CONDENSATE RECOVERY BY CYCLING AT DECLINING PRESSURE

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CONDENSATE RECOVERY BY CYCLING AT DECLINING PRESSURE

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Discussion of this paper is invited. Such discussions may be presented at the 18th Annual Meeting and considered for publication in C.I.M. journals if filed with the Technical Program Chairman prior to the meeting.

ABSTRACT

The practice of reservoir pressure maintenance by gas cycling has been adopted in many retrograde (wet) gas reservoirs to prevent condensation and ensuing loss of hydrocarbon liquids.

An investigation of the factors involved in condensate recovery by gas cycling was made for this paper. The principle factors are (1) the sweep patterns developed by the cycled gas and the resulting wet gas recovery and (2) the revaporization of the liquid condensate within the reservoir upon contact by dry injected gas.

It is concluded that cycling condensate reservoirs under conditions of declining pressure rather than constant pressure is advantageous both from a recovery and an economic standpoint. By operating at declining pressure, the wet gas displaced from the swept areas is recovered concurrently with wet gas recovered by gas expansion from the unswept portions of the reservoir. Any liquid condensed in the swept areas is revaporized by dry injection gas

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*Present address - Continental Oil Company, Department of International Operations New York, New York and recovered as an enriched gas.

By this mode of operation, high condensate recovery is obtained, gas sales may be possible at an earlier stage of depletion, more flexibility in field and plant operations is feasible, and reduction in investment and operating costs is achieved.

Calculations of reservoir performance are presented for the Windfall Devonian Leduc reef reservoir, Alberta, Canada, exploited by this scheme.

INTRODUCTION

Hydrocarbon accumulations in which the fluids exhibit retrograde condensation upon reduction of reservoir pressure comprise an important and ever increasing fraction of reservoirs exploited in North America. This type of accumulation is usually described as a gas condensate or wet gas reservoir. In 1965, approximately 15% of all the reservoirs exploited in North America were of this type(1). The recovery of natural gas liquids from these accumulations must be made in the vapor phase because the liquid saturation retrograded within the pore space of the reservoir at reduced pressures is usually below the critical level at which the liquid will form a continuous phase and thus will flow or could be displaced as a liquid.

When the retrograde gas reservoir is depleted solely by pressure reduction (blow-down) some or all of the following disadvantages are apparent:

1. Loss of valuable condensate in the reservoir.
2. Declining loading of the liquid facilities of the plant during the life of the project.
3. Declining well productivities, which must be offset by installation of compressors and/or by drilling of additional wells.

In order to prevent, or at least reduce, such a liquid loss due to retrograde condensation, the contents of gas-condensate reservoirs are often displaced through cycling operations. The wet gas is produced, stripped of liquefiable hydrocarbons and perhaps sour gases and the residual gas is reinjected into the reservoir for the purpose of displacing further wet gas. Frequently an additional make-up volume of gas is reinjected in order to maintain full reservoir pressure and prevent any retrograde condensation at all.

Although cycling appears to be an ideal solution to the retrograde condensation problem, there are a number of factors which affect adversely this method of operation:

1. Income from gas sales is deferred.
2. Substantial initial investment for compression and injection is required.

3. Make-up gas must be purchased or otherwise be available for full pressure maintenance.

4. The cycling operations plus the subsequent blow-down period result in prolonged project life with inefficient gas plant usage during the final stage and high cumulative operating costs.

5. Very little of the wet gas in the portions of the reservoir unswept during cycling operation will be recovered during the final blow-down operations.

Therefore, in evaluating the economics of exploiting any wet gas reservoir, all the above inherent advantages and disadvantages must be carefully evaluated.

For the particular cycling operation under consideration (the Windfall D-3 reservoir), the original exploitation scheme called for full pressure maintenance. However, the increasing costs of developing a supply of injection gas and the potential loss of valuable sulfur in the injection gas, led to the decision to re-examine the reservoir performance under reduced gas injection rates.

For the present study the factors involved in the operation of this reservoir were examined to determine the relative efficiency and economics of different methods of operation. In particular, the purpose of the study was to investigate the performance of the Windfall reservoir under cycling operations at declining pressure to determine if gas injection could be significantly reduced without loss of condensate recovery.

In order to obtain a quantitative comparison of the merits of full gas cycling operations and partial cycling - simultaneous controlled blow-down operations, the following engineering data were required.

1. Volumetric sweep efficiencies of each of the schemes evaluated as a function of time.

2. Retrograde behavior of the original wet gas.

3. Revaporization characteristics of the retrograded liquid upon contact with dry injection gas.

THE WEST WHITECOURT PROJECT

The Windfall Devonian Leduc (D-3) wet gas reservoir is located about 120 miles north-west of Edmonton, in the Western Canadian province of Alberta. The field is located in the West Whitecourt Project area jointly owned by Hudson's Bay Oil and Gas Company Limited, Pan American Petroleum Corporation, and Canadian Fina Oil Limited. Within that 550,000 acre lease block there are also several other gas fields, about 25 miles south-west of Windfall, namely Pine Creek, Beaver Creek, and Pine North-West. The total original raw gas in place in these four pools exceeds two trillion scf.

After delineation of these accumulations in the late 1950's, it appeared that a desirable depletion method would be full pressure maintenance of the Windfall reservoir to be achieved by injecting dry gas from the Pine Creek and Beaver Creek reservoirs. This project was initiated in early 1962.

Dry gas currently containing approximately 35% sour gases, mainly hydrogen sulphide, is produced from the Pine Creek and Beaver Creek reservoirs and after wellhead dehydration, it is transported at about 1900 psi through a twenty-six mile pipe line to Windfall (2). In Windfall, the gas is compressed to about 4000 psi and it is injected into the D-3 formation of that field to maintain the reservoir pressure and displace the wet gas (3). The Windfall reservoir contains medium sour (15% H_2S) wet gas initially averaging about 76 barrels of stabilized condensate per million scf of raw gas (4). The residue gas, which at this time is all produced from the Windfall reservoir, is under sales contract at an average daily rate of 100 million scf which corresponds to 165 MM scf per day of raw gas produced.

Because of the magnitude of this project, the factors involved in its operation, such as injection gas requirements, gas and sulfur market conditions, and capital investment requirements, have undergone continuous review. As a result of changes in these factors since the start of cycling operations, an extensive review of the entire production injection cycling scheme was undertaken.

General Information on the Windfall D-3 Wet Gas Reservoir:

Productive area:	12,200 acres
Average pay thickness:	117 ft.
Rock volume:	1,418,000 acre-ft.
Reservoir temperature:	219°F
Original "Z" factor:	0.837
Original reservoir pressure:	3,778 psia
Original gas-in-place in the Reservoir	820 MMM cu. ft.

The production - injection - pressure performance is presented in Fig. 1.

METHOD OF ANALYSIS

Two principle processes were considered in the investigation of reservoir performance under the different schemes of exploitation; the sweep patterns of the injected gas, and the condensation and revaporization characteristics of the retrograde liquid in the reservoir. The combination of these two processes then determined the overall recovery performance.

Sweep Studies

In any injection operation, the megascopic flow patterns developed by the injected fluid are an important factor controlling the efficiency of the project. These flow patterns determine the sweep efficiency which is the ratio of the reservoir volume swept at any time to the total reservoir volume. In order to study and to compare the effects of pressure reduction on the sweep patterns during cycling operations, a mathematical model was developed to calculate pressure distribution within the reservoir and to track the locations of the injected gas fronts under various operating conditions as a function of time. The production of wet gas and of dry break-through gas was also obtained from the model for each time step. The pertinent model is described in Appendix I.

The well development pattern and reservoir configuration were set up on this model and a match obtained between the calculated and observed performance of the reservoir over the initial four years cycling. This matching required some adjustment of reservoir parameters (Figure 2). The future performance was then calculated for the reservoir on the basis of this model for different development patterns and injection-production schedules imposed on it. Several distinct programs were studied, each of which was run to an assumed abandonment pressure of about 1,600 psi supplying information on the sweep patterns, reservoir pressures and the wet gas and injected gas recoveries, all as a function of time (Fig. 3). An example of a map of sweep patterns, as printed out by the computer, is presented in Fig. 4. Both the continued 100% volume replacement of produced raw gas, and the change to 60% volume replacement starting in 1966 were considered.

Condensation-Revaporization Behaviour of the Reservoir Fluids

The condensate recovery is also a function of the fluid composition and interactions between liquid and gas phases within the pore space. Several subsurface and recombined surface samples obtained from the four reservoirs were analyzed in the laboratories in order to determine the phase behaviour of all the pertinent hydrocarbons as a function of declining reservoir pressure.

Numerous laboratory studies reported over the past twenty years in the petroleum engineering literature have shown that the recovery of liquid hydrocarbons by the process of vaporization can be an important factor in increasing recovery. The vaporization can occur in varying degrees from a conventional oil, a volatile oil, or a retrograde condensate (5, 6, 7, 8, 11). In order to investigate this phenomenon quantitatively for the condensate reservoir under consideration, a second mathematical computer model, described in Appendix II, was developed.

This ten-cell mathematical model simulates dry gas injection into a linear system containing retrograde liquid and rich gas. It was used to determine the dry gas injection volumes required to evaporate and to produce the revaporized liquid phase at different pressure levels. This linear multicell model yields information on phase changes, saturation distribution and the changing liquid and gas compositions of each of the individual cells as a function of pore volumes of dry gas injected in small increments into the model. The produced fluids are flashed to surface conditions in order to obtain values for the liquid recovery and the wet gas and enriched gas produced.

In order to utilize this model a system of empirical K-values (equilibrium vaporization ratios) was developed which described the behaviour of the Windfall reservoir fluid. The procedure for determining K-values is based upon obtaining an acceptable match of volume percent liquid between the laboratory measured data and those calculated for several pressure levels; (9, 10) Tables I and II. Details of this procedure are described in Appendix II.

An assumption implicit to the use of this calculation and its application to the revaporization phenomenon within the reservoir is that the liquid and gas phases coexisting at any point within the reservoir are in essentially complete equilibrium. Numerous literature references(12, 13, and 14) support this assumption.

The calculations on the linear displacement model showed that all of the liquid condensate formed within the reservoir at a given pressure level would be vaporized and displaced by the injection of varying quantities of dry gas. The volume of dry gas required to vaporize and to produce all of the revaporized condensate as enriched dry gas is a function of pressure, as would be expected, with increasing volumes of injected dry gas required at lower pressures (Fig. 5).

Since during a simultaneous partial cycling-controlled blow-down operation the reservoir pressure declines below that at which the revaporization occurred, the behaviour of the enriched gas, which contains the revaporized liquid, has also to be ascertained. Additional calculations made on a one cell model indicated that once the retrograde liquid has been revaporized by the contact with dry injection gas, further pressure drop does not result in liquid dropout (Table IV).

Application of Revaporization to Sweep Studies

Having available the above basic engineering studies, the recovery of gas and condensate under the different exploitation schemes may be quantitatively evaluated by superimposing the pertinent revaporization study on the corresponding sweep efficiency study. The sweep studies provided pressure information over the entire area of the reservoir, determined the location of the displacement front between the in-place wet gas and the injected gas, and obtained the wet and dry gas production rates for each of a series of time steps. The calculations on the ten-cell linear displacement model provided the information necessary to calculate the rate of revaporization behind the injected gas front.

In order to apply the revaporization displacement calculations to the sweep studies, the results were plotted to show the volumetric ratio of movement between the leading front of the injected gas and the trailing front where revaporization is complete and completely dry gas flows. This ratio was determined as follows:

At the point in the injection of the dry gas where the gas composition at the outflow end of the system is identical to that of the injected gas, the revaporization and displacement of the condensate is complete. The true dry gas front has advanced a unit distance at this time, the unit here being one pore volume of the system. At the same time the front of the injected gas containing the revaporized condensate has advanced a distance equivalent to the total volume of injected gas expressed in pore volumes of the system. Thus, at the 3000 psi level a total of 1.4 pore volumes of dry gas was injected at the time the dry gas reached the outflow end of the system (Figure 5). Therefore, at this pressure, the "dry" gas moves at a velocity ratio of 1.0/1.4 or .714 to the "enriched" gas front. This ratio is actually the volumetric ratio of movement of the fronts since the linear arrangement of the cells is not essential. Figure 6 is a plot of the volumetric ratio of movement of the completely dry 100% recovery front to the enriched gas front at each of the pressure levels studied. The ratio of movement of 95% and 90% recovery fronts are also shown.

With this relationship established it was possible to plot for each time step at the corresponding pressure level the movement of the front of completely dry gas with relation to the injected gas front, with the injected gas front location taken from the sweep studies. Between these two fronts there exists a zone carrying the revaporized condensate as an enriched gas. The formation, the growth, and the production from this enriched gas zone are then followed for each time increment of the sweep studies. Figure 7 shows an example of the formation and depletion of the enriched gas zone about one injection area in the reservoir.

Within the zone of revaporization formed between the leading front of injected gas and the trailing front of completely dry gas the composition of the enriched gas that is formed varies. The gas is richest at the leading edge of the zone and leanest at the trailing edge. For the subject evaluations an average composition of the enriched gas was calculated for each pressure level and it was assumed that this average composition applied to the enriched gas produced at that pressure. Figure 8 is a plot of the average enriched gas composition as a function of pressure ahead of the 100%, 95% and 90% recovery fronts. The decline in condensate content of the original wet gas with pressure is also plotted.

RESULTS

The quantitative results of the engineering studies discussed in the preceding section are summarized in the following tabulation: (all gas volumes are given at standard conditions)

	Straight Blow-down	Cycling with Partial Replacement	100% Replacement Cycling
End Point of study (cycling plus blow-down) - (date):	1/1/80	1/1/77	1/1/78
Cumulative gas production -			
Dry - (MMM cu. ft.):	--	321	412
Wet - (MMM cu. ft.):	464	619	609
Total - (MMM cu. ft.):	464	940	1021
Cumulative dry gas injection - (MMM cu. ft.):	--	466	588
Final reservoir pressure - (psig):	1600	1584	1670
Condensate recovery from wet gas - (10^6bbl):	25.8	42.0	45.5
Condensate recovery from enriched gas - (10^6bbl):	--	3.3	0.5
Total condensate (C5+) recovery - (10^6 bbl):	25.8	45.3	46.0
(Percent of orig. C5+ in place):	(43.0)	(75.5)	(76.6)
Maximum reservoir volume swept - (10^3 Ac-Ft):	--	971	1019
(Percent of orig. rock volume):	(--)	(68.7)	(71.9)

The attached Figure 9 represents some of the above results on a yearly cumulative basis and shows also the magnitude of individual contribution of the wet gas production and of the revaporization to the production of condensate in the partial cycling-controlled blow-down scheme at the partial replacement level.

CONCLUSION

In summary, the investigations discussed in this paper show that within the range of partial replacement studied, i.e. full 100% replacement as compared with the case where replacement is reduced to 60% of withdrawals, no significant change in condensate recovery occurs. Since only one partial replacement cycling level was studied, it is not concluded definitely that this level represents the optimum operating conditions. A qualitative review of the many different sweep studies which were investigated would tend to indicate that the optimum replacement level could be somewhat lower than that studied.

The following general conclusions can also be made:

1. The daily cycling rate and the reservoir pressure, constant or gradually decreasing, do not affect significantly the ultimate recovery of condensate, as long as partial dry gas cycling is pursued.
2. The ultimate recovery of condensate can be maximized by a well engineered manipulation of production and injection scheduling so that the injected dry gas traverses the maximum reservoir volume and efficient wet gas and enriched gas recovery is realized.
3. Within certain limits, ultimate condensate recovery may be increased more by the drilling of additional wells to obtain improved sweep efficiency than by maintaining a high cycling level.

The advantages which could be realized in reservoirs of the Windfall type operated with a voidage replacement level in the order of 60% rather than 100% from the beginning of the cycling are as follows:

1. Savings in capital expenditures amounting up to some 15% of total.
2. Savings in operating costs of about 15% on an annual basis. However, because of shorter life, these savings amount to some 20% on a cumulative basis.
3. Reduction of injection gas requirements by some 40 percent.
4. Increased operational flexibility because less producing wells need be converted to injectors and some of them need not be used continually at their full production or injection capacity.

Because of these inherent advantages it is suggested that this scheme of simultaneous cycling - controlled blow-down operations might constitute an important conservation concept for exploitation of wet retrograde gas reservoirs.

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APPENDIX I

SWEEP MODEL DESCRIPTION

The main part of this numerical model consists of calculations of unsteady-state pressure distributions and dry gas frontal movement by a succession of steady-states approximation. The model which is composed of several major parts or sub programs, offers the following benefits: The chances for making mechanical errors are minimized through automatic processing and presentation of data; the calendar time necessary to do a study is shortened; and, the percentage of the manpower effort available for creative engineering is maximized.

Formulating the capacity (k_xh, k_yh) and grid volume (ϕh) matrices constituted the major data input problems. A rectangular array (105 x 51) containing 5355 grid points was selected for the particular study. Figure 4 indicates the grid density used. Each block represents an area of 6.2 acres. A numerical matrix of thickness values was machine generated by expanding a coarse grid of values into a fine grid through use of an interpolation scheme. The boundary irregularities and sharp discontinuities along the leading edge of the reef were entered manually. This grid system was processed by the contouring program to provide a map of reservoir geometry for further computation. Initially, the permeability and porosity were assumed to be uniform. The capacity and grid volume matrices were obtained by multiplying the machine generated isopach by k and ϕ respectively.

In the model, all wells must be located at a grid point. In order to satisfy this condition, some wells had to be moved for a distance less than 365 feet. A rate schedule for the time span of the pressure calculations is needed for each well. New wells may be added anytime. Changing a well status from injector to producer or vice versa is easily accomplished.

The differential equation governing isothermal flow of a non-ideal gas obeying Darcy's law is: (symbols are defined at end of Appendix)

$$\frac{\partial}{\partial x}\left(\frac{k_xh}{2\mu Z}\frac{\partial P^2}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{k_yh}{2\mu Z}\frac{\partial P^2}{\partial y}\right) = \phi h \frac{\partial}{\partial t}\left(\frac{P}{Z}\right) + q(x,y,t) \qquad (1)$$

In this study, constant compressibility and viscosity were assumed. An approximation to the time derivative of pressure

$$\frac{\partial P}{\partial t} = \frac{1}{2P}\frac{\partial P^2}{\partial t}$$

was assumed to simplify equation (1) to

$$\frac{\partial}{\partial x}\left(k_xh\frac{\partial P^2}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_yh\frac{\partial P^2}{\partial y}\right) \quad \frac{\phi\mu h}{P}\frac{\partial P^2}{\partial t} + Q(x,y,t) \qquad (2)$$

The finite difference solution for equation (2) at any grid point (i,j), time step n + 1 from n, and sweeping in the x- direction is

$$\left[(k_x h)_{i+1/2,j}\left(P^2_{i+1,j}-P^2_{i,j}\right)_{n+1}-(k_x h)_{i-1/2,j}\left(P^2_{i,j}-P^2_{i-1,j}\right)_{n+1}\right]\frac{1}{\Delta x^2}$$
$$+\left[(k_y h)_{i,j+1/2}\left(P^2_{i,j+1}-P^2_{i,j}\right)_n-(k_y h)_{i,j-1/2}\left(P^2_{i,j}-P^2_{i,j-1}\right)_n\right]\frac{1}{\Delta y^2}$$
$$=\frac{\mu(\phi h)_{i,j}}{\Delta t\left(P_{i,j}\right)_n}\left[\left(P^2_{i,j}\right)_{n+1}-\left(P^2_{i,j}\right)_n\right]+Q_{i,j,n} \qquad (3)$$

The alternating direction implicit procedure - ADIP(15) was used to solve for the pressure distributions. A detailed explanation for a similar set of equations (16) is given elsewhere and will not be repeated here.

Before any predictive runs could be made, it was necessary to match past field performance. Since pressure gradients control gas movement rather than absolute pressure levels, the match was made on the basis of gradients between wells. Areal variations in permeability necessary to obtain this match are shown in Figure 2. An example of the resultant computed pressures and gradients for April 16, 1964, compared with actual field pressures and gradients is presented in Figure 10.

The cycling operations are based on a succession-of-steady-states approximation. That is, during a fixed time period, one of the calculated pressure distributions is assumed to be "the" pressure distribution for the entire period. In this study, periods ranged from 2-18 months.

In order to track the location of the front of the injected gas, the circumference of the front about each injection well was defined initially with 40 points. Subsequently, the frontal movement was determined for each pressure distribution by calculating for each point the x- and y- components of velocity using Darcy's law. When the distance between two adjacent points became greater than 50 feet, another point was inserted at the midpoint on the chord joining them. As points entered the producing wells they were removed from the tracking calculations. All points were moved for short time step intervals and the point velocities recalculated at their new position. At prescribed intervals, the area inside each front was obtained by evaluating a line integral about the front. Weighted average pressure and grid volumes were obtained to determine the gas volume contained within each front. Once the calculated volume matched that specified by the injection-production schedule of the dry gas, calculations for that front were bypassed for the remainder of the period investigated. The calculations were continued until all volumes had been matched for that period. The data were then displayed in the form of maps and printouts. An example is shown in Figure 4.

SYMBOL DEFINITIONS

Where: P = pressure, psi
ϕ = porosity, fraction
h = thickness, feet
μ = viscosity, cp
Z = gas compressibility factor
x,y = special co-ordinates
kx = permeability in x-direction, function of location
ky = permeability in y-direction, function of location
t = time, days
i = subscript denoting x-direction
j = subscript denoting y-direction
n = subscript denoting time position
$\Delta x, \Delta y$ = distance between grid points, feet
$Q, q(x,y,t)$ = withdrawal (or injection) term

necessary constants to account for consistency in the units have been added.

APPENDIX II

REVAPORIZATION MODEL DESCRIPTION

K-Value System

In order to obtain a satisfactory match between the calculated and experimental values of composition and retrograde liquid saturation for the Windfall reservoir fluid, a system of K-values was developed using the technique of Jacoby, et al(9).

The original reservoir fluid contained 22.64 mole per cent non-hydrocarbons of which the predominate component was H_2S (15.32 mole per cent). There are very few published K-value data for this type system. However, the work of Robinson (17) shows that presence of CO_2 and H_2S affects the methane K-values. This effect is sensitive to the relative concentrations of these materials. Based on this premise a system of K-values was developed by matching the available experimental data.

Since the data on the recombined sample were obtained by differential liberation, the matching calculation had to be differential. The C_7+ fraction was broken up into components n-C_7 through n-C_{14}+ using a distillation curve. The initial hydrocarbon K-values were calculated from the NGAA coefficients at 5000 psia convergence pressure. N_2, CO_2 and H_2S K-values were calculated using Lohrenz's(10) equations at the same convergence pressure. The K-values for the heavier components were calculated by extrapolation of the n-C_8 and n-C_{10} K-values as a function of their reciprocal absolute normal boiling temperature. The K-values of the methane, ethane, and C_7+ were adjusted by trial and error until a satisfactory match of the experimental composition and retrograde liquid was achieved. Caution was exercised in altering the K-values to insure that they would plot as a smooth curve (i.e. log K versus log P). Also, the system of K-values was forced to match the dew point pressure using Lohrenz's(10) methods.

Revaporization Model

This model simulates constant pressure, constant temperature, and steady-state linear flow in a core containing ten equal volume cells. It assumes that only the gas phase is mobile due to the low retrograde liquid phase saturations (6 per cent maximum). Therefore, the only method of removing liquids from the system is by revaporization. Rigorous volumetric and compositional material balances as well as phase equilibrium are maintained in each of the cells at all times.

The mechanics of the calculations for each desired pressure level are as follows:

1. Initially, each cell contains retrograde liquid and rich gas.

2. Dry gas enters cell 1 and displaces an equivalent volume of gas into cells 2 through 10. The total content of the fluids in each cell is flashed to obtain the phase distribution compositions.

3. The composition of the gas produced from the tenth cell is calculated and compared with that of the injection gas.

4. The calculations are continued until the produced and injected gases have the same composition.

These calculations were made at pressures of 3200, 3000, 2800, 2600, 2400 and 2000 psig. The composition of the gas and liquid phases, per cent liquid, and liquid content of the produced gas were calculated and reported for each increment of injection.

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TABLE I

COMPARISON OF EXPERIMENTAL AND CALCULATED RETROGRADE LIQUID CONDENSATION

Pressure psig	Volume % Retrograde Liquid	
	Experimental	Calculated
3,782 Dewpoint	0.00	0.00
3,600	0.11	0.52
3,200	1.33	1.43
3,000	2.39	2.44
2,800	3.50	3.49
2,600	4.50	4.48
2,400	5.20	5.46
2,000	5.77	5.80
1,500	5.58	5.65
1,000	5.19	5.43

TABLE II

COMPARISON OF EXPERIMENTAL AND CALCULATED GAS COMPOSITIONS

	Composition of Vapor Phase, Mole %							
	P=3,200 psig		P=3,000 psig		P=2,500 psig		P=2,000 psig	
Component	Exp.	Calc.	Exp.	Calc.	Exp.	Calc.	Exp.	Calc.
C_1	62.91	62.48	63.31	62.71	64.14	63.60	64.82	64.08
C_2	4.05	4.06	4.13	4.07	4.02	4.09	4.11	4.10
C_3	2.55	2.52	5.53	2.52	2.43	2.51	2.44	2.50
iC_4	0.63	0.67	0.65	0.67	0.60	0.66	0.63	0.65
nC_4	1.34	1.37	1.30	1.37	1.37	1.35	1.25	1.33
iC_5	0.99	0.77	0.71	0.77	0.71	0.74	0.77	0.72
nC_5	0.53	0.74	0.55	0.74	0.65	0.71	0.57	0.68
C_6	0.86	1.04	0.92	1.03	0.87	0.95	0.77	0.89
C_{7+}	3.50	4.05	3.34	3.80	2.48	2.91	2.24	2.45
H_2S	15.32	15.16	15.07	15.17	15.17	15.21	15.07	15.22
N_2	2.72	2.68	2.70	2.70	2.95	2.74	2.75	2.76
CO_2	4.60	4.46	4.70	4.46	4.59	4.54	4.58	4.62
	Properties of Heptanes Plus							
Mol. Wt.	121.0	125.7	119.0	123.3	116.0	116.1	112.0	113.3
Sp. Gr.	0.781	0.783	0.778	0.777	0.775	0.756	0.771	0.751

TABLE III

CALCULATED LIQUID PHASE COMPOSITION BY DIFFERENTIAL DEPLETION

	Liquid Phase Composition Mole %					
Component	3,200 psig	3,000 psig	2,800 psig	2,600 psig	2,400 psig	2,000 psig
C_1	34.39	32.10	29.00	25.38	23.74	20.60
C_2	3.39	3.34	3.28	3.18	3.13	3.00
C_3	2.62	2.66	2.72	2.81	2.85	2.91
iC_4	0.83	0.86	0.90	0.96	0.99	1.05
nC_4	1.81	1.88	1.99	2.17	2.25	2.42
iC_5	1.24	1.32	1.45	1.63	1.72	1.91
nC_5	1.30	1.39	1.54	1.75	1.85	2.07
C_6	2.53	2.75	3.10	3.61	3.88	4.41
C_{7+}	30.81	33.47	36.91	40.63	42.23	45.24
H_2S	12.70	12.80	12.95	13.14	13.19	13.14
N_2	1.00	0.92	0.83	0.72	0.67	0.57
CO_2	7.37	6.50	5.32	4.03	3.51	2.67
	Properties of Heptanes Plus					
Mol. Wt.	162.8	161.1	158.0	153.9	152.0	149.0
Sp. Gr.	0.850	0.847	0.843	0.837	0.834	0.830

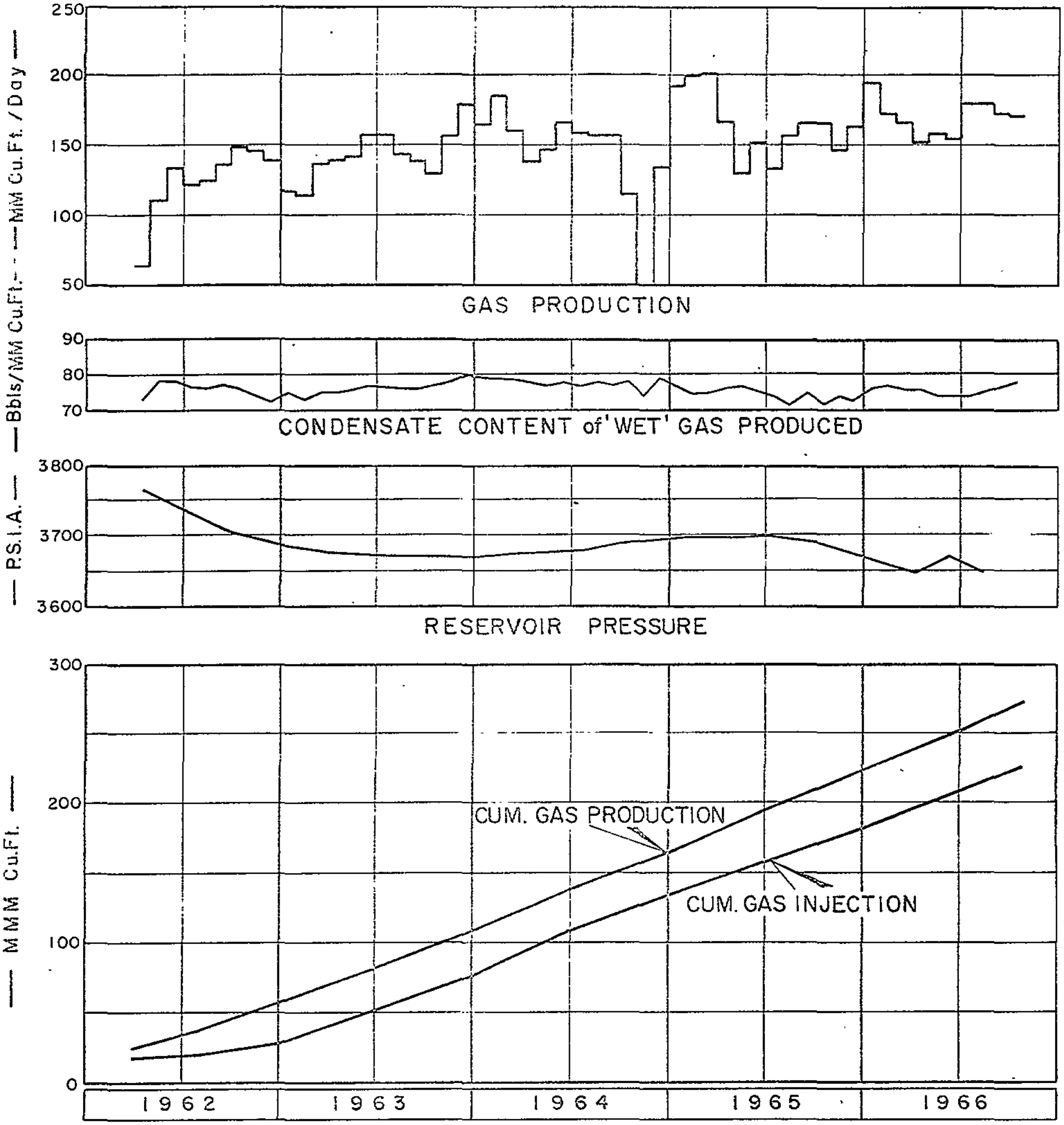
TABLE IV

CALCULATED RETROGRADE LIQUID CONDENSATION FROM ENRICHED INJECTION GAS

Pressure psig	Volume % Liquid Sample A*	Volume % Liquid Sample B**
3,000	0.00	
2,900		
2,800		
2,700		
2,600		
2,500		
2,400		0
2,300		
2,200		
2,100		
2,000		
1,900		
1,800		
1,700	0.00	0
1,600	0.02	0
1,500	0.06	0
1,400	0.10	0
1,300	0.13	0
1,200	0.15	0
1,100	0.16	0
1,000	0.16	0
900	0.16	0
800	0.16	0
700	0.14	0
600	0.13	0
500	0.10	0

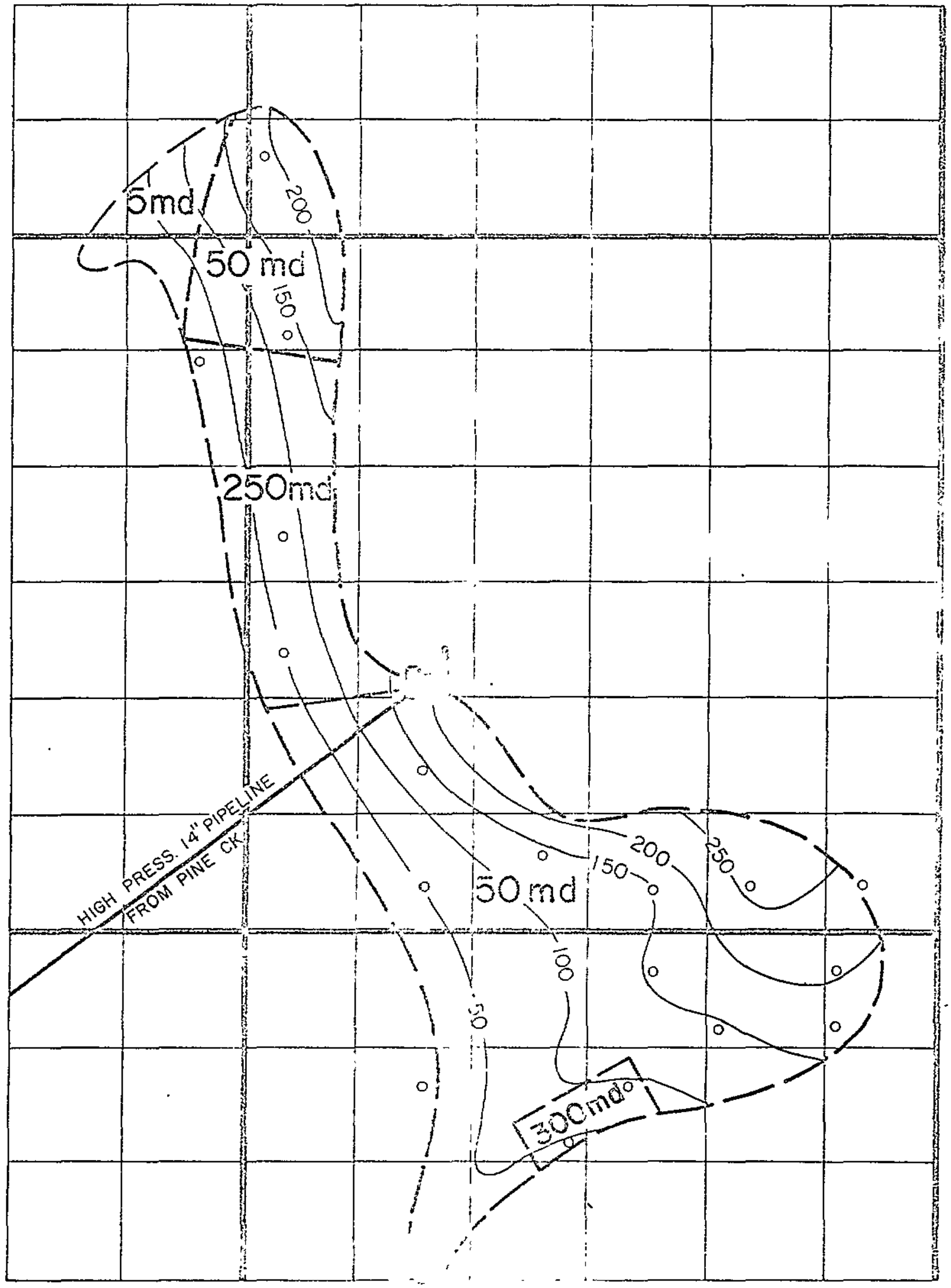
*Sample A is the single phase gas existing after removing the rich gas and injected 0.60 P.V. of Pine Creek gas into a cell originally containing 2.39% retrograde liquid corresponding to the 3,000 psig liquid in Table III.

**Sample B is the single phase gas existing after removing the rich gas and injecting 4.20 P.V. of Pine Creek gas into a cell originally containing 5.20% retrograde liquid corresponding to the 2,400 psig liquid in Table III.



WINDFALL D-3
PERFORMANCE DATA

FIGURE I



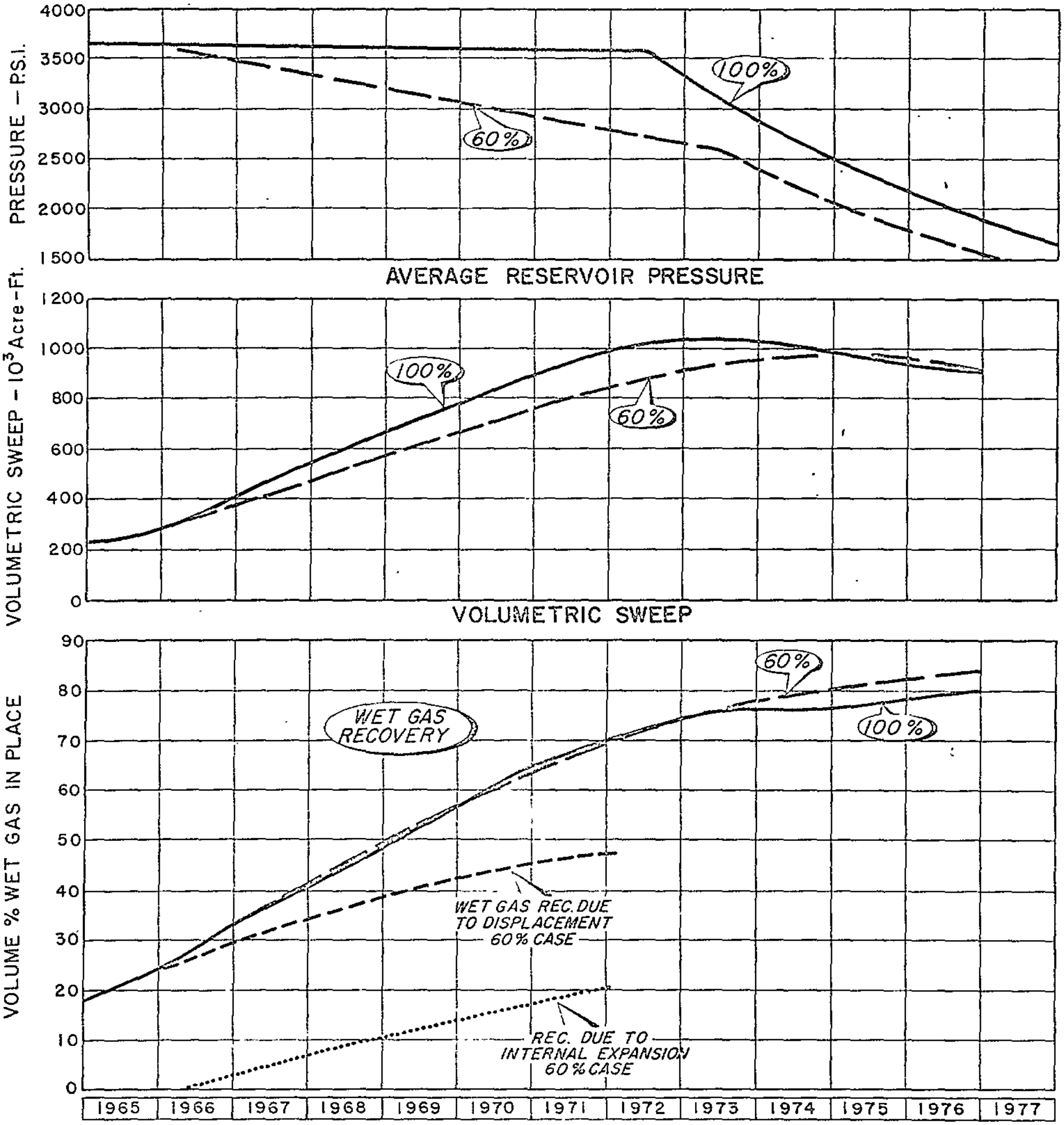
[illegible] -3

GROSS ISOPACH & ISOPERMEABILITY MODEL

MILES

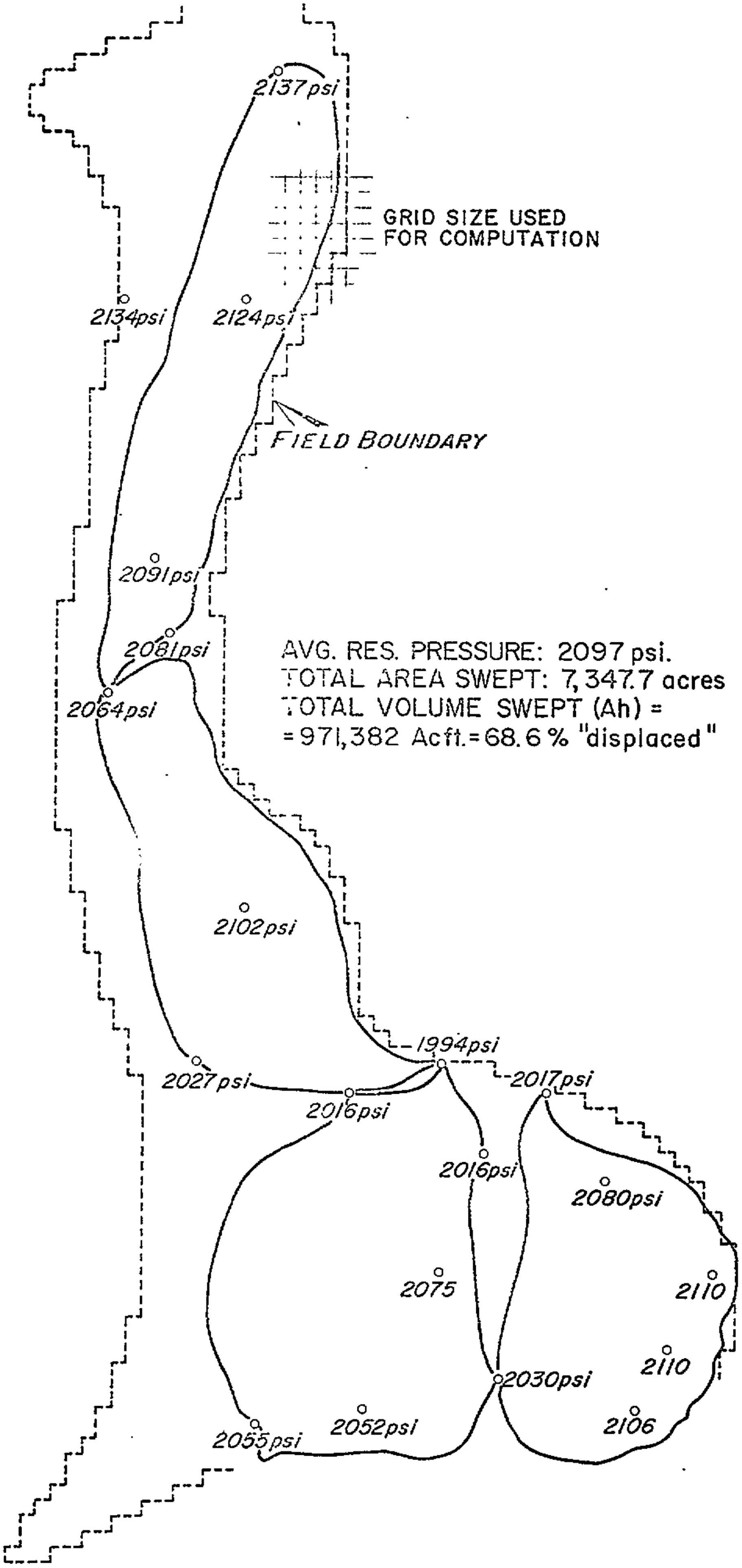
0 1 2

FIGURE 2



CALCULATED SWEEP & WET GAS RECOVERY
100% and 60% REPLACEMENT

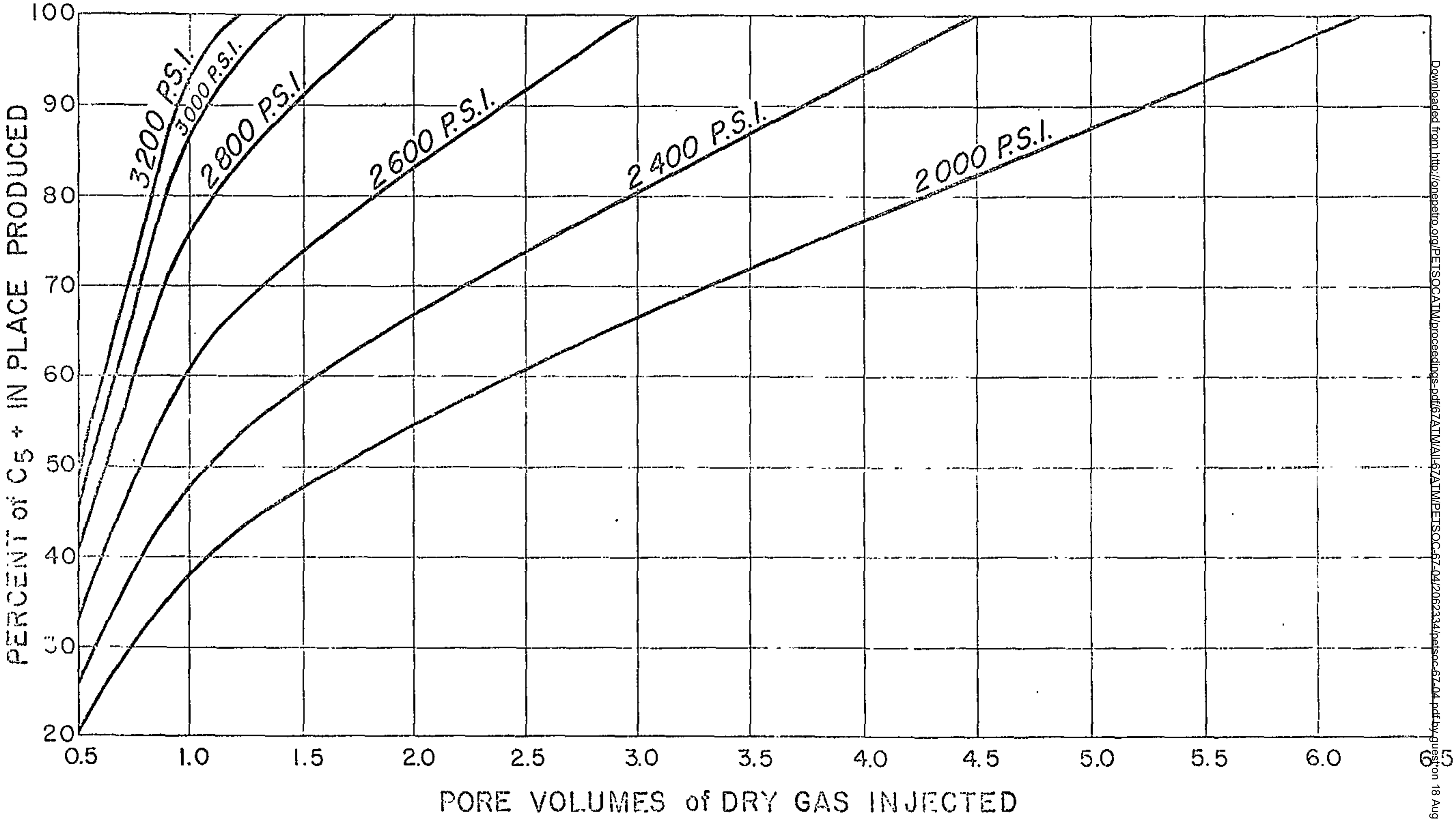
FIGURE 3



AVG. RES. PRESSURE: 2097 psi.
TOTAL AREA SWEPT: 7,347.7 acres
TOTAL VOLUME SWEPT (Ah) =
= 971,382 Acft. = 68.6 % "displaced"

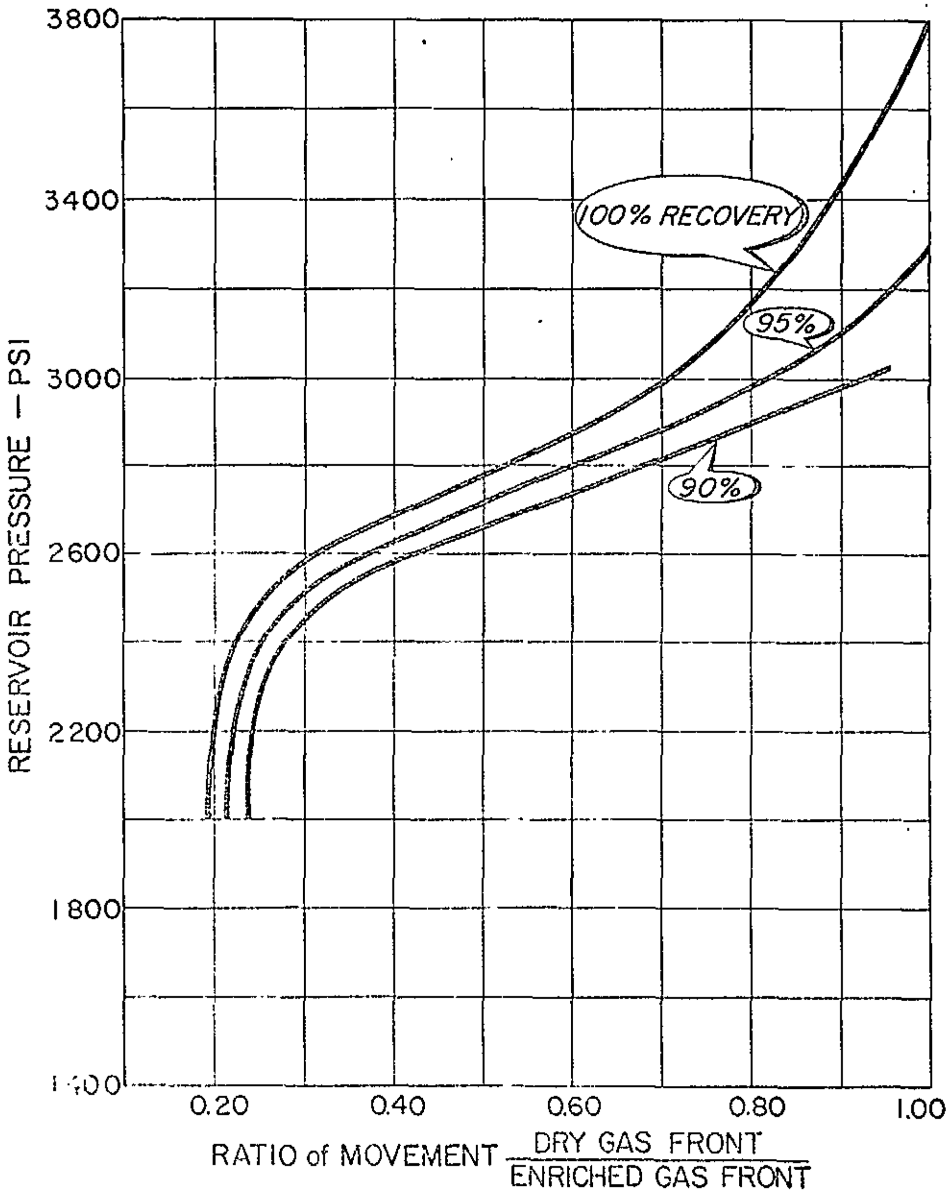
LOCATION OF DRY GAS Jan.1, -75

· FIGURE 4 ·



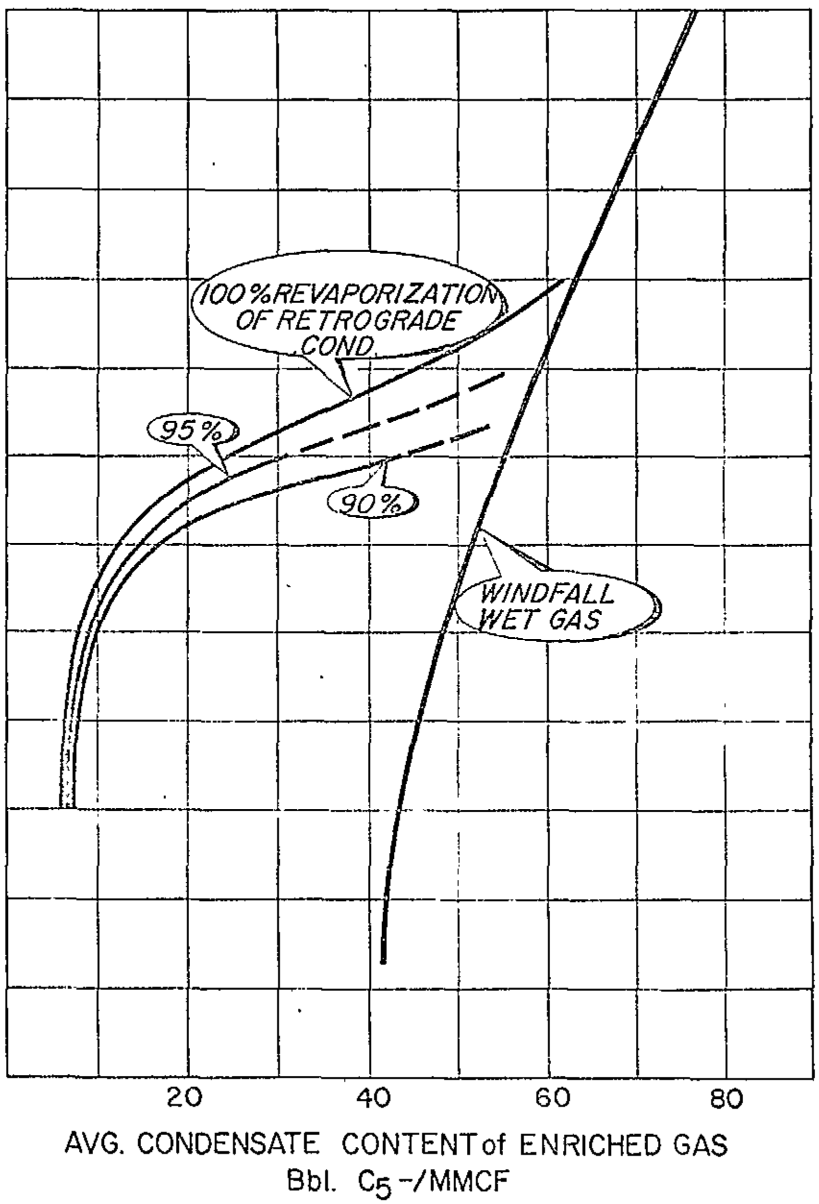
RECOVERY OF PENTANE+ FROM 10-CELL MODEL
REVAPORIZATION CALCULATION

FIGURE 5



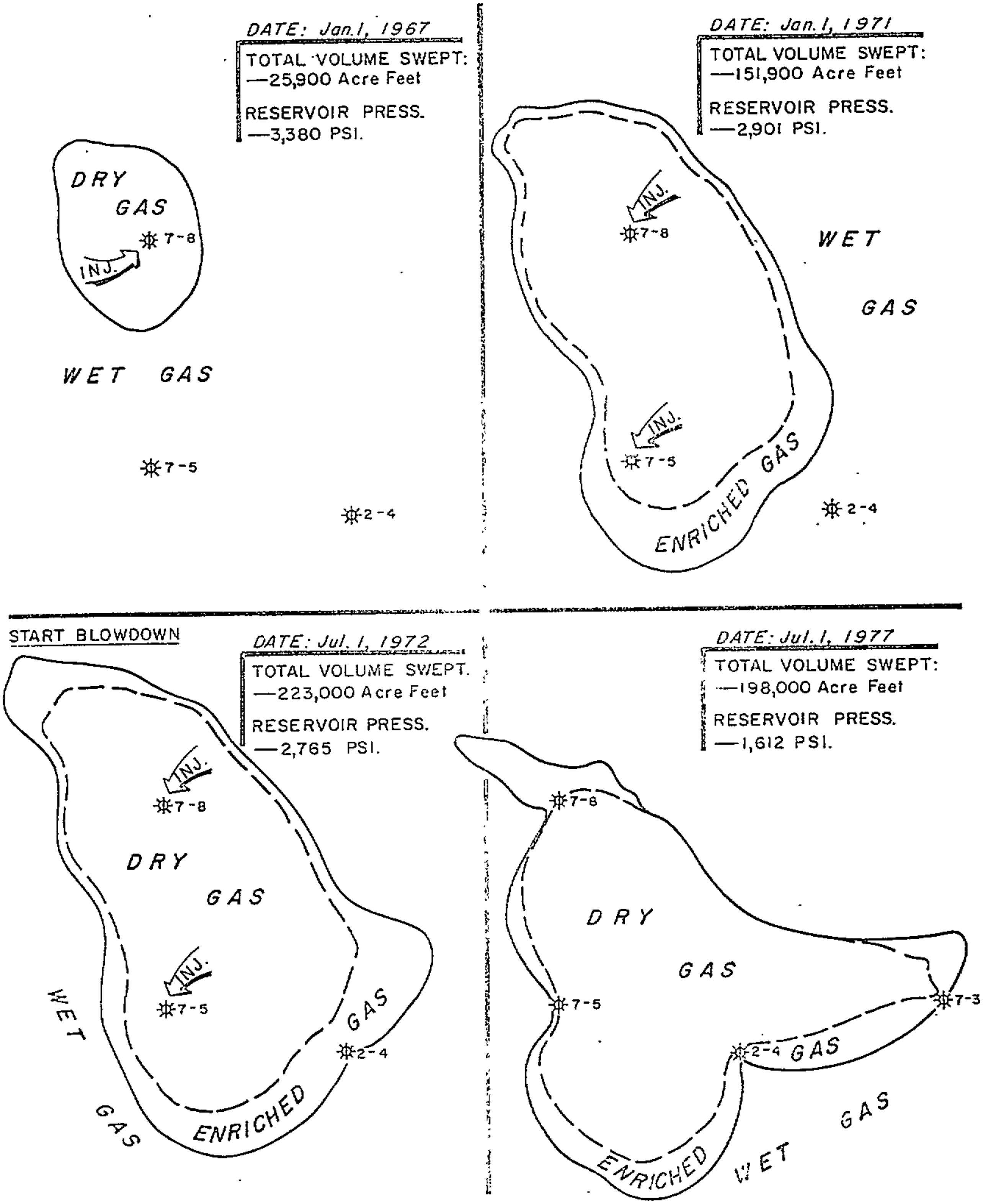
VOLUMETRIC RATIO of MOVEMENT of DRY GAS FRONT to ENRICHED GAS FRONT

FIGURE 6



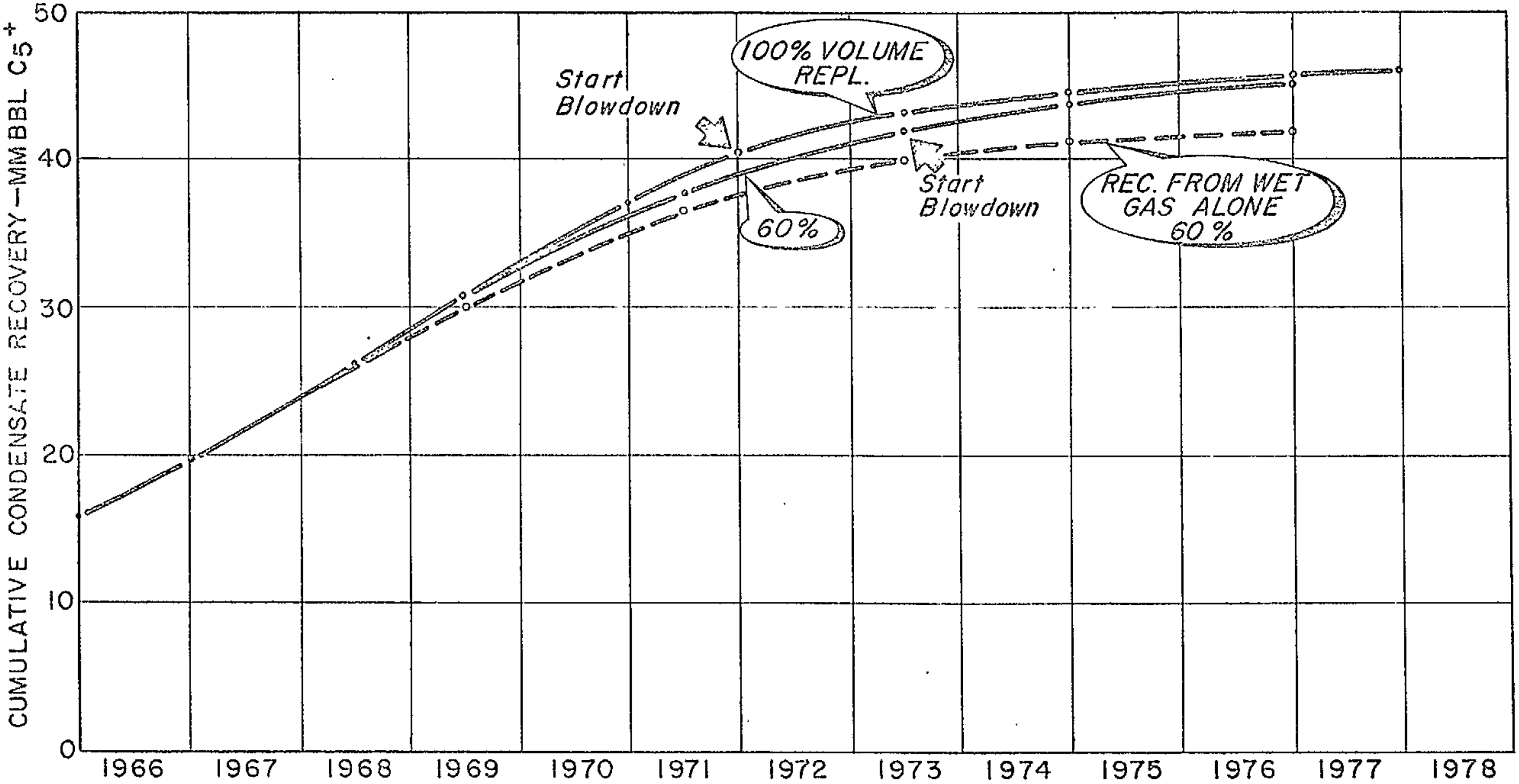
CONDENSATE CONTENT OF ENRICHED GAS

FIGURE 8



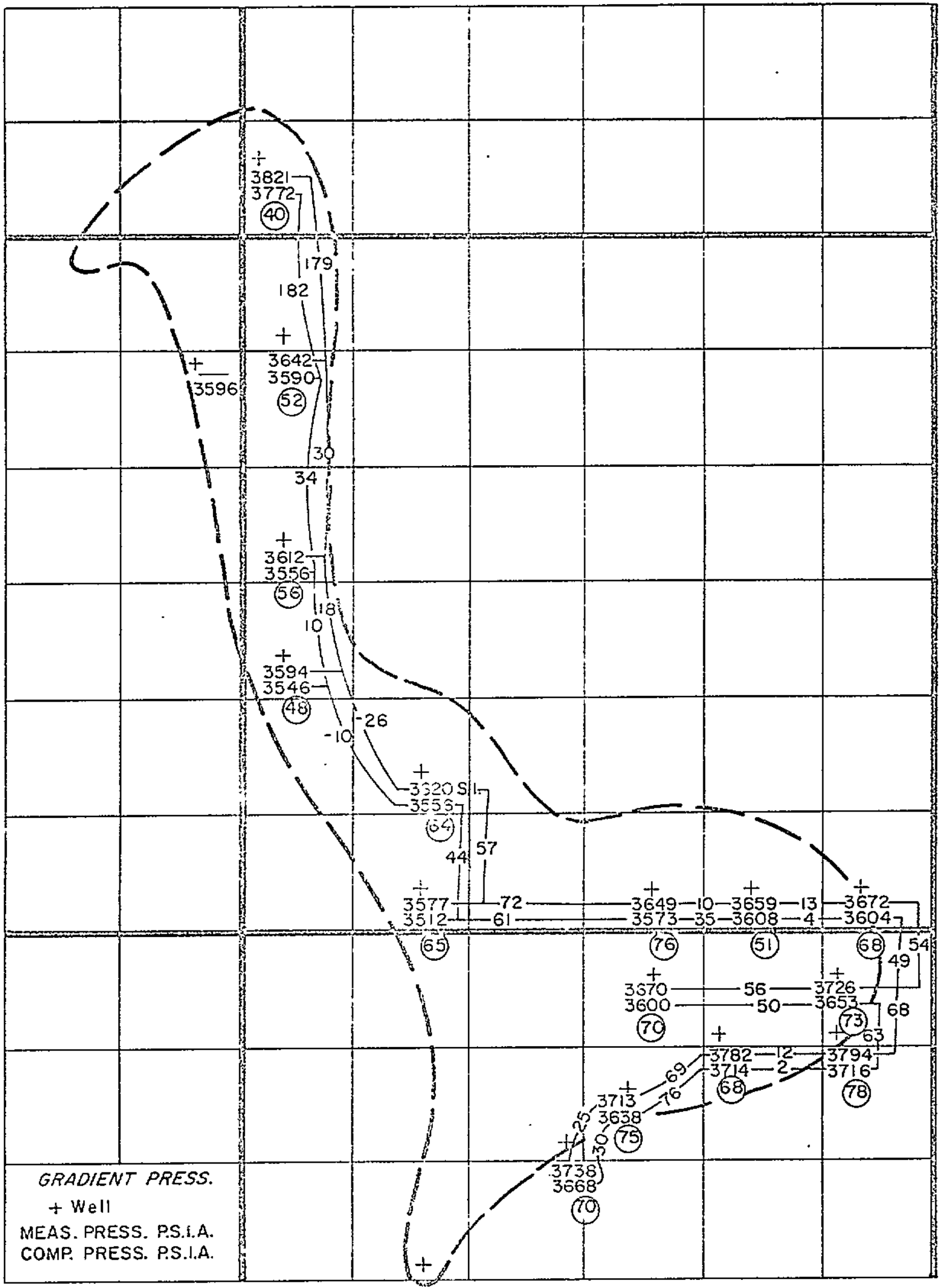
FORMATION & DEPLETION of ENRICHED GAS ZONE

FIGURE 7



CALCULATED CUMULATIVE RECOVERY of PENTANES +

FIGURF 9



WINDFALL FIELD
COMPARISON OF MEASURED PRESSURES WITH
COMPUTER PRESSURES ON 4/16/64

FIGURE 10