AN OBJECTIVE APPROACH TO ANALYZING WATERFLOOD PERFORMANCE

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Abstract

An easy-to-understand method of analyzing the performance of existing waterfloods is presented and its use is demonstrated with examples from West Texas and other areas. Example projects having both favorable and poor performance are shown. The recommended technique requires a detailed description of reservoir properties such as net thickness, porosity, oil and gas saturation, and compilation of individual wells' production and injection history. Graphic displays are used to define efficiency of individual flood elements. Comparison of elements within a waterflood are made to determine relative efficiency and further, which elements need an overhaul or are candidates for infill drilling.

The calculation procedures are based on a simplified material balance, decline curve analysis, water-oil displacement efficiency, and pressure performance of injection wells, but are easily hand done, not requiring computer assistance.

Statement of the Problem

Since the advent of waterflooding, there have been an abundance of calculation methods proposed for predicting future waterflood performance. Craig has listed 35 methods, so we can conclude the problems and solutions of predicting have been well-defined. The literature has, to a great extent been silent on methods the operating engineer can use to analyze the actual can-of-worms performance left to him by the reservoir engineer. We do not find that the problem of analyzing actual performance has been well enough defined to the point that the operating engineer has references to methods that provide for a thorough interpretation that can be carried on throughout the life of the flood. In the beginning, the operating engineer has a rate and reserve forecast, and more times than not, actual flood performance will be less favorable. This usually has resulted from the reservoir engineer underestimating the severity of reservoir heterogeneities and the actual time required to reach full injection rate. Once the flood is under way, further performance studies might be done using several predictive methods. Whichever method matched the actual performance would be pronounced as the correct procedure. The flaw in comparing actual to predicted is that the forecasting program input data are usually based on averages of data that are subject to very large variations. For example, the calculation might be done using an initial gas saturation of 10%, whereas in the field, gas saturation may vary areally from 0% to 20%. Individual areas of the field, then, can show a performance that varies considerably from an average performance. In addition, seldom is a detailed geologic reservoir description adequately done.

Regardless of forecasting method, the actual performance may not be the best that can be done, and this is the problem to be examined.

Overview of Proposed Procedure

This paper proposes a quantitative approach to waterflood analysis. A rather precise definition of rock properties and saturations is required on initiating the study, and a considerable amount of time may be required to set up the procedure, but in the end, performance will be examined using easy-to-understand analytical techniques and performance is quantified rather than defined in terms of obscure subjective phrases such as, "it's not doing good," or "it's performing better than the offset floods." The technique will not be concerned with how actual compares to a forecast, but will examine the actual performance using a material balance plotting technique and decline curves on individual elements within the flood, and these are compared to determine efficiency of each element. Certainly a range of efficiencies in a flood will be found, and we can somewhat presume that the highest efficiency elements are a potential goal for all elements within the flood.

The biggest problem in performance analysis is having a thorough reservoir description of rock and fluid properties available. If the reservoir engineer making the original forecast did a comprehensive analysis, then a satisfactory description will be in the waterflood study. The situation will more likely be that only a part of the description needed will be available, and that additional data will need to be developed. For example, maps of net pay, oil and gas saturation at start of flood, and porosity are needed. Usually, you will find the net pay maps, porosity maps, but seldom saturation maps.

The proposed procedure has the following steps of analyses:

1. Pore Volume Description

2. Production-Injection Data Compilation and Decline Curves on each well.

3. Saturation Description

4. Subdivision of the total flood area to individual elements.

5. Compilation of Element Properties

6. Injection Allocation to Elements

7. Bubble Maps

8. Material Balance

9. Evaluation of Element Performance

In addition to analyzing past and present performance, which is performance at the existing spacing, we will want to look at infill drilling potential. To put this potential into proper perspective, we need to introduce two considerations:

1. Maximum Recovery - This term is the estimate of the OOIP that can be recovered by waterflooding if volumetric sweep efficiency is 100%. A simplified form of the equation is:

$$E_R = 1.0 - \frac{B_{oi}}{B_{ox}} (1.0 - E_D)$$

where:

$$E_D = \frac{S_{oi} - S_{or}}{S_{oi}} = \text{displacement efficiency}$$

S_{oi} = $(1 - S_{cw})$ = initial oil saturation, fraction

S_{cw} = initial connate water saturation, fraction

S_{or} = residual oil to water displacement, fraction

B_{ox} = formation volume factor at start of flood, RVB/STB

B_{oi} = initial formation volume factor, RVB/STB

Typical rock properties might yield a maximum recovery efficiency of:

$$E_R = 1.0 - \frac{1.3}{1.1}\left[1.0 - \frac{.75 - .25}{.75}\right] = 0.61 \text{ (or 61\%)}$$

2. Normal West Texas waterflood recovery statistics show ultimate recovery for waterfloods on 20 to 40-acre spacing will range from 25% to 45%, with the 20-acre floods averaging in the upper 30's, and the 40-acre floods averaging about 30%.

If we compare a 100% volumetric sweep efficiency waterflood that would recover 60% to 70% of the original oil in place to actual performance that results in recovery of about 35%, it is obvious that stakes for very close spacing are large. The question is, how close do wells have to be drilled to attain near 100% sweep and recover the oil that is trapped due to problems such as rock inhomogeneities and also be economically feasible? The answer to this question can only be approached by thorough reservoir analysis being backed up by actual infill drilling performance.

DETAILED PROCEDURE OF PERFORMANCE ANALYSIS

Pore Volume Description

The two components needed to determine the reservoir pore volume are porosity and net pay thickness contour maps. These properties are probably more amenable, on a geologic basis, to contouring separately rather than as the ϕh product.

The problem with determining ϕ and h on each well is definition of the so-called pay "cut offs". Conventionally, a porosity vs. permeablity correlation is drawn using core data. A minimum permeability is established, which in effect determines a minimum porosity, and then all porosities on the log above that level are considered to be pay. The minimum permeability level should be based on the lowest value that has displaceable oil saturation to waterflood and will take water when injection starts. A correlation of displaceable oil saturation versus permeability is not a commonly developed lab displacement test and may require reservoir engineering ingenuity to develop.

Since the reserve and oil-in-place contribution of the lower permeability pay is small compared to the total, or it should be small if k_L cutoff is correctly determined, an error in the minimum pay cut-off may not be significant. It is correct to conclude this if connate water increases as permeability decreases and the reservoir engineer has correctly averaged water saturation.

Well Production and Injection Compilation and Decline Curves

Complete records of cumulative production data, oil, water and gas, are needed from discovery to start of flood on a well-by-well basis. These data are used to calculate saturation maps. It will be convenient to post this cumulative data at start of flood on a net pay thickness map. Production and injection data after start of injection needs to be compiled on an incremental time basis (Exhibit 1). Analysis calculations will be based on performance changes over time increments so there should be a generous number of intervals to spot changes.

Individual producing well plots of water-oil ratio will be needed, as this will be the prime tool for estimating remaining reserves at existing spacing. Injection well rate and surface pressure measurements are needed for making Hall plots on each injection well. The Hall[1] plot will be the evaluation tool for injection rate efficiency.

Compilation of Rock and Fluid Properties

Material balance, relative permeability, and capillary pressure calculations will be done so we will need a set of field averaged oil PVT properties with data such as formation volume factor, viscosity, and gas in solution. If these data have not been measured, reservoir oil PVT curves can be constructed from measured surface properties. From field data of gas-oil ratio, surface viscosity, oil gravity, initial bottom hole pressure, and bottom hole temperature, correlations of PVT properties can be constructed using methods in the literature. In most cases, correlations will yield data that are sufficiently accurate for saturation calculations purposes.

If lab measurements of gas-oil and water-oil relative permeability relationships and capillary pressure are not available, data from the same zone in nearby fields should be used.

The question with all rock measurement data is how well they really represent average reservoir conditions. If the displacement tests have not been taken on fresh cores (for maintaining reservoir wettability) the chances that the lab tests represent actual reservoir displacement are not good.

Saturation Description

Contour maps of fluid saturation prior to start of waterflood need to be constructed over the entire flood area. The methods which can be used to calculate this are:

1. Log analysis (water saturation)

2. Capillary pressure calculations (water saturation)

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[1] Hall, H. N.: "How to Analyze Waterflood Injection Well Performance," World Oil (October, 1963), p. 128.

3. Relative permeability calculation (water saturation and gas saturation)

4. Material Balance Calculations (gas saturation and oil saturation)

This is a considerable list of techniques for calculating one set of data, but in order to confirm and cross check, all possible saturation methods should be used and then judgement applied to determine the best answer. Most saturation calculation techniques determine water saturation and then the hydrocarbon saturation is the difference from 100%. Also, the calculation procedures define saturations that have different meanings. For example, a gas saturation calculated using relative permeability techniques and one calculated from material balance techniques do not necessarily represent the same kind of value. A gas saturation calculated from a material balance is an average over the drainage area and a gas saturation calculated using relative permeabilities and an instantaneous producing gas-oil ratio is a value at the wellbore. A water saturation calculated by log analysis and one determined from capillary pressures theoretically should be consistent, and any substantial deviations need to be resolved. Because of permeability variation and its effects on the capillary pressure curves and wettability problems with laboratory displacements, it may be that reliable log calculations give the more accurate estimate. Log analysis and capillary pressures both represent average water saturations at a height above the water-oil contact for a given level of permeability.

When drawing contour maps on saturations, keep in mind that values calculated using producing gas-oil ratios or water-oil ratios and relative permeability curves represent a point value at a well and a material balance values represent an average in a well's drainage area. Log estimates and capillary pressure calculations represent vertical distributions of water saturation and should be averaged over the total pay interval of the well and then mapped as points. The final saturation contour map should honor point data of logs, relative permeability, capillary pressure, and the volume averaged saturations of material balance.

Subdivision of Field Waterflood Area to Individual Elements

The total waterflood area needs to be subdivided into individual elements. Elements are most easily defined in the floods with repeating patterns, such as the common five-spots which have the equivalent of one injection well per producing well. It is most convenient in the calculations to have the producing well at the center of the element and injection wells on the corners. Obviously, this leads to a considerable bookkeeping effort in large waterfloods. In some very large waterfloods it may be convenient to have larger than one producing well elements. If areas of the field show poor performance, then possibly these elements should be further subdivided to individual well elements. In order to provide a quantitative description of performance, we must define individual well element efficiency, so we know exactly which wells need further study.

Basically, the boundaries of each element are planes across which no fluid flows. It is nearly impossible for this condition to completely hold throughout the life as patterns become unbalanced and rates change, but the use of fixed element boundaries should not present too substantial a problem. For the situations of considerable cross flow between patterns, it may be more appropriate to use as the minimum element, one that has no true flow boundaries. In the beginning, it may not be obvious that cross flow has occurred until the individual element material balance calculations are made. For the first pass, use small elements for the analysis and then account for cross flow.

Once the elements have been drawn, overlay the element boundaries on the gas and water saturation contour maps and the net thickness and porosity maps. From these maps, estimate the initial water and gas saturation of each element and its average thickness, porosity, and area.

Compilation of Pre-Injection Element Data

There needs to be a data compilation and fact sheet for each element listing rock properties, OOIP, initial saturations, saturation at start of flood, and several initial material balance and displacement calculations. This is a one-time setup calculation as these values will not change except as element boundaries may change. The form used by ARCO Oil and Gas Company is shown as Exhibit 2.

Allocation of Injection to Elements

Production and injection data after start of waterflood have previously been tabulated on a time basis. Also, each element has been defined from a volume and saturation standpoint and, for a five-spot case, is made up of one producing well in the center and on the corners of the element one-fourth of four different injectors. The problem now is to allocate a fraction of the water injected into each injection well during a time period to each of the elements being served by the injection well. We have two methods which are appropriate. These are:

1) Angle Open to Flow

$$\text{Allocation (Fraction)} = \frac{\text{Angle of Wellbore Open to Element}}{360°}$$

2) Adjusted Angle Open to Flow

$$\text{Allocation (Fraction)} = \frac{(\text{Angle Open to Flow Fraction})\left[\dfrac{(p_{wf} - p_e)}{\ln \dfrac{h}{h_e} \times \dfrac{r_e}{r_w}}\right]}{(\sum \text{Numerator Values for Injection well})}$$

where: $(p_{wf} - p_e)$ = bottom hole injection pressure minus bottom hole pressure of the producer in the element

$\frac{h}{h_e}$ = injection well thickness/producing well thickness

$\frac{r_e}{r_w}$ = distance from injection well to producing well/ injection well radius

Using an angle open to flow allocation assumes a uniform set of rock and pressure conditions surrounding the injection well. In a five-spot each element would be allocated one-fourth of the cumulative injection. For cases where conditions surrounding the injection well vary, we have derived an adjusted equation which accounts for several of these variations. The equation has corrections for producing well pressure, distance of the producing wells from the injection well, and differences in net thickness of the elements surrounding the injection well. In most cases, the adjusted allocation fraction will remain constant through the flood, and need not be recalculated during each time interval.

We have not developed guidelines that can be used to decide when the adjusted equation should be used. Obviously, if a sample calculation is done and the adjusted allocation is considerably different than the angle open to flow fraction, then the adjusted equation should be used. Exhibit 3 shows a 5-spot element with the data needed for an allocation calculation.

Bubble Maps

A valuable visual tool for evaluating performance is the water-oil bubble maps showing the approximate location of the fronts in the elements. This is not so much an analytical tool as a visual tool to display progress (Exhibit 4). For simplicity's sake, we usually draw the fronts as arcs of circles prior to breakthrough and use reservoir engineering art to shape the fronts to conform to mobility ratios and producing water-oil ratios after breakthrough. Obviously, stratification and multiple zones will complicate the construction if it is desired to do this detail. The bubble radius in each element surrounding an injection well should be based on the fluid volume allocated to the element in the allocation calculations.

The basic equation for the radial fronts is:

$$r_{water} = \left[\frac{5.61(W_i - \Delta W_p)E_{inj}}{E_{WB}\ \pi\ \alpha\ \phi\ h(1-S_{cw}-S_{or})}\right]^{1/2}$$

$$r_{oil} = \frac{r_{water}}{\left[\frac{\Delta S_g}{1-S_{cw}-S_{or}}\right]^{1/2}}$$

The "α" term corrects the cylinder equation to account for the net allocation (W_i - ΔW_p) term only being a fractional part of the total fluid leaving the wellbore.

where: r = radius, feet

$W_i - \Delta W_p$ = allocated net injection, bbls

ϕ = porosity, fraction

$(1 - S_{cw} - S_{or})$ = displaceable pore space, fraction

E_{inj} = injection efficiency, fraction (Can vary from 0.5 to 1.0. Represents the volume of water actually effective in displacing oil.

E_{WB} = volumetric sweep efficiency behind waterfront, fraction (This fraction usually in the .60-.90 range)

ΔS_g = change in gas saturation, fraction

h = thickness, feet

α = fraction of wellbore open to element

Material Balance Calculation

At this point, all needed data has been compiled for each element so that we can now calculate element performance and efficiency. The material balance equation will make the simplifying assumption of incompressible flow, and for the purpose of our method, this is satisfactory. The element can be thought of as a fixed volume tank in which we have fluid coming in, fluid being produced, and an efficiency of oil displacement. The element has a starting material balance condition that is defined by gas saturation and pressure at start of flood, converted to element recovery factor at start of flood, and an end point that is the maximum recovery efficiency. The material balance of the element will be represented by a plot of cumulative fractional recovery versus volumetric sweep efficiency on coordinate paper. Production points on the graph are the incremental calculations using the increments of production and injection allocated to the element. ARCO's calculation form is a part of Exhibit 1.

Volumetric sweep efficiency is defined by the equation:

$$E_V = \frac{W_i - \Delta W_p}{V_D}$$

where: V_D = displaceable pore volume, bbls

$W_i - \Delta W_p$ = net element injection, bbls (water injected minus injected water produced)

Obviously, the path of this plot must start at the point defined by recovery at start of flood and go toward a recovery equal to maximum recovery efficiency. When E_V equals 1, all moveable oil in the element displaceable by water would have been produced, and recovery is maximum recovery efficiency.

The path of the flood performance is bounded by an obtuse triangle defined by these two points and a third point. This third point is the net injection required to displace the existing gas saturation at start of flood as a fraction of the total displaceable pore volume. See Exhibit 5. Point 3 in ARCO terminology is $\overline{A}$ (ABAR) and is equal to $\frac{\Delta S_g}{1 - S_{cw} - S_{or}}$. Performance of the element must lie within the triangle because the material balance confines it to that area. Typical performance will follow a curve as shown.

In some cases the calculated volumetric sweep efficiency places the performance outside the triangle. Upon examining the data, we usually find that displaceable pore volume and produced water are correct, but that we need to adjust the injected water. For instance, metered volumes reported from the field can be incorrect. Flow of water into an element from an adjacent element caused by a pressure imbalance will cause the actual performance of the first element to be to the left of its triangle and the performance of the adjacent element to be to the right of its triangle. Loss of injected water to zones above or below the intended zone of injection will cause the actual performance to be to the right of the triangle. In this case the correction applied to the injected water to place the performance back into the triangle is a direct measure of injection efficiency. Exhibits 6-10 are material balance graphs on five West Texas elements demonstrating the need for injected water corrections.

As the element approaches depletion at a high water-oil ratio, efficiency and recovery change only slightly with time because now we are simply cycling water. The material balance points will start laying very close to each other, because there is no gain in recovery efficiency.

This material balance curve does not show remaining economic reserves, but it does show what the potential can be, which is the difference between the cumulative production and maximum recovery efficiency.

In addition to the material balance graph, a performance plot is needed to determine remaining reserves at the conditions of existing spacing, and we suggest that a semilog plot of water-oil ratio versus cumulative oil be used. Water-oil ratio more nearly reflects reservoir displacement efficiency than other decline curves such as oil rate versus time. Of course, the WOR curve must be converted to an oil rate to find the economic limit.

Evaluation of Element Performance

Three of the four fundamental element descriptive tools that should be routinely calculated are depicted on Exhibit 11:

1. Material Balance Graph of Cumulative Recovery vs. Volumetric Sweep Efficiency - This performance plot allows calculation of the injection efficiency, the correction factor which adjusts the allocated injection so that the performance plot lies within the confining obtuse triangle. If changes in the slope of the performance plot are noted, well records should be examined for determining causes. For example, it may be found that there was a change in slope concurrent with an increase in surface pressure. Obviously, injection well profile surveys should be made if injection efficiencies are well below 100%. The graph allows comparison between elements to determine relative efficiency and pinpoint the poor performers.

2. Water-Oil Ratio vs. Cumulative Recovery - This graph defines the remaining reserves of the element under present spacing. An examination of this compared to the difference between cumulative recovery and displacement efficiency relates to infill drilling reserves.

3. Hall Plot on Injection Wells - This display shows if wellbore damage is occurring and is a needed tool so that we are assured of maximum injection rate. Changes in slope in the Hall plot may be correlative to changes in the material balance plot and clues to field problems and time of occurrence.

4. Bubble Map of Water and Oil Fronts - The fourth tool is a visual display of the approximate location of fronts. In the radius calculation, the volume should be corrected for the injection efficiency determined from the material balance. A field bubble map is a handy device for overseeing if unbalanced pattern conditions exist on a field basis. Optimally, we would want the volumetric sweep efficiency in all elements to track, as this will probably result in minimum field life and maximum economic benefit.

NOMENCLATURE

$\bar{A}$, (ABAR) = fraction of pattern area occupied by water bank at fillup (fillup is defined as condition of no gas saturation)

B_{ox} = formation volume factor of oil at start of flood, RVB/STB

E_D = displacement efficiency, fraction

E_{INJ} = injection efficiency, fraction of water effective in displacing oil

E_R = recovery efficiency, fraction of OOIP

E_V = volumetric sweep efficiency of pattern volume, fraction

E_{WB} = volumetric sweep efficiency within the water bank, fraction

G_p = cumulative gas production at start of flood, MMCF

N_p = cumulative oil production at start of flood, STB

ΔN_p = incremental oil production after start of flood, STB

OOIP = original oil in place, STB

RVB = reservoir barrels

S_{gx} = gas saturation at start of flood, fraction

S_{oi} = initial oil saturation, fraction

STB = stock tank barrels

V_D = displaceable volume, RVB

V_p = pore volume, RVB

W_i = cumulative water injection after start of flood, RVB

W_p = cumulative water production at start of flood, RVB

ΔW_p = incremental water production after start of flood, RVB

PRODUCTION – INJECTION DATA AFTER START OF WATERFLOOD

Performance Data

Analysis start time is start of injection.

Oil production at start of injection, Np = ____________ MSTB

Time interval ending	Waterflood cumulative Oil production	Total cumulative Recovery	Cumulative water injection	Cumulative water Production	Volumetric Efficiency	Percent fillup	Displaceable Volume Injected	Water bank Radius
	ΔN_p	$\frac{\Delta N_p + N_p}{OOIP}$	W_i	ΔW_p	$\frac{W_i - \Delta W_p}{V_D}$	$\frac{W_i - (\Delta N_p + \Delta W_p)}{V_{Fillup}}$	$\frac{W_i}{V_D}$	r
	MSTB	Fraction	MBbls	MBbls	Fraction	Percent	Fraction	Feet

EXI. . 1

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Waterflood Material Balance Analysis

		Map
Field		
Reservoir		
Element area	Acres	
Average thickness	Feet	
Date start of injection		
Cumulative production at start of injection		
Oil (N_p) =	MSTB	
Gas (G_p) =	MMCF	
Water (W_p) =	MBbls	
Rock and fluid data		
ϕ =	S_{cw} =	
B_{ox} =	S_{or} =	
B_{oi} =		

N

Pattern volumetric data

V_p = 7758 x $\emptyset$ x h x Area = 7758 x ______ x ______ x ______ = ______ RVB

V_D = V_p x $(1.0 - S_{cw} - S_{or})$ = ______ x (1.0 – .______ – .______) = ______ RVB

O.O.I.P. = $\dfrac{V_p \times (1.0 - S_{cw})}{B_{oi}}$ = $\dfrac{\text{______ x (1.0 – .______)}}{\text{______}}$ = ______ STB

$S_{gx} = S_{oi}\left[1.0 - \dfrac{B_{ox}}{B_{oi}}(1 - E_R)\right]$ = .______ $\left[1.0 - \dfrac{\text{______}}{\text{______}}(1 - .\text{______})\right]$ = ______

$V_{fillup} = V_p \times S_{gx}$ = ______ x .______ = ______ RVB

Disp. eff. (E_D) = $\dfrac{S_{oi} - S_{or}}{S_{oi}}$ = $\dfrac{.\text{______} - .\text{______}}{.\text{______}}$ = ______

ABAR = $\dfrac{S_{gx}}{1.0 - S_{cw} - S_{or}}$ = $\dfrac{.\text{______}}{.\text{______}}$ = ______

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EXHIBIT 2

INJECTION ALLOCATION FOR NON UNIFORM 5–SPOT ELEMENT

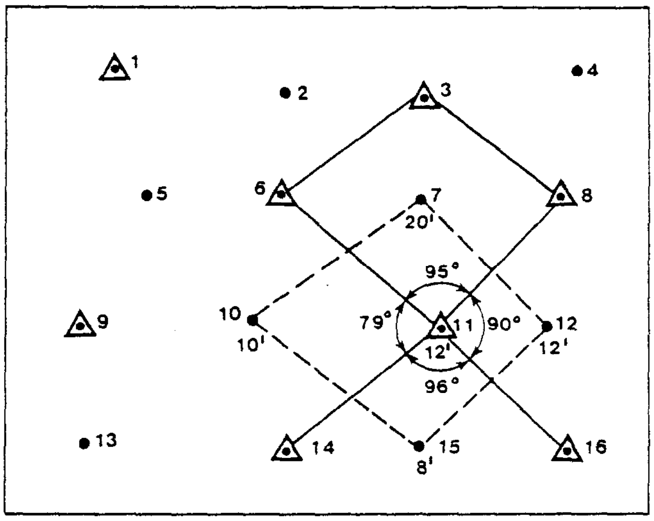

EXHIBIT 3

BUBBLE MAPS

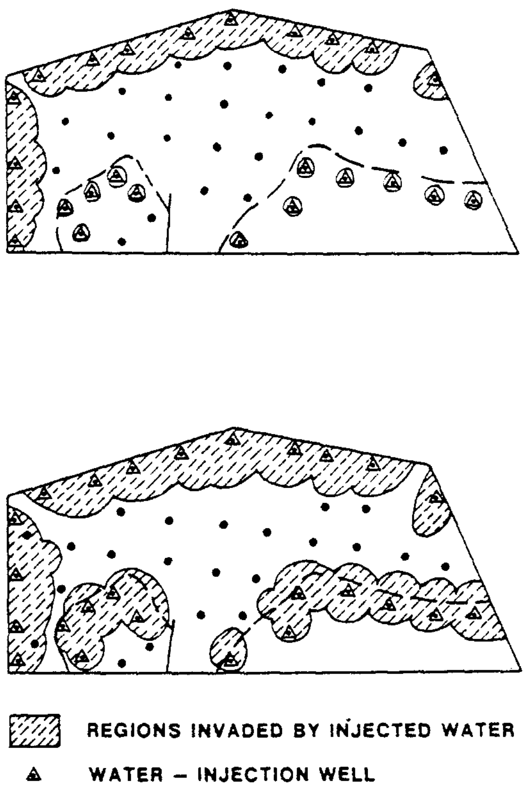

EXHIBIT 4

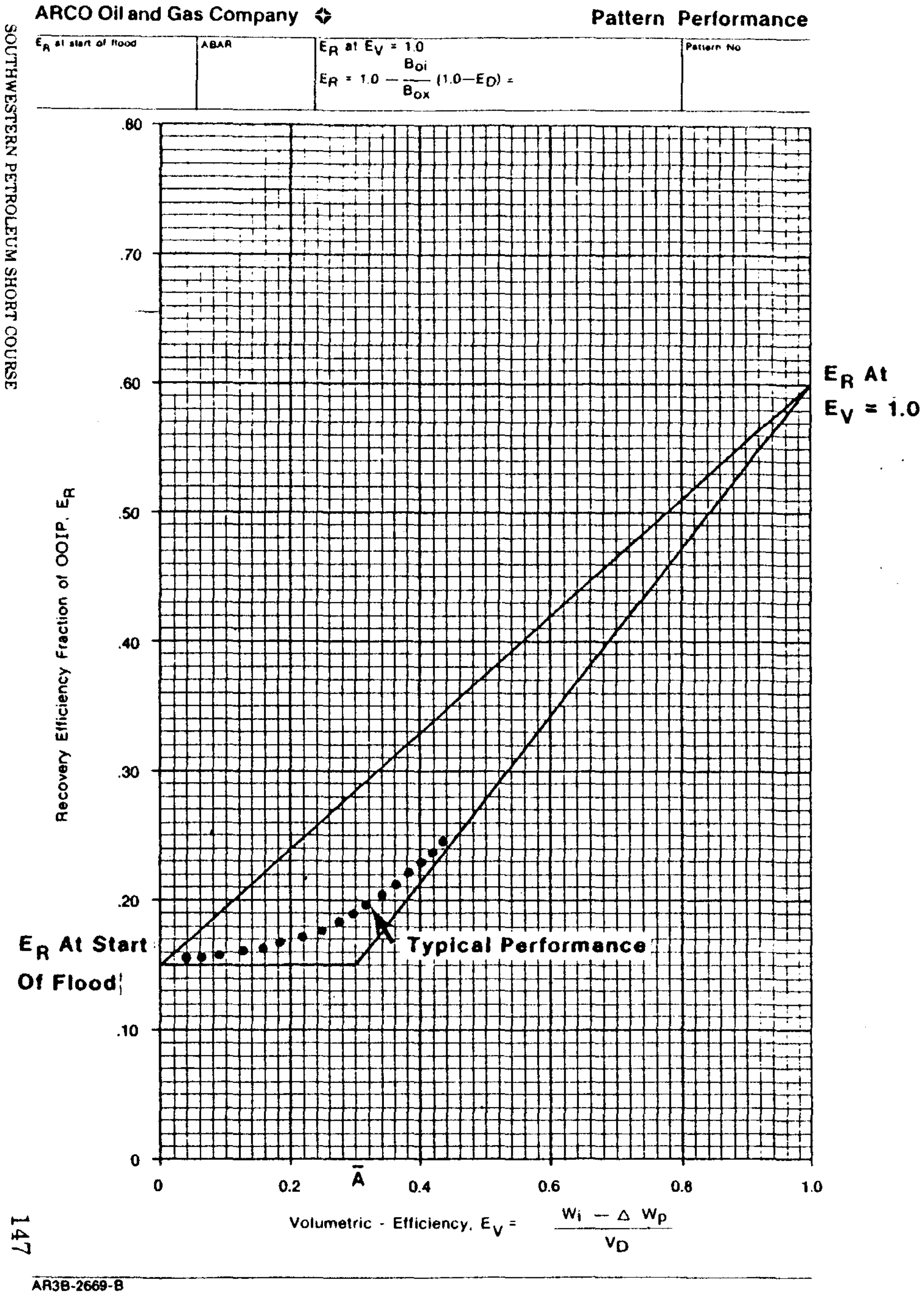

EXHIBIT 5

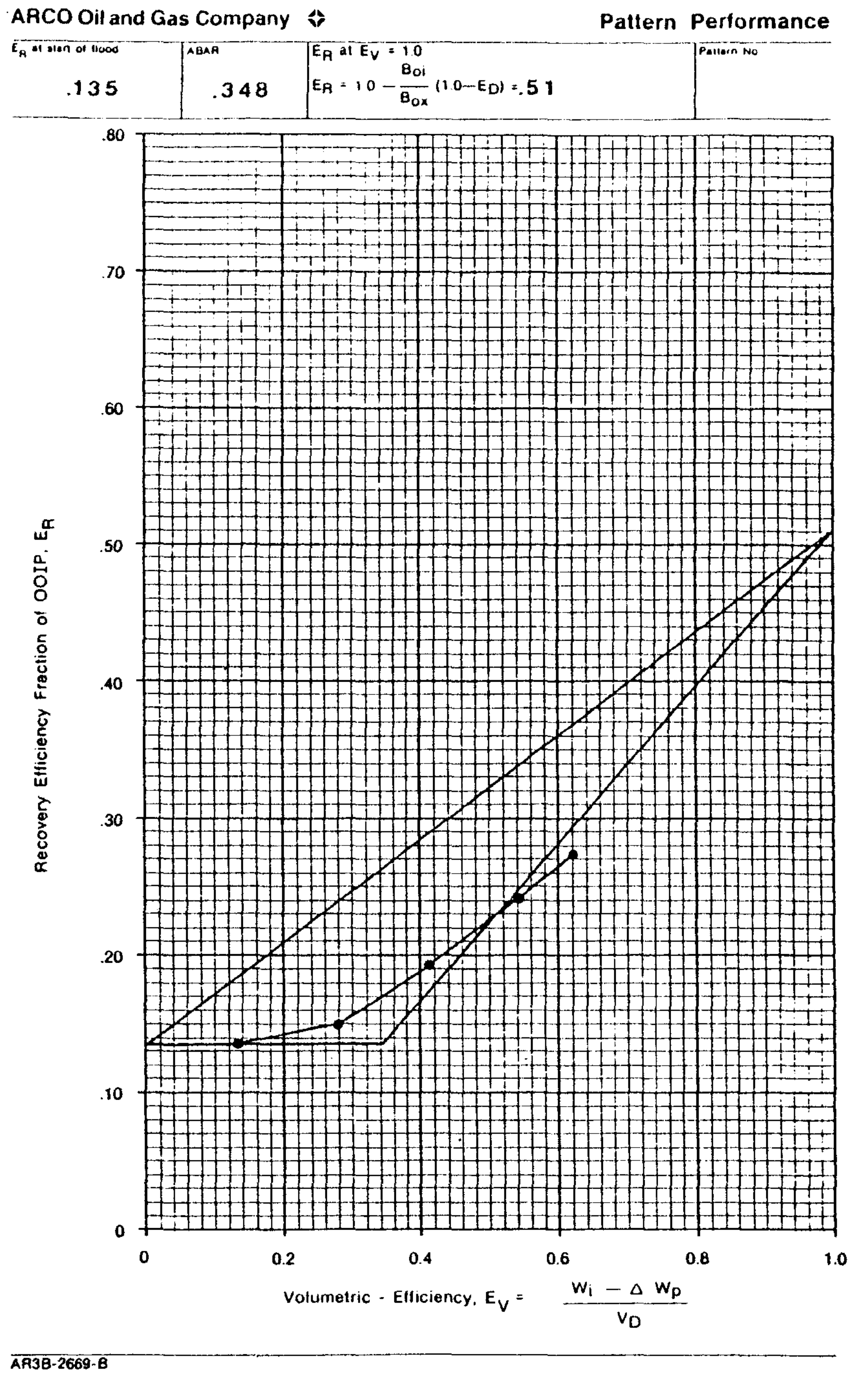

EXHIBIT 6

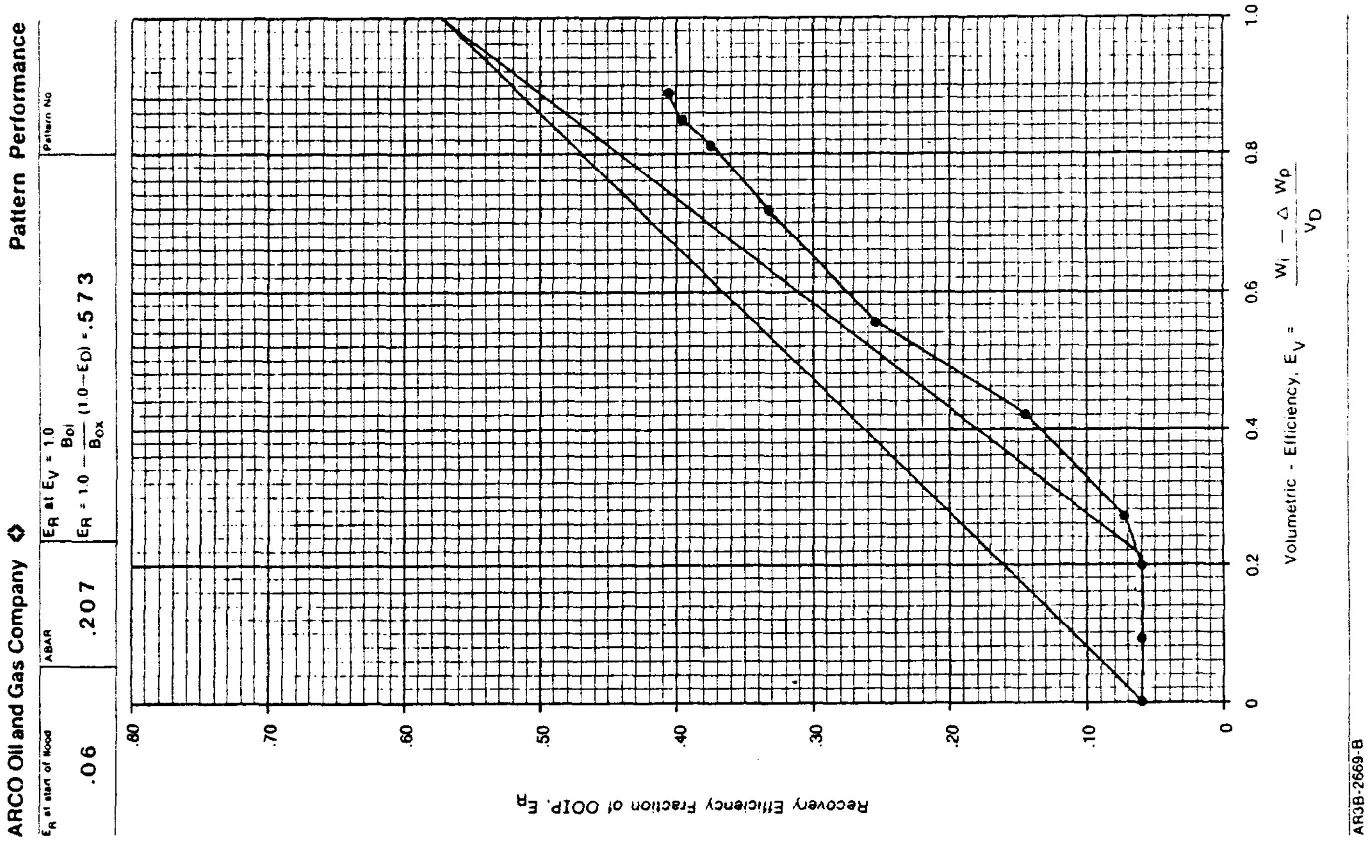

EXHIBIT 7

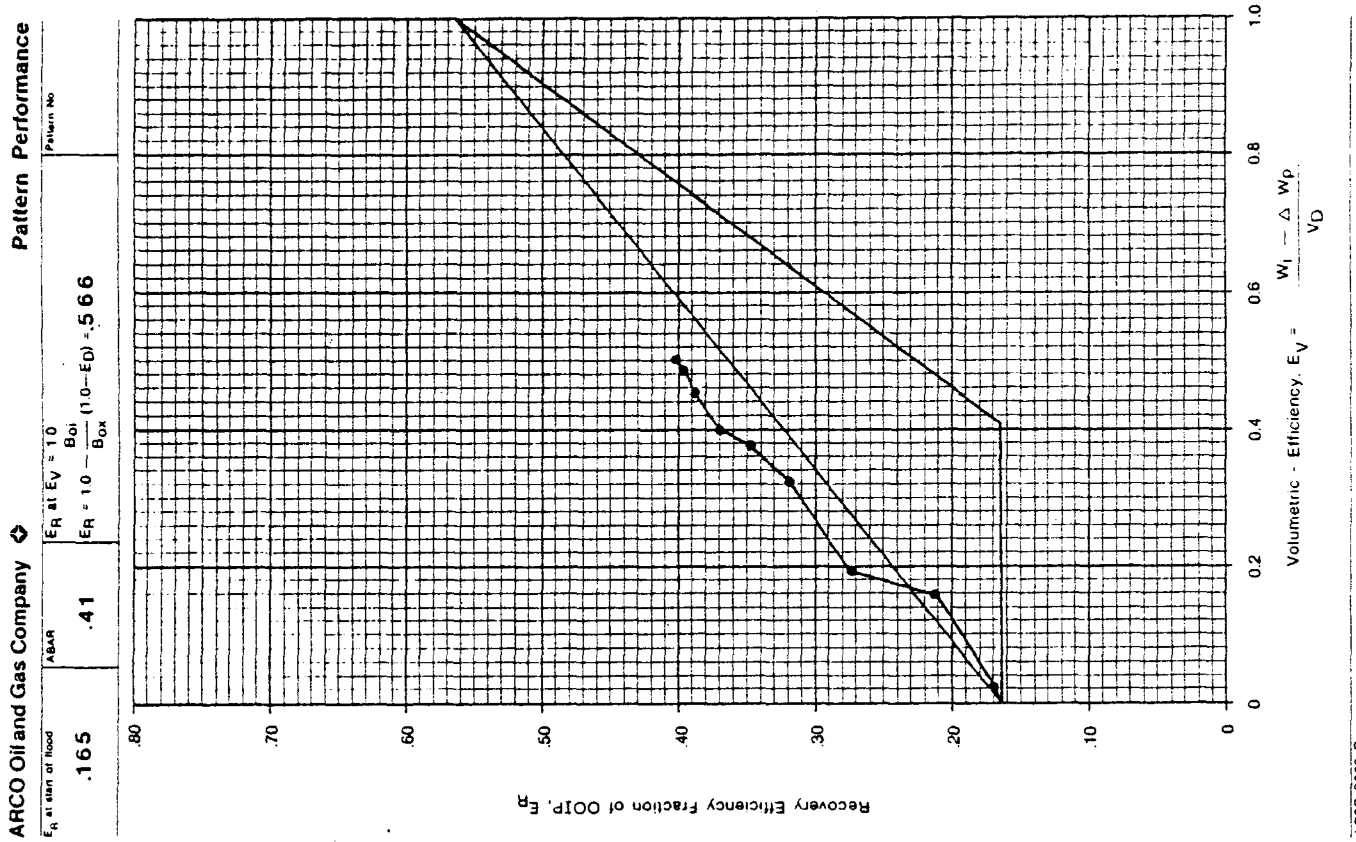

EXHIBIT 8

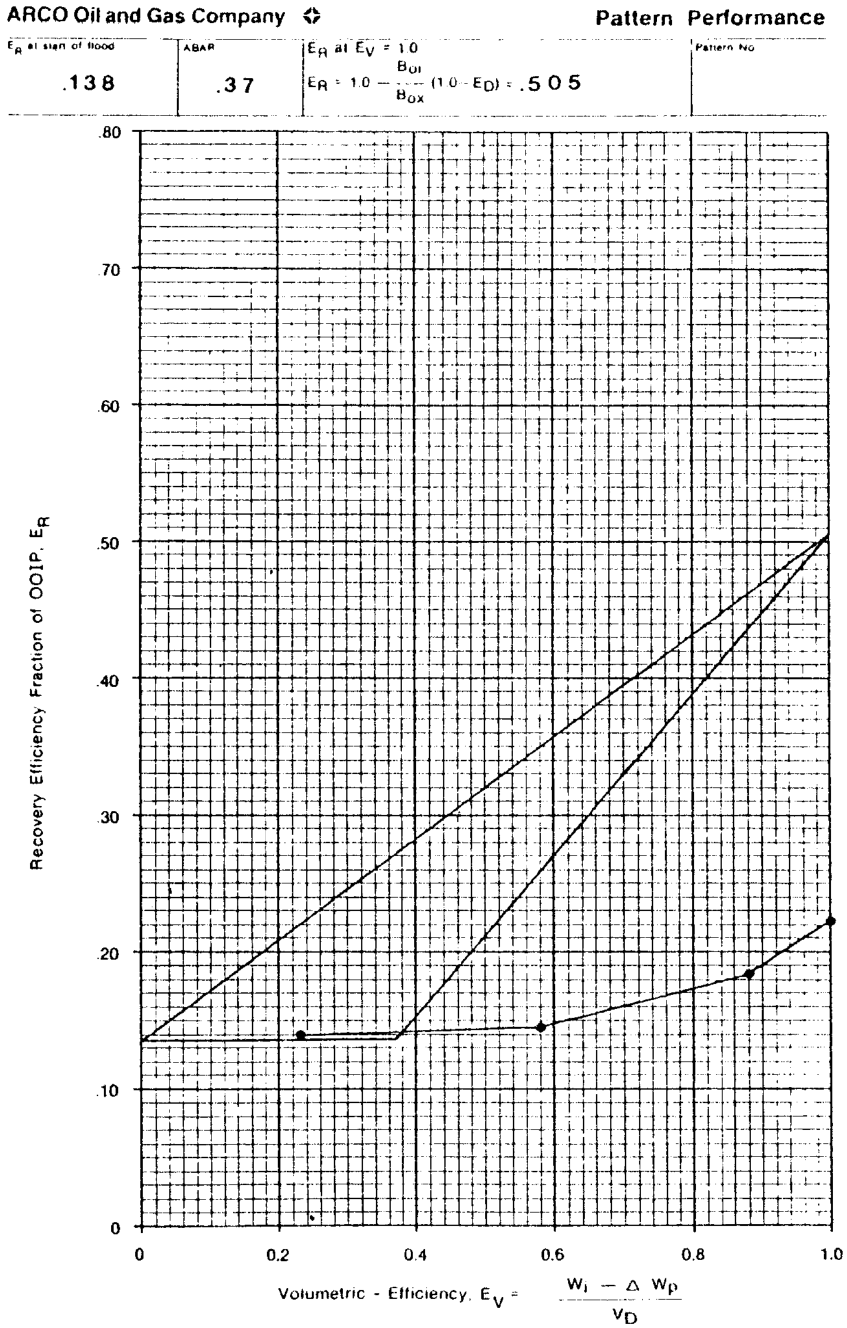

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EXHIBIT 9

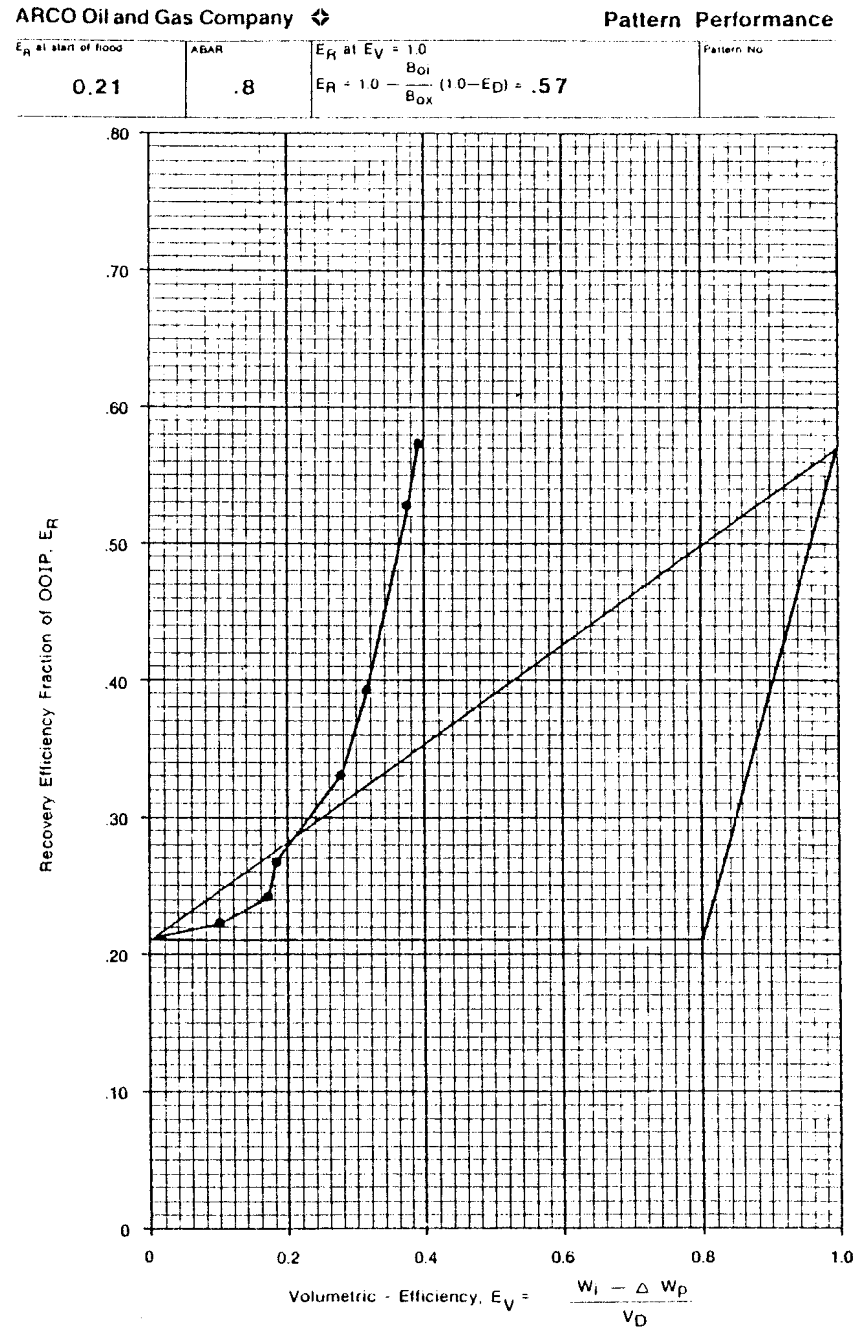

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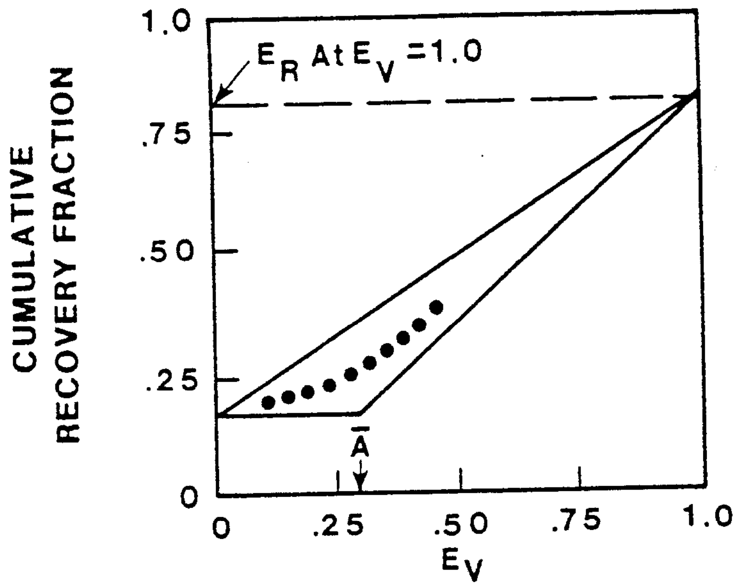
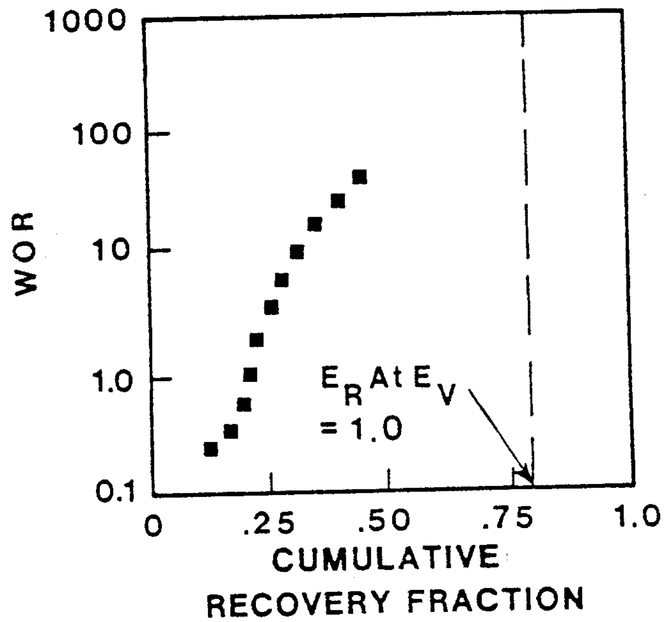
EXHIBIT 10

TYPE CURVES NEEDED FOR ELEMENT ANALYSIS





HALL PLOT

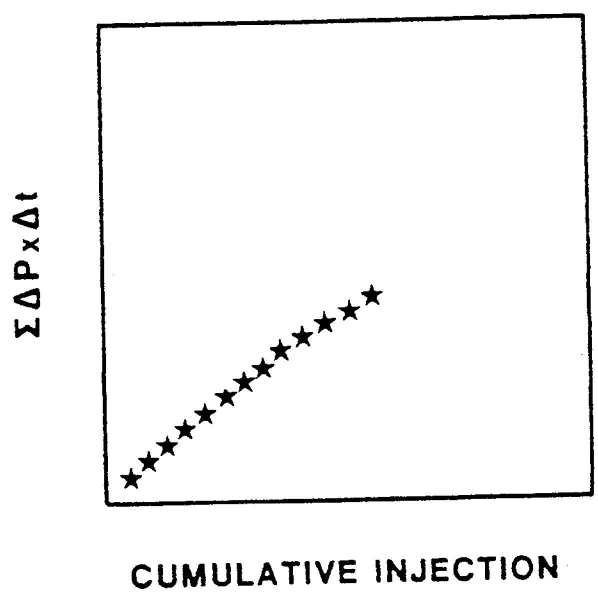


EXHIBIT 11