# Reservoir Operation And Control

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## INTRODUCTION

A successful waterflood project is the product of sound engineering planning and dedicated operation control from pilot to plug-out of the property. A field which produced with little engineering supervision during its primary life can often produce even more oil by secondary recovery if the operator will devote sufficient attention to all phases of the waterflood operation. A detailed engineering study which utilizes all of the available well information, reservoir data, and production records is essential. This paper assumes that such a study has been made and that waterflood feasibility has been established. The considerations in planning and operating from that point forward will not be reviewed.

## PATTERN

The three general categories of pattern which are popularly used (Figure 1) are (1) the peripheral type of injection pattern, (2) the line drive pattern, and (3) the 5 spot pattern with its variations of inverted 5 spot, 7 spot and 9 spot.

Theoretical work has indicated the staggered line drive or nine-spot pattern to be more efficient than the other configurations when all other conditions are equal. However, in determining which pattern will most effectively flood a specific pool the geology of the reservoir and its structural configuration should be examined. For example, the best pattern for a long, narrow, shoestring sand will probably not be the most efficient pattern for a large unfaulted anticline. The reservoir rock characteristics also affect the choice of pattern. If the permeability of the productive zone is relatively high and indicated to be continuous from well to well throughout the pool, a line drive flood or a peripheral flood will probably be the most efficient and economic method of waterflood development. If, on the other hand, the well data indicate a variation in pay quality or continuity from well to well it may be necessary to go to a 5 spot pattern in order to effectively sweep all of the reservoir.

A second consideration in pattern choice is the reservoir mechanism which produced the primary oil. For example, if material balance and water influx calculations are applied to a reservoir, it may be found that a field which has produced most of its production by solution gas drive will also have received some effects from a limited water drive on one flank, or a gas cap which might have been present. If either of the above is indicated the pattern must be modified to maximize the benefit of these recovery mechanisms or minimize the detrimental effect which these phenomena might have on the ultimate secondary recovery. For example, in a field which has a large gas cap, either original or secondary, it usually is necessary to plan a line of injection wells at the gas-oil contact to maintain a protective barrier to migration of oil into the gas cap during the waterflood operation. Sometimes a limited water drive may have watered out certain edge wells which can be used as injection wells for an effective peripheral flood.

Once the geology and reservoir characteristics of the pool are determined, economic considerations are in order. For example, if the pool has produced by solution gas drive and the well data indicate continunity of pay and uniform permeability characteristics, in most cases a line drive or a peripheral drive will be most economic. This is usually because of the lower development costs resulting from fewer injection wells, smaller injection facilities and a smaller water supply requirement. This is not always the case, however. In the event that the property were acquired by purchase for the purpose of waterflooding and the purchase price involved a substantial capital outlay, it may be that the more rapid increase in production and shorter flood life which could be achieved by a spot-pattern flood would offset the savings which might result from the lower development costs of a line drive or peripheral flood.

Another factor which might modify a pure economic analysis would be a recognition of the risk factors involved in flooding a particular reservoir. If a pool were in an area that had had no flooding history or if it were a reservoir rock which had not been flooded successfully in an adjacent field, management could decide that a pilot flood should be instituted before going to full scale development. In this event, for prompt results, some type of spot pattern would probably be used. Once that is done it will frequently be more practical to expand from that pattern stepwise to limit risk capital exposure. When the field is in an area that has had successful flooding history and reservoir characteristics are similar full scale develepement can be instituted initially. In that case development costs for peripheral or line drive are usually more attractive.

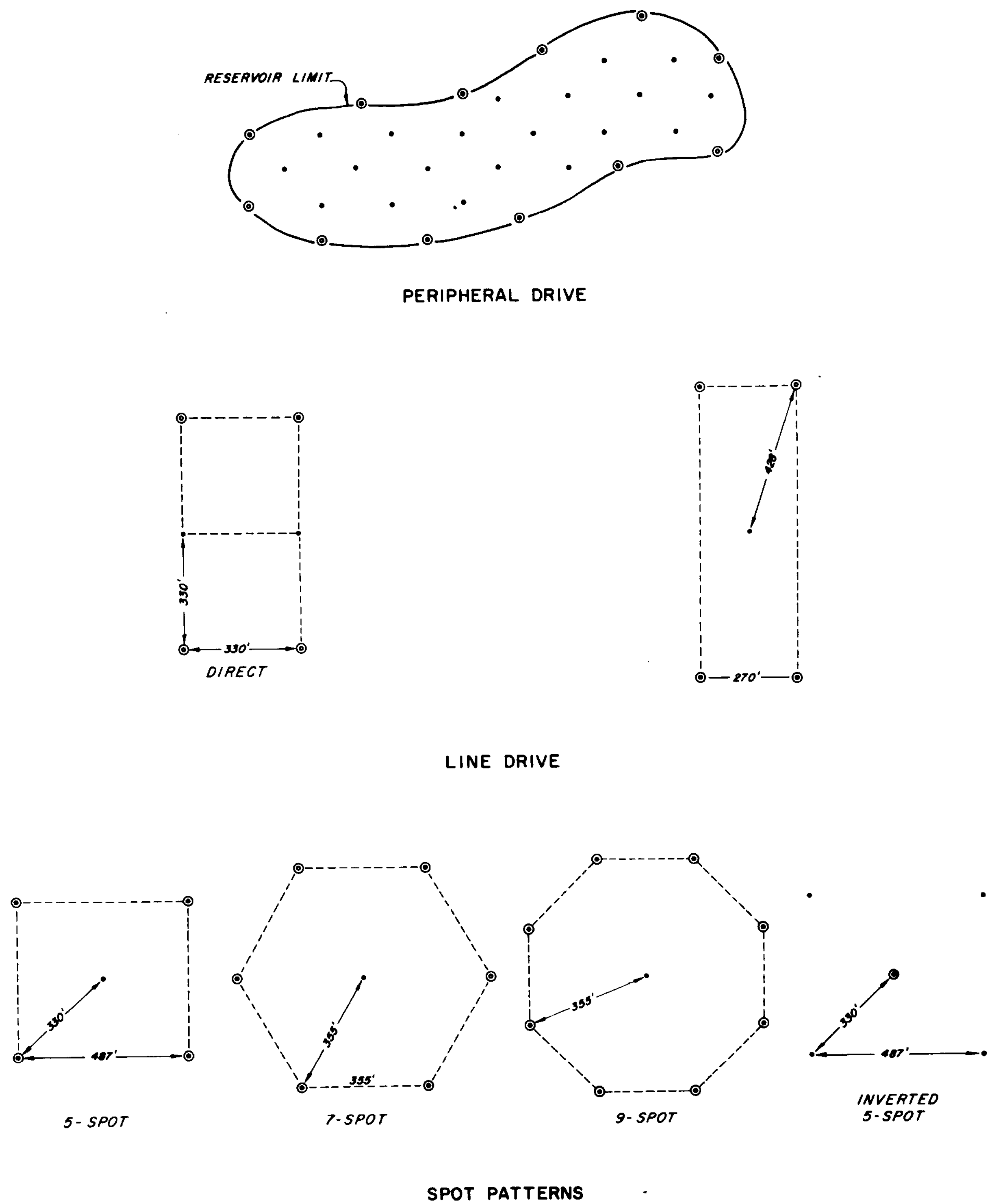
There are other considerations that are not exclusively production or engineering matters which can affect the choice of a project pattern. One of these is the regulation by governmental bodies which might dictate the pattern which will be used in a certain field. One state has a fixed rule on waterflood proration and in this state the proration rule is based upon allowable earned from 40 acre production units. The proration formula assumes that the project will be developed on a 5 spot pattern. It is possible, however, to present evidence which justifies modification of this approach so that a line drive or peripheral flood can be instituted.

All the discussion thus far has assumed that the operator planning the development has complete control of the reservoir, but unless a unit has been formed, this is seldom true. For that reason it is necessary to either unitize all of the productive area on some equitable participation basis or to develop the project with so-called "leaseline cooperation" which usually involves compensating injection wells so that equal volumes of oil are driven on and off of the offsetting leases. In a situation where unitization is not feasible a spot pattern flood is almost invariably chosen since it lends itself most readily to equitable leaseline cooperation agreements.

An example of a 5 spot pattern flood is the

FIGURE 1

EXAMPLES OF WATERFLOOD PATTERNS



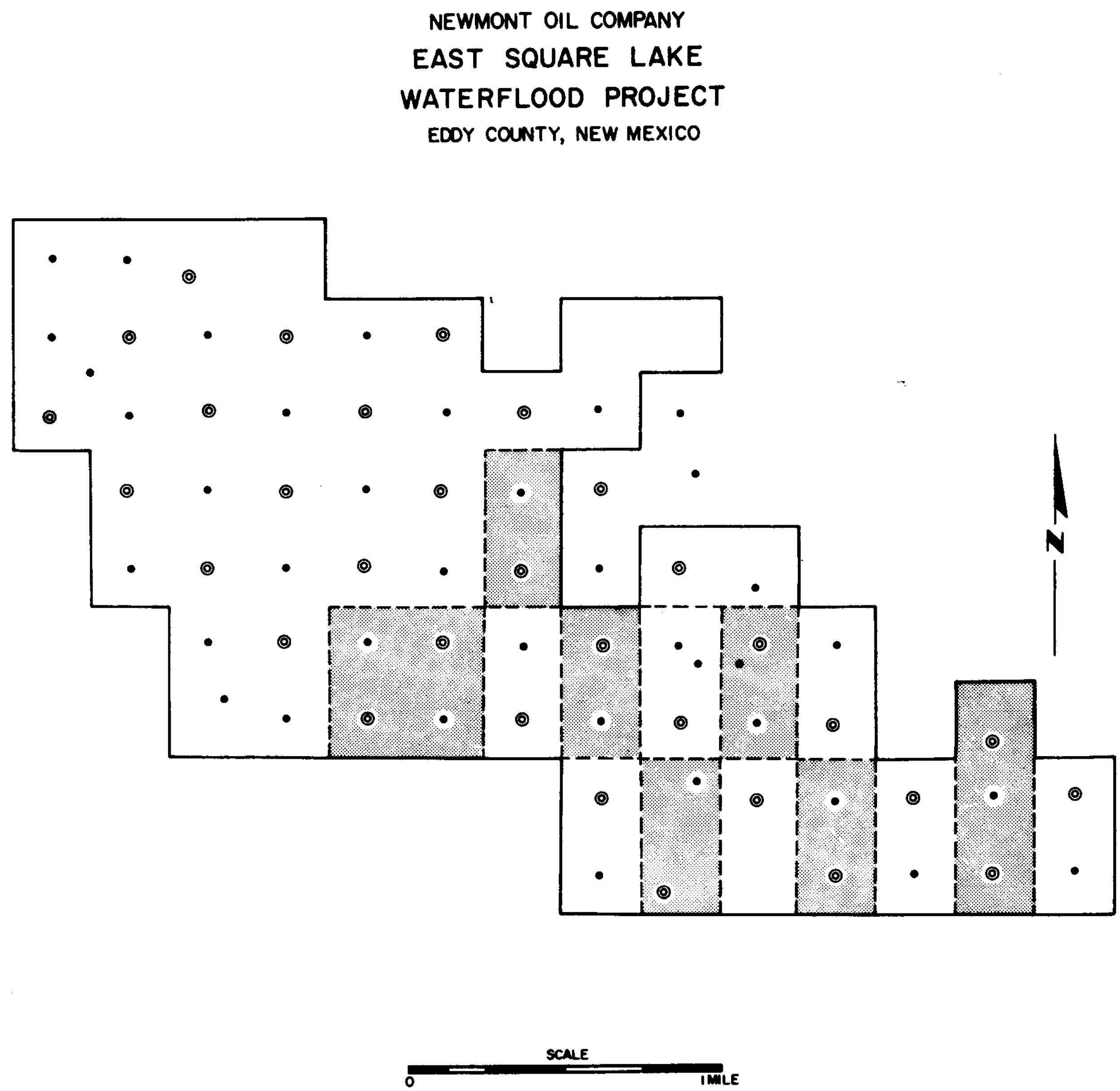

NEWMONT OIL COMPANY
EAST SQUARE LAKE
WATERFLOOD PROJECT
EDDY COUNTY, NEW MEXICO
N
SCALE
0
1 MILE

FIGURE 2

FIGURE 3A
SOJOURNER SAND UNIT
HASKELL COUNTY, TEXAS

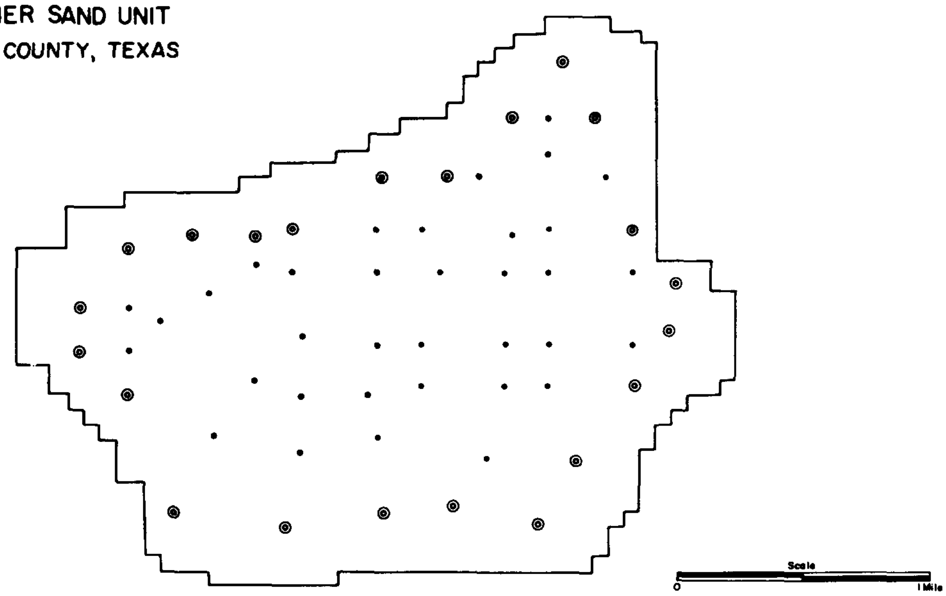
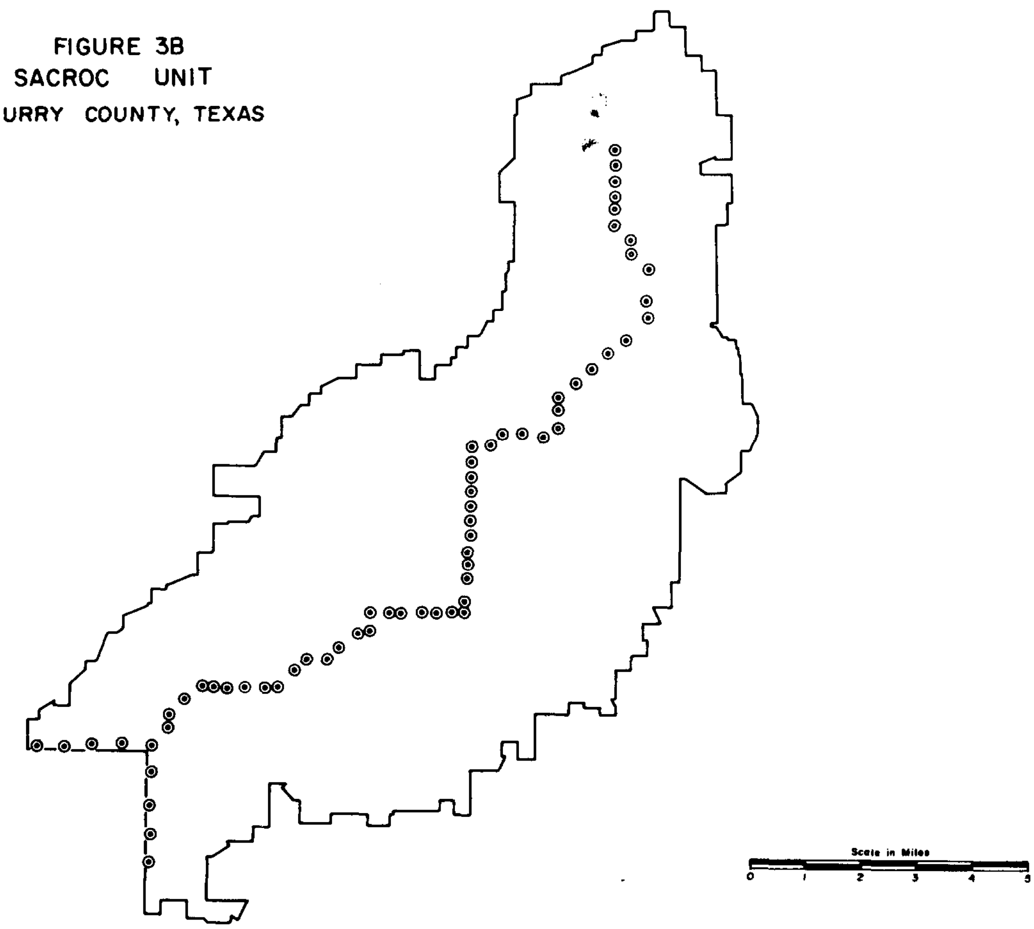



FIGURE 3B
SACROC UNIT
SCURRY COUNTY, TEXAS



Square Lake project in Eddy County, New Mexico. In Figure 2 this project is shown with the pattern of injection wells marked and the areas of cooperative leaseline injection indicated by crosshatching. In this field the original development was on uniform 40 acre spacing and therefore the 5 spot waterflood development has been conducted by the conversion of alternating wells to effect 80 acre 5 spots. For evaluation a double 5 spot pilot was commenced and subsequent development has been an expansion from that pattern.

An example of a peripheral flood which is working efficiently is the Sojourner Sand Unit in Haskell county, Texas. The peripheral pattern was recommended because of the irregular spacing of primary drilling. This project is shown in Figure 3-A.

An example of a successful line drive project (figure 3-B) is the SACROC Unit in Scurry County, Texas which involves center-to-edge water injection along the logitudinal axis of this Pennsylvanian Reef. In this particular field a staggered line drive along the crest of the reef was chosen for the following reasons:

1. The water drive is in the same direction as the pressure gradients.
2. Water is injected into the thickest part of the reef permitting a much larger volume to be injected.
3. Only 2 instead of 4 waterfronts are present to observe and control.
4. The center line injection is particularly adapted to shutting in of inefficiently producing edge wells when compared to a peripheral type flood, and
5. The center-to-edge type injection system in SACROC cost almost $1,500,000 less than a modified peripheral pattern.

As can be seen from the 3 examples just given, each field has its own distinct characteristics and must be analyzed individually. Each of these projects is being conducted successfully and while some other pattern might have worked as well, the management for each of these operations chose a pattern which has efficiently done the job.

## INJECTION CONTROL

Once the pattern has been chosen and the injection wells drilled, decisions must be made concerning the type of injection control which will be used for the project. Injection controls fall generally into 3 categories. One, pressure balancing, is simply maintaining the same surface injection pressure on all injection wells. This is done on the premise that pressure equalization will achieve the most uniform flood front and will compensate for variations in reservoir rock permeabilities. The second form of control is volumetric or rate control which uses the theory that injecting equal volumes into each injection well will achieve a more balanced flood without the danger of premature water breakthough from 1 side of a pattern. This is usually based upon either the net acre-feet in the pattern or the net feet of effective sand thickness in the spacific well. The third alternative is a combination of pressure and volumetric balancing and this alternative is probably used to some extent in nearly every flood.

As examples of the different approaches for injection rate control, the field which were previously mentioned can be examined. In the Sojourner Sand Unit core analyses indicated that the maximum injection rate per well would be approximately 300 BPD at 1800 lb surface injection pressure. A pilot water injection program indicated that the injection wells would take from 600 to 900 BPD with 600 lb of surface pressure and subsequent performance has confirmed this. Since sufficient volumes can be injected at reasonable pressures a balance of fluid injection versus fluid withdrawals has been achieved by the volumetric regulation of injection rates in this project.

In the Square Lake project the pressure balancing method for injection control is used because the information is tight and economic injection rates require a maximum plant pressure just below the formation breakdown pressure. Injection rates after fillup originally averaged 400 bbl per well per day at a plant pressure of 1750 psi. Recently the plant was modified to deliver water at an average pressure of 2100 psi and this has resulted in increases in injection rates. During the pilot phase of this project it was determined by pressure breakdown tests and fracture treatment pressures that the plant pressure could not safely exceed 2300 psi without pressure parting of the formation. Since permeability varies from well to well, some well rates have been adjusted by a throttling valve at the well head so that this project is actually controlling injection by a combination of pressure and volume balance.

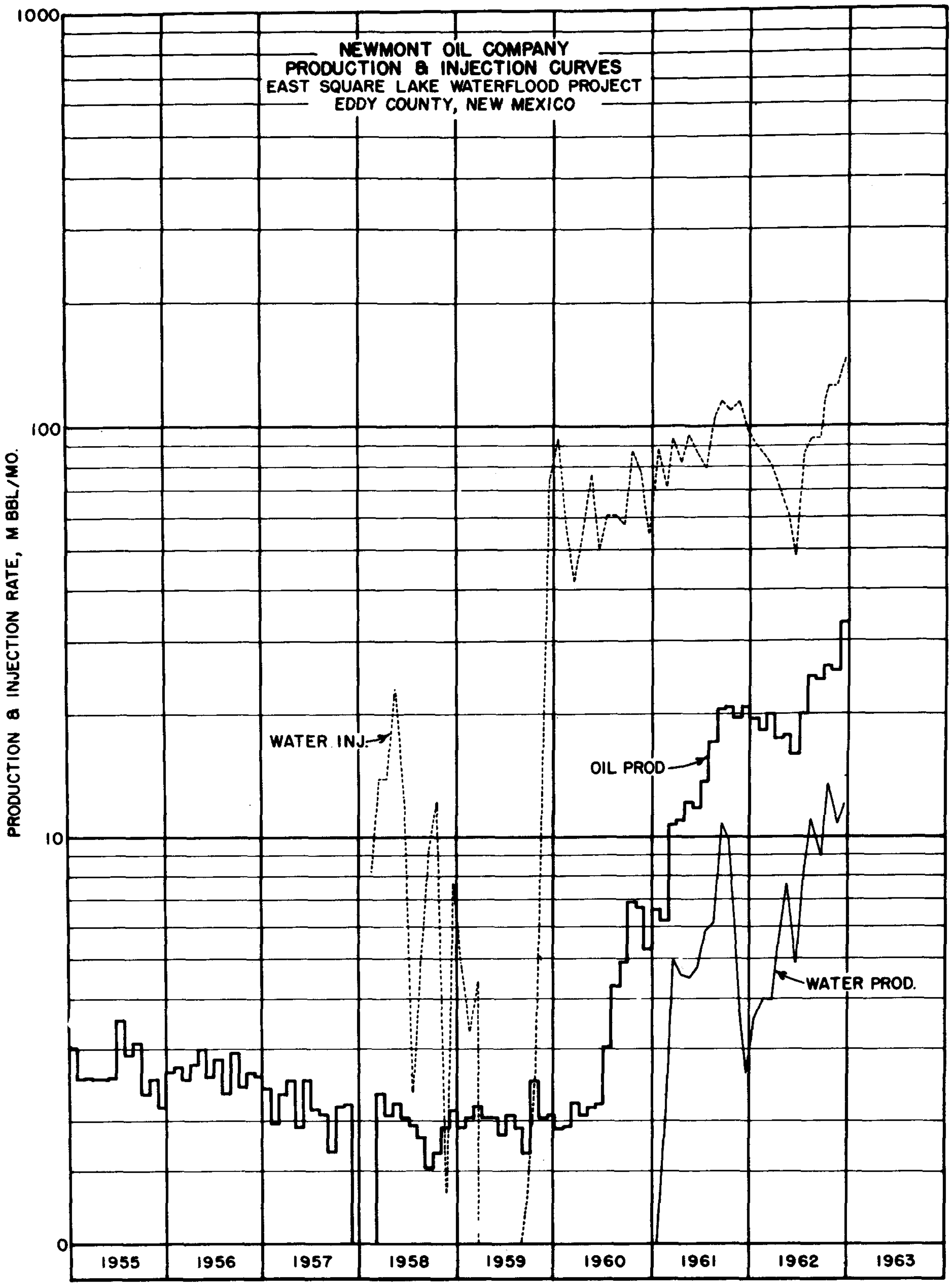
Since the SACROC Unit is a pressure maintenance project rather than a true stripper waterflood the volumetric control of injection has been utilized. This project has been designed so that total injection volumes will exceed withdrawal volumes by approximately 25%. The injection system was designed and built to inject 200,000 BWPD at a plant discharge pressure of 2340 psig. Volumetric control is essential in this project since the total unit allowable gives credit for injected fluids as well as transfer of allowables from shut in wells.

## OPERATIONAL CONTROL

Since a substantial development budget usually accompanies a waterflood engineering study the planning phase of a project gets ample attention from management; but the development and operation phases of the project are not always so closely watched. This relaxation of supervision after a project has been approved has often resulted in a loss of ultimate recovery and, in some instances, may have resulted in economic failure for the project.

Waterflood planning is only good as long as it works. Sufficient flexibility should be built into the development and operational procedures for a waterflood so that changes can be made when performance dictates. Usually these changes should be made promptly for best results and often the changes require management approval. Getting management to change its mind takes solid facts based on performance.

Field personnel should be educated to the necessity for knowing and reporting what every well in a project is doing. Provision should be made for accurate measurement of injection volumes on a project and individual well basis. Most operators use individual meters for injection wells and a master meter for each plant. A routine production testing procedure for each producer should be followed so that every well is



NEWMONT OIL COMPANY
PRODUCTION & INJECTION CURVES
EAST SQUARE LAKE WATERFLOOD PROJECT
EDDY COUNTY, NEW MEXICO
1000
100
10
0
PRODUCTION & INJECTION RATE, M BBL/MO.
WATER INJ.
OIL PROD
WATER PROD.
1955
1956
1957
1958
1959
1960
1961
1962
1963


FIGURE 4

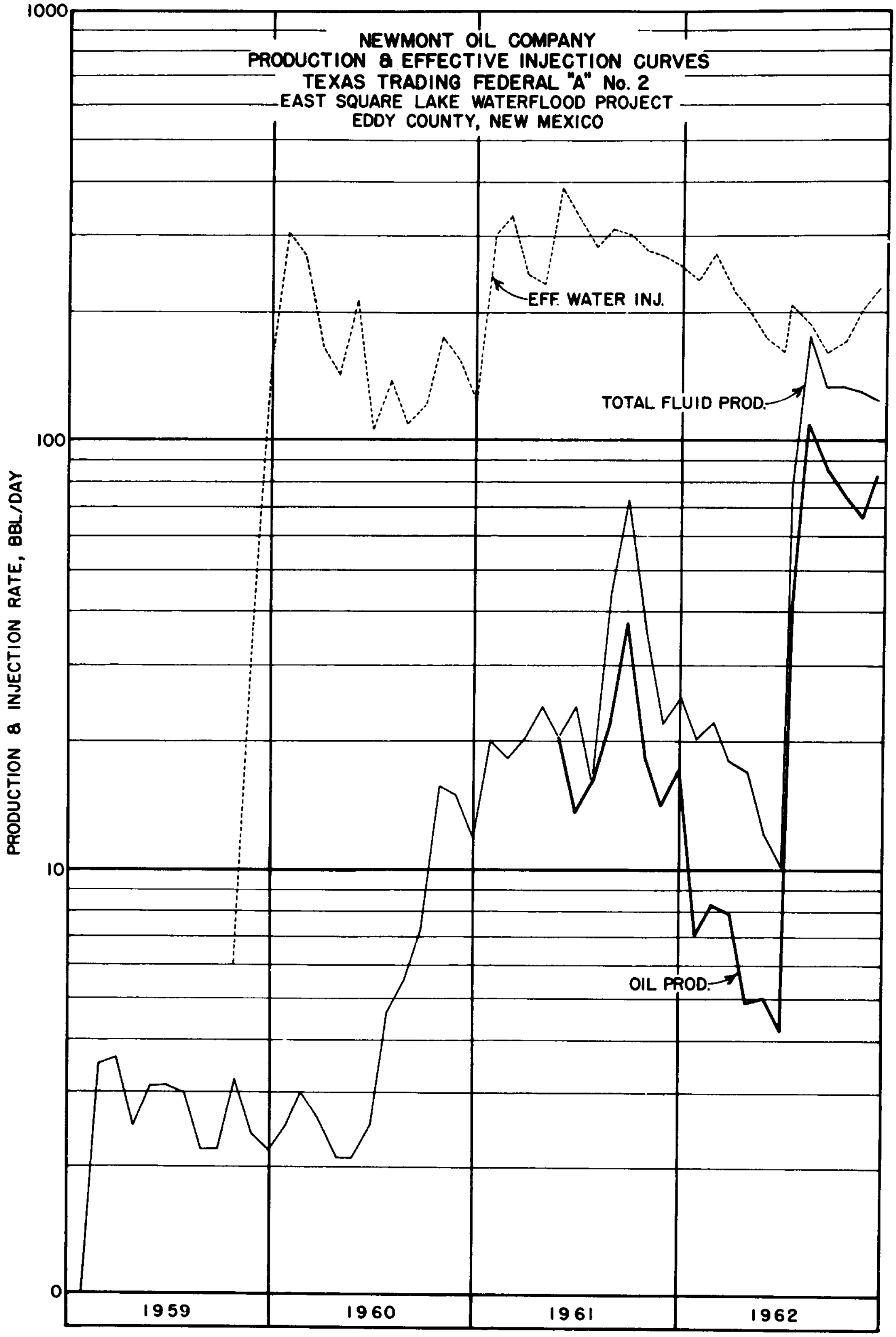

NEWMONT OIL COMPANY
PRODUCTION & EFFECTIVE INJECTION CURVES
TEXAS TRADING FEDERAL "A" No. 2
EAST SQUARE LAKE WATERFLOOD PROJECT
EDDY COUNTY, NEW MEXICO
1000
100
10
0
PRODUCTION & INJECTION RATE, BBL/DAY
EFF. WATER INJ.
TOTAL FLUID PROD.
OIL PROD.
1959
1960
1961
1962

FIGURE 5

tested regularly and often enough to reflect its waterflood performance. A family of curves (Figure 4) showing oil and water production and water injection should be maintained to reflect the performance of the project. Individual production and inject on curves should also be plotted monthly. In addition to individual production and injection curves some operators use a combination of these data as a performance indicator. Figure 5 shows an effective injection curve with a fluid production curve for a center 5 spot producer. The volume injected into each well is prorated to the affected producers and the sum of these fractions is plotted as the effective injection. Our company uses this system for a graphic presentation of the production versus injection fluid balance for each 5 spot.

For operational control the data and curves just mentioned should be examined monthly by experienced engineering personnel to recognize symptoms of potential operating problems. For example, if the injection well curves show a consistent decrease in injection rates while the plant pressure remains constant a plugging action of the injection water can be suspected. This would suggest a review of the water filtration and chemical treatment system. Sometimes a plugging condition can occur downstream from the filters. This type of plugging usually requires chemical treatment for corrosion inhibition or for the control of bacterial growth. A sharp increase in injection rate in 1 well with no change in operating conditions can indicate a casing leak; a sharp drop in injection in a well can suggest that the pay may be covered with cavings.

A comparison of effective injection versus fluid production may indicate a restriction in the producing well. This was the case in the well shown in Figure 5. Investigation showed that the pay face was being shut off by a gyp deposit. The well was treated and fluid production restored. From this experience a program of chemical treatment was instituted which has prevented recurrence of this problem in this well and other producers in the project.

Another tool for determining the efficiency of waterflood operation is a fluid level locator for pumping wells. These devices measure the distance to the fluid level by measurement of the time required for sound to travel from the tubing collars to the surface. Used on a routine basis this tool is helpful in assuring the producing wells are lifting all of the fluid which enters the bore hole. When other performance data show symptoms of well bore restrictions, a pressure build-up test can be made with the fluid level locator. The well is shut in and fluid level measurements are taken at regular intervals. A careful examination of the rate of fluid build-up from a plot of fluid head build-up in feet versus time in minutes is necessary for an estimation of formation damage. A good indication of formation damage is when the rate of build-up is constant.

In addition to the performance data which are gathered by routine methods special surveys are often helpful. There are several injectivity profile services as well as spinner and radio-active tracer surveys available. These surveys, when used individually or in combination, furnish valuable information concerning the points of water entry and an estimate of the volumes taken over the pay intervals. They can pin point mechanical problems such as casing leaks but are also helpful in checking the efficiency of the water injection program. For example, the Newmont Square Lake project commenced injection simultaneously into 3 thin pay zones in an open hole section approximately 200 ft in length. Injectivity surveys indicated that very little water was entering the lowest sand member because of caving and lower permeability at the plant pressure of 2100 psi. The 2 upper zones were taking relatively equal volumes at this pressure. Liners were cemented through the open hole section and the pay zones were selectively perforated in 2 injection wells to test the feasibility of dual injection. By isolating the zones with packers it was found that the lower zone would take economic volumes when the injection pressure was raised to 2500 psi. Since previous performance had indicated that the upper zones could not be subjected to a pressure in excess of 2300 psi without pressure parting of the formation it was concluded that dual injection would be necessary to effectively sweep the lower zone. Using these test data and an engineering analysis of the reserves to be recovered from the lower zone the management approved a program of workovers and plant modification to accomplish dual injection for this project.

## ECONOMIC CONTROL

The previous discussion has touched on various operational factors which can be controlled or corrected if careful collection and analysis of performance data is conducted on a routine basis. In addition the overall performance of the project must be checked periodically to determine if the original reservoir performance predictions are valid. Because of the higher cost of waterflood operations any significant changes in the performance of a project should be reviewed economically as soon as possible to determine what budget changes are necessary. Prompt action, when all the facts are in, can radically change the cash flow picture for a project. If the Square Lake project had delayed development of the lower zone until the upper 2 zones were depleted, the oil from that zone would have been worth considerably less because of the longer operating period required. On the other hand, caution should be used in carrying forward a development program if the project response is not meeting expectations. Regular reviews of the project development budget should be made and correlated with project performance. Sufficient flexibility should be built into the budget so that it can be modified as operating conditions dictate.

## SUMMARY

A waterflood demands the best that our petroleum technology has to offer. From the pumper to the executive who approves the budget, concentration and interest and understanding are necessary to attain maximum economic recovery from a project. To be most effective a waterflood program should have sufficient flexibility so that engineering data can be translated into field action with minimum delay. Good liason between the field and headquarters can make waterflood production as popular as any wildcat program.