schematic Illustrating Four Directional Flow Concept.

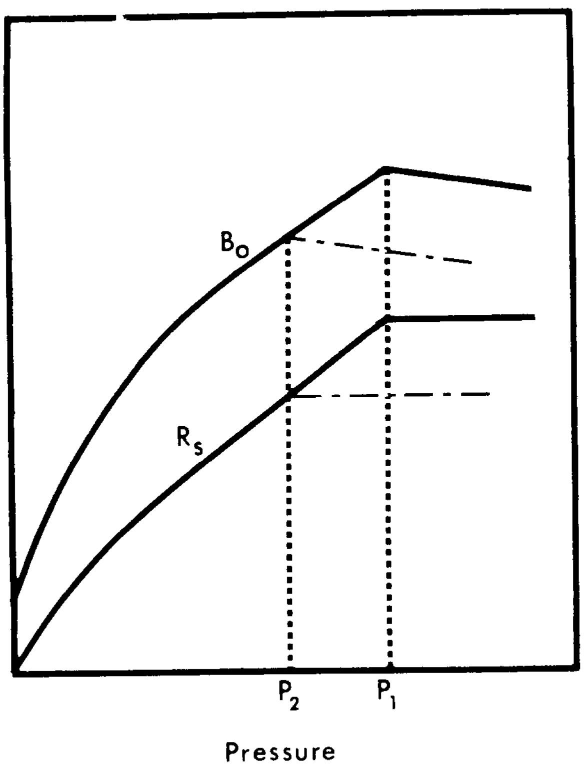

FIGURE 3

PVT Data at Original and Subsequent Reservoir Conditions.

pressure, P_1. Instead, the adjusted saturation pressure may be as shown as P_2 on Fig. 3 where the oil formation volume factor and gas solubility curves above saturation are shown with the dashed lines.

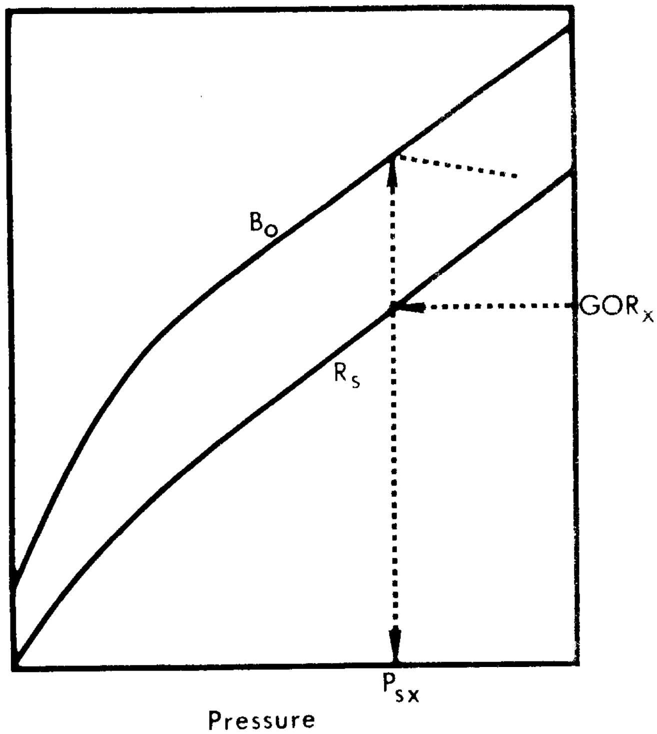

FIGURE 4

Use of PVT Data for Fully Saturated Conditions.

Figure 4 illustrates the concept used to handle the varying bubble-point situation. It shows that rather than supplying the simulator with the formation volume factor and gas solubility relationship tied to the original amount of gas present, data are supplied for fully saturated conditions throughout the entire pressure range in which simulation will take place. Then with respect to each block and for each time step taken in the simulation process, the model computes the applicable fluid properties by first determining the saturation pressure for an individual block at that moment in time, based upon the amount of gas available to go into solution. If the pressure in the block is less than the computed saturation pressure, use the saturated curves. On the other hand, if the pressure in the block is in excess of the saturation pressure, construct undersaturated curves tying into the saturated curves at the saturation pressure.

An additional difficulty inherent in simulation, wherein transition through the bubble point is involved, can be illustrated in Fig. 5.

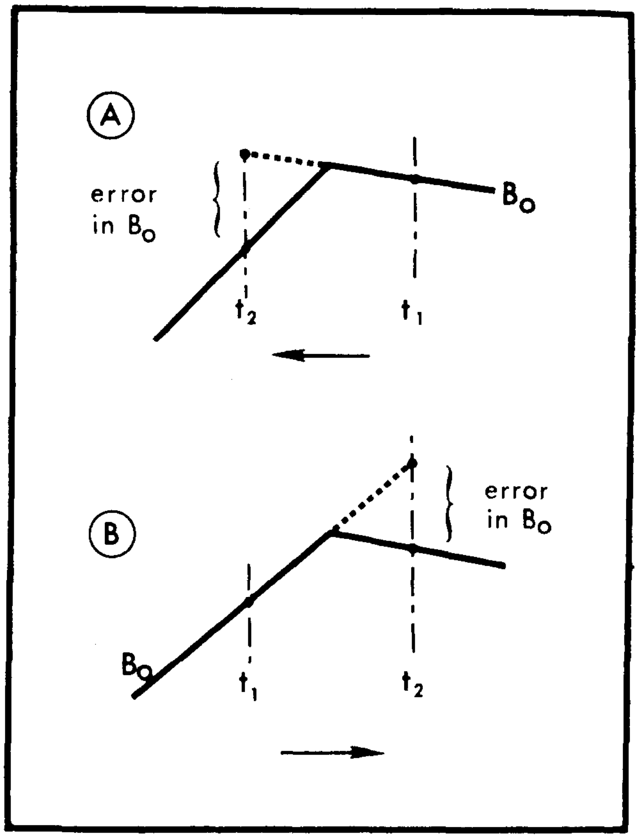

FIGURE 5

Schematic Illustration of Potential F.V.F. Error When Passing Through the Bubble-Point.

For the time-steps being taken in the simulation process, it is necessary to develop equations, expressing the compressibility, etc., of the materials involved. The conventional procedure for doing this is to assume that the derivatives of the PVT curves, that is the slopes of the curves, are constant for the finite time-step being taken. Figure 5-A shows that when dropping through the bubble point and the simulation process is proceeding from T_1 to T_2 and when the slope of the B_O curve at T_1 is used, a significant error in the determination of the oil formation volume factor at T_2 results. Similarly, as pressure is being increased in a waterflood situation, requiring that the bubble point be traversed as shown in Fig. 5-B, the assumption of the constant derivative of the oil formation volume factor curve will lead to an error as also shown in Fig. 5-B.

This problem has been avoided in the author's experience by simply using a convergence procedure to solve the applicable flow equations. By this procedure the conditions at the end of each time-step are determined such that reliance upon the ability to differentiate PVT curves is not needed. In other words, first estimate what the pressure will be at T_2 (thereby making it possible to compute the PVT properties rigorously as a function of pressure) and then, by trial, determine if the estimated pressure is correct. If such pressure is not correct, a second iteration is required and so on until the estimated pressure at time 2 is within the material balance limits desired.

FRONT TRACKING PROBLEM

A second special requirement of a simulator to handle waterflood or gas injection operations involves the ability to better define significant saturation profiles in the model. The basis for the conventional establishment of fluid saturations can be illustrated with reference to Fig. 6 which is one-quarter of a five-spot where injection is taking place in the corner grid in the lower left-hand corner and withdrawals are being taken from the corner grid in the upper right-hand corner. Since each of the squares in this figure is treated as a reservoir block, the migration of fluids across each of the four faces of each cell will be computed for each time step and in this manner fluid is, in effect, permitted to flow from block to block. Since the reservoir blocks are treated as having only four sides, it is necessary for the water to first flow either to the cell immediately above the injection block or to the cell immediately right of the injection block and sufficiently fill these two abutting cells before it is permitted to flow to the cell diagonally offsetting the injection cell. Thus, the injected material goes in a stairstep fashion as it proceeds diagonally from the injector to the producer. This requires a given drop of water to travel a considerably longer distance to get to the producing well. As one might suspect, this will result in waterflood fronts having somewhat unrealistic shapes.

To better simulate the movement of flood fronts, a procedure is suggested which, in effect, permits fluids to flow directly into any of the eight blocks surrounding a typical block rather than just the offsetting four blocks. This is shown schematically in Fig. 7. Experience in using this

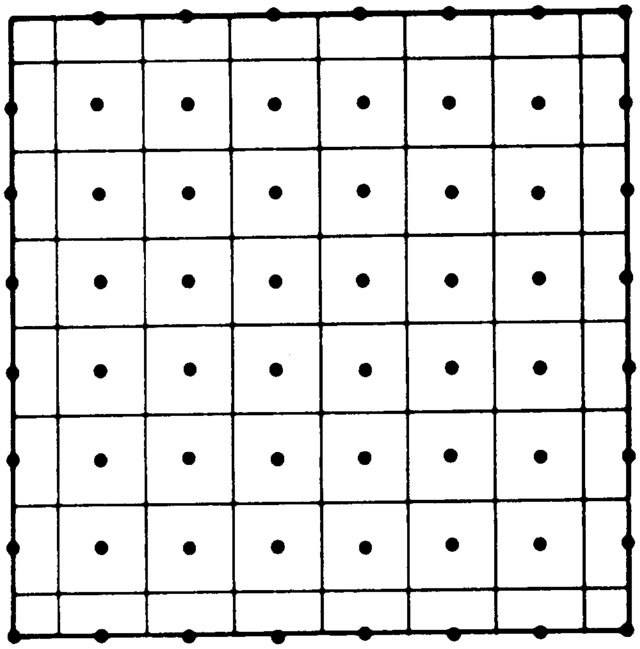

FIGURE 6

Grid Configuration for Five-Spot Pattern.

approach shows very realistic front movements plus a side advantage of greater model stability.

To determine the significance of using the eight-flux procedures as shown in Fig. 7 versus the conventional four-flux procedure as shown in Fig. 2, two model runs were set up under identical conditions. A quarter of a five-spot was used, having an eight-by-eight mesh as shown in Fig. 6.

TEST RUNS

The fluid properties used in the model runs were adjusted so as to obtain a constant mobility ratio of 1. Grid properties were all equalized, resulting in a homogeneous pattern. While the same model was used in both tests, in the four-flux case, the permeabilities in the diagonal directions were set to zero thus forcing the eight-flux model to behave as a four-flux model.

The water injection rate was held equal and constant in each run and pressure and saturation maps printed out at 10 per cent sweep intervals. That is, when 10 per cent of the pattern's displaceable volume had been replaced with water, the first set of maps was printed. Likewise, the

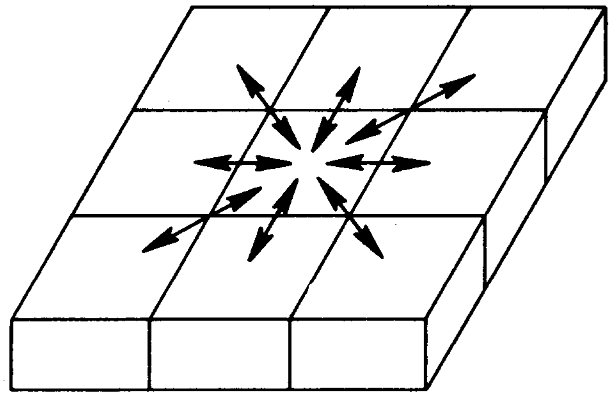

FIGURE 7

Matrix Model Schematic Illustrating Eight Directional Flow Concept.

second set was printed when 20 per cent of the displaceable volume had been replaced, and so on until breakthrough had occurred.

In these runs, the water saturation ahead of the water front was 30 per cent, being connate water saturation. The maximum water saturation behind the front was 80 per cent. To compare the four and eight-flux results, the 50 per cent water saturation line was obtained and drawn on each of the water saturation maps by linear interpolation between control points. The flood front results obtained from these maps compared at equal times are shown on Figs. 8, 9, 10, and 11.

In the case of the eight-flux runs, the flood front lines were quite symmetrical; however, in the four-flux runs saturation variations in image cells were noted. For the purposes of the front position maps herein presented, the water saturations in the image cells were averaged before interpolation to get the 50 per cent water saturation line.

Thirty-day time-steps were taken in both of the tests. At this size step, the eight-flux run was smooth; i.e., no pressure or saturation instability or variations were noted. These variations were noted in the four-flux run; however, they were not overly severe until immediately before water breakthrough into the producing well. At this time the four-flux run became unstable and computations were terminated. A 15-day time-step run was attempted for the four-flux case and obtained the same results.

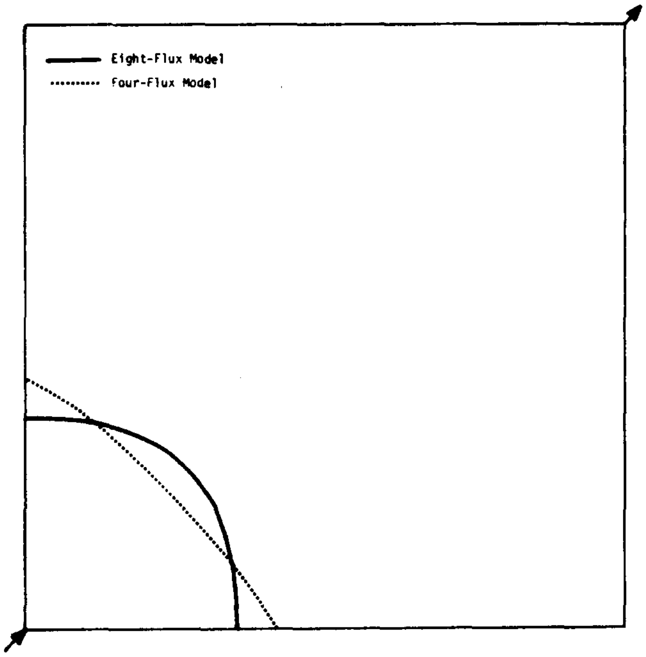

FIGURE 8

Calculated Water Front Position at 10% Conformance.

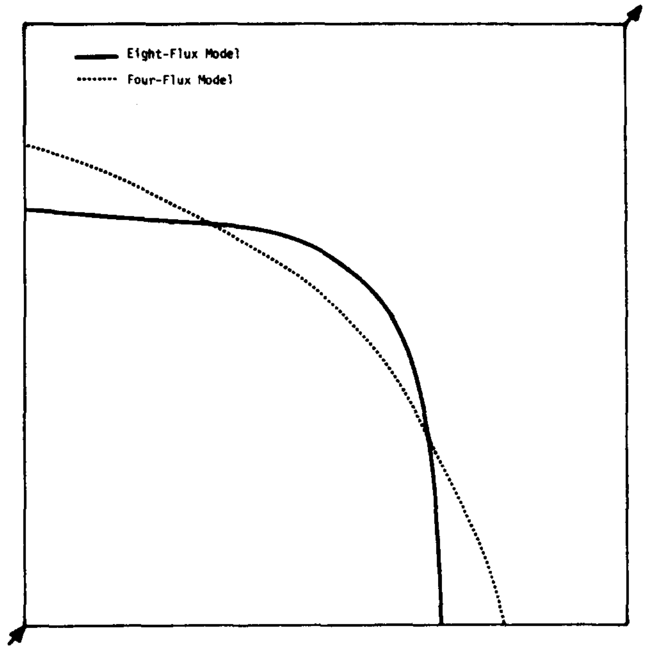

FIGURE 10

Calculated Water Front Position at 40% Conformance.

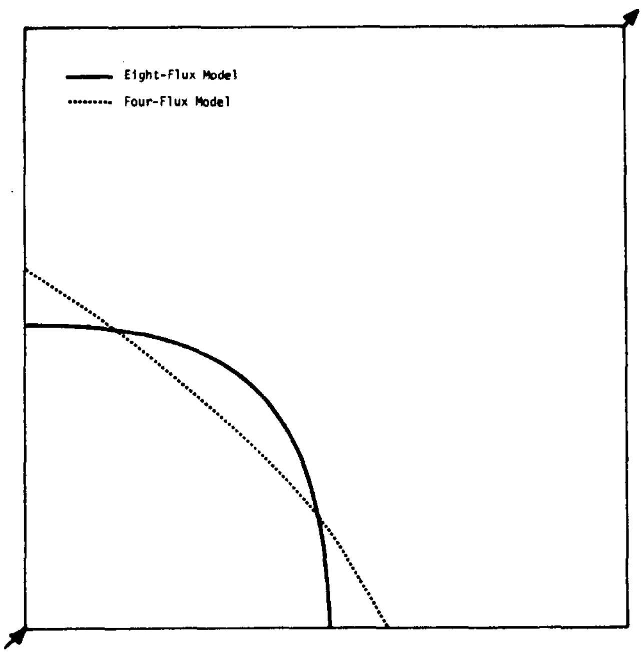

FIGURE 9

Calculated Water Front Position at 20% Conformance.

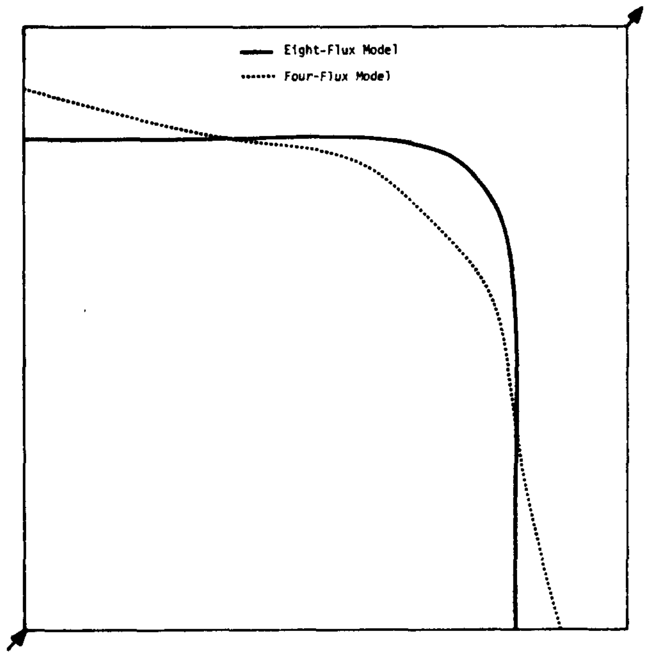

FIGURE 11

Calculated Water Front Position at 60% Conformance.

INTERPRETATION OF RESULTS

Examination of Figs. 8, 9, 10, and 11 shows that the eight-flux fronts are considerably more radial, as they realistically should be. Comparatively, the four-flux run shows frontal advancement to be too slow in a diagonal direction and too fast parallel to the grid's axes. To illustrate this difference, a plot of the diagonal location of the 50 per cent water saturation line versus volumetric sweep was made for the two runs. (See Fig. 12.) Using the eight-flux results as a base, the per cent "error" incurred in the four-flux results were computed by the formula:

$$\text{Error} = \frac{C_8 - C_4}{C_8} \times 100$$

where,

C_8 = eight-flux conformance
C_4 = four-flux conformance

These results are also plotted on Fig. 12. As might be expected, the "error" is largest when the flood front is still in the vicinity of the injection well. It is interesting to note that the data from these tests extrapolate to give a maximum "error" value of 42 per cent at the beginning, which compares favorably with the maximum increase in flow-path length of 41.4 per cent caused when the fluids travel in a stairstep fashion rather than diagonally. As the front traverses more and more grids, the per cent difference decreased to a low of 15 per cent. In general, these results show that the rate of diagonal frontal advancement in situations similar to those tested is 15-35 per cent slow when using the four-flux procedures.

Figure 13 shows a comparison of the four-flux and eight-flux frontal positions measured parallel to the grid axes rather than diagonally. Here, the "error" is similar in magnitude to the diagonal "error" except in the opposite direction. Accordingly, in these situations one can expect the rate of frontal advancement in the four-flux models to be 20-30 per cent faster than the rates computed when using eight-flux procedures.

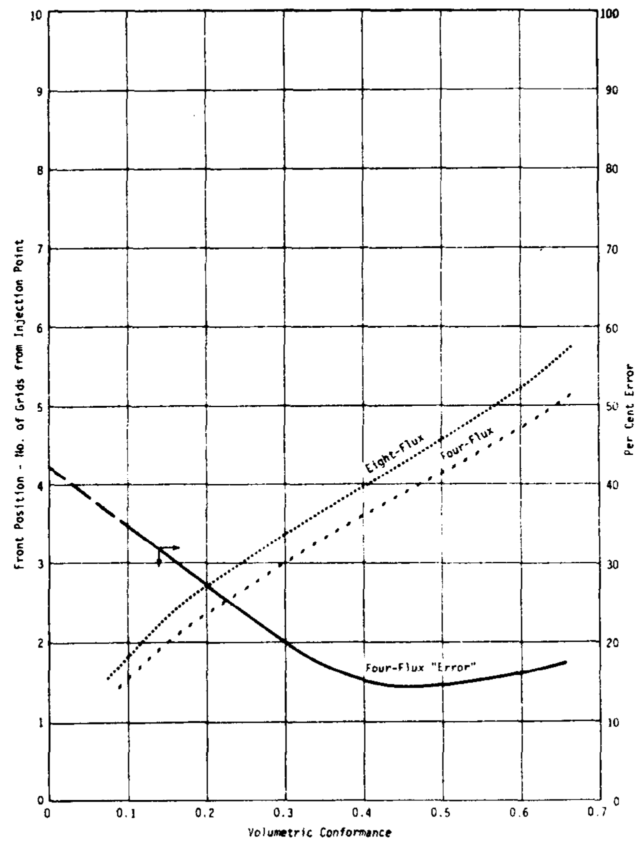

FIGURE 12

Comparison of Flood Front Advancement Diagonal to Grid Axes.

SIGNIFICANCE OF FRONT TRACKING IN FIELD SIMULATION

The significance of obtaining the most accurate front tracking capabilities can be illustrated with reference to Fig. 1. In this hypothetical situation water is injected into four wells as shown by the triangles. The producing wells labeled A and B, being reasonably close to two of the injectors, are key wells in the sense that it is important that the user cause the simulator to duplicate the actual performance as has been observed in the field. In other words, it will be necessary for an engineer to, within reasonable limits, modify the block properties in the vicinity of these wells until the model predicts response at the same time and to the same degree that was observed in field operations. But observe what simulation errors may be caused in the event one is inaccurately tracking the waterfront. With respect to Well A, the injected water must approach it in a diagonal fashion from either of its two offsetting injection wells. If, through model restrictions, the water is not permitted to flow diagonally as rapidly as it should, the simulator will therefore put more water else-

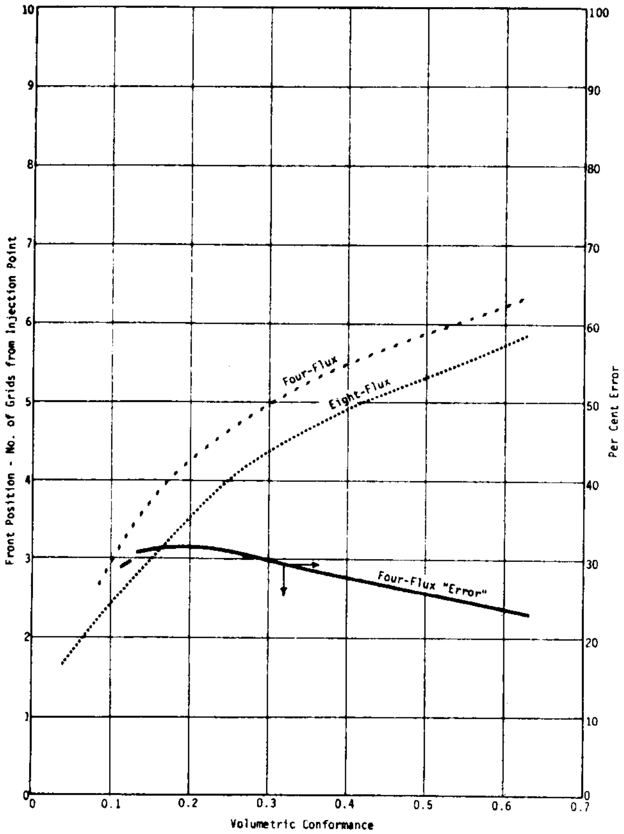

FIGURE 13

Comparison of Flood Front Advancement Parallel to Grid Axes.

where with the result that it will accept more water than it should before calculating breakthrough in the diagonally located producing well. This will result in the user of the simulator needing to provide less space for the injected water to occupy so that it will show up sooner in producing Well A. He will accordingly have to decrease the net pay or increase the residual oil saturation.

With respect to Well B, the injector to the south of it has a direct "shot" at it. An error in front tracking as described earlier will cause the simulator to predict the water to arrive at this well sooner than it really should and accordingly the engineer will be increasing the net pay south of producing Well B or decreasing the residual oil to match field performance. As shown in Figs. 12 and 13, depending solely on whether a well was diagonally or directly offsetting an injector, the net pay in a typical simulation study may be varied from 40 to 65 feet when the true pay was 50 feet.

CONCLUSIONS

1. The simulation of injection operations (water injection or gas injection) requires special attention to front tracking and the bubble-point problem.
2. A convergence procedure for solving the transition through the bubble point has worked well in modeling experience with little material balance error.
3. The use of the eight-flux procedures as opposed to the four-flux procedures gives a good approximation for the actual placement of flood fronts without noticeably reducing the computational efficiency.
4. Failure to account for the diagonal travel of flood fronts can lead to substantial modeling error.