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SPE 30775

Water Control Diagnostic Plots

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This paper was prepared for presentation at the SPE Annual Technical Conference & Exhibition held in Dallas, U.S.A., 22-25 October, 1995.

ABSTRACT

A new technique to determine excessive water and gas production mechanisms as seen in petroleum production wells has been developed and verified.

Based on systematic numerical simulation studies on reservoir water coning and channeling, it was discovered that log-log plots of WOR (Water/Oil Ratio) vs time or GOR (Gas/Oil Ratio) vs time show different characteristic trends for different mechanisms. The time derivatives of WOR and GOR were found to be capable of differentiating whether the well is experiencing water and gas coning, high-permeability layer breakthrough or near wellbore channeling.

This technique was applied on wells in several fields in Texas, California, the Gulf Coast and Alaska. Plots using the actual production history data determined the production problem mechanisms. Together with well tests and logs, the technique was used to select well treatment candidates and to optimize treatments to enhance the return of investment.

References and illustrations at end of paper.

INTRODUCTION

Over the last 30 years, technical efforts for water control were mainly on the development and implementation of gels to create flow barriers for suppressing water production. Various types of gels were applied in different types of formations and to solve different types of problems.[1,2] Quite often, excessive water production mechanisms were not clearly understood or confirmed. Although many successful treatments were reported, the overall treatment success ratio remains low.[3]

Through these field trials, the art of treatment job execution was progressively improved. Good practices in the process of candidate selection, job design, gel mixing and pumping and job quality control were recognized and adapted. More effective tools and placement techniques were also used. The desire to define different types of excessive water production problems began to surface.

In general, there were three basic classifications of the problems. Water coning, multilayer channeling and near wellbore problems are most noticeable among others. Field experience showed successful job design would not be the same for different mechanisms. However, there are no effective methods to discern these differences. In reality, the problem could be very complex, and usually is the combination of several mechanisms taking place over a period of time and compounding one with the other.

This paper presents a methodology which can be used to quickly diagnose and evaluate the mechanisms. It mainly uses plots generated from available production history data. The set of plots include (1) production history for the entire period or waterflood period for water, oil and gas, (2) WOR and its derivatives, (3) cumulative oil produced or recovery efficiency, and (4) oil and gas rate declines. These plots provide a composite picture of the past and current production behaviors and the remaining production potential of the well. The methodology can become an effective tool for the selection of water control treatment candidates to enhance treatment success.

CONVENTIONAL PLOTS

Conventionally, water cut vs time linear plots were used to show the progress and severity of the excessive water production problems.[4] The correlation between water cut or fractional water flow and average reservoir water saturation for two-phase flow is well known.[5] However, it is not practical since saturation distributions throughout the reservoir are changing with time. Averaging fluid saturation from material balance does not shed any light on fluid flow behaviors in heterogeneous formations. Although these plots can also show a drastic change in the water cut indicative of the sudden failure of well completion or rapid breakthrough of a high water conductivity channel, the information provided by water-cut plots is limited. Regardless of multilayer channeling or coning, the shapes of the water-cut plots are very similar.

Linear or semilog WOR plots have been used to evaluate recovery efficiency.[6,7] A special plot (known as X-plot) that uses a correlation of a modified fraction flow function with the recovery efficiency has also been shown to be capable of representing normal waterflood volumetric sweep efficiency.[8,9] These plots could be useful to evaluate production efficiency, but they do not reveal any detail on reservoir flow behaviors.

For multilayer flow, the WOR had been expressed as the ratio between the sum of the product of the permeability and the height of the water-out layers and that of the remaining oil production layer.[5] Again, this overall estimation approach in evaluating excessive water production behavior does not shed any clue on the timing of the layer breakthrough and the relationship between the rate of change of the WOR with the excessive water production mechanism.

DIAGNOSTIC PLOTS

A set of diagnostic plots have been generated by conducting a series of systematic water-control numerical simulation studies using a black oil simulator. This three-dimensional, three-phase simulator is capable of modeling the performance of reservoir flow under different drive mechanisms and waterflood schemes. Log-log plots of the WOR (rather than water cut) vs time were found to be more effective in identifying the production trends and problem mechanisms. It was discovered that derivatives of the WOR vs time can be used for differentiating whether the excessive water production problem as seen in a well is due to water coning or multilayer channeling.

Figure 1 shows a clear distinction between a water coning and a multilayer channeling development using the same set of PVT and saturation function data, permeability and porosity distribution, and having the same initial conditions. The only difference in the model setup is the flow geometry. For coning, a water/oil contact (WOC) was defined and a bottomwater influx was simulated by constant pressure water injection at the edge and only into the bottomwater layer. The top 20% of the oil zone was perforated. For channeling, the bottomwater layer was eliminated. The water injection was modeled with constant pressure water injection into all layers at the edge. All layers were perforated.

By inspecting Fig. 1, three periods of WOR development can be discerned. During the early time period, the WOR curves remain flat showing expected initial production. The value of the initial WOR depends on the initial water saturation and its distribution among all layers as well as the relative permeability functions. The time length of this period depends on the waterdrive mechanism and its ending is marked by the departure of the WOR from a constant value.

For coning, the departure time is often short depending on various parameters but predominantly on the distance between the WOC and the bottom of the nearest perforation interval, vertical-to-horizontal permeability ratio, bottomwater influx rate, production pressure drawdown or rate, and relative permeability functions. Physically, the water coning departure time is the time when the bottomwater cone has approached the bottom of the perforation interval.

For channeling, again the departure time depends on various factors but mainly on the well spacing, injection rate at the injectors, producer drawdown pressure or rate, initial water saturation and distribution among layers, and relative permeability functions. Physically, the departure time of the WOR curve for channeling corresponds to the water breakthrough at a layer in a multilayer formation. This layer may not necessarily be the layer having the largest permeability. The initial water saturation and its distribution in the layers may become a very dominant factor, if the permeability contrast among the layers is not large.

The second time period shows the WOR increasing with time. The rate of increase differs for a different problem mechanism. Figure 1 shows a striking difference between coning and channeling. For coning, the rate of the WOR increase is relatively slow and gradually approaches a constant value at the end of this period. During this period, the bottomwater cone not only grows vertically upward to cover most of the perforation interval but also expands radially. The oil saturation within the cone is gradually decreased to the residual oil saturation level.

For channeling, the water production from the breakthrough layer increases very quickly. Accordingly, the WOR increases relatively fast. The slope of the water channeling WOR depends on the relative permeability functions and initial saturation conditions. At the end of this second period, the WOR increase could actually slow down entering a transition period. This corresponds to the production depletion of the first breakthrough layer. The end of this transition period shows the WOR increase resumes at about the same rate. This corresponds to the water breakthrough at the next highest water conductivity layer.

The transition period could be very short depending on the layer permeability contrast. Typically, the transition period could become insignificant when the layer permeability contrast is less than 4. The change of the WOR in the transition period was found to be also affected by the layer crossflow and capillary pressure function.

In the third period and for coning, a pseudosteady-state cone has been developed. The well mainly produces bottomwater. The water cone becomes a high water conductivity channel. The WOR increase becomes very fast resembling that of a channeling case. This second departure point can be regarded as the beginning of the third period. For channeling, the WOR increase resumes the same rate after going through the transition period. The second highest water conductivity layer is being depleted. All channeling WOR slopes, including the one in the coning situation, would be very close because they are mainly controlled by relative permeability functions.

Further extensive studies repeatedly confirmed that the time derivatives of the WOR can be used to differentiate coning from channeling. Figures 2 and 3 show the WOR and WOR' derivatives for channeling and coning, respectively. The WOR' (simple time derivative of the WOR) shows nearly a constant positive slope for channeling and a changing negative slope for coning. The WOR' trend for channeling behavior in the third period of a water coning situation is shown in Fig. 4. Again, the WOR' vs time plot shows a positive slope.

The WOR derivative plot becomes very helpful to determine the excessive water production mechanism when limited production data are available. Figure 5 illustrates this advantage. The limited data were obtained from the results of the Second SPE Comparative Solution Project which involved a case study for bottomwater coning.[10] The apparently increasing WOR trend shown in Fig. 5 could be easily taken as layer channeling. However, the WOR' shows a negative slope, characteristic of a coning case.

For gas coning in an oil well, water coning or channeling in a gas well, or gas and water coning in an oil well, the GOR (Gas/Oil Ratio) or WGR (Water/Gas Ratio) and their derivatives can be used. Again, slopes of the GOR' and WGR' vs time curves indicate different mechanisms: positive slope for channeling and negative slope for coning. An example of the GOR and GOR' plot is shown in Fig. 6.

For a strong bottomwater drive, the well spacing becomes a key factor for the occurrence of the second departure point from coning to bottomwater channeling. Figure 7 shows a series of simulation plots as a function of well spacing (10- to 150-acres) and at a vertical-to-horizontal permeability ratio of 0.1. For 10- to 20-acres spacing, the second departure point becomes indiscernible. Bottomwater appeared to be just channeling up vertically to the perforations which are located at the top of the production formation. The larger the well spacing, the further the delay of this departure time. This phenomenon would also depend on several other factors, such as drawdown rate or pressure, water influx rate, and again the relative permeability functions.

Immediately after the beginning of the waterflood, injection water could very rapidly break through very high conductivity channels or (thief) layers. For instance, a 3-ft layer having a 10-darcy permeability among the 100-md adjacent layers could become a water recycling conduit. Figure 8 shows such a situation in the WOR change. The WOR rapidly increases after the injection water breakthrough at the production well. With a high vertical-to-horizontal permeability ratio, the water could cone up at the wellbore and the water cone could rapidly expand to cover the entire zone. At this time, the water production rate starts to approach the total injection rate. The WOR' curve in Fig. 8 shows this evolution: a very steep positive slope within a very short time after water breakthrough, followed by a period of a negative slope indicative of cone buildup and a late period of gradual positive slope corresponding to the completion of the water-recycling conductive vertical channel construction.

VERIFICATION

Support from the operating companies was overwhelming during the long process of the diagnostic plot verifications. The monthly average production rates and, in a few cases, the daily rates were provided together with the well workover history, logs and recent well test results. Numerical simulations for an individual well or for a group of wells involved in a displacement pattern were also conducted for further confirmation of complex problem mechanisms, which usually entailed a different problem mechanism for a different time period and a superposition of these problems.

Figure 9 shows an excellent example of a good and normal production process in a linedrive waterflood displacement process in a multilayer sandstone formation in California. Note that the first WOR departure point and the slope are clearly defined. In this second period, the WOR' plot shows a clearly linear and positive slope, characteristics of a water channeling case. The duration of this period was about 4000 production days or 11 years. This reflects consequential water breakthrough at several layers or intervals which have a small permeability contrast (< 4). There occurred two to three times, near wellbore incidents in the late time period, as shown by the spiking of the WOR and particularly WOR' in the plots. At these points, the WOR' values exceeded well beyond 1.

Production changes could affect the appearance of the diagnostic plots. These changes could be the change in drawdown pressure at the production well, and changes in the injection rate and layer injection distribution at the associated injection wells. Figure 10 is a good example showing the WOR and WOR' deviations from the linear slope in the second period. This well and the well shown in Fig. 9 are adjacent wells in a linedrive pattern. A nine-well linedrive model was progressively built to simulate the continuous changes in the producers and the injectors. The history match results confirmed that the causes of the deviation were the pressure distribution changes and the disproportional overall water and oil production corresponding to the changes in the drawdown pressure in each layer. Note that the WOR regains the original slope after achieving a pseudostable pressure condition.

For some reservoirs, the initial WOR could be very high. A good example is shown in Fig. 11. It is for a typical well producing from a limestone/dolomite formation in west Texas. The initial WOR was about 4 (80% water cut). The reason could be a high initial water saturation. Waterflood started in this field at about 2000 days. The overall WOR trend shows a linear slope indicative of a normal displacement behavior. For this well, the WOR slope is about 0.5.

In certain parts of the formation, there could be high-permeability streaks or fissured layers associated with the wells in a waterflood displacement pattern. Rapid water breakthrough can be seen at the producers. Figure 12 shows this drastic WOR increase from a well producing from a dolomite formation in northeastern New Mexico. Note that the initial WOR was less than 0.1. The WOR slope was about 4 and recently shifted very fast to larger than 10. The WOR' drastically changed as well, a symptom of rapid water breakthrough.

For water coning, a good sandstone example from the Gulf Coast area is shown in Fig. 13. At around 1000 days, water coning began and the WOR derivative started to decline and show a changing negative slope. Construction of a pseudosteady-state cone was completed at about 2000 days (3 years later). Since then the cone became a water channel for producing bottomwater, and the WOR showed a linear positive slope.

Quite often, a near wellbore problem could suddenly occur during a normal displacement and production. Figure 14 shows such a dramatic event taking place recently in a sandstone Alaskan well. The initial WOR was constant but above 1. The WOR rapidly increased and followed a linear slope (about 3) after the implementation of a waterflood. Recently, the WOR increase accelerated and the slope turned almost to infinity. The WOR' trend and evolution substantiated this analysis. The peak WOR' was a very high value of 10. The well was then treated with a small volume of polymer gel. Posttreatment results showed the water rate was reduced by 50%.

RECOMMENDED PRACTICES

The available production history data base could be very large. There could be a different production mechanism for a different period of time. The following is a partial list of possible production changes and workover operations that could trigger a change in the production history:

- reservoir pressure decline
- production decline due to skin damage
- implementation of waterflood or gas displacement
- addition or alteration of perforations
- choke size adjustment
- gas lift vs flowing

- reservoir and well stimulation
- cement squeeze.

A good practice is to plot (log-log) the entire production history to get a big picture, and then discern the periods in which the production mechanism changes. Select any period of interest and plot the WOR or other variations (such as GOR and WGR) with their time derivatives to identify the excessive water production mechanism in that period. This should be done not only for the wells with known water production problems, but also for good wells in the same area producing from the same formation. Some suggested procedures include the following:

- look for the normal production behavior
- determine the normal WOR or GOR or WGR slopes
- check the trend of their derivatives
- use expanded plots for the period of interest.

A good example is a well in the Midland area. The entire production history is shown in Fig. 15.1, and its associated diagnostic plots are in Fig. 15.2. It shows four distinctive periods of productions.

The first period was from well production start-up to about 1200 days (May 1961 to July 1964). In this period, the oil rate was progressively increased in three stages by altering either one or several of the above-mentioned production change implementations (adding new perforations, increasing choke size, changing into bigger pump, etc.). The WOR values in the period remained flat and constant at or about 0.4, 0.2 and 0.3, respectively.

The second period was from about 1200 days to 3100 days (July 1964 to October 1969). The oil rate started to decline and the water rate started to increase. The WOR plots showed an initial normal depletion followed by an accelerated WOR change which could be induced by a rapid layer depletion as hinted by the peak value of the WOR'.

The third period was from 3100 days to about 7000 days (October 1969 to August 1980), which showed a very unique condition in which all phases (oil, water and gas) of the production rates decline simultaneously. This was due to gradual reservoir pressure depletion. In other cases, it could be due to the development of a skin damage but normally within a much shorter time period. A pressure testing could be used to discern the difference if needed. A waterflood program was implemented at the end of this period.

The expanded plots for this waterflood period are shown in Figs. 15.3 and 15.4. For the first two years, the water displacement process appeared to be quite normal, although there was no oil rate response until April 1982. A bigger pump was used in July 1982. The oil rate gradually increased to about 50 BOPD in December 1985. The water rate increased accordingly. The WOR plots in Fig. 15.4 showed a constant value for this period.

A submersible pump was installed in early 1986. The oil rate began to rapidly decrease and the water rate accelerated. The WOR plots showed a drastic change in slope when the WOR' reached a very high value of 100. The water rate was 3000 BOPD with a WOR of 3000. This is a very clear case of rapid layer breakthrough and water recycling.

The well received a gel treatment in 1993. Since then, the well has been producing about 600 BWPD and 15 BOPD with a normal decline behavior. Recently, the WOR has been around 45 (97.8% water cut).

CONCLUSIONS

It can be concluded that the log-log plot of production data and the WOR provide more insight and information for well performance evaluation. It can be applied either for the entire well life or any chosen period, such as the waterflood period. With a detailed workover history, the results of the analysis improve the understanding of reservoir flow behavior and determine the predominant mechanisms of excessive water production.

Using the WOR' (time derivative of WOR), coning and channeling can be discerned. Furthermore, the change in slope of the WOR and WOR' and the value of the WOR' become good indicators to differentiate normal displacement and production behavior, multilayer water breakthrough behavior, rapid layer depletion and water recycling behavior.

This technique has several advantages:

1. It mainly uses available production history data.
2. It can be used to rapidly screen a great number of wells.
3. It entails the best reservoir engineering principles and practices.
4. It could yield results to form the basis for conducting a production mechanism survey, compare mechanisms between adjacent wells, good production wells vs problematic production wells, and by area or by well pattern.
5. With the WOR vs cumulative oil production plot and the oil rate decline curves, it would become an effective methodology to select candidate wells for water control treatments.

There should be more production and reservoir engineering opportunities and benefits by using this diagnostic technique as one further progresses along this approach.

ACKNOWLEDGMENTS
The author wishes to thank ARCO Long Beach Incorporated, THUMS, City of Long Beach Department of Oil Properties, and ARCO Alaska for their strong support during the early part of this technique development; Chevron engineers in Midland, New Orleans, Lafayette, LaHabra and Houston for their belief and appreciation in this concept and approach, and technical support in this project; and Amoco engineers in Houston, Midland and Calgary for data support and untiring technical discussions. Special thanks are extended to the management and engineers of Schlumberger Dowell for their persistent encouragement, particularly Joe Mach for his unswerving support during the development of this technique, and Sharon Jurek for her help in the preparation of this manuscript.

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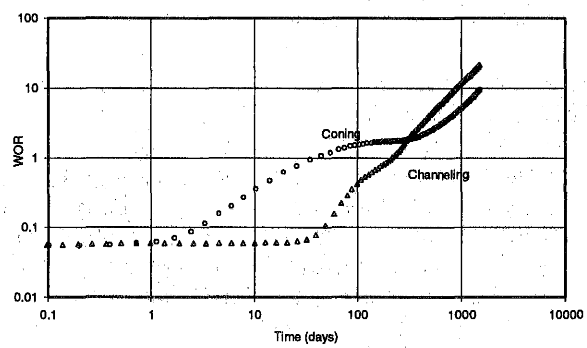

Figure 1—Water coning and channeling WOR comparison.

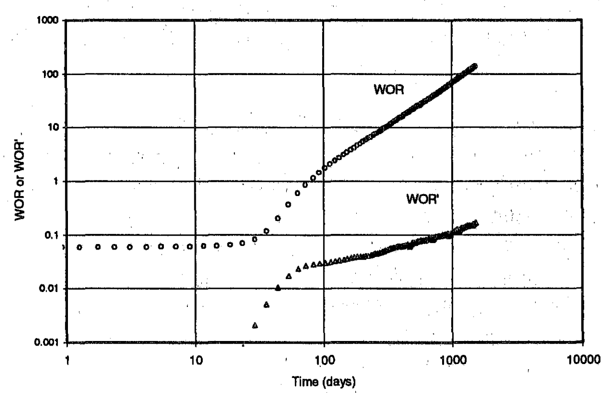

Figure 2—Multilayer channeling WOR and WOR' derivatives.

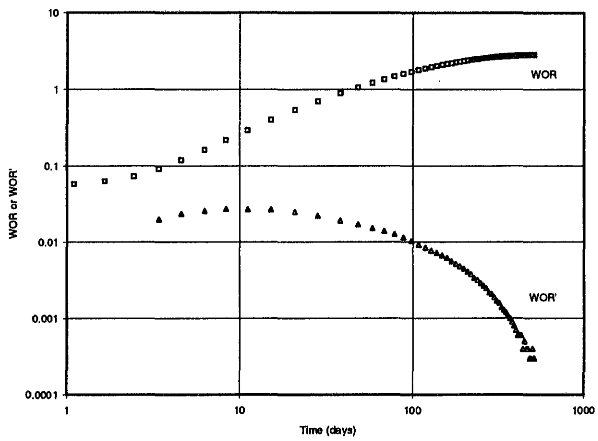

Figure 3—Bottomwater coning WOR and WOR' derivatives.

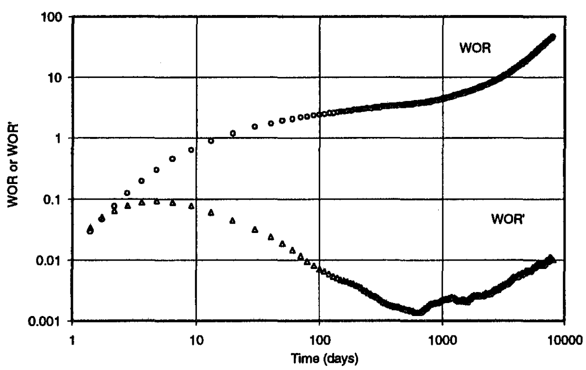

Figure 4—Bottomwater coning with late time channeling behavior.

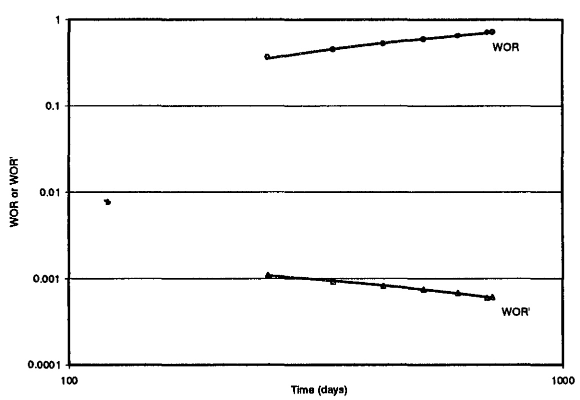

Figure 5—WOR and WOR' derivatives from the coning case history of the second SPE comparative solution project.

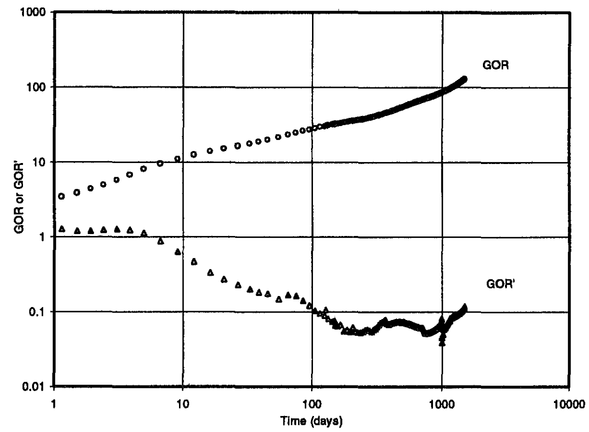

Figure 6—GOR and GOR' derivatives for gas coning in an oil well.

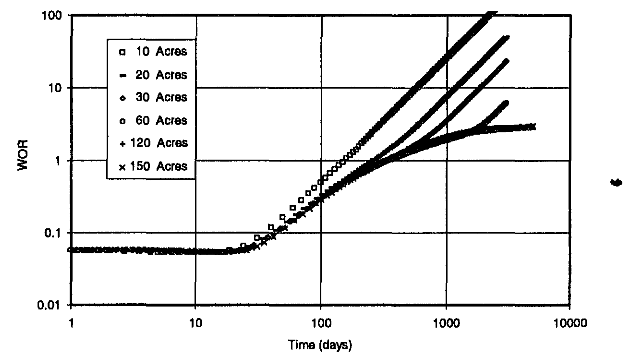

Figure 7—Bottomwater coning WOR vs well spacing.

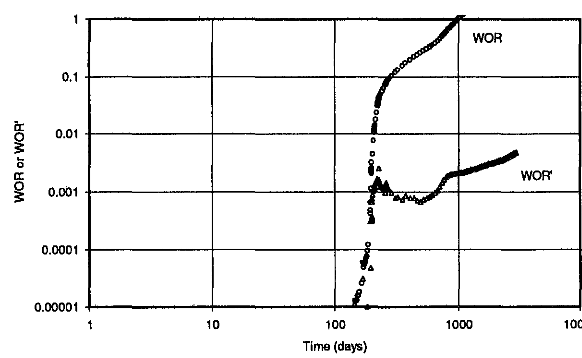

Figure 8—WOR and WOR' derivatives for thief layer water recycling.

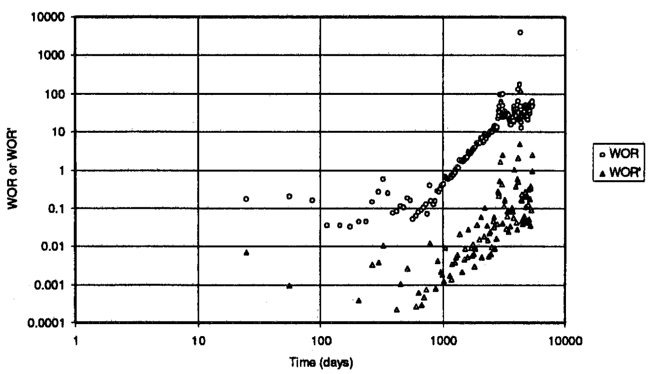

Figure 9—Field Example 1: Multilayer Channeling.

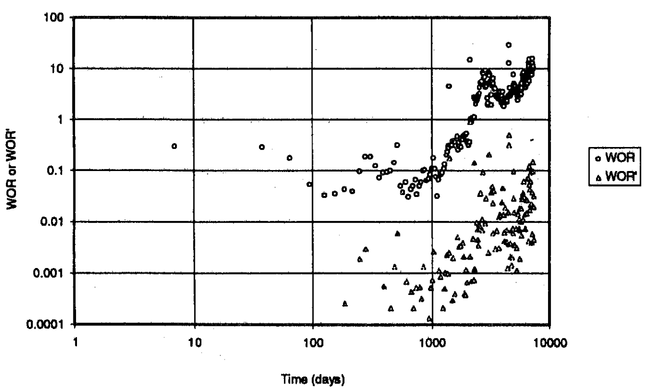

Figure 10—Field Example 2: Multilayer Channeling With Production Changes.

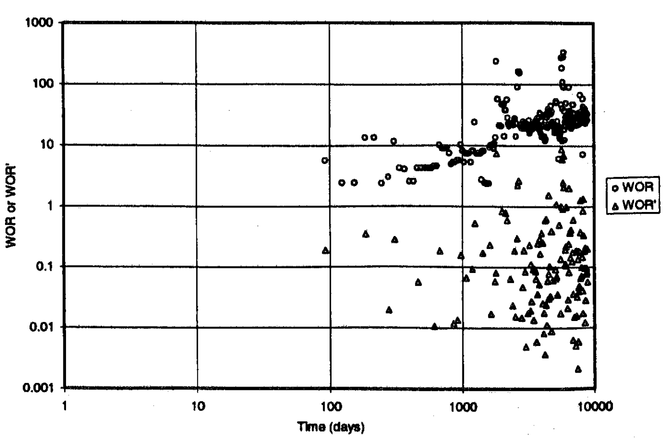

Figure 11—Field Example 3: Normal Displacement With High WOR.

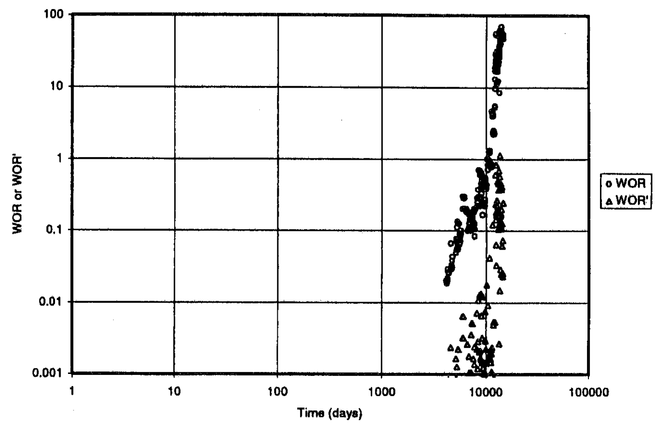

Figure 12—Field Example 4: Rapid Channeling.

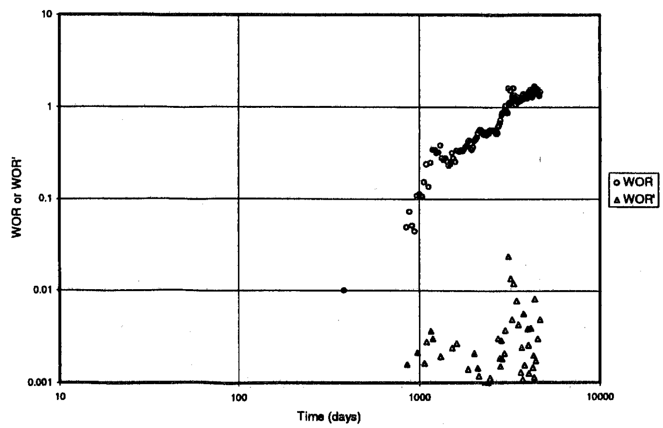

Figure 13—Field Example 5: Bottomwater Drive Coning.

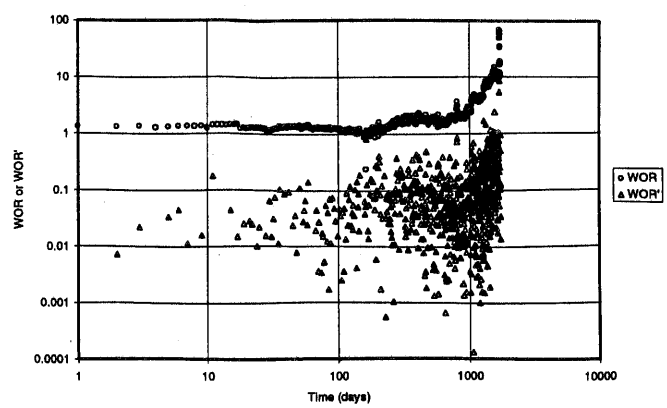

Figure 14—Field Example 6: Near Wellbore Water Channeling.

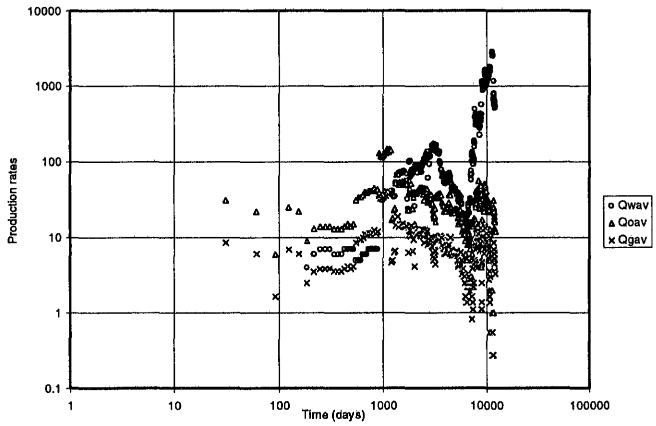

Figure 15.1—Field Example 7: Complete Production History.

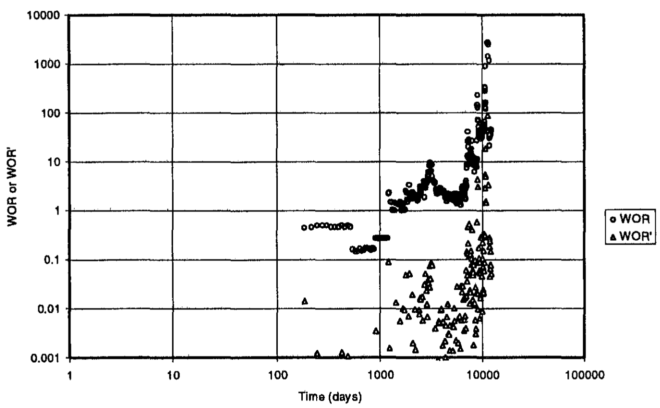

Figure 15.2—Field Example 7: Diagnostic Plots for Entire Period.

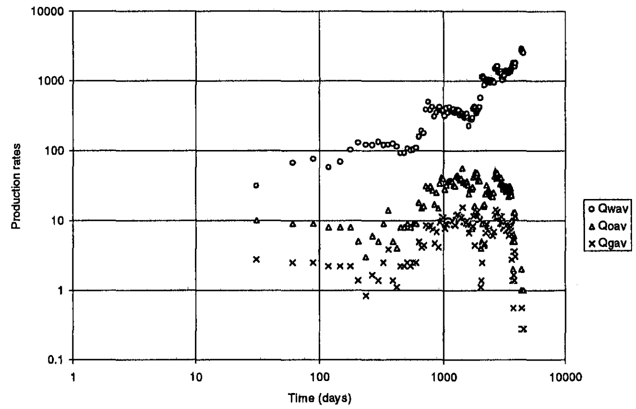

Figure 15.3—Field Example 7: Waterflood Production History.

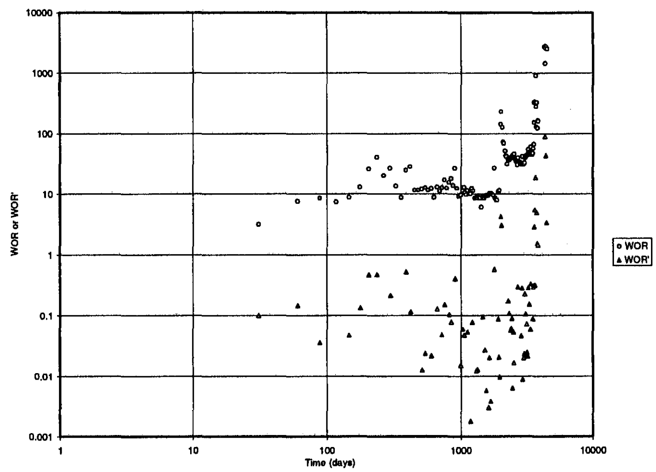

Figure 15.4—Field Example 7: Waterflood Expended Diagnostic Plots.