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NUMERICAL CONING APPLICATIONS

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ABSTRACT

This paper discusses the effect of completion interval on aquifer storage operations. The study was performed using a single-well, two-dimensional reservoir simulator model.

Results are presented for two reservoir geometries, a homogeneous and a highly stratified heterogeneous reservoir model. For both geometries, the effect of completion interval upon such parameters as water arrival time, injectivity and productivity indices, and gas bubble thickness were studied for two different rate schedules. Results showed that completion interval did not affect bubble thickness for the homogeneous model, but did show some effect for the heterogeneous model. For both models the depth and length of completion interval did affect such parameters as water arrival time, water cut and productivity indices.

INTRODUCTION

Well completion intervals and depths used in aquifer storage operations frequently consist of five or ten feet perforated intervals located immediately below the caprock. In some cases the gas bubble thickness as estimated from neutron logs seems to stabilize or at least grow very little from year to year when thickening would be expected due to gravity drainage and/or inventory growth during the early life of the storage operation. The question then arises as to whether recompletion from a small perforated interval of five feet to a larger interval of fifteen or twenty feet might tend to thicken the bubble as well as

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References and illustrations at end of paper.

increase the injectivity and productivity indices. A counter argument to this proposal is the claim that in reservoirs where "reasonable" vertical fluid and pressure communication exist, the completion interval has little or no effect on bubble thickness, and in fact would only increase water production problems during the withdrawal stage of operations. A problem arises in how does one decide what is reasonable vertical communication. Obviously where there is no vertical communication as in the case of noncommunicating layers, the longer the completion interval, i.e., more individual layers opened to injection, the better the expected performance will be as long as the injection is balanced between the layers. Most real cases lie between these two extremes, that of complete and zero vertical communication, so an uncertainty does exist as to whether a deeper completion interval would improve or worsen overall performance.

The questions that this paper investigated are:

(1) In aquifer storage operations, what is the effect of completion interval or the proper interval for an injection-withdrawal well so as to:

    (a) create as thick a bubble as possible within the limit of control that an injection well has on the thickness

    (b) give as high productivity and injectivity indices as possible

    (c) minimize water cut during withdrawal?

(2) To what extent are the answers dependent upon reservoir heterogeneity and rate of operation?

A secondary question examined in this paper is the effect of reducing the completion interval during the withdrawal cycle upon reducing water cut and increasing the time before water arrival occurs.

Only recently has the capability arisen to efficiently simulate on the computer two and three phase displacements in the drainage area of a single well, taking into account the sharp fluid saturation gradients that exist near the wellbore [1, 2, 3]. The simulator used in this study was a two-phase, two-dimensional model that predicts saturation and pressure distributions versus time for compressible fluid flow. The equations describing the model are well known and given in the three aforementioned references.

THE RESERVOIR MODELS

Two reservoir models were chosen with two significantly different reservoir descriptions. The first was a homogeneous model with a constant vertical and horizontal permeability of 750 md. The second was a highly stratified model with the top twenty feet of sand having permeabilities varying from 10 to 1,490 md. Porosity was assumed to be constant for both models at 20 per cent, and the wellbore and external radii were assumed to be 3.3 inches and 2,980 feet, respectively. Figure 1 shows model details for both cases. The initial condition was taken to be a gas bubble following a shut-in condition at the end of a withdrawal season. The initial gas saturation distribution consisted of 8 feet of gas below the caprock, underlain by 227 feet of water in the total thickness of 235 feet. Initial pressure was 1,000 psia. The initial gas in place associated with the single well drainage volume was 2.65 BCF. The use of a circular system with closed external radius of 2,980 feet corresponds to the situation of a number of wells spaced approximately one to a square mile section, all injecting and producing at equal rates from a formation with a slightly dipping caprock.

In all cases gas was injected at 10 MMCF/day for 90 days and then produced at constant rates of 10 MMCF/day in some cases and 3 MMCF/day in other cases. The injection of 0.9 BCF into the initial 2.6 BCF of gas in place, followed by the subsequent withdrawal of roughly 0.9 BCF corresponds to a top storage of 0.9/3.5 or about 26 per cent which is a reasonable figure for an aquifer storage reservoir. Table I gives all pertinent data concerning volumes in place and production rates.

The variables that were predicted in all cases were the gas saturation distribution, the pressure distribution, water arrival time and water cut performance, and the productivity and injectivity indices. Equivalent bubble thicknesses were obtained from the gas saturation distribution.

RESULTS

Figure 2 is a plot of gas bubble thickness versus distance from the well at the end of the 90 day injection cycle and a 20 day production cycle and shows absolutely no effect of well completion interval on bubble development thickness for the homogeneous 750 md. reservoir model. Figure 3 shows the effect of rate of withdrawal for the homogeneous with good vertical communication. This shows that a production rate of 10 MMCF/day is too high for this reservoir but indicates the directional effect of greater water problems associated with the deeper 20 foot completion interval. If a water-gas ratio of 20 BBLS/MMCF is taken as a reasonable level for well drown-out, the 20 foot interval would produce for only 5 days while the 5 foot interval would produce for 8 days. Figure 4 shows the same data as Figure 3 but for a more reasonable production rate of 3 MMCF/day where a more significant effect of completion interval is seen. The well produced for 40 days from the 5 foot interval before watering out, but produced for only 20 days from the 20 foot interval. Figures 3 and 4 also indicate the well known difficulties inherent in using aquifer storage for peaking (high rates over short time periods) as opposed to base loading. Figure 5 shows that the higher water cut problems introduced by the 20 foot interval are at least partially offset by a higher PI, meaning a higher wellbore pressure. A higher wellbore pressure means that the well has the ability (potential) to produce at a higher water-gas ratio. A recent paper by Tek [4] gives a method for predicting well lifting capacity, which technique should be combined with the coning calculations to determine when a well waters out as a function of completion interval and rate. Using this combination it should be possible to select optimal rate-completion intervals for any specific operation. This would allow an operator to maximize gas recovery and could probably be used to optimize base load and peak load requirements for any aquifer storage field. A general conclusion for this paragraph is that in aquifers where there is good vertical communication, deeper completion intervals do not affect bubble thickness, but significantly worsen water cut problems. This conclusion was reached from a study of only the homogeneous reservoir with good vertical and horizontal permeabilities.

Figure 6 is a plot of gas bubble thickness versus distance from the well at the end of the 90 day injection cycle and a 60 day production cycle for the stratified reservoir model. The figure shows that completion interval affects the bubble thickness only out to a radius of 200 feet. After 200 feet, the bubble thicknesses are virtually identical for both the 5 and 20 foot interval cases. Figure 7 shows appreciably worse water cut problems for the 20 foot completion interval, which is in part due to distributing the same total amount of gas more "thinly" in the top 4 layers, than is achieved by injection into only the single top layer (each layer was 5 feet thick, so the 5 foot completion interval covered only one layer while the 20 foot interval was spread over the top 4 layers). Figure 7 also shows that recompletion of the 20 foot interval to a 10 foot production interval after 32 days of withdrawal, had only a temporary effect on water production, as by 60 days the 10 foot interval was again producing at a water-gas ratio of 43 BBLS/MMCF. Figure 8 shows the effect of completion interval on the productivity and injectivity indices for the stratified reservoir, which again shows the larger interval to give improved indices.

As mentioned earlier in this paper, most real reservoir cases will lie between complete and no vertical communication. A general answer to the problem of the effect of completion interval is, therefore, difficult to obtain, since so many different layered and areal heterogeneities can be considered. Meaningful answers to the questions will probably come only in context of specific situations where layer properties are obtained from core and log data and history matching is done using a coning (single-well) reservoir simulator.

CONCLUSIONS

1. In a reservoir with good vertical communication, completion interval has no effect on bubble thickness and a deeper completion will result in increased water production problems during a withdrawal cycle.

2. For a highly stratified system studied in this paper, the effect of completion interval upon bubble thickness was a localized effect that was observed only within 200 feet of the wellbore. The effect of the deeper completion interval was again to increase water production problems.

3. In reservoirs of complex heterogeneity or suspected poor vertical communication, the best method would be to study the specific problem and perform history matching.

REFERENCES

1. MacDonald, R. C. and Coats, K. H.: "Methods for Numerical Simulation of Water and Gas Coning," SPE 2796, presented at the Second Symposium on Numerical Simulation of Reservoir Performance, Dallas, Texas, February 5-6, 1970.

2. Spivak, A. and Coats, K. H.: "Simulation Techniques for Two- and Three-Phase Coning Studies," SPE 2595, presented at the 44th Annual Fall Meeting of the SPE, Denver, Colorado, September 28-October 1, 1970.

3. Ridings, R. L. and Letkeman, J. P.: "A Numerical Coning Model," SPE 2812, presented at the Second Symposium on Numerical Simulation of Reservoir Performance, Dallas, Texas, February 5-6, 1970.

4. Tek, M. R. and Gould, T. L.: "Steady and Unsteady State Two-Phase Flow Through Vertical Flow Strings," SPE 2804, presented at the Second Symposium on Numerical Simulation of Reservoir Performance, Dallas, Texas, February 5-6, 1970.

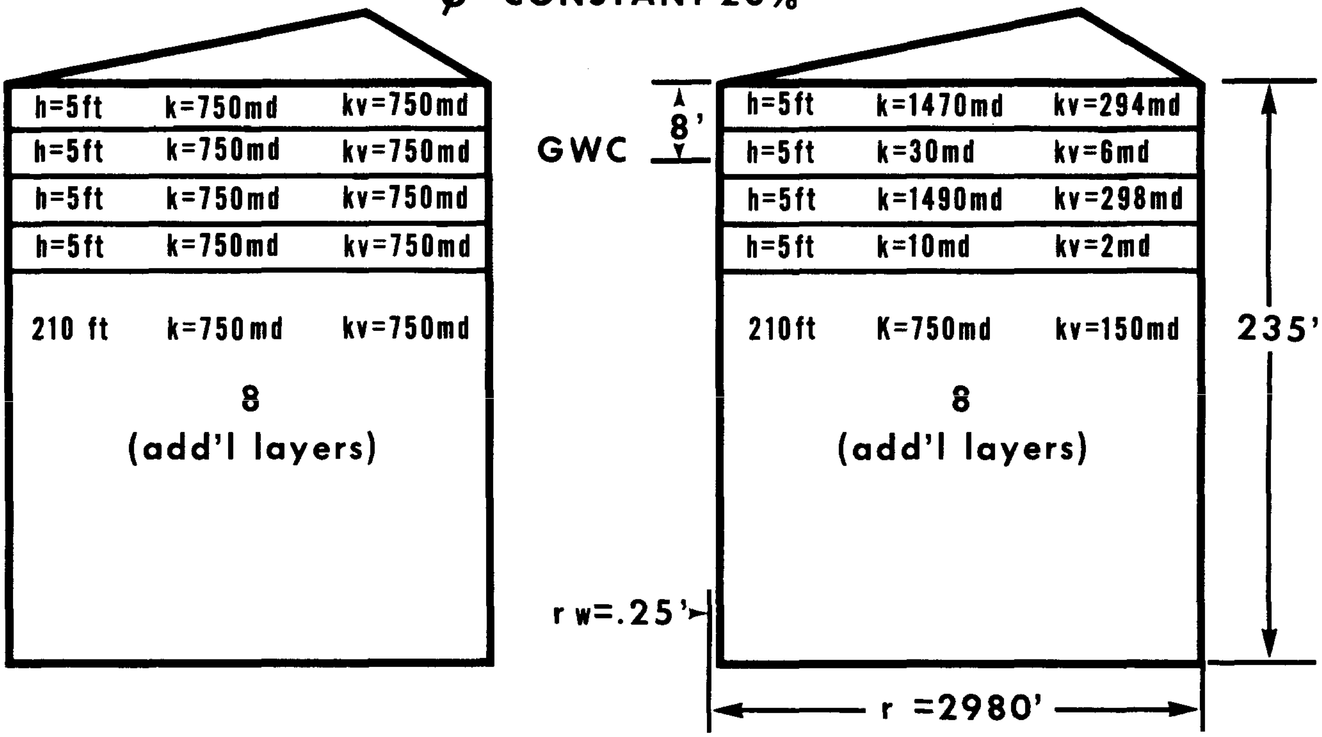
TABLE I

	Homogeneous Reservoir	Stratified Reservoir
Initial Gas in Place BCF	2.6	2.6
Initial Water in Place MMSTB	226.5	226.5
Injection Rate, All Cases MMCF	10	10
Production Rates MMCF/D	3 & 10	3 & 10
Initial Pressure psia	1,000	1,000
Pressure at End of Injection Cycle psia	1,248	1,248
Pressure at End of 40 days withdrawal	1,203 @ 3 MMCF 1,093 @ 10 MMCF	1,203 @ 3 MMCF 1,093 @ 10 MMCF

FIGURE 1

RESERVOIR DESCRIPTIONS

ϕ =CONSTANT 20%



HOMOGENEOUS CASE

STRATIFIED CASE

FIGURE 2

GAS BUBBLE THICKNESS vs DISTANCE FROM WELL

Homogeneous Reservoir

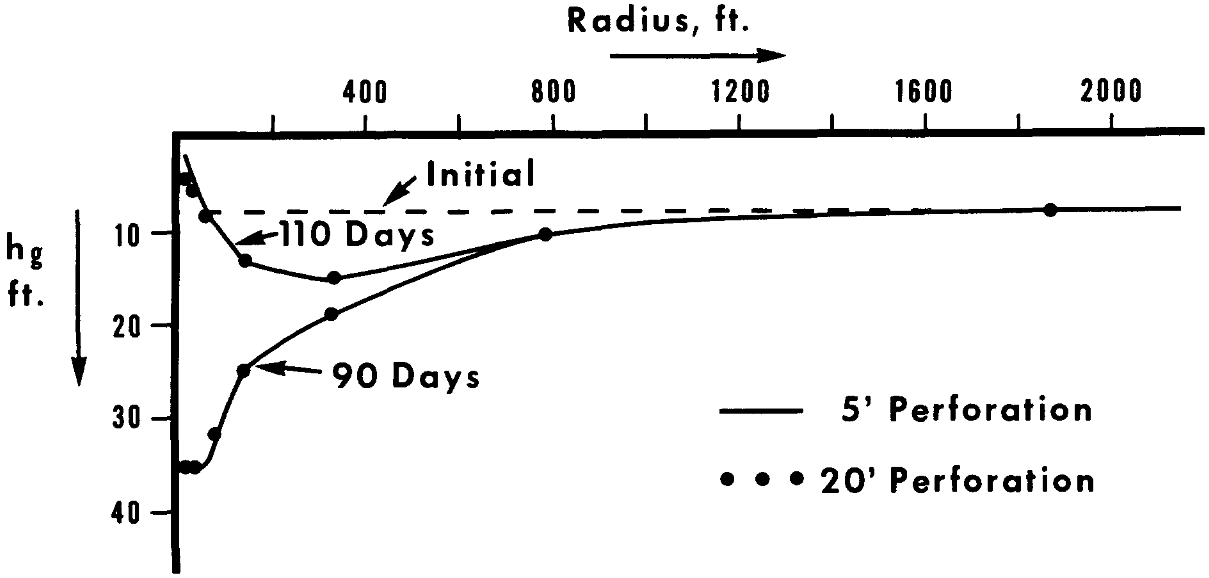


FIGURE 3

WATER–GAS RATIO vs TIME OF PRODUCTION

Homogeneous Reservoir
Producing Rate = 10,000 Mcf/d

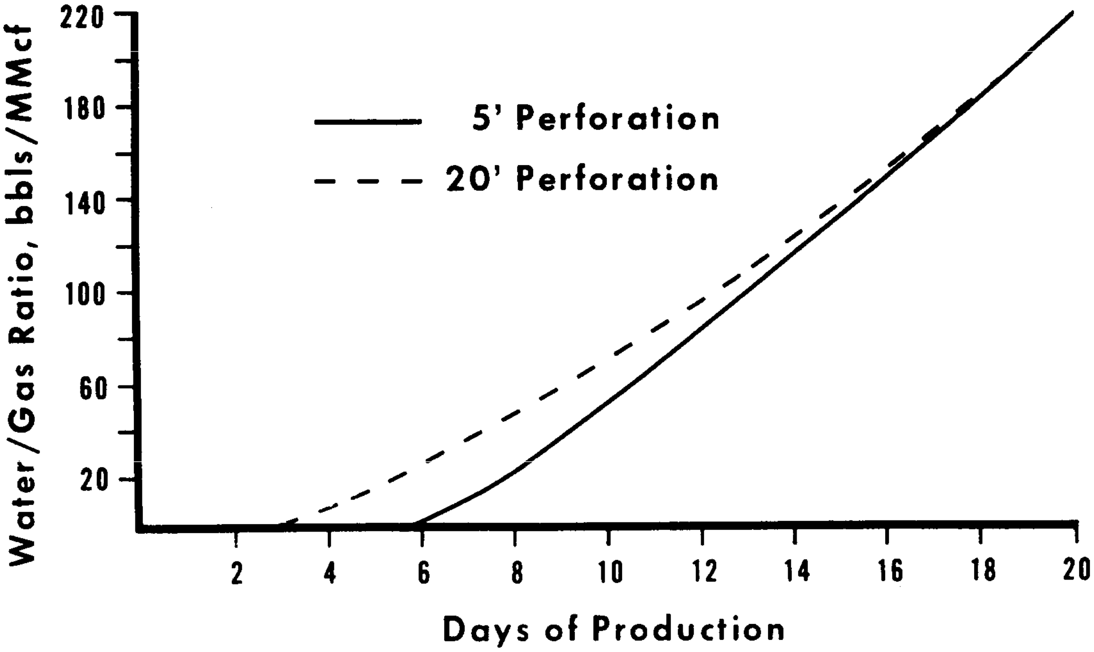


FIGURE 4

WATER–GAS RATIO vs TIME OF PRODUCTION

Homogeneous Reservoir
Producing Rate = 3,000 Mcf/d

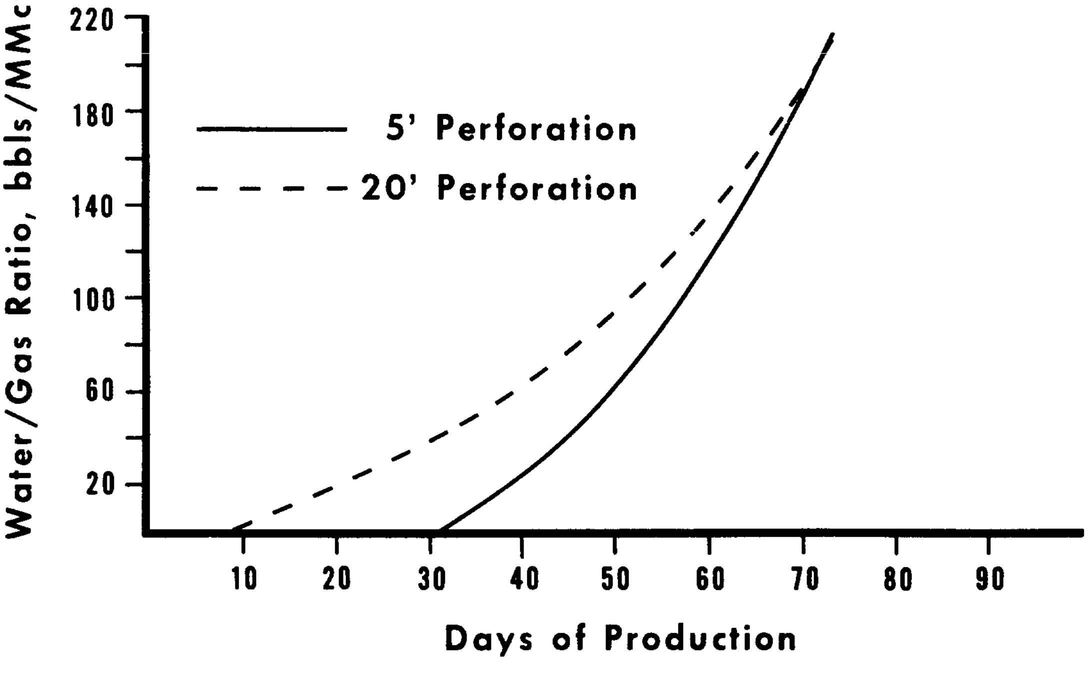


FIGURE 5

INJECTIVITY AND PRODUCTIVITY INDICES vs TIME

Homogeneous Reservoir

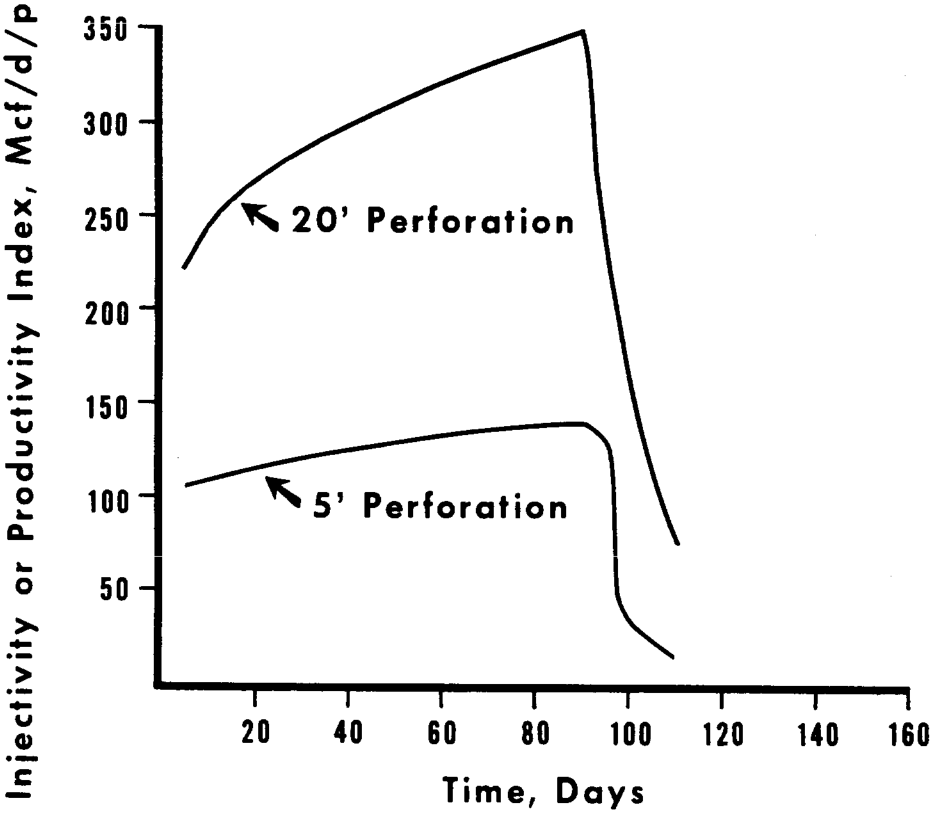


FIGURE 6

GAS BUBBLE THICKNESS vs DISTANCE FROM WELL

Heterogeneous Reservoir

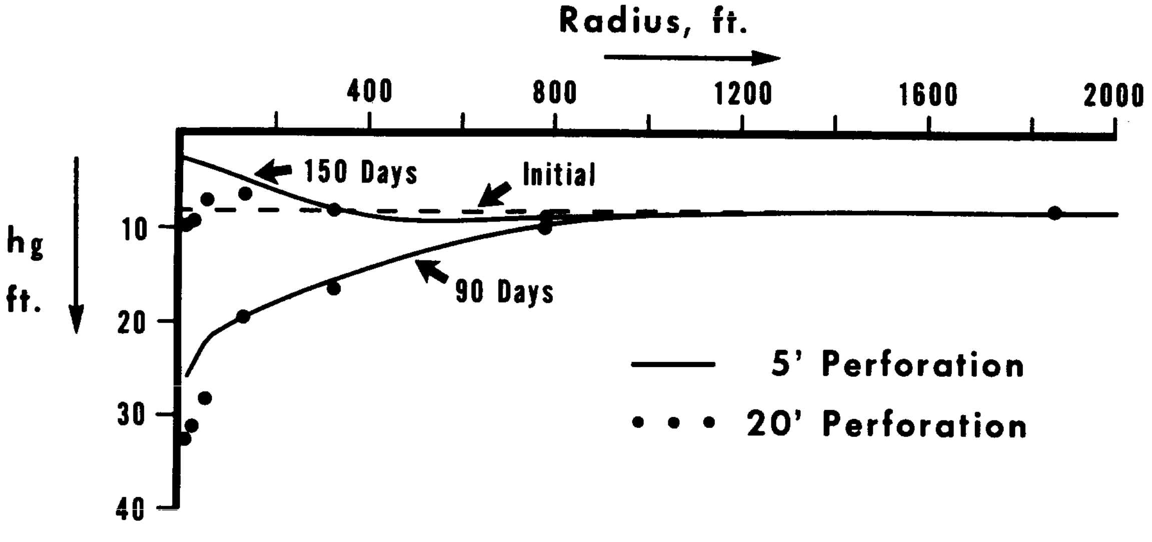


FIGURE 7

WATER–GAS RATIO vs TIME OF PRODUCTION

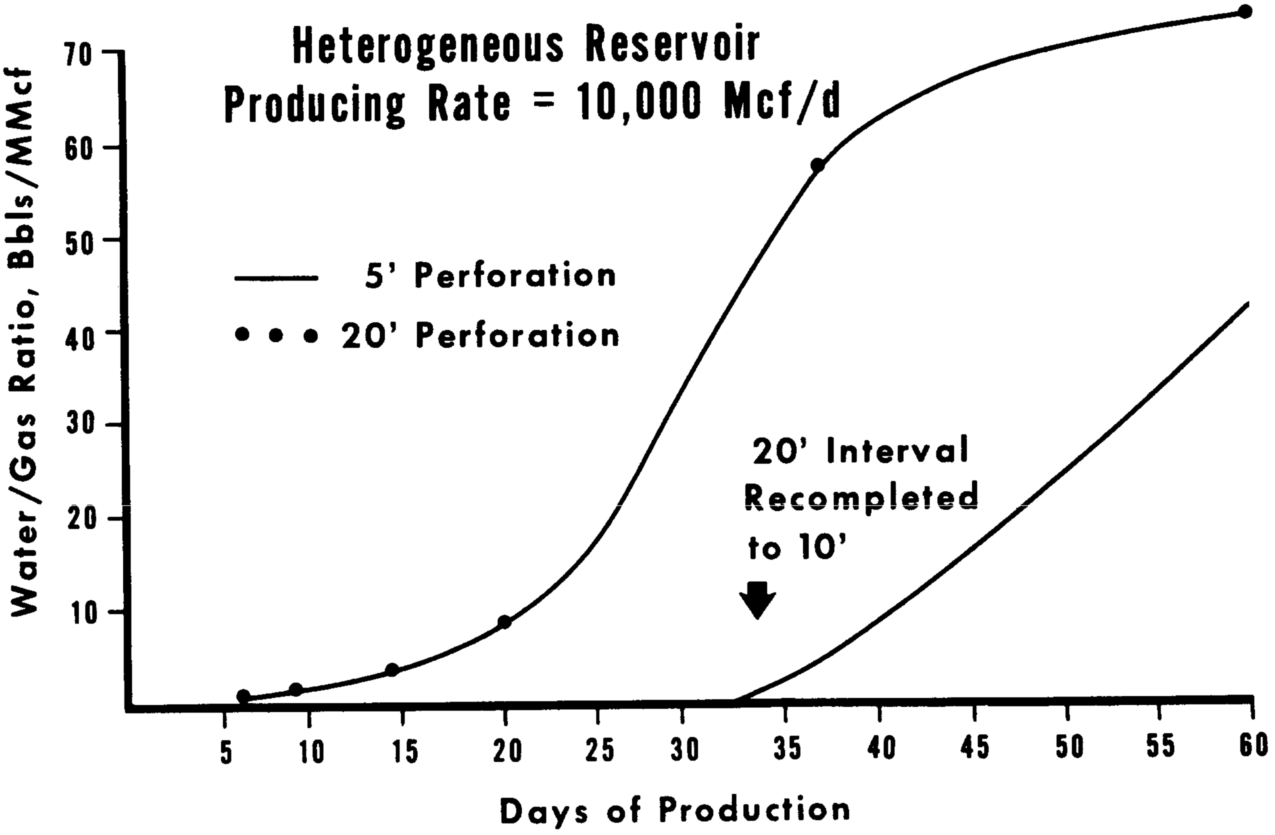


FIGURE 8

INJECTIVITY AND PRODUCTIVITY INDICES vs TIME

Heterogeneous Reservoir