Simplified Calculations On Economics And Feasibility Of Water Flooding

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The relative weight or importance of the following data used to estimate waterflood recoveries is indicated from actual calculations on several reservoirs in different areas: original oil and water saturations, residual saturations from cores or flood pot data, per cent primary recovery, shrinkage of oil remaining, the resulting mobile oil subject to recovery, formation flood (conformance factor) efficiency from permeability profiles, and pattern efficiencies (reservoir volume or area affected) up to un-economic water percentages.

Sample calculations were made to show the effects of varying some of the most important factors influencing water flood recoveries and economics. Installation costs are not considered except generally. The influence of relative permeability data and mobility ratios on recoveries are not discussed.

PROCEDURE AND DATA NEEDED

In general procedure has been as follows:

A. First, the pore space is totaled. Core data is needed, of course, although if core data is not available, electric log interpretation may have to be used. The apparent lack of realization of the necessity of core data in these times is somewhat discouraging.

B. Next, the pore space fraction occupied by connate (interstitial) water is subtracted. Core data is used if available, or electric log interpretation if necessary. Irreducible water saturation tests on core plugs should be used to check core data calculation of connate water.

C. Thirdly, the pore space fraction occupied by unrecoverable residual oil based on core data residual oil or flood pot tests if available is subtracted. If core data residual oil is used it is assumed that 100 per cent shrinkage occurred when the core sample was brought to the surface from the original or existing reservoir conditions. This core data saturation is therefore corrected by multiplying by the applicable formation volume factor to arrive at the volume of pore space occupied by reservoir residual oil that cannot be flushed out by water just as the core residual oil is assumed could not be flushed by the drilling fluid.

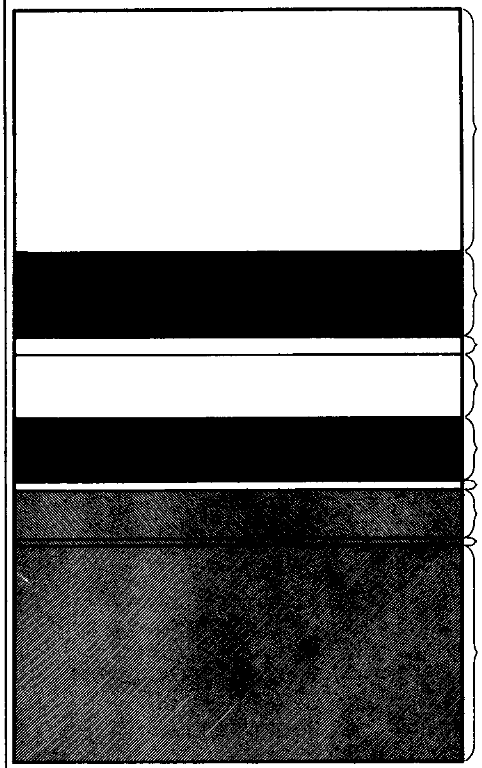
D. Further, the primary recovery (at start of water flooding) corrected to pore space volume occupied before produced is subtracted. Per cent primary recovery (of stock tank oil in place) times fraction of pore space origianlly occupied by total reservoir oil (or barrels of reservoir oil per acre-foot) results in recovery corrected for shrinkage in terms of fraction of pore space.

E. Next, the pore space volume caused by shrinkage of oil remaining to depleted reservoir pressure is subtracted. Reservoir sample data obtained at original or above saturation pressure and the curves on gas-in-solution and shrinkage (formation volume factor) obtained from analysis of such samples are necessary as are bottom hole pressure data on the depleted or partially depleted reservoir. The shrinkage, in per cent, from saturation pressure (or in barrels per acre-foot) after primary gives the shrinkage in terms of fraction of pore space (or in barrels per acre-foot). This computation leaves remaining mobile reservoir oil subject to recovery by water flooding for the volume of the formation through which water can be moved to displace the mobile oil present in the pore spaces. Too, correcting for shrinkage in volume upon release of the remaining pressure and change in temperature when brought to the surface leaves remaining mobile stock tank oil subject to recovery by water flooding.

F. If each horizontal layer of the formation had the same permeability and same porosity, the water front from injection wells would reach the producing well in each layer at the same time and the producing well would change from 100 per cent oil to 100 per cent water (disregarding the pattern efficiency). In this case the formation efficiency would be 100 per cent. However, if the porosities or pore volume in each layer are different, the total section will be flooded out, but the layers having the lesser pore space will be flooded out before the layers having greater pore space. And, if both porosities and capacity to transmit fluid (permeability) are both different in the different layers then they will be flooded out in direct proportion to their capacity and inversely in proportion to their total pore space. This method is similar to the Stiles method except that calculation of recovery at different per cent water cuts and water and oil production rates at different points are disregarded. Some equations used in other methods to calculate recovery curves up to certain per cent water cuts are based on the theory that the beginning of water injection results in the commencement of oil production from all layers instead of the start of the formation of the oil bank in all the layers (in which water enters). These equations also cannot take into account compressibility of the gas and oil as changes occur during injection. Disregarding the pore volumes of water that would be put through the formation to reduce the saturations to residual, the per cent of the formation volume affected up to the time when the well is producing 95 per cent water (or un-economically) is the formation flood efficiency based on permeability profile data from cores.

G. The pattern efficiency based on the type pattern used is the per cent of the enclosed area (and volume) affected in each pattern (or total area) up to the time when the well is producing about 95 per cent water. The theoretical per cent of the areal extent of a five-spot pattern affected is considered to be 72.4 per cent up to the time of first production of water in a homogeneous reservoir. The consensus of opinion now is that from 85 per cent to 95 per cent of the total pattern area is affected up to 95 per cent water.

H. The formation efficiency and the pattern efficiency combined (sometimes called flood efficiency) represents the total reservoir volume in the pattern



	PERCENT	PERCENT OF ORIG. OIL IN PLACE	PORE SPACE FRACTION	BBLS. PER ACRE FOOT
ORIGINAL TOTAL SATURATION			1.000	1,272
CONNATE WATER FRACTION			0.322	410
PRIMARY RECOVERY CORRECTED FOR SHRINKAGE (STOCK TANK OIL)	20.0%	20.0%	0.136	173
SHRINKAGE OF PRIMARY OIL PROD.			0.023	29
SHRINKAGE OF ALL OIL REMAINING DURING PRIMARY PROD.	12.5%		0.068	86
WATERFLOOD OIL RECOVERED		18.1%	0.113	130
SHRINKAGE OF WATERFLOOD OIL			0.009	11
LOSSES - FORMATION EFFICIENCY	(64.1%)		0.063	80
LOSSES - PATTERN EFFICIENCY	(90.0%)		0.011	14
IMMOBILE RESIDUAL OIL		35.5%	0.289	368

FIG. 1

TABLE 1

FORMATION VOLUMES FLOODED

FORMATION EFFICIENCIES FROM CORE DATA

MORRIS SAND - COLEMAN COUNTY, TEXAS

		FEET OF PERM. SAND	M D. FEET	AVG. PERM. MD.	POROSITY PERCENT-FEET	AVG. POROSITY PERCENT	AVG. RESIDUAL OIL SAT.	AVG. WATER SAT.	AVG. CALC. CONNATE WATER SAT. CORE LAB. EST.	FORMATION VOLUME FACTOR	POROSITY FT. WITH 95% OF PROD. CAPACITY	% OF PROD. VOLUME FLOODED TO 95% WATER
LOUIS FRANKLIN ET AL												
L. Emet Walker	No. 1	17'	558.2	32.8	287.2	16.9 %	23.3 %	21.8 %	21.8 %	1.20	201.4	70.1 %
ECHO OPERATORS COMMITTEE												
Dibrell	No. 6-1	8'	278.1	34.8	139.2	17.4 %	26.9 %	33.1 %	32.0 %	1.20	102.0	73.3 %
Miller	No. 7	21'	2439.2	116.2	322.9	15.4 %	24.7 %	33.6 %	33.0 %	1.19	194.0	60.1 %
ANZAC OIL CORPORATION ET AL												
M. B. Miller	No. 6	20'	1335.9	66.8	326.2	16.3 %	23.5 %	40.4 %	39.0 %	1.21	178.7	54.8 %
W. B. FULTZ												
M. B. Miller	No. 1-A	20'	956.8	47.8	322.4	16.1 %	24.9 %	33.5 %	34.0 %	1.19	179.1	55.5 %
M. B. Miller	No. 6-A	9'	240.5	26.7	161.0	17.9 %	21.2 %	28.7 %	29.0 %	1.19	108.9	67.6 %
M. B. Miller	No. 7-A	9'	220.0	24.4	142.7	15.9 %	24.6 %	34.8 %	35.0 %	1.19	126.6	88.7 %
TOTALS AND AVERAGES:		104'	6028.7	58.0	1701.6	16.4 %	24.1 %	32.6 %	32.2 %	1.20	1090.7	64.1 %

Weighted Average Porosity	16.4 %	
Calculated - Pore Space - Barrels Per Acre-Foot	1272	B/AF.
Calculated - Pore Space Occupied by Reservoir Oil (1272) (0.678)	862	B/AF.
Calculated - Stock Tank Oil in Place (862/1.20 Bbl./Bbl.)	718	B/AF.

TABLE 2

ESTIMATED WATER FLOOD RECOVERIES

MORRIS SAND - COLEMAN COUNTY, TEXAS

	PERCENT	PERCENT OF ORIGINAL OIL IN PLACE	PORE SPACE FRACTION	BARRELS PER ACRE - FOOT
Original Reservoir Conditions, Saturations of Oil and Water		-	1.000	1,272
Connate Water Saturation		-	0.322	410
Original Oil Saturation		100.0 %	0.678	862
Primary Recovery	20.0 %			(144)
Primary Recovery, Corrected for Shrinkage (144)(1.20)		20.0 %	0.136	173
Reservoir Saturation Disregarding Shrinkage of Oil Remaining		80.0 %	0.542	689
Shrinkage (Orig. Est. 820 PSIG to 50 PSIG) (1.20 - 1.05)/1.20	12.5 %		0.068	86
Reservoir Saturations Before Flooding		80.0 %	0.474	603
Residual Saturation, Percent Pore Space by Core	24.1 %	35.5 %		
Residual Saturation (Corrected for Shrinkage)(24.1)(1.20) % of Pore Space	28.9 %		0.289	368
Mobile Oil Subject to Recovery by Flooding		44.5 %	0.185	235
Stock Tank Oil in Remaining Mobile Oil after Shrinkage (235/1.05)			0.176	224
Percent of Vertical Formation Flooded to 95% Water	64.1 %			
Average Water Flood Recovery from Total Section (224) (0.641)		20.0 %	0.113	144
Enclosed Five-Spot Pattern Efficiencies are Estimated at 90%; Others are Arbitrarily Reduced According to the Position of the Producing and Injection Wells	90.0 %			
Average Water Flood Recovery From Total Acre-Feet in Totally Enclosed Five-Spot Patterns, Barrels Per Acre-Foot (90%) (144)		18.1 %	0.102	130
Patterns Affected from Three (3) Injection Wells (60%) (144)	60.0 %			86
Patterns Affected from Two (2) Injection Wells (45%) (144)	45.0 %			65
Patterns Affected from One (1) Injection Well (30%) (144)	30.0 %			43

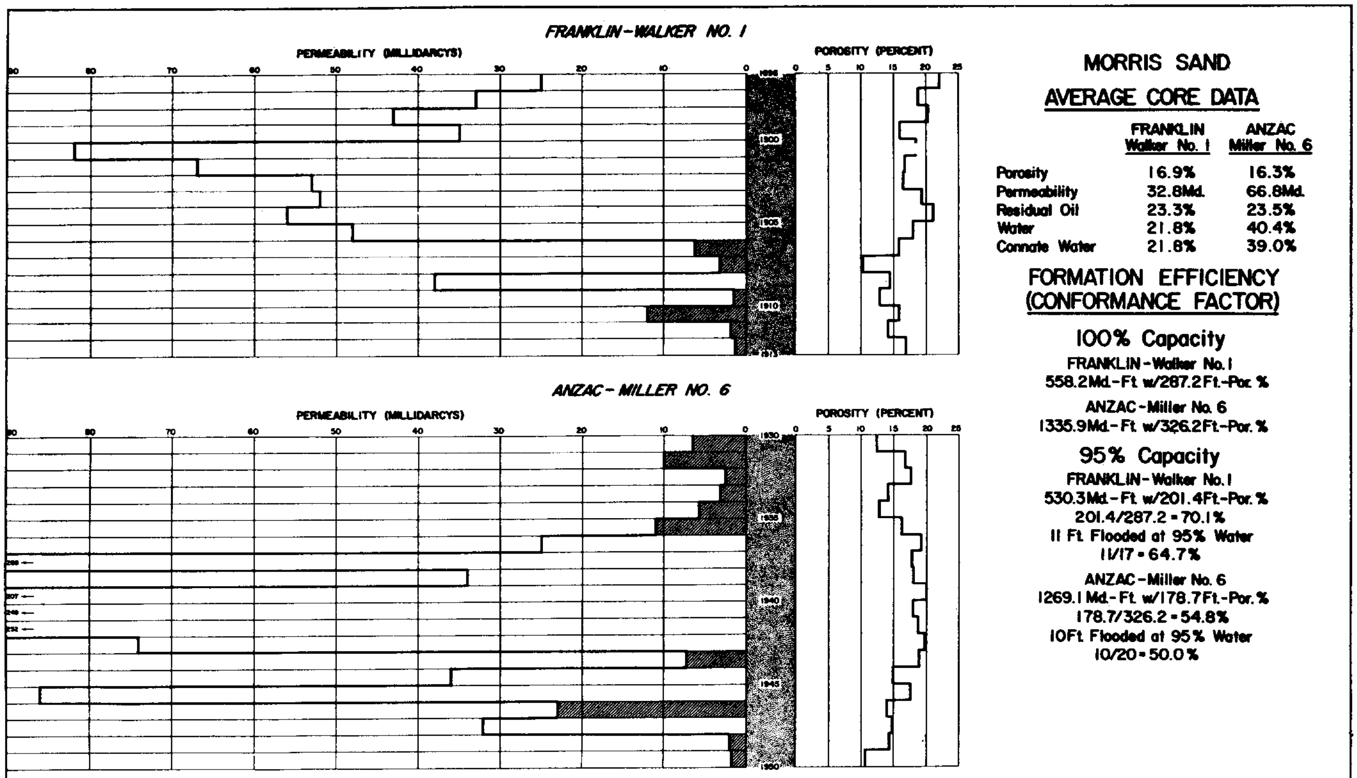


FIG 2

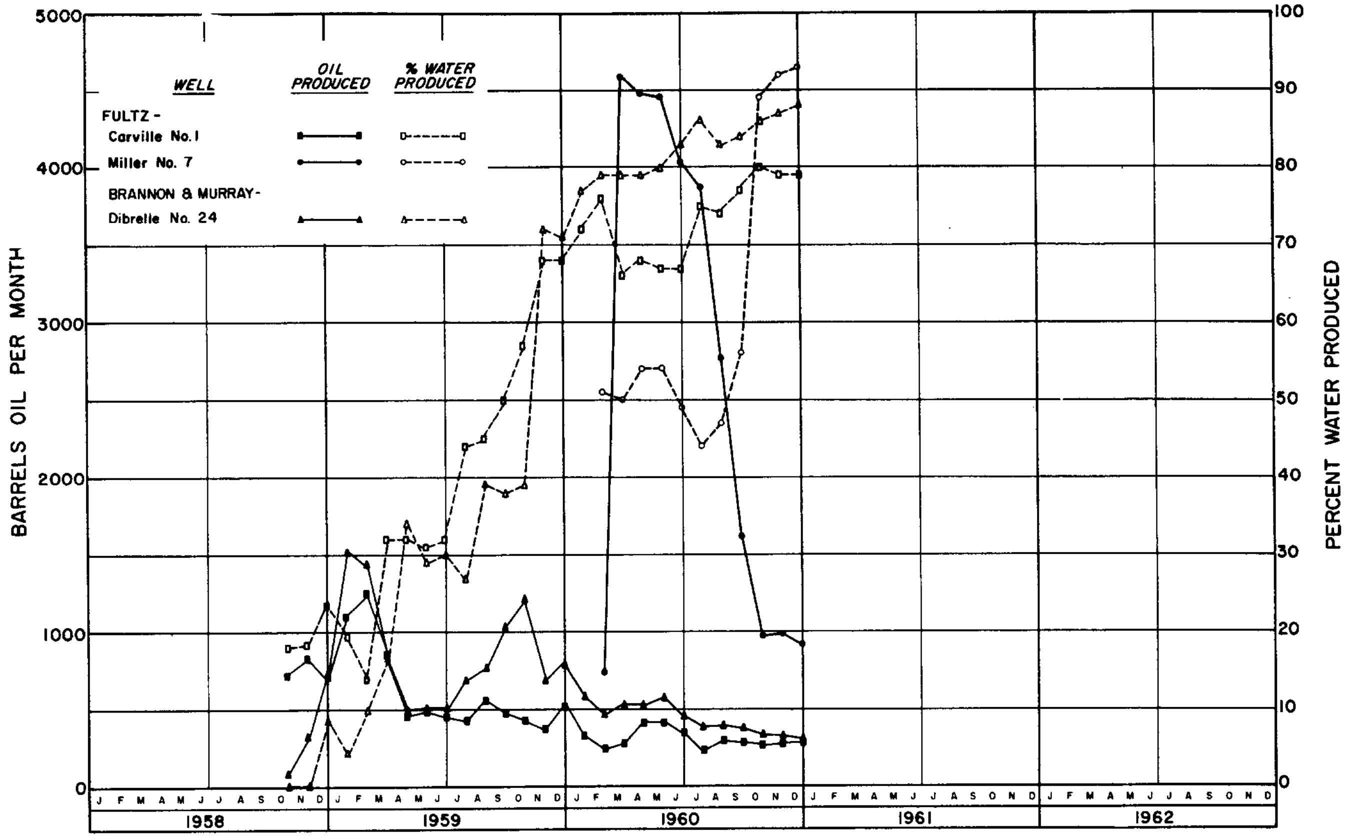


FIG. 3

WELL PRODUCTION HISTORIES

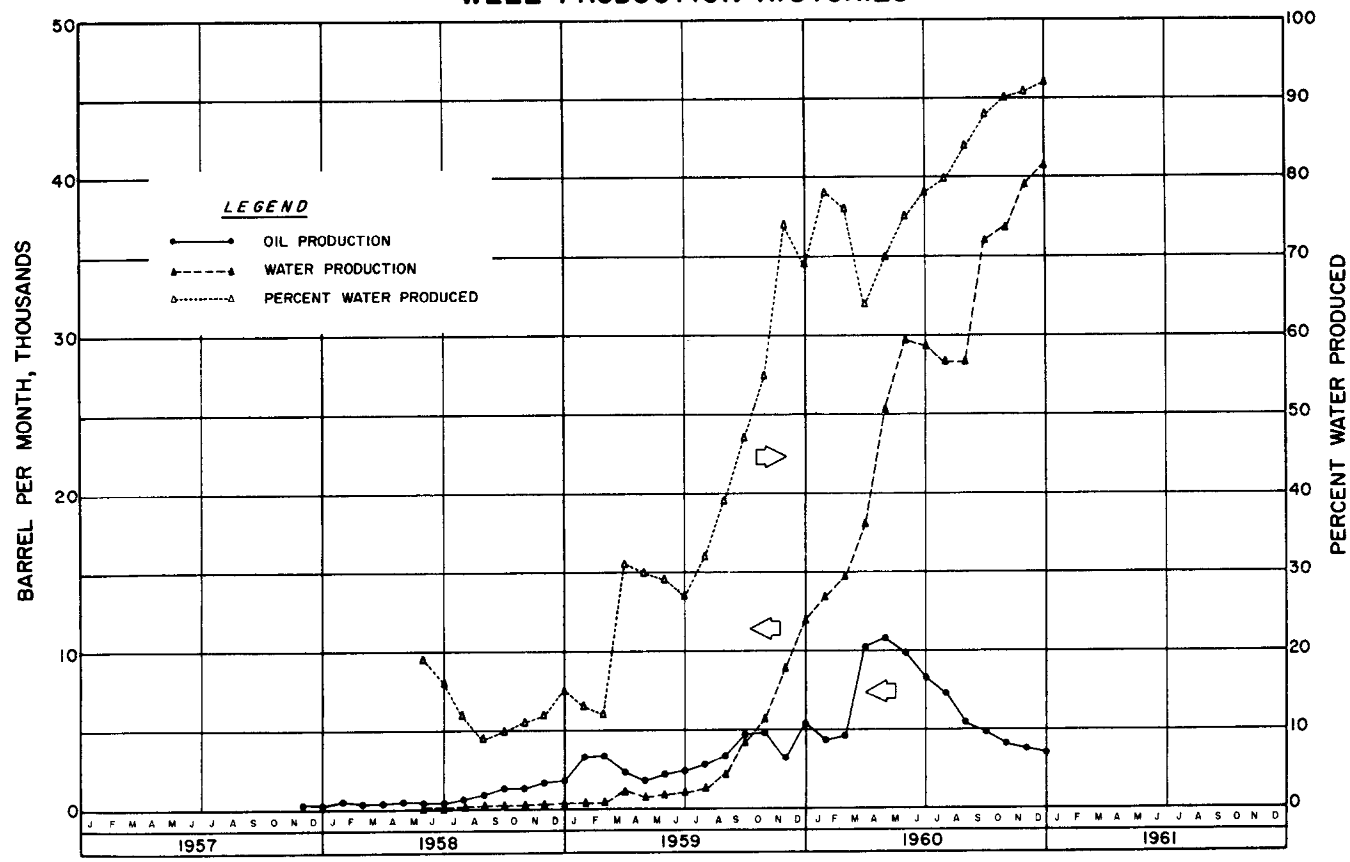


FIG. 4

UNIT FLOOD PRODUCTION HISTORY

TABLE 3

ESTIMATED ORIGINAL OIL IN PLACE AND PERCENT PRIMARY RECOVERY

RICKLES FIELD, STEPHENS COUNTY, TEXAS

	RICKLES (UPPER) CONGLOMERATE	SECOND (LOWER) CONGLOMERATE	FIELD TOTALS
Weighted Average Porosities, Percent	16.10	13.83	
Weighted Average Connate Water Saturation, Percent	26.0	29.0	
Formation Volume Factors (shrinkage), Bbl./Bbl. (1900 PSIG)	1.57	1.57	
Estimated Original Reservoir Oil in Place, B/AF	924	762	
Estimated Original Stock Tank Oil in Place, B/AF	589	485	
Calculated Productive Formation Volume, Acre Feet	5,987	5,794	11,781
Estimated Original Oil in Place, Stock Tank Barrels	3,526,343	2,810,000	6,336,343
Total Primary Recoveries, Barrels	971,456	628,494	1,599,950
Total Primary Recoveries, B/AF	162	108	136
Total Primary Recoveries, Reservoir B/AF	254	170	214
Total Primary Recoveries, Percent of Stock Tank Oil in Place	27.5%	22.3%	25.3%
Total Primary Recovery, Percent of Pore Space	17.5%	14.2%	
Shrinkage, B/AF of Reservoir Oil Remaining After Production (1900 PSIG to 100 PSIG) (1.57-1.275/1.570 equals 18.80%)	126	111	
Reservoir Saturation Before Flooding, B/AF	544	481	
Reservoir Saturation Before Flooding, Pore Space Fraction	0.436	0.449	

touched or affected by injected water up to about 95 per cent water. These percentage efficiencies applied to the total remaining mobile oil subject to recovery by water flooding result in a figure of water flood recovery for each "normal" five-spot pattern (or other pattern) in barrels per acre-foot.

I. In all projects there will be irregular patterns where producing wells are out of center or located along the edges of the reservoir for which the pattern efficiency will be less because of being affected from only one, two or three wells (or could be more if more than one well is located in a pattern). Reduction in recoveries from effects from less than a completely enclosed pattern were amply demonstrated by George Buckles in "Water Flooding in the South Ward Field" presented in 1951 in Bulletin 11 of Texas Petroleum Research Committee. In this report production data showed that a well affected from one injection well produced only 10 per cent and one affected from two injection wells produced only 37 per cent of that amount produced by a well in a totally enclosed pattern. For irregular patterns the basic pattern efficiency has to be modified by estimating the relative efficiency due to well location and shape of the patterns.

J. After making the above calculations in order, a table is set up showing each pattern area productive volume, pattern per cent area-feet, pattern efficiency, water flood recovery in barrels per acre-foot and gross barrels, net barrels to Working Interest owners, value of Working Interest oil, pattern share of investment in water flood, pattern share of operating costs and pattern development costs (if any) and remaining estimated net value of each pattern.

CALCULATED EFFICIENCIES AND RECOVERIES ECHO MORRIS SAND PROJECT

The above steps are calculated in order and the chart, Fig. 1, shows typical data on recoveries and losses with relative volumes of each indicated on the "barrel".

The data shown on Fig. 1 are based on Table 1, which is a summary of core data and average formation efficiencies for seven wells in the Echo Morris Sand Field and Table 2, which shows the calculations in the order they were made.

Table 2 shows the actual calculations which are the basis for the data on Fig. 1. Data is shown in per cent of stock tank oil in place, fraction of pore space, and barrels per acre-foot.

Permeability data are not converted into relative depth layers and are not averaged by wells to obtain a composite permeability profile. Instead the data are averaged by adding total feet-porosity per cent having 95 per cent of the permeability capacity for all wells and dividing by total feet represented. This computation assumes that the higher permeability streaks are connected from well to well in this field regardless of their location in the producing section.

Fig. 2 shows the permeability profiles of two wells and the simplified method of calculation of the conformance factor or formation efficiency which was averaged for seven wells on Table 1.

Fig. 3 is a production history chart showing the water flood history of three wells (one well was drilled inside a pattern after fill-up occurred) and Fig. 4 is a production history chart of the Echo Morris Sand Water Flood project. If the ultimate recovery by water flooding is as much as 176,000 barrels (126,000 barrels to January 1, 1961, plus 50,000 barrels estimated) this total will amount to 76 per cent of the primary recovery of 233,000 barrels. Comparison of barrels per acre-foot of secondary oil to barrels per acre-foot of primary oil recovered will not be representative; however, the recovery of 176,000 barrels from 1,731 gross acre-feet is 102 barrels per acre-foot. The "pilot flood" pattern has recovered 139 barrels per gross acre-foot, and the high water percentages and volumes indicate the adverse effects of the permeability profile.

The assumed effective formation volume in the reservoir may be much too high, for some wells were logged which were drilled in with cable tools and only three partial core analysis were available before water flooding commenced. This analysis resulted in the gross section being identified as "net sand" in most of the wells in the project area.

Some of these cores used are in the same reservoir but in an extension developed outside the project area. According to persons familiar with Morris Sand Areas developed by M. G. Cheney and the Anzac Oil Corporation the Morris is typically a sand having usually a few feet of relatively high permeability, loosely cemented "Brown" saturated sand in a section grading from tight limy sand at the top and into tight shaly sand in the bottom with the cable tool core barrel sometimes used unable to recover the "good" sand. Primary production in better productive areas of the Morris has been long-lived as the tighter sections have continued to feed oil into the more permeabile sand sections.

MAJOR FACTORS INFLUENCING RECOVERY CALCULATIONS

The major factors that can make large differences in calculated recoveries (assuming porosities are known and pattern efficiencies are determined by the well locations) are as follows:

1. Connate water;
2. Shrinkage;
3. Residual Oil (im-mobile);
4. Primary recovery;
5. Permeability profile effects (formation efficiencies).

The adverse effects of low formation efficiency has been demonstrated in the actual case reported on the Morris Sand project.

1. Connate (interstitial) water per cent governs the amount of pore space occupied by reservoir oil and for the same residual oil a higher connate water saturation with the same percentage primary recovery leaves less mobile oil subject to recovery by water flooding. Connate water percentages affect the relative permeabilities to oil and water (and gas) and, along with mobility ratios, affect the residual oil volumes attainable up to maximum water/oil ratios. Discussion of these are not within the scope of this paper; however, connate water content could be so high that formation relative permeabilities to water would not allow formation of an oil bank, resulting in very low water flood recoveries. When connate water percentages are above 40 per cent actual there should be obtained laboratory data on the effects of relative permeabilities on water/oil ratios and recoveries.
2. The effects on calculated water flood recovery caused by shrinkage of the reservoir oil upon the reduction of pressure accompanying the primary production under the gas-in-solution recovery mechanism have not been of much notice to the ordinary oil operator in the shallower fields where most of the water flooding has taken place to date. In deeper fields, decisions made before the reservoir is depleted and all shrinkage is allowed to occur can make a large difference in water flood recoveries. Table 3 on the Rickles Conglomerate Field, Stephens County, shows the high shrinkage (formation volume factors) and relatively high primary recoveries and Table 4 shows the effects of this shrinkage on the calculated re-

TABLE 4

WATER FLOOD RECOVERY CALCULATIONS

BASED ON PRIMARY RECOVERY, ESTIMATED SATURATIONS OF RESIDUAL OIL AND SHRINKAGE

RICKLES FIELD, STEPHENS COUNTY, TEXAS

	RICKLES CONGLOMERATE				SECOND CONGLOMERATE			
	PERCENTAGE	PERCENT PORE SPACE	PORE SPACE FRACTION	B/A FOOT	PERCENTAGE	PERCENT PORE SPACE	PORE SPACE FRACTION	B/A FOOT
Original saturation oil & water		100.00	1.000	1249		100.00	1.000	1073
Connate water saturation		26.00	0.260	325		29.00	0.290	311
Original oil saturation		74.00	0.740	924		71.00	0.710	762
Primary recovery, corrected for shrinkage (1900 PSIG to 0 PSIG)		20.30	0.203	254		15.80	0.158	170
Reservoir saturation disregarding shrinkage		53.70	0.537	670		55.20	0.552	592
Shrinkage (1900 PSIG to 100 PSIG) (1.570-1.275/1.570) reservoir oil remaining.	18.80%	10.10	0.101	126	18.80%	10.30	0.103	111
Reservoir saturation before flooding		43.60	0.436	544		44.90	0.449	481
Residual saturation, percent pore space by core.		(19.20)				(17.9)		
Residual saturation (corrected for shrinkage) (19.2)(1.57)=30.1%;(17.9)(1.57)=28.1%		25.0 Est.	0.250 Est.	312 Est.		25.0 Est.	0.250 Est.	268 Est.
Mobile oil subject to recovery by flooding.		18.6	0.186	232		19.9	0.199	213
Stock tank oil in remaining mobile oil after shrinkage (232/1.275); (213/1.275)				182				167
Percent of vertical formation flooded to 95% water:	72.2%				56.8%			
Average water flood recovery from total section, B/AF: (0.722)(182); (0.568)(167)				131				95
Enclosed five spot pattern efficiencies are estimated at 90%; others are arbitrarily reduced according to the position of the producing and injection wells (Vol. of pattern affected).	90.0%				90.0%			
Average water flood recovery from total acre-feet in totally enclosed five spot patterns, B/AF.				118				86
Patterns affected from 3 injection wells (60%)				79				57
Patterns affected from 2 injection wells (45%)				59				43
Patterns affected from 1 injection well (30%)				39				29

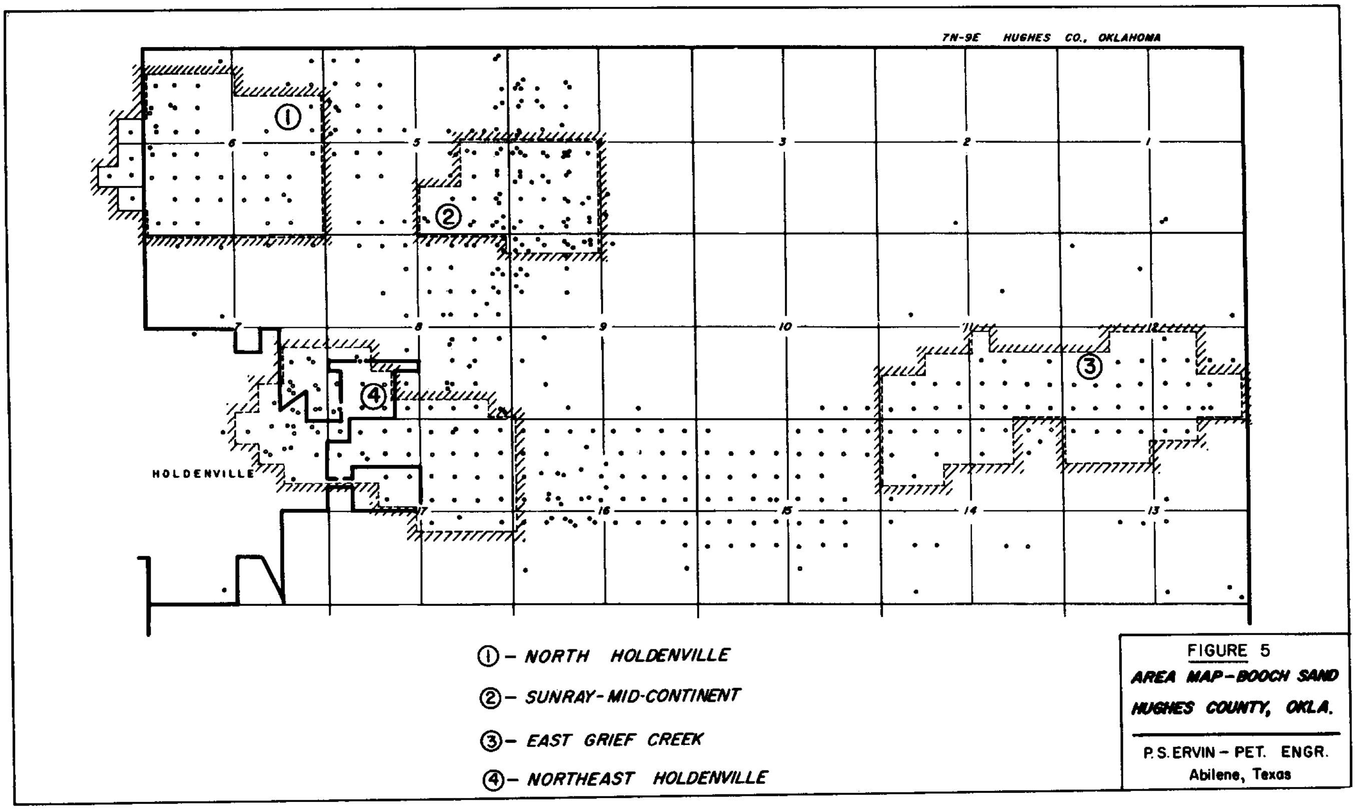


FIGURE 5
AREA MAP-BOOCH SAND
HUGHES COUNTY, OKLA.

coveries by water flooding. Because of irregular well locations and patterns, the recoveries by patterns averaged 87 and 62 barrels per acre-foot instead of 118 and 86 in the Upper and Lower Conglomerate, respectively, and because of this average and investment caused by abandoned wells this project appeared to be marginal and was not recommended. Gas caps and water levels present in both reservoirs affected the primary recoveries and the decision not to attempt to flood.

3. The effects of high or low values for the immobile residual oil are easily seen in the calculations. Because of the lack of flood pot data (which is sometimes too optimistic and is dependent on the number of pore volumes of water used) the values of oil saturation obtained from core data corrected for the shrinkage occurring when brought to the surface are used as the value of the residual oil after flooding.
4. The old assumption that secondary recoveries will approximately equal primary recoveries is not in line with the actual results obtained in many floods, and there is no real reason why they should be. Very large differences have already been proven in such fields as the South Ward Yates Sand, KMA Strawn, Spraberry Pilot Floods, Kirk Field Marble Falls Lime, and Bartlesville Sand Floods in Oklahoma. Muskat in T. P. 1917, Petroleum Tech., Sept., 1945, "Effect of Reservoir Fluid and Rock Characteristics on Production Histories of Gas-Drive Reservoirs" and others have shown by calculation and theoretical reservoir histories the effects of gas-in-solution, connate water, reservoir pressure, shrinkage, viscosities, and gas oil ratios on primary recoveries which can vary from 10 per cent to 33 per cent of oil in place in a completely homogeneous reservoir. Our calculations show that the higher that the primary recovery has been the lower the secondary water flood recovery will be for the same residual saturation.
5. Normal permeability profile effects can be so adverse as to cause loss of primary oil in a project started before depletion has occurred. Uncontrolled artificial stimulation such as fracturing — if it causes horizontal fractures of considerable extent - may provide economic production in some cases where none would be possible, might in other cases increase the primary recovery of oil that would be recovered later as secondary oil and might cause loss of secondary oil that would be recovered if the actual permeability profile efficiency had not been decreased by such fracturing treatment. Some cores of the Lake Sand in Eastland and Callahan Counties reportedly show much worse permeability profile (formation) efficiencies than do the cores available in the Morris Sand of Coleman County. An interesting subject along this line might be the results of the Bankline Oil Company – Bankline (Lake Sand) Field Water Flood, Eastland County, Texas, commenced in 1953, compared to its primary recoveries. Average data was reported by R. O. Major in "Unique Filter System Featured in Pilot Flood" in the October, 1953, issue of World Oil. Fig. 5 is an area map showing Booch Sand producing areas near Holdenville, Oklahoma. Table 5 shows North Holdenville Field reservoir and primary recovery data and Table 6 shows calculation of estimated water flood recoveries as used in a report on economic feasibility. Fig. 6 is the permeability profile and formation efficiency of the core of one (1) Booch Sand well. Fig. 7 is the recommended five-spot pattern for the water flood. Table 7 shows a comparison of the calculated recoveries with the actual recoveries in a nearby flood of the Grief Creek Booch Sand Field which had high primary recoveries. Secondary recovery was only 54 per cent of the primary; however, formation data on this field may be inaccurate. Table 8 shows the economics of the project by patterns in order to evaluate the investment in the water flood and necessary develop-

TABLE 5

NORTH HOLDENVILLE FIELD
HUGHES COUNTY, OKLAHOMA
BOOCH SAND PRIMARY RECOVERY - FIELD SUMMARY

Weighted average porosity (core - M. J. Mitchell - Harjo Heirs No. 4)	16.2%
Connate water content (Holdenville Field Booch Sand report - Ward Edinger - eight logs.)	38.0%
Shrinkage (Formation volume factor), bbl. reservoir oil/bbl. stock tank oil - estimated - (Edinger report)	1.17
Barrels of reservoir oil in place per acre-foot	779.0
Barrels of stock tank oil in place per acre-foot	666.0
Productive area assigned (35 wells at 10 acres/well) acres	350.0
Weighted average thickness, gross feet	13.68'
Weighted average thickness, net feet (82%)*-1	11.22'
Productive reservoir volume, gross acre-feet	4788.20
Productive reservoir volume, net acre-feet (82%)	3926.32
Estimated original oil in place, stock tank barrels	2,614,929
Cumulative primary recovery to Jan 1, 1960, barrels	408,772
Cumulative primary recovery, bbl. per acre	1,168
Cumulative primary recovery, bbl. per gross acre-foot	85.4
Cumulative primary recovery, bbl. per net acre-foot	104.1
Cumulative primary recovery, per cent of stock tank oil in place	15.63%

* - Core data shows 5' of 28' cored had zero permeability;
23'/28' = 82.14%

ment wells. That the estimated water flood recovery (from a smaller area and reservoir volume enclosed) came out so close to the actual primary was a coincidence. Investment in the water flood installation and additional wells needed were worked out in detail and operating costs were estimated as closely as possible. Table 9 shows results of calculations and effects on recoveries of varying these five important factors in the North Holdenville Booch Sand Field of Hughes County, Oklahoma. Estimated water flood recoveries varied from 89 to 281 barrels per acre-foot.

CONCLUSIONS

1. The minimum data needed for secondary recovery economic feasibility studies include core data and a bottom hole sample analysis. Along with the core data should be included tests of irreducible water saturation and flood pot tests for residual oil saturation, and if possible relative permeability data on the formation rock. Average cost per well for this information an a project area will ordinarily be only a fraction of the possible loss or gain from proposed operations.
2. If connate water, primary recovery and the immobile residual oil values are in a normal range, the shrinkage of the reservoir oil can be so great and permeability profile effects can reduce the formation efficiencies so drastically that any economic return from water flooding operations will be prevented.
3. The porosity per cent times ft in the proportion or percentage of the total porosity per cent times ft which has 95 per cent of the productive capacity in millidarcy-ft of the total formation millidarcy-ft is the percent of the formation volume which will be flooded out at the time a well is producing 95 per cent water. This figure can be assumed to be the formation efficiency or conformance factor.
4. By averaging such data for each well on which core data is available an average field formation efficiency can be calculated. If water/oil ratios or water through-put have to be known then the calculations involved in the Stiles method have to be made for

TABLE 6

NORTH HOLDENVILLE BOOCH SAND FIELD
HUGHES COUNTY, OKLAHOMA
WATER FLOOD RECOVERY CALCULATIONS
BASED ON PRIMARY, RESIDUAL OIL, AND SHRINKAGE

	PERCENTAGE	PERCENTAGE OF PORE SPACE	FRACTION OF PORE SPACE	BBL. PER ACRE-FOOT
Average pore space from 23 samples (M. J. Mitchell - Harjo Heirs No. 4)		16.2%	1.000	
Connate water contact (calc. from 8 elec. logs - Edinger report)		38.0%	0.380	
Total pore space, B/AF				1,257
Total pore space occupied by reservoir oil, fraction			0.620	
Total pore space occupied by reservoir oil, B/AF				779
Wtd. average percent pore space occupied by residual oil (core data)		15.85%		
Wtd. average percent pore space occupied by residual oil Corr. for shrinkage (15.85%) (1.17) = 18.54%; use 25.0%		25.0 %	0.250	314
Pore space fraction of mobile oil subject to recovery by primary and water flooding			0.370	465
Percentage primary recovery and fraction of pore space (0.1563) (0.620)	15.63%		0.097	122
Shrinkage of remaining oil during primary production (1.17 - 1.05/1.17) = (0.0957) (0.620)			0.059	74
Remaining mobile oil subject to recovery by water flooding, fraction			0.214	
Remaining residual oil subject to recovery by water flooding, B/AF				269
Stock tank oil in remaining residual oil after shrinkage, B/AF (269/1.05)				256
Total capacity in 23 feet = 165.3 md				
95% capacity (95% water cut) = 157.0 md. = 18 feet.				
Percent of acre-feet flooded to 95% water (18/23 = 78.3% core data of Harjo Heirs No. 4)	78.3%			
Average water flood recovery from total section, B/AF (0.783) (256 B/AF)				200
Enclosed five spot pattern efficiencies (area of the pattern affected) are estimated at 85%; others are arbitrarily reduced according to the position of the producing and injection wells and the primary recovery.	85.0%			
Average water flood recovery from total acre-feet in totally enclosed five-spot patterns (0.85) (200 B/AF), B/AF				170
Partially enclosed five-spot patterns (0.45) (200 B/AF), B/AF				90
Poor primary recovery area five-spot patterns (0.20) (200 B/AF), B/AF				40

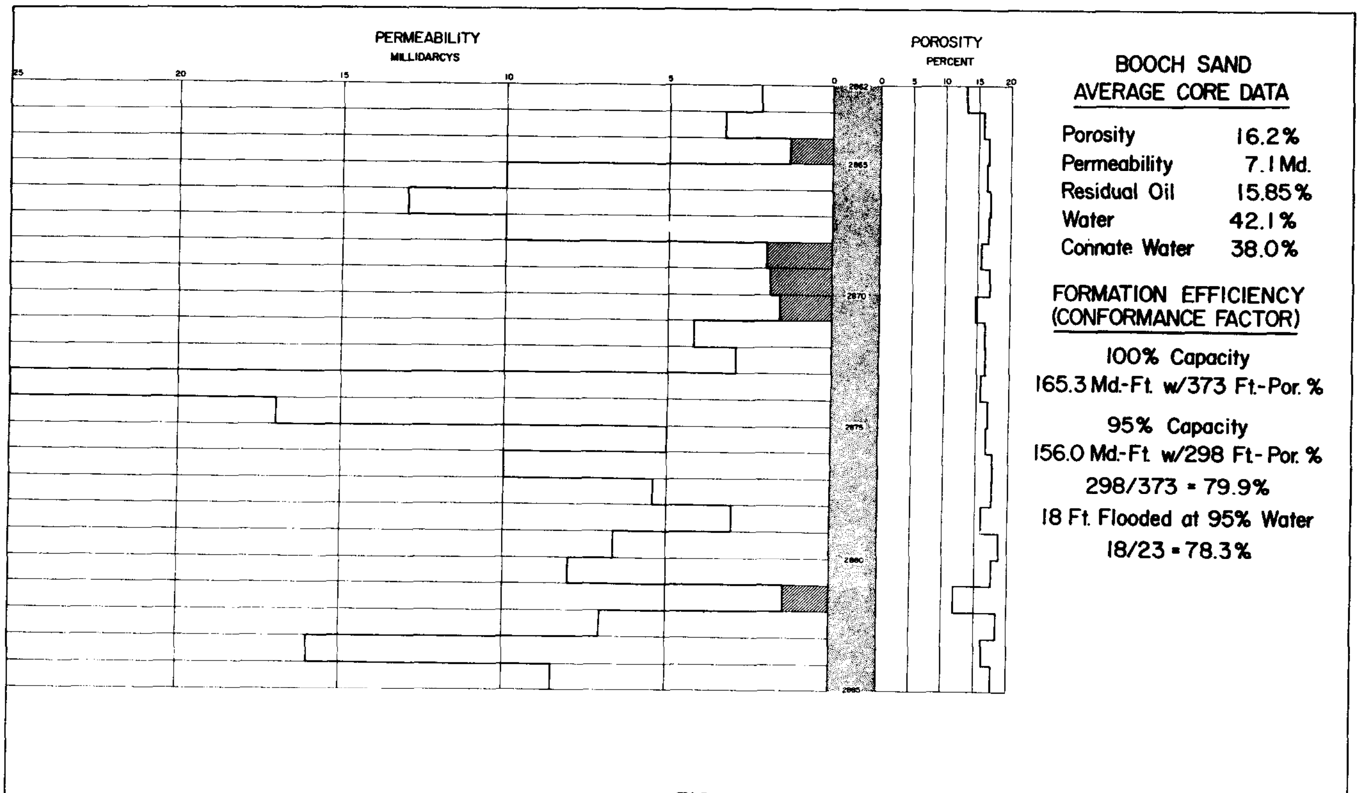
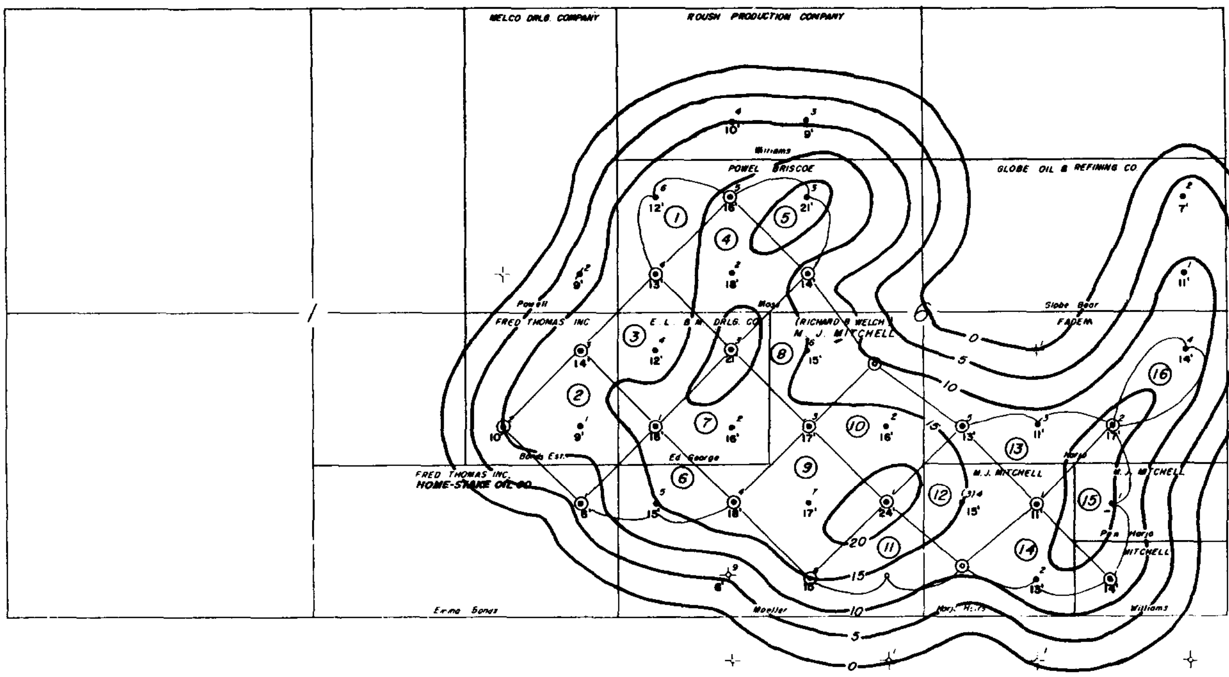


FIG 6



SUMMARY

8- Complete 5-Spot Patterns
8- Edge Incomplete Patterns
Drill Two Injection Wells
Drill One Producing Well
Re-enter One Injection Well
18- Injection Wells
16- Producing Wells

FIGURE 7

PROPOSED FIVE SPOT PATTERN OF WATER FLOOD DEVELOPMENT

NORTH HOLDENVILLE FIELD
HUGHES COUNTY OKLA.

P. S. ERAN — ABILENE, TEXAS
PET. ENG. — AUG. 26, 1959

SCALE: 0 — 500'

TABLE 7

NORTH HOLDENVILLE AND EAST GRIEF CREEK FIELDS
HUGHES COUNTY, OKLAHOMA
COMPARISON OF BOOCH SAND RECOVERIES PRIMARY AND SECONDARY

	NORTH HOLDENVILLE BOOCH SAND FIELD	EAST GRIEF CREEK BOOCH SAND FIELD FLOOD (Stanolind-Unit Operator)
Discovery date	3-30-54	1946
Water flood started	-	Aug. 1951
Primary recovery - Jan 1, 1960	408,772	
Total recovery, March 31, 1960		1,597,041
Primary recovery	408,772	1,039,631
Productive area assigned (10 acres/well)	350	450
Gross sand thickness, weighted average	13.68'	19.22'
Net sand thickness, weighted average	11.22'	15.76'
Net productive acre-feet	3926	7092
Primary recovery, B/net A.F.	104.1	146.6
Estimated oil in place (for 16.2% porosity and 38.0% connate water, both areas)B/AF	666.0	666.0
Percentage primary recovery B/net A.F.	15.63%	22.01%
Secondary recovery, bbls.	409,130 (est.)	557,410 (actual)
Secondary recovery, area affected in proposed pattern	251.45	450
Secondary recovery, acre-feet affected in proposed pattern	3189	7092
Secondary recovery, weighted average feet in proposed pattern	12.68'	15.76'
Secondary recovery, B/net acre-feet	128.3 (Est.)	78.6 (Actual)
Secondary recovery percent	19.26% (Est.)	11.80% (Actual)
Total recovery, primary and secondary	34.90% (Est.)	33.80% (Actual)

Table 8

NET VALUE OF EACH FIVE-SPOT PATTERN
PROPOSED FIVE-SPOT PATTERN OF WATER FLOOD DEVELOPMENT
NORTH HOLDENVILLE BOOCH SAND FIELD
HUGHES COUNTY, OKLAHOMA

	AREA IN ACRES	AVG. GROSS FEET	AVG. NET FEET (82%)	NET ACRE-FEET	PATTERN PERCENT ACRE-FEET OF TOTAL	PATTERN EFFICIENCY (AREA AFFECTED TO 95% WATER)	WATER FLOOD RECOVERY B/AF *-2	WATER FLOOD RECOVERY BARRELS	OPERATORS 13/16 W.I. BARRELS	GROSS VALUE AT $2.70 PER BBL.	PATTERN SHALE OF INVESTMENT IN WATER FLOOD	PATTERN SHARE OF OPERATING COSTS	PATTERN WELL DEVELOPMENT COSTS	NET VALUE OF PATTERN
										$	$	$	$	$
Pattern 1	8.15	13.69	11.23	91.52	2.870	20%*-1	40	3,661	2,975	8,033	1,688	5,682	-	663
2	20.75	11.45	9.39	194.84	6.109	85%	170	33,123	26,912	72,662	3,594	12,096	-	56,972
3	20.12	14.21	11.65	234.40	7.350	85%	170	39,848	32,377	87,417	4,324	14,553	-	68,540
4	20.13	17.73	14.54	292.69	9.178	45%*-1	90	26,342	21,403	57,788	5,400	18,172	-	34,216
5	9.30	18.70	15.33	142.57	4.470	20%*-1	40	5,703	4,634	12,512	2,630	8,851	-	1,031
6	14.03	14.50	11.89	166.82	5.231	45%	90	15,014	12,199	32,937	3,077	10,357	-	19,503
7	20.12	17.51	14.36	288.92	9.059	85%	170	49,116	39,906	107,746	5,330	17,937	-	84,479
8	18.90	15.12	12.40	234.36	7.348	85%	170	39,841	32,371	87,402	4,324	14,551	7,741	60,786
9	20.08	17.88	14.66	294.37	9.230	85%	170	50,054	40,659	109,779	5,430	18,275	-	86,074
10	18.20	17.05	13.98	254.44	7.978	85%	170	43,255	35,144	94,889	4,694	15,796	7,742	66,657
11	13.21	16.24	13.32	175.96	5.517	45%	90	15,836	12,867	34,741	3,246	10,924	26,089	(-5,518)
12	18.43	16.23	12.49	230.19	7.218	85%	170	39,132	31,795	85,847	4,247	14,292	5,161	62,147
13	14.31	13.35	10.95	156.69	4.913	45%	90	14,102	11,458	30,937	2,890	9,728	2,055	16,264
14	14.42	14.16	11.61	167.42	5.250	45%	90	15,068	12,243	33,056	3,089	10,395	5,161	14,411
15	13.62	15.20	12.46	169.71	5.321	45%	90	15,274	12,410	33,507	3,130	10,536	2,056	17,785
16	7.68	14.98	12.28	94.31	2.957	20%	40	3,772	3,065	8,276	1,740	5,855	2,056	(-1,375)
Totals:	251.45		12.68(Avg)	3189.21	100.00	64.2% (Avg.)	128.3(Avg)	409,130	332,418	$897,529	$58,833	$198,000	$58,061	$582,635

Plus salvage of 16 wells: 51,160
Total net return all patterns: $663,795
***-1: Poor recovery from the area due to gas cap (?)**
***-2: Water flood recovery at 100% pattern efficiency is 200 B/AF**

Net return for gross investment ($582,635/$116,894) is $4.98 per $1.00 invested.
Net return for net investment (582,635/$65,734) is $8.86 per $1.00 invested.

TABLE 9

NORTH HOLDENVILLE BOOCH SAND FIELD
HUGHES COUNTY, OKLAHOMA

WATER FLOOD RECOVERY CALCULATIONS BASED ON PRIMARY, RESIDUAL OIL, AND SHRINKAGE

			WATER FLOOD RECOVERY CALCULATIONS IN FRACTION OF PORE SPACE AND B/AF.				
	PERCENTAGE	PERCENTAGE OF PORE SPACE	VARY CONNATE WATER TO 25 %	VARY SHRINKAGE TO 1.45 BBL./BBL.	VARY RESIDUAL OIL TO CORE DATA PERCENT	VARY PRIMARY RECOVERY TO 25.0%	VARY PERM. PROFILE EFFICIENCY TO 50%
Average Pore Space from 23 Samples (M. J. Mitchell-Harjo Heirs No. 4)		16.2 %	1.000	1.000	1.000	1.000	1.000
Connate Water Content (Calc. from 8 Elec. Logs - Edinger Report)		38.0 %	0.250	0.380	0.380	0.380	0.380
Total Pore Space Occupied by Reservoir Oil, fraction			0.750	0.620	0.620	0.620	0.620
Weighted Average Percent Pore Space Occupied by Residual Oil (Core Data)		15.85%					
Weighted Average Percent Pore Space Occupied by Residual Oil Corrected for Shrinkage		25.0 %	0.250	0.250	0.185	0.250	0.250
Pore Space Fraction of Mobile Oil Subject to Recovery by Primary and Water Flooding			0.500	0.370	0.435	0.370	0.370
Percentage Primary Recovery and Fraction of Pore Space	15.63 %		0.097	0.120	0.097	0.155	0.097
Shrinkage of Remaining Oil During Primary Production			0.050	0.138	0.050	0.050	0.059
Remaining Mobile Oil Subject to Recovery by Water Flooding, fraction			0.353	0.112	0.288	0.165	0.214
Remaining Residual Oil Subject to Recovery by Water Flooding, Barrels per Acre-Foot			444	141	362	207	269
Stock Tank Oil in Remaining Residual Oil after Shrinkage, Barrels per Acre-Foot			423	134	344	197	256
Percentage of Acre-Feet Flooded to 95% Water	78.3 %						
Average Water Flood Recovery from Total Section, Barrels per Acre-Foot			331	105	269	154	128
Enclosed Five-Spot Pattern Efficiencies (Area of the Pattern Affected) are Estimated at 85%; others are arbitrarily reduced according to the position of the producing and injection wells and the Primary Recovery	85.0 %						
Average Water Flood Recovery from Total Acre-Feet in Totally Enclosed Five-Spot Patterns, Barrels per Acre-Foot			281	89	229	131	109

each set of core data available. ("Use of Permeability Distribution in Water Flood Calculations" by Wm. E. Stiles, Dallas, Texas, Division AIME meeting, October 4th and 6th, 1948.)

5. Since every project will have edge patterns or irregular patterns due to well locations the normal five-spot pattern efficiency of 85 to 95 per cent at 95 per cent water (72.4 per cent at first production of water) will have to be modified or reduced based on the well locations in the patterns and whether the producing well is to be affected from less than four water injection wells. The average field pattern (coverage) efficiency will always be less than the assumed perfect five-spot pattern efficiency.
6. Directional permeability trends and fracture system trends will sometimes govern flood patterns and adversely affect recoveries. Millidarcy-ft capacity maps should be prepared if enough data is available.
7. Except for the unknown effects of oil-wet and water-wet formations and relative permeability effects where connate water is high, ordinary core data, flood pot tests and results of reservoir sample analysis can furnish enough information to determine within reasonable limits economic feasibility of possible water flooding projects.
8. There is no real basis for the assumption that secondary recovery should usually equal the primary recovery; in fact, secondary recovery will vary inversely with the primary as shown in the calculations. Detailed data on the actual primary recovery by leases and by wells instead of average for the reservoir are usually very necessary parts of any investigation.
9. In fields and areas in the West Central Texas area it has been found that these methods and procedures will usually give adequate answers to determine economic feasibility. However the difficulty that has encountered is that most operators do not know the value and necessity of core data, flood pot, and special tests on cores and the necessity for reservoir sample data obtained early in the production history of the reservoir, along with reservoir pressure history from discovery down to date.

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