STATE OF NEW MEXICO

ENERGY AND MINERALS DEPARTMENT

OIL CONSERVATION DIVISION
HOBBS DISTRICT OFFICE

GARREY CARRUTHERS
GOVERNOR

December 29, 1987

POST OFFICE BOX 1980
HOBBS, NEW MEXICO 88241-1980
(505) 393-6161

OIL CONSERVATION DIVISION
P. O. BOX 2088
SANTA FE, NEW MEXICO 87501

RE: Proposed:
MC ____
DHC ____
NSL ____
NSP ____
SWD X
WFX ____
PMX ____

Gentlemen:

I have examined the application for the:

Penroc Oil Corp. State AF #2 O 8-18-35
Operator Lease & Well No. Unit S-T-R

and my recommendations are as follows:

OK JS

Yours very truly,

Jerry Sexton
Jerry Sexton
Supervisor, District 1

/ed

CAMPBELL & BLACK, P.A.
LAWYERS

JACK M. CAMPBELL
BRUCE D. BLACK
MICHAEL B. CAMPBELL
WILLIAM F. CARR
BRADFORD C. BERGE
MARK F. SHERIDAN
J. SCOTT HALL
PETER N. IVES
JOHN H. BEMIS
MARTE D. LIGHTSTONE

GUADALUPE PLACE
SUITE I - 110 NORTH GUADALUPE
POST OFFICE BOX 2208
SANTA FE, NEW MEXICO 87504-2208
TELEPHONE: (505) 988-4421
TELECOPIER: (505) 983-6043

January 8, 1988

HAND DELIVERED

RECEIVED
JAN 8 1988
...ATION DIVISION
Case 9303

William J. LeMay, Director
Oil Conservation Division
New Mexico Department of
Energy, Minerals and Natural Resources
State Land Office Building
Santa Fe, New Mexico 87503

Re: Protest to Application of Penroc Oil Corporation for Disposal of Produced Waters, Lea County, New Mexico

Dear Mr. LeMay:

By Application dated December 23, 1987 Penroc Oil Corporation seeks Oil Conservation Division approval to dispose of produced waters into the Devonian formation through its State AF Well #2 located in Section 8, Township 18 South, Range 35 East (Unit O), Lea County, New Mexico. Atlantic Richfield operates its Lea 4011 State #1 Well in Unit N of Section 8, Township 18 South, Range 35 East, from which it is currently producing from the Devonian formation. Inasmuch as Penroc is proposing to dispose produced waters into the Devonian formation only 1300 feet away from Atlantic Richfield's offsetting producing Devonian well, Atlantic Richfield protests the application of Penroc Oil Corporation.

Your attention to this letter is appreciated.

Very truly yours,

William F. Carr

WILLIAM F. CARR
WFC/mlh

ATTORNEY FOR ATLANTIC RICHFIELD
cc: Ron Sponberg
Atlantic Richfield

Danny Campbell
Arco Oil & Gas Company
Post Office Box 1610
Midland, Texas 79702

maralo inc.

New Mexico Oil & Gas Conservation Commission
Oil Conservation Division
P.O. Box 2088
Santa Fe, New Mexico 87504

January 11, 1988

Case File

ATTN: Mr. Bill Le May

RE: PENROC OIL CORPORATION
SWD APPLICATION
STATE AF-2
SOUTH VACUUM FIELD, LEA CO., NM

Gentlemen:

We are in receipt of the above application for a SWD well at a location 330' FSL and 2130' FEL, Section 8, T-18-S, R-35-E and recommend that the disposal interval be **below** 12,000', as there appears to be an oil column in the interval proposed by the operator, i.e. 11,837'(?) to 11,850'.

There is a discrepancy between the Penroc data and the information contained on the attached scout ticket. The scout information indicates 7" casing was set at a TD of 11,850', and the Devonian perforated 11,840 - 11,848', as compared to the Penroc diagram that indicates the well production tested via the open hole from 11,837 - 11,850'.

In any case, a drill stem test of the Devonian from 11,840 - 11,850' recovered 928' of free oil - no water, suggesting the presence of an oil column on the down-thrown side of the major fault controlling the South Vacuum accumulation.

Using Penroc's structural data, it is possible to infer that a higher structural position is present in Sections 16 and 17, southeast of the subject well.

For this reason we respectfully request that the injection/disposal interval be confined to depths below 12,000'.

Very truly yours,

R. A. Lowery

R. A. Lowery
Production Manager

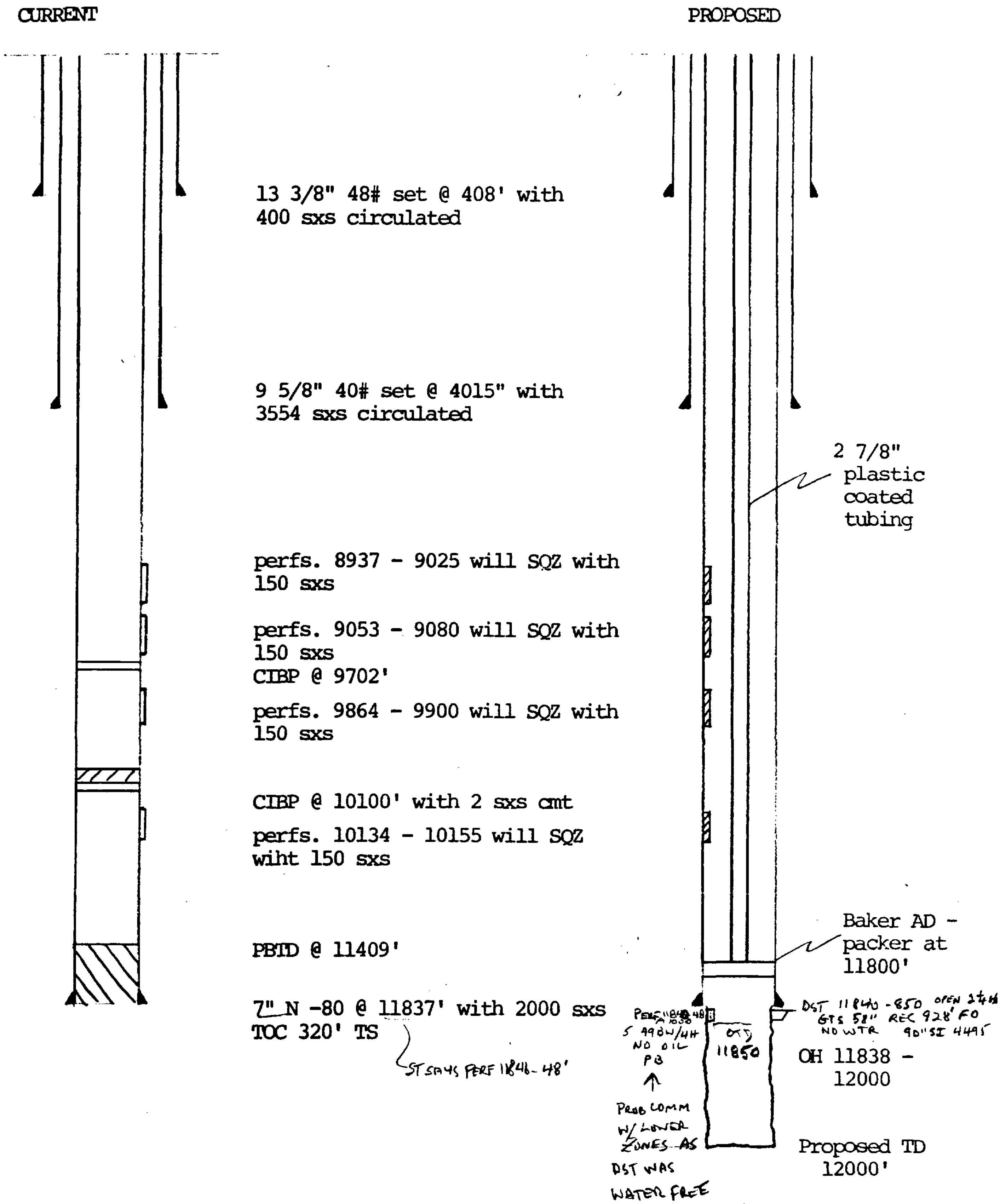
JAN 15 1988
OIL CONS...
SANTA F...

RWK/dp

Attachments

cc: Penroc Oil Corporation

PENROC OIL CORPORATION
STATE "AF" NO. 2



COUNTY LEA FIELD Undesignated STATE N.M.

OPR TEXAS PACIFIC OIL COMPANY MAP

2 State of New Mexico "AF"

Sec. 8, T-18-S, R-35-E CO-ORD

330' fr S Line & 2130' fr E Line of Sec.

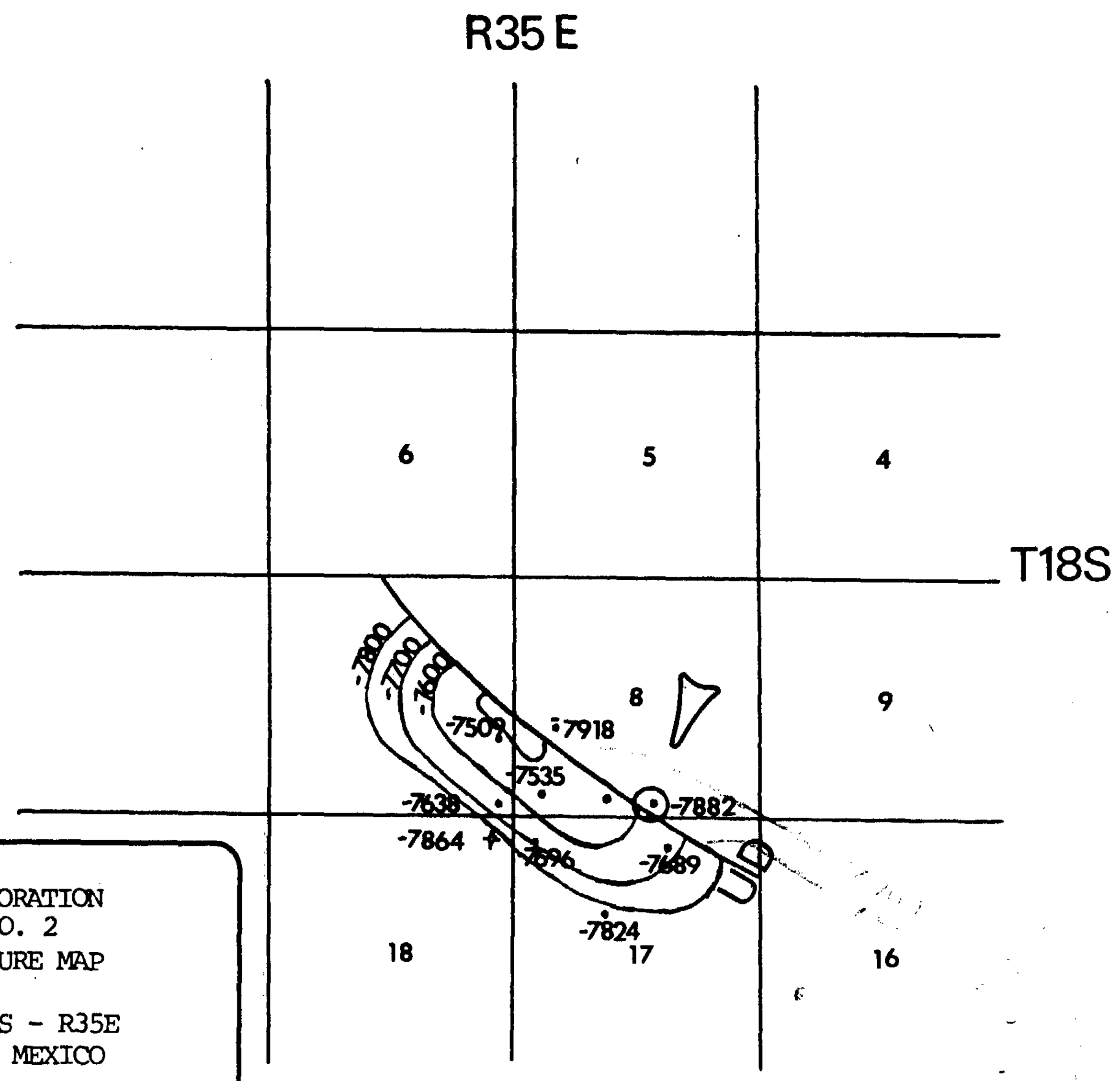
Spud 12-22-63 CLASS EL

Comp 4-3-64

CSG & SX - TUBING			FORMATION	DATUM	FORMATION	DATUM
			LOG:			
13 3/8"	408'	400	Anhy 1670			
9 5/8"	4015'	3754	Yates 3162			
7"	11850'	2000	Queen 4298			
			SA 4982			
			B Spg 6448			
LOGS EL GR RA IND HC A B			Spg Rf 8933			
			TD 11850', PBD 11409'			

IP Abo Perfs 9053-80' Flwd 264 BOPD. Pot. Based on 12 hr test of 132 BO thru 24/64" chk., TP 200#, GOR 970.

Set whipstock @ 10812'.
DO to 10841' & PB to 10316'.
3-2-64 TD 10981', prep to drill off whipstock.
Set Whipstock @ 10498' & DO to 10654'.
PB w/cmt to 10150', DO to 10860' & Set Whipstock.
3-9-64 Drlg. 11185' lm., ch. & sh.
3-16-64 Drlg. 11652' lm. & sh.
3-23-64 TD 11850', pulling test tool. DST 11840-850', tool plugged.
DST 11840-850', tool plugged.
DST 11840-850', open 2 hrs 15 mins, GTS in 58 mins, @ TSTM, Rec 928' oil, no wtr, no ISIP Taken, FF 582-627#, 1 hr 30 min FSIP 4495#.
~~3-30-64 TD [illegible]~~
Perf 11840-848' W/1 SPF
Ac. 1000 gals. (11840-848')
Swbd 46 BLO + 24 BAW & 25 BFW, w/tr. oil in 5 hrs.
4-6-64 TD 11850', PBD 11409', SI for Storage.
Swbd 49 BW, w/tr. oil in 4 hrs (11840-848')
Set PP @ 11750'.
Perf 11419-506' W/1 SPF
Ac. 2000 gals.,
Swbd dry.
Set BP @ 11409'.
Perf @ 9053', 9058', 9064', 9068', 9074', & 9080' W/1 SPF,
Ac. 2500 gals. (9053-9080')
S & F 322 BO in 15 hrs thru 24/64" chk., TP 100#.



PENROC OIL CORPORATION
STATE "AF" NO. 2
DEVONIAN STRUCTURE MAP

SECTION 8 - T18S - R35E
LEA COUNTY NEW MEXICO

M. PIERCE

CAMPBELL & BLACK, P.A.
LAWYERS

JACK M. CAMPBELL
BRUCE D. BLACK
MICHAEL B. CAMPBELL
WILLIAM F. CARR
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February 29, 1988

RECEIVED
FEB 29
OIL CONSERVATION DIVISION

HAND-DELIVERED

Mr. David R. Catanach
Examiner
New Mexico Energy, Minerals
and Natural Resources Department
State Land Office Building
Santa Fe, New Mexico 87501

Re: Oil Conservation Division Case No. 9303
Application of Penroc Oil Corporation for Salt Water Disposal, Lea County, New Mexico

Dear Mr. Catanach:

Pursuant to your February 2, 1988 request, we are enclosing for your information a Pulse Test Design and a proposed Order denying the application of Penroc in the above referenced case.

As you recall, at the time of hearing, Penroc advised that the perforated interval in its State AF Well No. 2 would be from 12,000 feet to 12,200 feet. Their advertisement for this case however, references a perforated interval from 11,850 feet to 12,200 feet. The enclosed proposed Order, therefore, reflects an interval from 11,850 feet to 12,200 feet to be consistent with the case as docketed.

Arco remains opposed to this application unless Penroc, at its expense, obtains satisfactory data to establish that its injection will not be in communication with Arco's Lea 4011 Well No. 1. Without this new information, the evidence before you establishes pressure communication between these wells. Since these wells are in communication, the disposal of produced water in the Penroc "AF" Well No. 2 accelerate the date when the Arco Lea 4011 Well waters out, thereby causing the waste of hydrocarbons and impairing correlative rights.

If you need anything further from Arco to proceed with your decision in this matter, please advise.

Very truly yours,

WILLIAM F. CARR
WFC:mlh
Enclosures

STATE OF NEW MEXICO
ENERGY, MINERALS AND NATURAL RESOURCES DEPARTMENT
OIL CONSERVATION DIVISION

IN THE MATTER OF THE HEARING CALLED BY THE OIL CONSERVATION DIVISION FOR THE PURPOSE OF CONSIDERING:

CASE NO: 9303
ORDER NO._____

APPLICATION OF PENROC OIL CORPORATION FOR SALT WATER DISPOSAL, LEA COUNTY, NEW MEXICO.

ARCO OIL & GAS COMPANY'S PROPOSED ORDER OF THE DIVISION

BY THE DIVISION:

This cause came on for hearing on February 3, and March 2, 1988, at Santa Fe, New Mexico, before Examiner David R. Catanach.

NOW, on this _____ day of March, 1988, the Division Director, having considered the testimony, the record, and the recommendations of the Examiner, and being fully advised in the premises,

FINDS THAT:

(1) Due public notice having been given as required by law, the Division has jurisdiction of this cause and the subject matter thereof.

(2) The applicant, Penroc Oil Corporation, seeks an order authorizing the disposal of produced salt water into the undesignated Mid Vacuum-Devonian Pool in the perforated interval from 11,850 to 12,200 feet in its State "AF" Well No. 2 located 330 feet from the South line and 2,130 feet from the East line (Unit O) of Section 8, Township 18 South, Range 35 East, N.M.P.M., Lea County, New Mexico.

(3) Arco Oil & Gas Company operates its Lea 4011 State No. 1 Well, located in Unit N, Section 8, Township 18 South, Range 35 East, N.M.P.M., Lea County, New Mexico, the immediate west offset to the proposed injection well, which is producing in commercial quantities from the Mid Vacuum-Devonian Pool.

(4) Penroc presented evidence of a fault separating its proposed disposal well and Arco's Lea 4011 State No. 1 Well.

(5) That the evidence presented by Arco established a pressure communication existed between the proposed injection well and its Lea 4011 State No. 1 Well and that the injection and produced waters as proposed by Penroc could cause Arco's well to prematurely waterout, thereby resulting in a loss of hydrocarbons, causing waste, and impairing the correlative rights of interest owners in the Lea 4011 State No. 1 Well.

(6) That the application of Penroc Oil Corporation for disposal of salt water into the Mid Vacuum-Devonian Pool in the perforated interval from 11,850 feet to 12,200 feet in its State AF Well No. 2 should be denied.

IT IS THEREFORE ORDERED THAT:

(1) The application of Penroc Oil Corporation for disposal of produced salt water into the undesignated Mid Vacuum-Devonian Pool in the perforated interval from 11,850 feet to 12,200 in its State AF Well No. 2 located 330 feet from the South line and 2,130 feet from the East line (Unit O) of Section 8, Township 18 South, Range 35 East, N.M.P.M., Lea County, New Mexico is hereby denied.

(2) Jurisdiction of this cause is retained for the entry of such further orders as the Division may deem necessary.

DONE at Santa Fe, New Mexico, on the day and year hereinabove designated.

STATE OF NEW MEXICO
OIL CONSERVATION DIVISION

William J. LeMay
Director

(S E A L)

Internal Correspondence

Date: February 24, 1988

Subject: **Pulse Test Design**

From/Location: T. J. Plover - PRC E1835A

Telephone: 754-6936

To/Location: R. D. Campbell - MIO 346

Per our telephone conversation, here is a design of a pulse test for establishing interwell communication.

The well placements are shown in attachment 1. The ARCO well is a producer, with production of about 2000 STB/D of water and 50 STB/D of oil. The average reservoir pressure is assumed to be near the original unproduced reservoir pressure of about 4700 psig, since there is very strong aquifer support. The average reservoir pressure is assumed to be above the bubble point pressure for the oil. Most of the porosity is fracture porosity, with $\phi = 0.12$. Other oil and formation parameters are shown on attachment 1.

The fault between the ARCO producer and the proposed injector is not known with certainty to be a sealing fault. Establishing the fault effects on interwell communication is the primary goal of the interference test.

Attachment 2 shows the calculations for design of the pulse test. The ARCO well is designated as the pulsing well and the proposed injector is the observation well. The zones open to flow during the test, for both wells, is crucial. Any conclusions reached regarding interwell communication will only be applicable for the zones mutually open to flow during the test. Conclusions from this test would not generally be applicable to establishing interwell communication for other zones. The design follows the method given in SPE Monograph 5, Advances in Well Test Analysis, by R. C. Earlougher. See pages 111-118, especially example 9.5 on page 118, in Monograph 5. The time for each flow/shut-in cycle is 87.44 hours. During this cycle the well is shut-in (this is the pulse) for 26.23 hours and then flowed at 2050 stock tank barrels/day total fluid rate for 61.21 hours. This cycle is repeated as many times as desired, with each cycle corresponding to a pulse, or pressure wave, to be detected at the observation well. Theoretically only one pulse is required; the time required for the peak of the pressure pulse to reach the observation well is 6.82 hours. In practice it is better to cycle the pulsing well multiple times to send more pulses to be measured at the observation well. Because the pressure pulse at the observation well is small and may be difficult to accurately measure, multiple pulses increase the chances of obtaining good measurements. Analyzing multiple pulses also increases the reliability of the analysis by providing the opportunity to check for consistency between conclusions reached from analyzing each pulse.

The design presented here should yield a first even pulse of about 1.3 psig peak at the observation well. Should a flow rate less than the 2050 stock tank barrels/day be used in the test, the magnitude of the pressure peak of the pulse will be less than 1.3 psig. A very sensitive pressure transducer, such as a Hewlett-Packard type, should be used to achieve precise and accurate measurements.

If the wells are in communication and the path of communication between the wells contains significant amounts of directionally oriented natural fractures, then the actual pressure response at the observation well will not match this design. The data will still be analyzable. Directionally oriented natural fractures correspond to directional permeability. If the average permeability in the reservoir is 100 md as measured through a conventional single well pressure transient test, it is possible that the permeability between the two wells in the pulse test could be much greater or much smaller than 100 md. For greater permeability, the measured pulse would come more quickly than this design shows and would peak to a greater level. For lesser permeability, the measured pulse would arrive later and would be smaller than shown in this design. The practical implication is that observation well measurements should be continued even if no pulse is measured at the expected arrival time as indicated by this test design. The pulse may be detected at a later time, and measurements at the observation well must be maintained to insure seeing it.

The effect of the aquifer and high water saturation in the formation is to increase the propagation speed of the pressure pulse. The aquifer repressurizes the formation more quickly than solution gas drive alone would. The high water saturation causes the total system compressibility to be relatively low, again increasing the speed of the pressure pulse and reducing the attenuation of the pressure pulse as it travels through the formation. Attachment 3 shows these effects in a field application. See especially the last paragraph of page 317 of the article. For purposes of establishing interwell communication between the ARCO producer and the proposed injector, the aquifer and high water saturation should not hinder the usefulness of the test.

If no pulse response is seen during the test, then clearly no interwell communication exists through the open zones. If pulse response is seen, then interwell flow communication exists; the magnitudes and times of the pulses can be analyzed to determine the permeability and porosity-compressibility product by the method of Kamal and Brigham as shown in Monograph 5. The analysis method as originally described by Kamal and Brigham is shown in attachment 4.

Please note that prior to pulsing the ARCO well, pressure transients in the reservoir region between the two wells should already have been damped. This means that before beginning the test, the ARCO well should have been producing at a constant rate of 2050 stock tank barrels total fluid/day for greater than about twice the estimated travel time for the pulse, or about 15.6 hours. Also, the observation well (the proposed injector) should have been shut-in for about the same amount of time before the test. If the existing pressure transients are not allowed to damp out before the test, then the pressure pulses may be exceedingly difficult to distinguish from pre-existing transients.

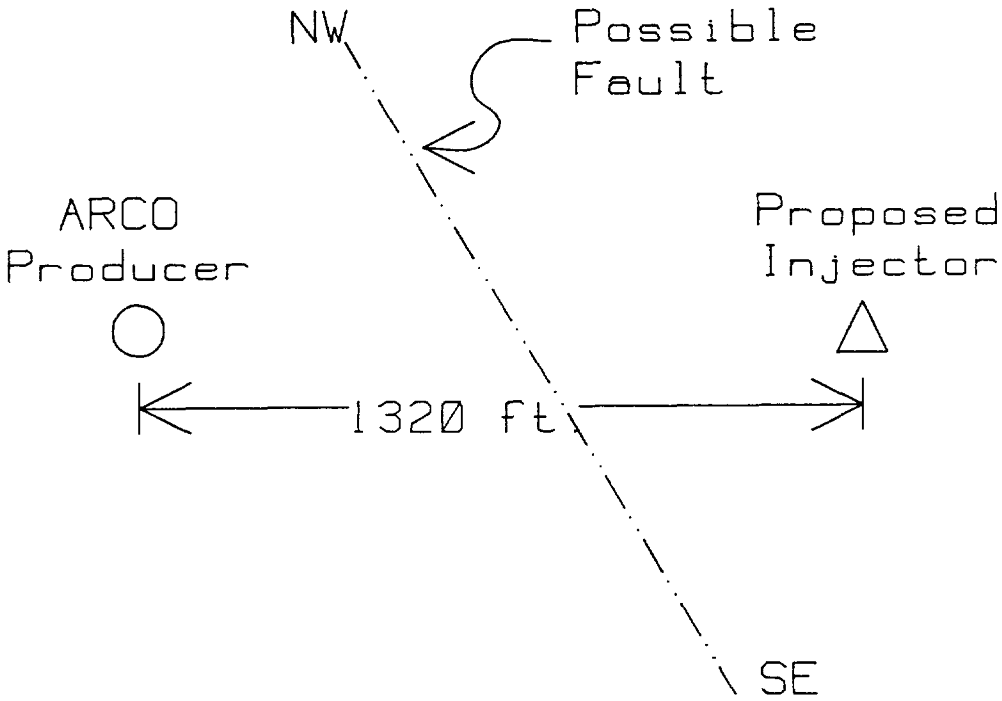
If you have any questions, please call me.

Tim Plover

TJP/vb
Attach.

cc: B.D. Gobran - PRC E1840
C. Martin - PRC E1702
M.L. McMlandrich - PRC E1838

Attachment 1



k = 100md
h = 300 ft
ϕ = 0.12

γ_o = 40° API

μ_o = 0.45 cp
μ_w = 0.47 cp
$B_{oi} = 1.6 \frac{RVB}{STB}$
$B_w = 1.0 \frac{RVB}{STB}$

$c_o = 32 \times 10^{-6}$ psi^{-1}
$c_w = 3 \times 10^{-6}$ psi^{-1}
$c_f = 173 \times 10^{-6}$ psi^{-1}

Initial Reservoir Pressure, P_i = 4700 psig; because of strong water drive average reservoir pressure assumed to be near P_i.

Flow rates q_o = 50 STB/D
q_w = 2000 STB/D

The formation possibly has natural fractures, but the orientation of the fracture system is not known.

Attachment 2

Assume that the ARCO well is the pulsing well, and the proposed injector is the observation well (in order to minimize lost ARCO production). All figures and equations mentioned below are in SPE Monograph 5.

1) To minimize shut-in time, choose a short pulse (as in Monograph 5 page 118), such as $F' = 0.3$.

2) Specify maximum $\Delta P_D [t_L/\Delta t_c]^2$ points from figures 9.15 and 9.16 for the first odd and even pulses.

First even pulse, $F' = 0.3$, curve maximum: $\Delta P_D [t_L/\Delta t_c]^2 = 0.00175$

at $t_L/\Delta t_c = 0.078$

First odd pulse, $F' = 0.3$, curve maximum: $\Delta P_D [t_L/\Delta t_c]^2 = 0.00075$

at $t_L/\Delta t_c = 0.07$

3) From figure 9.20, using the first even pulse, for $t_L/\Delta t_c = 0.078$, $\{(t_L)_D/r_D^2\}_{Fig.} = 0.112$

4) Given equation 9.18:

$$\phi c_t = \frac{0.0002637\, k t_L}{\mu r^2 \{(t_L)_D / r_D^2\}_{Fig.}}$$

then, rearranging:

$$t_L = \frac{\{(t_L)_D / r_D^2\}_{Fig.}\, r^2 \phi \mu c_t}{0.0002637\, k}$$

Because the water cut of the well is very high, and the average reservoir pressure is above bubble point, the following phase saturations are assumed:

$S_o = 30\%$
$S_w = 70\%$
$S_g = 0\%$

Then the total system compressibility is

$$c_t = S_o c_o + S_w c_w + c_f = (0.3)(32\times10^{-6}) + (0.7)(3\times10^{-6}) + (5\times10^{-6})$$

$$c_t = 1.67 \times 10^{-5}$$

Solving for t_L,

$$t_L = \frac{(0.112)(1320)^2 (0.12)(0.46)(1.67 \times 10^{-5})}{(0.0002637)(100)} = 6.82 \text{ hours}$$

5) The time for each production/shut-in cycle is given by

$$\text{Cycle time } \Delta t_c = \frac{t_L}{(t_L/\Delta t_c)} = \frac{6.82}{0.078} = 87.44 \text{ hours}$$

6) The pulse length (i.e., length of shut-in per cycle) is given by

$\Delta t_p = F' \Delta t_c = (0.3)(87.44) = 26.23$ hours

7) The production time per cycle is then

$\Delta t_c - \Delta t_p = 87.44 - 26.23 = 61.21$ hours

8) The permeability is estimated from the pulse test by equation 9.17:

$$k = \frac{141.2\, q\, B\, \mu \{\Delta P_D [t_L/t_c]^2\}}{h\, \Delta P\, [t_L/\Delta t_c]^2}$$

For design purposes we rearrange this equation to solve for the peak of the pressure pulse to be expected at the observation well:

$$\Delta P = \frac{141.2\, q\, B\, \mu \{\Delta P_D [t_L/\Delta t_c]^2\}}{h\, k\, [t_L/\Delta t_c]^2}$$

or (using B = 1.0 since most of the fluid flow is water),

$$\Delta P = \frac{(141.2)(2050)(1.0)(0.46)(0.00175)}{(300)(100)(0.078)} = 1.28 \text{ psi}$$

This ΔP should be readily measurable with a solid state pressure transducer.

A Field Application of Pulse-Testing for Detailed Reservoir Description

R. M. McKINLEY
MEMBER AIME
SAUL VELA
JUNIOR MEMBER AIME
L. A. CARLTON
MEMBER AIME

ESSO PRODUCTION RESEARCH CO.
HOUSTON, TEX.

HUMBLE OIL & REFINING CO.
NEW ORLEANS, LA.

Abstract

Johnson et al. have described a new well-testing technique that measures formation flow properties between wells.[1] The technique, called pulse-testing, requires a sequence of rate changes in the flow at one well and measurement of the resulting pressure changes at an adjacent well with a very sensitive differential pressure gauge.

This paper describes an extensive application of the technique in a producing oil field. Pulse-tests on 28 of 45 possible well pairs in the field provided a picture of the areal distribution of reservoir hydraulic diffusivity, transmissibility and storage. The primary objective in presenting these data is to demonstrate the potential of the method for reservoir description. A second objective is to show in three ways the qualitative and quantitative accuracy of reservoir parameters determined from pulse-tests: (1) pulse-test data show a nonuniformity in the field, closely correlating with the oil-water distribution as given by production data; (2) pulse-test values for permeability are comparable with core values; and (3) perhaps most important, the field responds to a conventional interference test in the manner in which pulse-test data predict it should.

Introduction

The pulse-testing technique by Johnson *et al.*[1] is an ideal source of data for purposes of reservoir description, for it provides a measurement of formation storage $S = \phi ch$, hydraulic diffusivity $\eta = k/\phi c\mu$ and transmissibility $T = kh/\mu$ between wells.*

This paper describes an application of this method in a producing oil field. Results were analyzed to give numerical values for the parameters η, T and S. These values were compared with oil-water production data (for the effect of fluid saturation), with core data and with data from an interference test.

The reservoir in which the pulse-test survey was run is the result of a structural trap formed by a fault along the east side of a north-south trending anticline. A down-structure aquifer provides a natural flank water drive for the pool. The producing formation is a dolomitic limestone having mainly vugular permeability; the formation oil has a gravity of 29° API with negligible dissolved gas. The field contains 19 wells, all on pump, arranged on 40-acre spacing along the top of the anticline.

Fig. 1 shows the location of all these wells except two at the south end of the field. The dashed line on the right-hand side of the figure represents the approximate location of the fault with respect to well positions.

Pulse-Test Survey and Analysis of Data

A pulse-test requires a pulsing well and a responding well. In the field, changes were made in the rate of flow at the pulsing well by stopping and starting the pump periodically and measuring the corresponding pressure

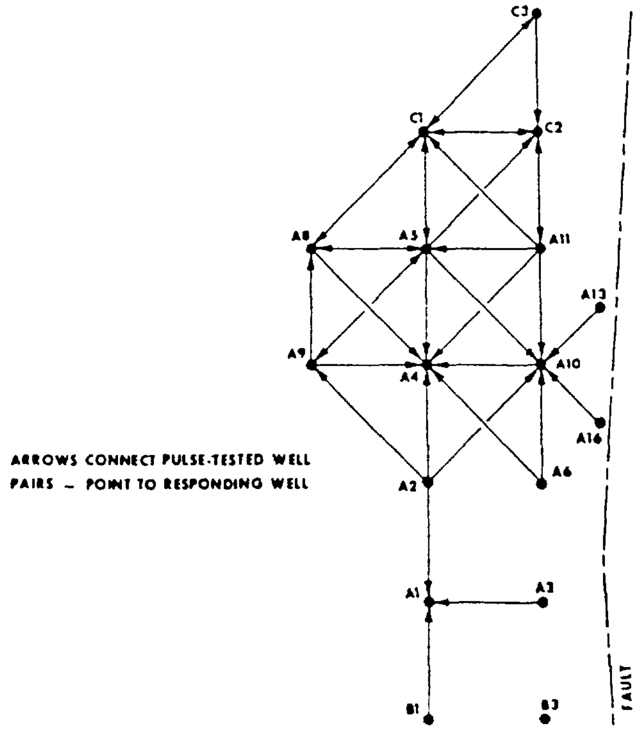


Fig. 1—*Pulse-test survey.*

Original manuscript received in Society of Petroleum Engineers office July 10, 1967. Revised manuscript received Feb. 3, 1968. Paper (SPE 1822) was presented at SPE 42nd Annual Fall Meeting held in Houston, Tex., Oct. 1-4, 1967.

[1]References given at end of paper.

This paper will be printed in *Transactions* volume 243, which will cover 1968.

*Throughout the paper the symbols T for transmissibility and S for storage have been used even though these symbols normally designate the quantities temperature and saturation, respectively. To avoid confusion Roman-type faces have been used rather than italics.

changes at the responding well. At the responder, the pump was unseated, the string was loaded with LPG (to give a liquid column to the surface) and a pressure gauge was attached directly to the top of the tubing string. All wells surrounding the test pair were left on pump.

Out of a possible 45 well pairs, 28 were pulsed in this fashion, which thoroughly covered the northern part of the field (Fig. 1). The solid lines in the figure connect the pairs of wells tested; the arrows point toward the responding well. In this way, response curves like that shown in Fig. 2 were obtained for several directions about each well.

In the pulse-test represented by Fig. 2, flow at Well A8 was shut off at time $t = 0$ for 90 minutes, then resumed for 90 minutes, etc. This stop-start sequence is shown by the dashed lines, which refer to the flow-rate scale on the right-hand side of the figure. The solid data points show the corresponding pressure changes at Well A4, which is 1,867 ft from Well A8. The pressure response in Well A4 lagged the rate change in Well A8 by 30 to 40 minutes. This lag time (t_{L_1}, t_{L_2}, t_{L_3}) is almost inversely proportional to the hydraulic diffusivity η of the formation between the wells.

The solid tangent lines in Fig. 2 are used to analyze the data. The analysis method[1] uses the exponential integral solution for radial flow in an infinitely homogeneous formation.[2] First, the peaks and valleys on the response curve are isolated by the tangent construction illustrated by solid lines in Fig. 2. Then the analysis method uses each time lag t_{L_i} and amplitude Δp_i to arrive at an estimate of the reservoir parameters η, T, and S, where $\eta = T/S$. For example, the three parts of the curve from Fig. 2 give the following numerical data.*

Part of Response Curve	$\eta = k/\phi c\mu$ md-psi/cp	$T = kh/\mu$ md-ft/cp	$S = \phi ch$ ft/psi
First peak	2.10×10^{9}	27,000	12.9×10^{-6}
First valley	2.44×10^{9}	34,000	13.7×10^{-6}
Second peak	2.44×10^{9}	33,000	13.5×10^{-6}

*These numbers were taken from interpretation charts prepared according to the suggestions contained in the Appendix of Ref. 1.

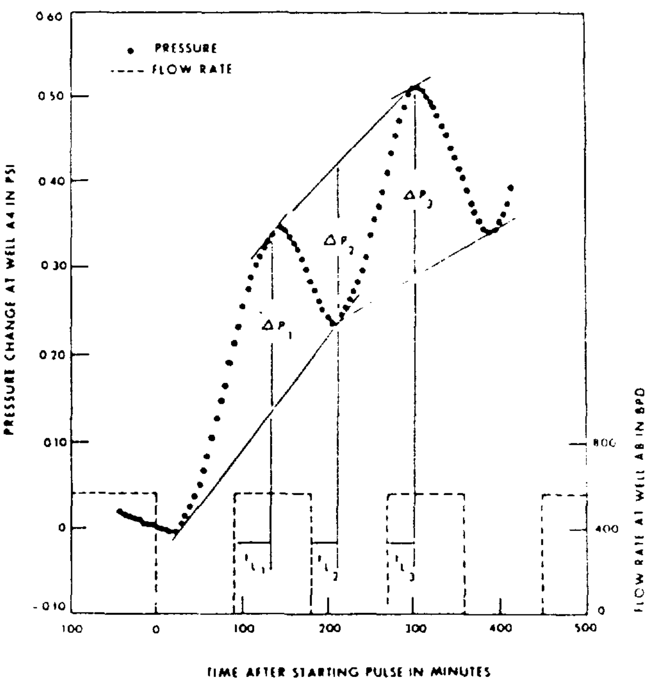


Fig. 2—*Pressure response at Well A4 to a pulse sequence at Well A8.*

(The variance in these values gives an estimate of the experimental error introduced by such occurrences as instrument drift and changes in reservoir pressure trends. A better method of estimating experimental error, however, is to rerun well-pair tests at various times during the survey. Five well-pair tests were rerun and the variance was found to be no greater than that indicated by repeated pulses in the original tests.)

The type of information that can be derived from the analysis of response curves when several wells about a given well are pulsed is illustrated in Fig. 3. The pressure responses at Well C2 were measured when the three surrounding and equally distant Wells C3, C1 and A11 were individually pulsed. The three response curves were normalized to unit production rate for comparison. Since a pulse-test pressure response is proportional to the corresponding flow rate change at the pulsing well, the responses can be normalized by dividing the pressure response by the flow rate change.

If the reservoir penetrated by Wells C3, C1 and A11 were homogeneous, the normalized pressure changes could be expected to be the same for all directions. As Fig. 3 shows, this reservoir is clearly not homogeneous. Moreover, by looking for the well pair with the most rapid response, one can say that the direction from Well C3 to Well C2 has the highest hydraulic diffusivity $\eta = k/\phi c\mu$. To say whether this results from higher mobility or lower storage requires further analysis.

Data obtained by analysis of response curves from our pulse-test survey appear in Table 1. The potential of the pulse-testing method for reservoir description can best be visualized, however, if the areal distribution of these data are portrayed in contour maps. This is done in Figs. 4 through 6, assuming that the data can be treated as point values located midway between the wells involved. Note that while the variation in S (Fig. 5) is not so large as that in T (Fig. 4), it is not a constant as is customarily assumed in the interpretation of well test data. The contour map of $1/\eta$ (Fig. 6) best poinpoints the nonuniformity of properties over the field.

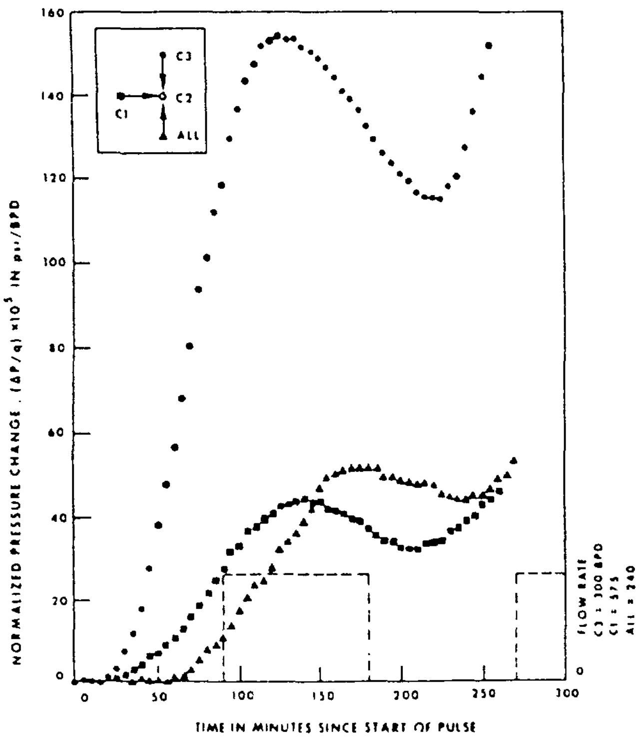


Fig. 3—*Pulse response in three directions around Well C2.*

More sophisticated interpretations of pulse-test response curves might be made using a nonlinear regression technique described by Jahns[7] to match the response curves to those calculated for a mathematical model of a heterogeneous reservoir. However, this would require extrapolation of reservoir trends existing at the start of the test.

In examining data from the pulse-tests conducted in this survey, note particularly the data at the beginning of Table 1 for well pairs pulsed in both directions: they illustrate a reciprocity principle of both theoretical and practical consequence. In a heterogeneous reservoir, it might be expected that a change in the direction of pulsing would affect pressure response; this generally is not true.

To explain the principle of reciprocity, suppose pulsing is performed between Wells A and B. First, Well A is pulsed at a constant rate q with a pulse length Δt, and the resulting pressure change induced at Well B, $\Delta p_B(t)$, is measured as a function of time. Next, the wells are pulsed in the opposite direction; i.e., Well B is pulsed at the same rate and at the same pulse length, and the pressure change at Well A, $\Delta p_A(t)$, is measured as a function of time. According to the reciprocity principle, these pressure changes are the *same* functions of time; i.e., $\Delta p_A(t) = \Delta p_B(t)$. On the other hand, if one constant rate q_A is used when pulsing Well A and a different constant rate q_B is used when pulsing Well B, then the reciprocity principle states that, for the same pulse length, the pressure responses per unit pulse rate (i.e., normalized pressure responses) are the same, $\frac{\Delta p_A(t)}{q_B} = \frac{\Delta p_B(t)}{q_A}$.

As is proven in the Appendix, this reciprocity principle is valid for either infinite or finite reservoirs. The proof requires that pressure should satisfy the single-phase diffusivity equation that forms the basis of most techniques for interpreting well test data.[8] While reservoir transmissibility and storage may have arbitrary spatial variation, they should not be functions of pressure.

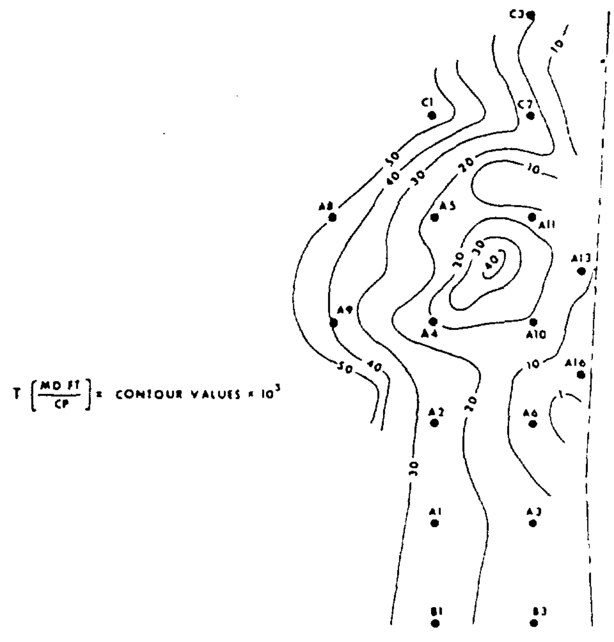


Fig. 4—*Contour map of transmissibility* T.

TABLE 1—SUMMARY OF PULSE-TEST DATA
(Numbers are Mean Values ± Standard Deviation of Mean)

Well: Pulser	Well: Responder	Number of Replications	$\eta \times 10^{-6}$, md-psi/cp	T, md-ft/cp	$S \times 10^{6}$, ft/psi
C2	A11	3	0.61 ± 0.15	12,000 ± 2,700	20.1 ± 2.8
A11	C2	3	0.69 ± 0.10	17,200 ± 2,500	25.0 ± 1.0
C3	C1	2	1.70 ± 0.20	34,300 ± 7,000	20.1 ± 3.3
C1	C3	1	1.73	35,000	20.3
A8	C1	2	4.65 ± 0.38	59,600 ± 4,600	12.8 ± 1.0
C1	A8	2	4.16 ± 0.41	53,200 ± 5,200	12.7 ± 1.0
C2	C1	6	1.11 ± 0.10	44,000 ± 3,200	39.1 ± 2.1
C1	C2	2	0.98 ± 0.07	37,800 ± 2,500	38.5 ± 1.0
A8	A9	4	3.60 ± 0.05	40,000 ± 2,000	11.0 ± 1.1
A9	A8	2	3.62 ± 0.10	46,000 ± 7,000	12.7 ± 1.3
A8	A5	7	0.75 ± 0.08	22,200 ± 3,100	29.4 ± 1.0
A5	A8	2	1.84 ± 0.15	38,000 ± 3,000	20.7 ± 2.0
A9	A5	4	1.09 ± 0.26	17,000 ± 5,000	15.6 ± 4.0
A5	A9	2	3.00 ± 0.15	37,000 ± 2,000	12.5 ± 1.4
C1	A5	3	1.12 ± 0.15	25,800 ± 3,500	24.0 ± 5.0
A5	C1	2	2.21 ± 0.11	37,800 ± 2,000	17.3 ± 1.0
A11	A5	3	0.78 ± 0.10	18,400 ± 3,400	25.8 ± 2.4
A11	C1	3	0.70 ± 0.15	10,700 ± 2,500	15.0 ± 2.9
A13	A10	2	1.11 ± 0.17	17,000 ± 2,400	14.8 ± 1.0
A5	C2	2	0.60 ± 0.15	10,000 ± 2,500	16.8 ± 3.2
A4	A10	2	1.17 ± 0.05	22,500 ± 3,000	19.3 ± 2.9
A11	A10	2	1.12 ± 0.20	23,000 ± 4,000	20.6 ± 2.8
A16	A10	2	0.50 ± 0.05	11,000 ± 1,900	22.1 ± 2.1
A5	A10	3	1.51 ± 0.20	46,000 ± 5,300	30.2 ± 4.1
A5	A4	2	0.88 ± 0.10	19,200 ± 2,300	22.0 ± 1.4
A9	A4	3	1.25 ± 0.11	19,000 ± 1,700	15.2 ± 1.0
A2	A10	2	1.25 ± 0.03	30,400 ± 2,300	24.3 ± 1.6
A2	A4	4	1.67 ± 0.07	26,200 ± 1,000	16.9 ± 2.0
A6	A4	3	0.97 ± 0.25	12,200 ± 3,000	12.4 ± 1.7
A6	A10	2	0.48 ± 0.06	6,000 ± 1,000	13.2 ± 1.0
A8	A4	3	2.40 ± 0.28	31,300 ± 2,100	13.4 ± 1.9
A11	A4	5	1.50 ± 0.30	35,000 ± 6,600	23.3 ± 2.4
A2	A9	2	3.44 ± 0.18	40,000 ± 2,300	11.6 ± 1.0
C3	C2	2	1.43 ± 0.18	16,600 ± 2,000	11.8 ± 1.1
A2	A1	2	3.15 ± 0.20	24,000 ± 2,500	7.7 ± 1.0
B1	A1	2	1.55 ± 0.40	23,000 ± 6,700	15.0 ± 3.0
A3	A1	2	0.90 ± 0.20	21,000 ± 4,600	23.7 ± 2.1

This principle is illustrated by the data in Fig. 7, in which normalized pressure responses are plotted as functions of time for Wells A8 and A9. Well A8 was first pulsed with Well A9 as the responder; then the direction was reversed. The normalized pressure responses for Wells A8-A9 and Wells A9-A8 are statistically the same. Well pairs C2-A11, C3-C1, A8-C1 and C1-C2 were also pulsed in both directions without significant differences in results.

Well A5, however, would not give reciprocal pressure responses with its neighbors. The consequence of this appears in Table 1 as different numerical results when the Well pairs A8-A5, A9-A5 and C1-A5 were pulsed in opposite directions. (The averages of the values for the two directions were used in preparing the contour maps, Figs. 4 through 6.) The reasons for this non-reciprocal response with Well A5 are not known. However, Well A5 may involve some types of reservoir situations for which the reciprocity principle would not be expected to hold. These situations are discussed in the Appendix.

As a consequence of the reciprocity principle, a single pulse-test conducted between two wells cannot provide a unique description of a heterogeneous reservoir. For instance, consider a pulse-test in a reservoir that has a tight spot around either Well A or Well B. Because of the reciprocity relationship, it will be impossible to tell from results of the pulse-tests between the wells which one the tight spot is around. To obtain this information, adjacent well pairs also must be pulse-tested.

The principle of reciprocity is important in other respects. First, it reduces the number of tests required to survey a reservoir (if the principle did not hold, twice as many tests would be necessary). Second, since the direction of pulsing is unimportant, the wells to be used as responders can be selected for convenience in testing. In addition, the fact that most of the wells reciprocated in this survey supports the validity of the single-phase diffusivity equation for the interpretation of pulse-test data.

Evaluation of Pulse-Test Results

Pulse-test results are compared here with data obtained from three other sources: (1) oil-water production data, (2) core analysis data, and (3) results from a conventional interference test. These comparisons collectively establish that pulse-test responses can be interpreted with the simple exponential integral equation to give meaningful values for reservoir transmissibility, storage and hydraulic diffusivity in a heterogeneous reservoir. Of real importance is the capacity of a sequence of pulses to provide several estimates of these parameters.

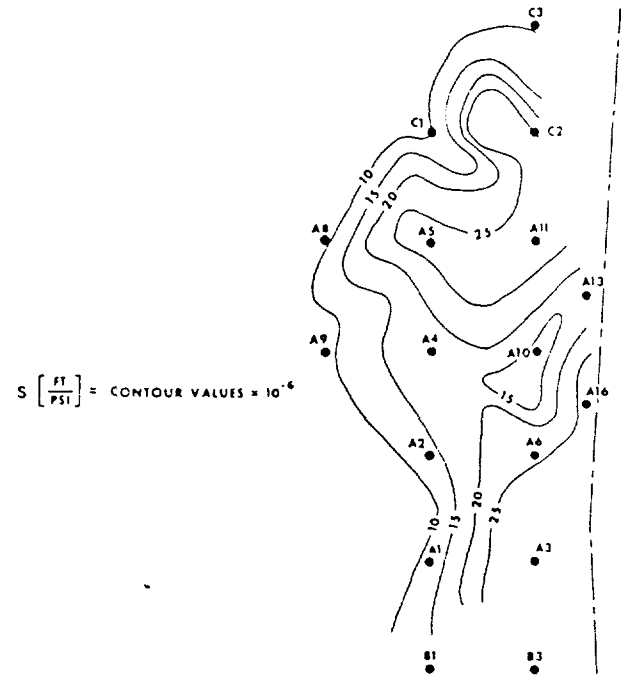


Fig. 5—*Contour map of storage* $S = \phi ch$.

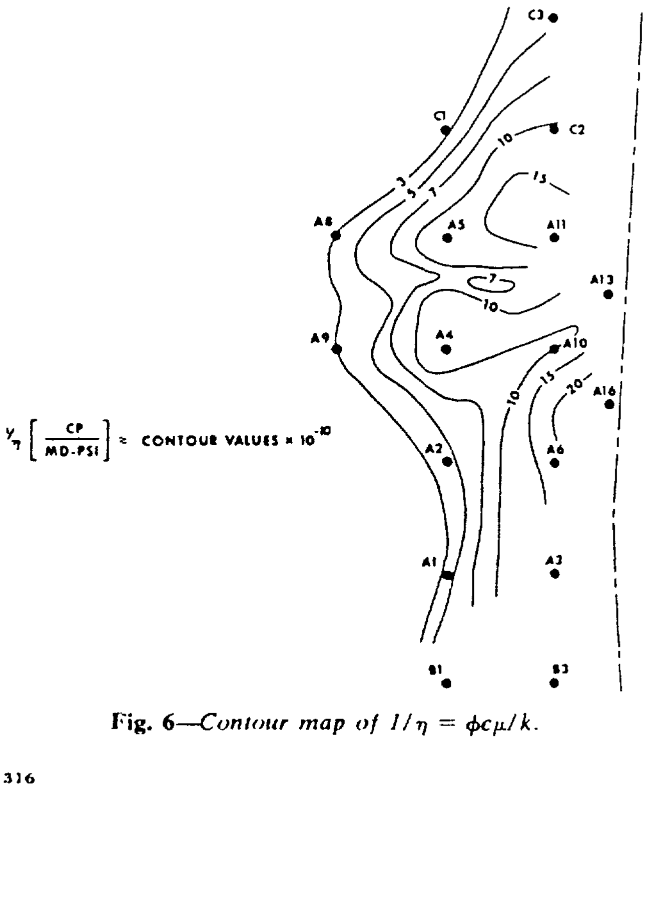


Fig. 6—*Contour map of* $1/\eta = \phi c\mu/k$.

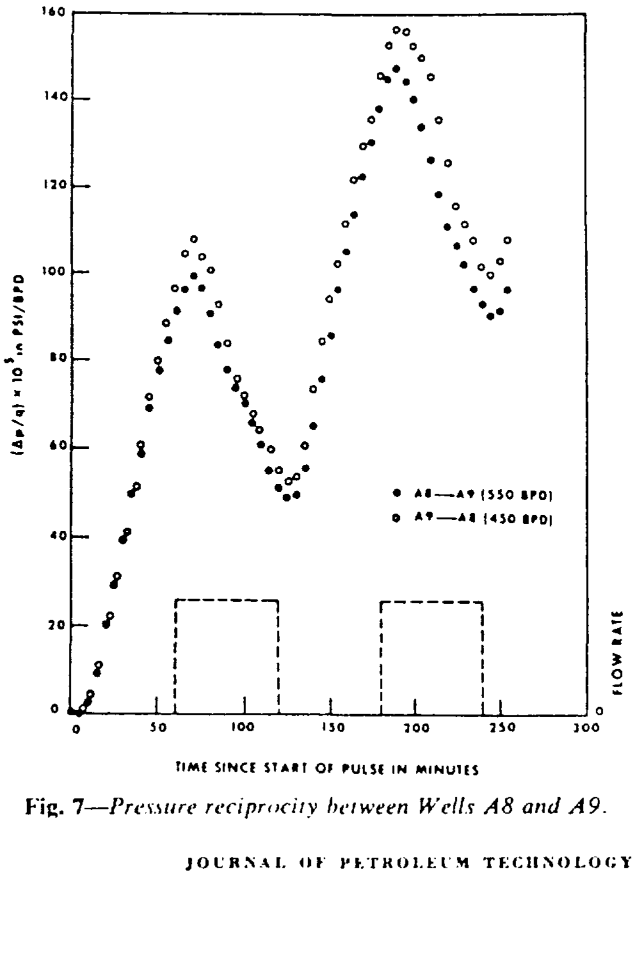


Fig. 7—*Pressure reciprocity between Wells A8 and A9.*

Oil-Water Production Data

Aquifer encroachment is reflected in the water production at individual wells. Water influx also is apparent in the pulse-test data. The value for $1/\eta = \phi c \mu / k$ should be larger for predominantly oil regions than for predominantly water regions because of the combined effects of lower mobility and higher compressibility. Fig. 6 does suggest a pattern of water advance into the field. Fig. 8 superimposes onto this contour map data on oil production (shown as dashed lines) as determined from the oil-water production at each well. The correlation between pulse-test data and phase production is excellent. This simply means that the fastest paths of fluid communication as determined by pulse-testing coincide with the principle paths of water influx.

Core Analysis Data

Cores were taken from Wells A2 and A13. For comparison, reservoir properties were estimated from pulse-test data along the watered-out zone (Wells C1-A8-A9) and in the region with a high oil saturation around Well A6. Values for total compressibility c and for permeability k in these areas were obtained from values of S (Fig. 5) and T (Fig. 4), respectively. Summarized below are the values obtained using these data and the reservoir and fluid properties h = 18 ft, μ_w = 0.6 cp at 125F (water), and ϕ = 0.11, μ_o = 16 cp at 125F (oil).

Location in Field	S ft/psi	c 1/psi	T md-ft/cp	k md
Watered-out zone	10×10^{-6}	5.1×10^{-6}	50,000	1,700
Well A6	24×10^{-6}	12×10^{-6}	5,000	4,500

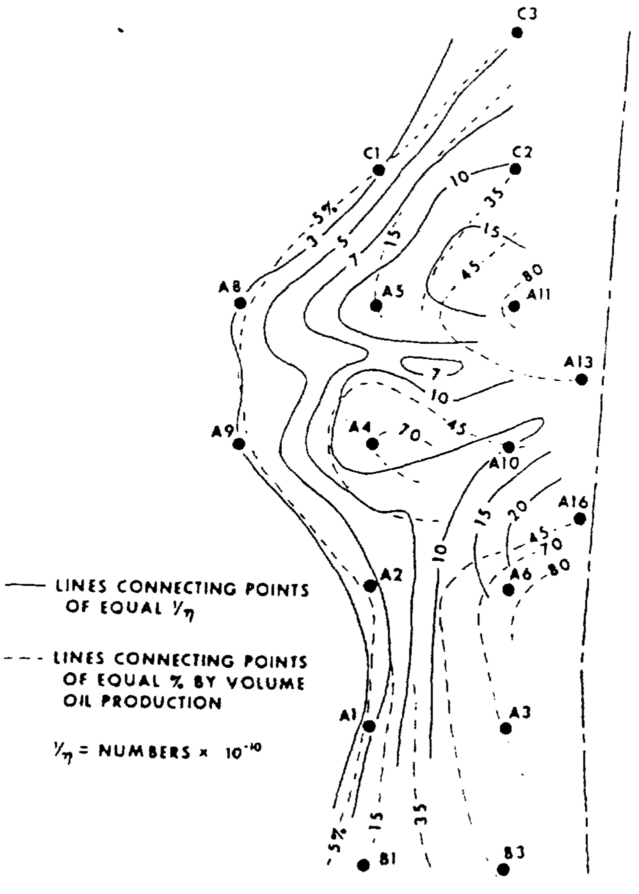


Fig. 8—*Pulse-test data correlating with oil-water production.*

The numbers for c are of the correct magnitude for water- and oil-bearing rock of 11 percent porosity. Cores from Wells A2 and A13 gave an average permeability of 1,200 md. The above pulse-test values of k agree as well with this average as could be expected for a vuggy formation.

Interference Test Data

The following interference test is an effective way to test the pulse-test data in Figs. 4 and 5 in predicting the pressure behavior of the field during a short enough time that existing saturation distributions are not altered appreciably. Pulse-test data were used to predict individual well responses to an interference test, and then the test was conducted. Predictions were made by solving numerically the single-phase, two-dimensional, pressure diffusivity equation. For these computations, the field was divided into grid blocks of approximately 1 acre each. The variable coefficients T and S were obtained for each grid block by imposing a computational grid onto Figs. 4 and 5. The aquifer was assumed to have homogeneous properties equal to the pulse-test values along the west edge of the field. The boundaries consisted of a no-flow boundary along the east side of the field (located 1,320 ft from the line of Wells C3-B3) and of three constant-pressure boundaries to the north, south and west of the field. These last three boundaries were placed at a distance equal to the radius of investigation for the interference test.

For the interference test a pump was installed in Well A8 to give a sizeable production rate, and a turbine meter was installed in the flow line from Well A8 to insure a constant rate. A stabilization period was followed by 3.5 days of continuous production from Well A8. The field again was allowed to stabilize and Well A8 again was produced for 3.5 days. This replication of the test provided estimates of the experimental error in the pressure responses measured in nine wells in the northern part of the field (Wells C3, C1, C2, A11, A5, A9, A4, A10 and A2). For each well, the responses from the two tests were averaged to give a single set of drawdown data.

These drawdown data agreed well with our predictions for most of the wells. If Well A10 is excluded, then the average of the absolute differences between the pressure drawdowns predicted and those measured after 70 hours of production at Well A8 was 1.1 psi out of about 25 psi. This is not significantly different from the average experimental error of 1.5 psi in the interference test data. This close agreement is gratifying, considering the strong influence that wellbore conditions exert on changes in liquid level in an open well.

Fig. 9 shows the predicted and measured drawdown for flank Well A9, located in a high-transmissibility, low-storage area. The pressure tends to level out early as pulse-test data predict it should. The pressure response in an area with a higher oil saturation is illustrated by the data of Fig. 10 for Well A11 where the pressure shows less tendency to level out. This is due to the lower transmissibility and higher storage in this area. The influence of heterogeneities in T and S is apparent in the pressure response at Well C1 (Fig. 11) as compared with that at Well A4 (Fig. 12). The two wells are located the same distance from Well A8 and from the fault. In this case, the higher transmissibility at Well C1 allows the aquifer to repressure this area more rapidly than around Well A4. This same capability of the aquifer to repressure the field causes the drawdown at Well C2 (Fig. 13) to level out faster than that at Well A11 (Fig. 10), even though Well A11 is closer to Well A8.

Fig. 14 shows the poor agreement between the predicted and measured drawdown at Well A10. The replication of the interference test at Well A10 was quite poor (± 4 psi). Reasons for this are not clear; however, the long delay in response at Well A10 (18 hours) suggests a threshold type of wellbore damage such as a mobility block at Well A10.

The over-all agreement between predicted and measured interference test results is certainly sufficient to establish the validity of the pulse-test data.

Conclusions

1. Analysis of pulse-test response curves with the exponential integral equation gives meaningful results in a heterogeneous reservoir.

2. Pulse-testing provides a detailed reservoir description that includes the parameters hydraulic diffusivity η and storage S, as well as transmissibility T. Pulse-test values are much less affected by boundary conditions such as aquifers and faults than are interference test values. Furthermore, the values are less affected by wellbore conditions than are those obtained from single-well tests. Also, single-well tests will not give values for η and S.

Nomenclature

c = total compressibility, 1/psi
h = effective formation thickness, ft
k = permeability, md
Δp = pressure change or pulse amplitude, psi
q = total flow rate, reservoir B/D; also used as a source term in Appendix
$S = \phi ch$ = effective storage, ft/psi
$T = kh/\mu$ = effective transmissibility, md-ft/cp
t_L = pulse-test time lag, minutes (Fig. 4)
u and v = functions defined in Appendix
δ = Dirac delta function used in Appendix
$\eta = k/\phi c\mu$ = hydraulic diffusivity, md-psi/cp
μ = viscosity, cp
ϕ = effective porosity, fraction

Acknowledgments

The authors wish to give special recognition to W. W. Harris of Esso Production Research Co. without whose assistance the pulse-test survey could not have been conducted. In addition, many other persons contributed vitally to this work. These include F. M. Bower, H. O. Jahns, C. R. Johnson and E. G. Woods at Esso Production Research Co. as well as E. E. Goings, formerly with Jersey Production Research Co. We also are indebted to Humble Oil & Refining Co. personnel for their help, especially R. L. Kelley, field superintendent.

The Geophysical Research Corp. of Tulsa, Okla., kindly provided us with a prototype of their surface-recording, down-hole pressure gauge, which was of use during the interference tests. Finally, we thank Esso Production Research Co. and Humble Oil & Refining Co. for allowing this work to be published.

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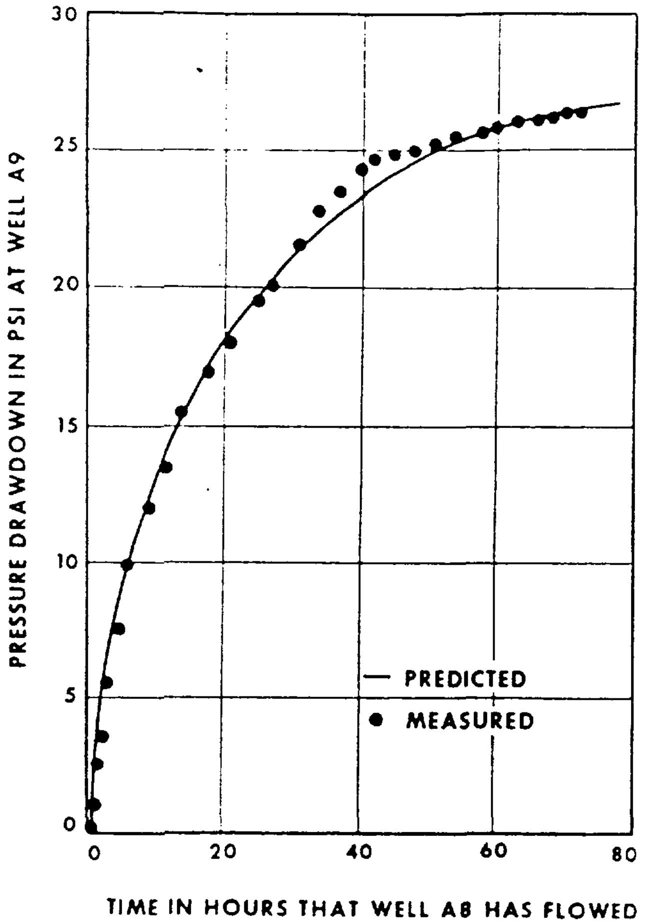

Fig. 9—*Drawdown at Well A9 due to production at Well A8.*

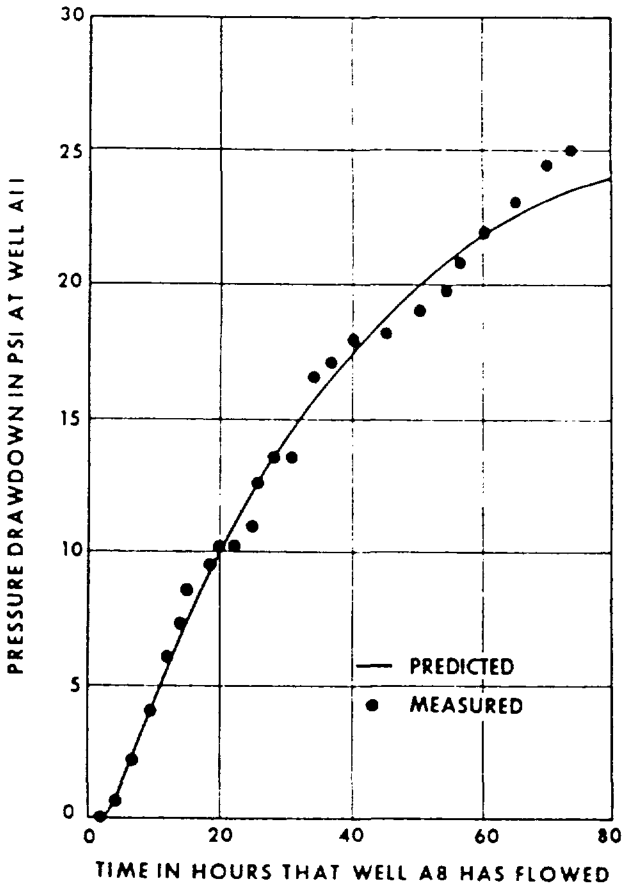

Fig. 10—*Drawdown at Well A11 due to production at Well A8.*

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APPENDIX

Reciprocity Principle for the Diffusion Equation in Heterogeneous Media

The reciprocity principle as applied to reservoir description may be stated as follows: the pressure response at Well A, $p_{BA}(t)$, caused by injecting fluid at Well B at a rate of $q(t)$ is equal to the pressure response at Well B, $p_{AB}(t)$, caused by injecting fluid at Well A at the same rate $q(t)$. The following restrictions must be met so that the reciprocity principle will apply.

1. The pressure response must satisfy the diffusion equation

$$\nabla \cdot (T \nabla p) = S \frac{\partial p}{\partial t} - q \quad . \quad . \quad . \quad (1)$$

The quantities T, S, p, q and t must be in a consistent set of units.

2. Transmissibility T and storage S of the reservoir must not be pressure sensitive. Note that this rules out the applicability of the reciprocity principle to the case where there are pronounced pressure-sensitive fractures in the reservoir, or pressure-sensitive skins around either the responding or the injection well or both.

Proof of the Reciprocity Principle

Consider a heterogeneous medium where Eq. 1 applies. (For proof of this theorem in a homogeneous medium see Ref. 4, Pages 857-869.) Assume that this medium has a region of interest with volume V, and a surface Σ enclosing this volume. The reciprocity condition to be proved is the following.

$$p(\vec{r}_2, t_2 | \vec{r}_1, t_1) = p(\vec{r}_1, -t_1 | \vec{r}_2, -t_2) \quad . \quad . \quad . \quad (2)$$

where $p(\vec{r}_2, t_2 | \vec{r}_1, t_1)$ (Green's function) represents the pressure response at $\vec{r}_2$ ($\vec{r}$ is the position vector in an n-dimensional space) at time t_2 due to a unit impulse point source at $\vec{r}_1$, at time t_1. Similarly, $p(\vec{r}_1, -t_1 | \vec{r}_2, -t_2)$ is the pressure response at $\vec{r}_1$ at time $(-t_1)$ due to a unit impulse point source at r_2 at time $(-t_2)$. A unit impulse point source means injecting a unit of fluid at a given point at a given time. Since $t_2 > t_1$, the time sequence for the right-hand side of Eq. 2 is still properly ordered.

For convenience, define two new variables u and v (Green's functions) by Eqs. 3 and 4.

$$u \equiv p(\vec{r}, t | \vec{r}_1, t_1) \quad . \quad . \quad . \quad (3)$$

$$v \equiv p(\vec{r}, -t | \vec{r}_2, -t_2) \quad . \quad . \quad . \quad (4)$$

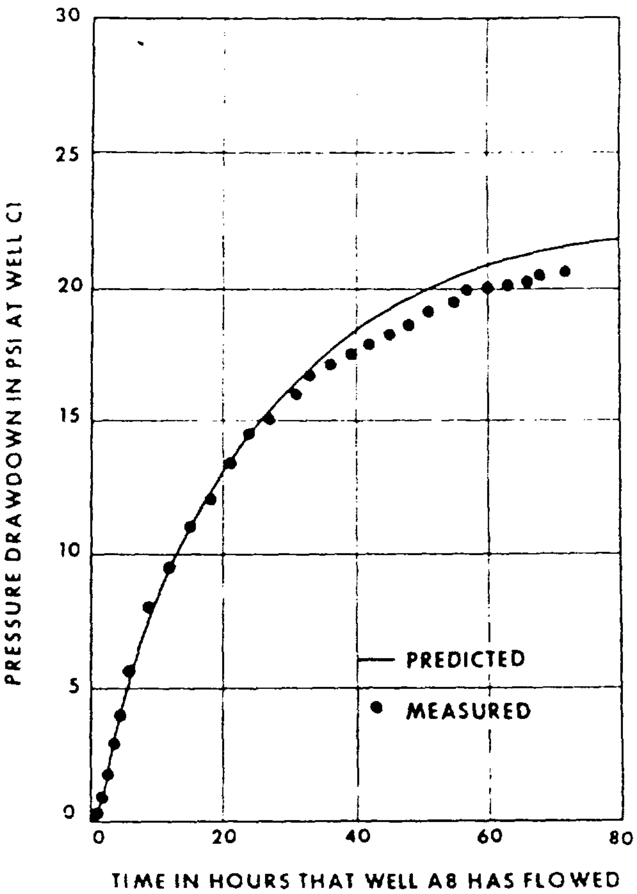

Fig. 11—*Drawdown at Well C1 due to production at Well A8.*

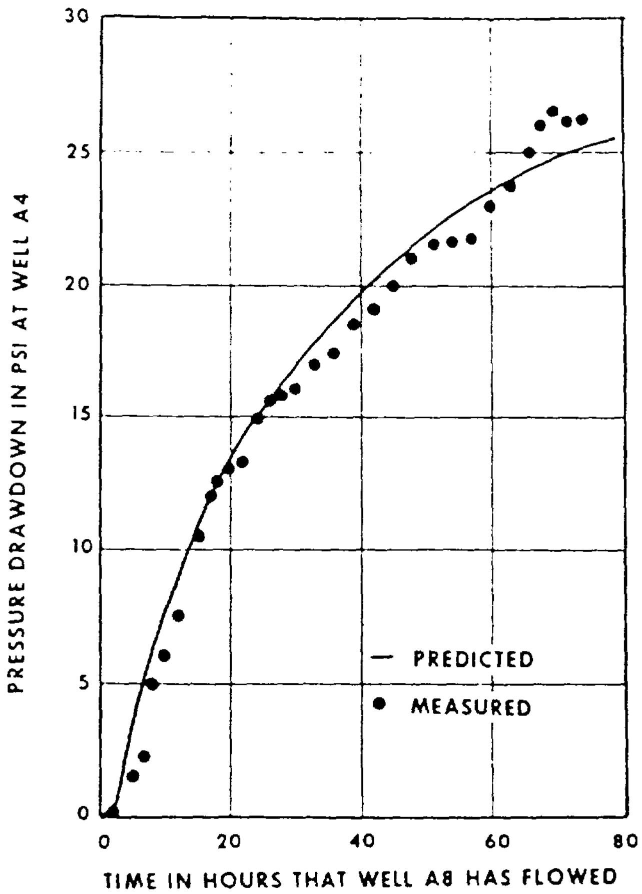

Fig. 12—*Drawdown at Well A4 due to production at Well A8.*

The boundary conditions to be satisfied by u and v are the following.

$$u = 0 \text{ for } t < t_1 \quad \ldots \quad (5)$$

$$\lim_{t \to \infty} u = 0 \quad \ldots \quad (6)$$

$$v = 0 \text{ for } t > t_2 \quad \ldots \quad (7)$$

$$\lim_{t \to \infty} v = 0 \quad \ldots \quad (8)$$

Boundary conditions (Eqs. 5 and 7) simply mean that the pressure response is zero before any fluid is injected; Eqs. 6 and 8 mean that the pressure response again will approach zero long after the fluid has been injected.

The diffusion equations to be satisfied by u and v in a heterogeneous medium are given by Eqs. 9 and 10, respectively.

$$T\nabla^2 u + \nabla T \cdot \nabla u - S \frac{\partial u}{\partial t} = -\delta(\vec{r} - \vec{r}_1)\,\delta(t - t_1) \quad \ldots \quad (9)$$

$$T\nabla^2 v + \nabla T \cdot \nabla v + S \frac{\partial v}{\partial t} = -\delta(\vec{r} - \vec{r}_2)\,\delta(t - t_2) \quad \ldots \quad (10)$$

Here T is the transmissibility of the system, S is the storage, ∇ is the gradient operator and the right-hand sides of Eqs. 9 and 10 are the unit impulse point sources; i.e., $\delta(x)$ is the Dirac delta function (Ref. 4, pages 122-123).

Multiplying Eq. 9 by v and then subtracting Eq. 10 multiplied by u obtains

$$\nabla \cdot T(u\nabla v - v\nabla u) + S\frac{\partial(uv)}{\partial t} = v\delta(\vec{r} - \vec{r}_1)\,\delta(t - t_1) - u\delta(\vec{r} - \vec{r}_2)\,\delta(t - t_2)\,, \quad \ldots \quad (11)$$

after some vector manipulation.

Next, integrate Eq. 11 over volume V and time t, with t going from $-\infty$ to $+\infty$. The first volume integral goes to a surface integral by the divergence theorem (Ref. 4, pages 37-38). The integral involving the unit impulse point source can be evaluated.* Results of these operations are given in Eq. 12.

$$\int_{-\infty}^{+\infty}\iint_{\Sigma} T(u\nabla v - v\nabla u)\cdot d\vec{A}\,dt + \iiint_{V} S\int_{-\infty}^{+\infty}\frac{\partial(uv)}{\partial t}\,dt\,dV' = p(\vec{r}_1, -t_1|\vec{r}_2, -t_2) - p(r_2, t_2|r_1, t_1) \quad \ldots \quad (12)$$

The surface integral in Eq. 12 vanishes if

$$u\nabla v - v\nabla u \equiv 0 \text{ on } \Sigma \quad \ldots \quad (13)$$

*This is true because of the filtering property of the Dirac delta function which states that $\int\int\int_{-\infty}^{+\infty} f(x, y, z)\,\delta(x - x_0)\,\delta(y - y_0)\,\delta(z - z_0)\,dx\,dy\,dz = f(x_0, y_0, z_0)$.

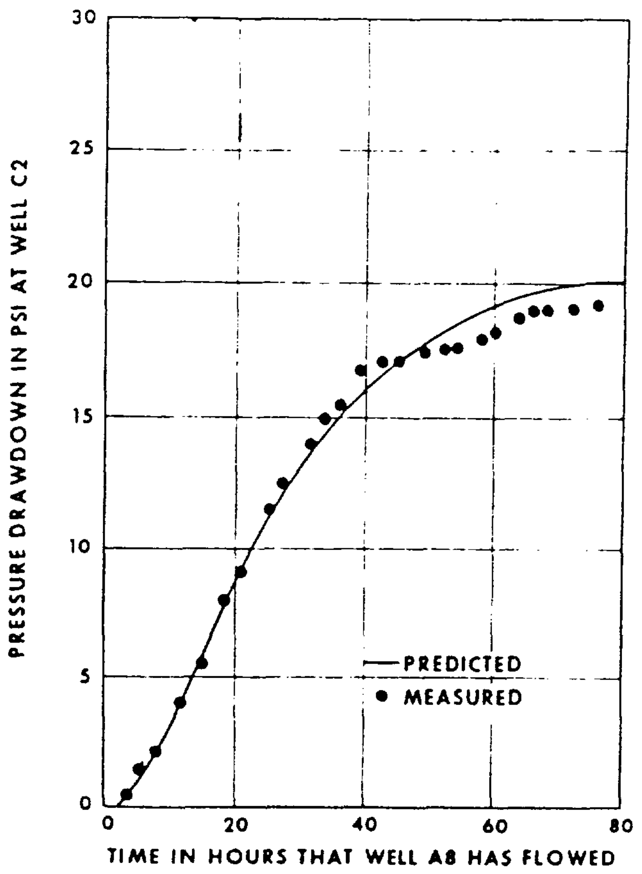

Fig. 13—*Drawdown at Well C2 due to production at Well A8.*

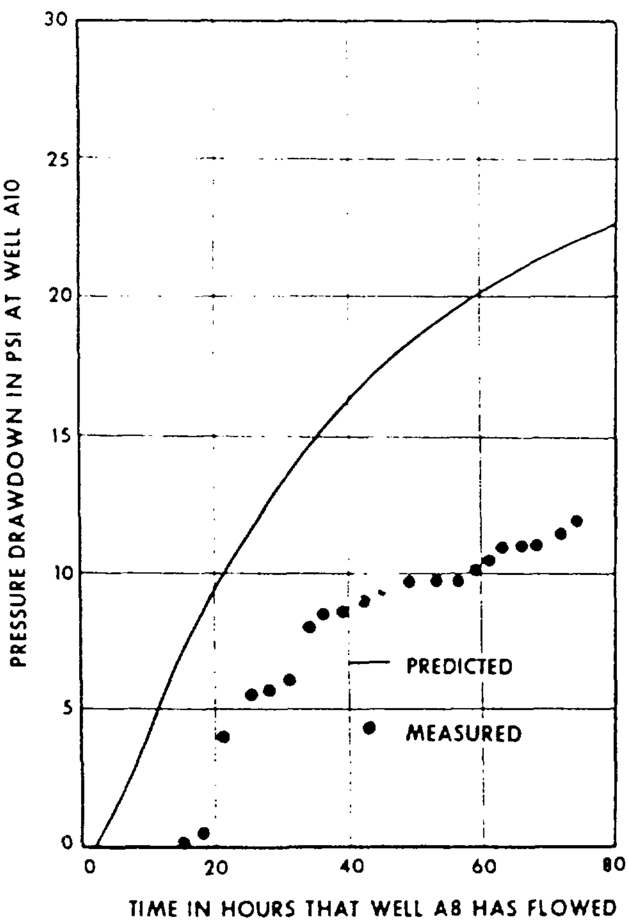

Fig. 14—*Drawdown at Well A10 due to production at Well A8.*

The condition in Eq. 13 is satisfied if *any one* of the following three boundary conditions holds.

1. Constant pressure on the boundary.

$$u \equiv v \equiv 0 \text{ on } \Sigma \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (14)$$

2. No flow on the boundary.

$$\nabla u \equiv \nabla v \equiv 0 \text{ on } \Sigma \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (15)$$

3. Constant pressure on part of the boundary and no flow on the rest of the boundary.

$$u \equiv v \equiv 0 \text{ on part of } \Sigma \quad . \; . \; . \; . \; . \; . \; . \; . \quad (16)$$

$$\nabla u \equiv \nabla v \equiv 0 \text{ on the rest of } \Sigma \quad . \; . \; . \; . \; . \; . \; . \quad (17)$$

Thus, the surface integral vanishes if Condition 1, 2 or 3 holds. It will also vanish for an infinite medium since

$$\lim_{|\vec{r}| \to \infty} u \equiv \lim_{|\vec{r}| \to \infty} v \equiv 0 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (18)$$

The inner integral of the second term in Eq. 12 vanishes because of the time boundary conditions described by Eqs. 5 and 7.

$$\left[p\,(\vec{r}, t|\vec{r}_1, t_1) \cdot p\,(\vec{r}, -t|\vec{r}_2, -t_2)\right]_{-\infty}^{+\infty} = 0 \quad . \; . \quad (19)$$

Therefore, Eq. 12 reduces to

$$p\,(\vec{r}_2, t_2|\vec{r}_1, t_1) = p\,(\vec{r}_1, -t_1|\vec{r}_2, -t_2) \quad . \; . \; . \; . \quad (20)$$

which proves the theorem for Green's function.

The proof can be generalized to a constant rate of injection and a line source by superposition since it was proved for Green's function.

Suppose this superposition is carried out and the pressure response at $\vec{r}_2$ and time t caused by injection at a unit rate at $\vec{r}_1$ from time $t=0$ is denoted by $P_{21}(\vec{r}_2, t|\vec{r}_1)$. Likewise, $P_{12}(\vec{r}_1, t|\vec{r}_2)$ denotes the pressure response at $\vec{r}_1$ and time t due to unit rate of injection at $\vec{r}_2$ from time $t = 0$. Eq. 20 then becomes

$$P_{21}(\vec{r}_2, t|\vec{r}_1) = P_{12}(\vec{r}_1, t|\vec{r}_2) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (21)$$

The pressure responses for injection rates that are arbitrary functions of time are obtained by convolution with the unit rate responses.

$$p(\vec{r}_2, t|\vec{r}_1) = \int_0^t q_1(t') \left(\frac{\partial P_{21}}{\partial t}\right)_{t-t'} dt' \quad . \; . \; . \quad (22)$$

$$p(\vec{r}_1, t|\vec{r}_2) = \int_0^t q_2(t') \left(\frac{\partial P_{12}}{\partial t}\right)_{t-t'} dt' \quad . \; . \; . \quad (23)$$

Assume that the injection rates $q_1(t)$ and $q_2(t)$ are multiples of the same function of time, i.e.,

$$q_1(t) = q_1^* f(t)$$
$$q_2(t) = q_2^* f(t) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (24)$$

where q_1^* and q_2^* are constants while $f(t)$ is an arbitrary function of time. It then follows from Eqs. 21 through 24 that

$$\frac{p(\vec{r}_2, t|\vec{r}_1)}{q_1^*} = \frac{p(\vec{r}_1, t|\vec{r}_2)}{q_2^*} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (25)$$

This is the generalized reciprocity principle. ★★★

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Attachment 4

Pulse-Testing Response for Unequal Pulse and Shut-In Periods

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ABSTRACT

A theoretical study was carried out to develop the general equations relating time lags and response amplitudes to the length of the pulse cycles and the pulse ratios of these cycles for pulse tests with unequal pulse and shut-in times. These variables were related to the reservoir parameters using appropriate dimensionless groups. The equations were developed by using the unsteady-state flow model of the line source for an infinite, homogeneous reservoir that contains a single-phase, slightly compressible fluid. A computer program was written to calculate the values of the three corresponding time lags and the response amplitudes at given dimensionless cycle periods and pulse ratios using these general equations.

For different values of the pulse ratio ranging from 0.1 to 0.9, the time lags and response amplitudes were calculated for dimensionless cycle periods ranging from 0.44 to 7.04. This range of cycle period and pulse ratio covers all practical ranges over which pulse testing can be used effectively. Curves relating the dimensionless time lag to the dimensionless cycle period and the dimensionless response amplitude were constructed for each case. It was also found that both the dimensionless cycle period and the dimensionless response amplitude can be represented as simple exponential functions of the dimensionless time lag. The coefficients of these relations are functions only of the pulse ratio.

INTRODUCTION

Two wells are used to run a pulse test. These two wells are termed the pulsing well and the responding well. A series of flow disturbances is generated at the pulsing well and the pressure response is recorded at the responding well. Usually, alternate periods of flow and shut in (or injection and shut in) are used to generate the flow disturbances at the pulsing well. The pressure response is recorded using a highly sensitive differential pressure gauge.

Pulse testing has received considerable attention because of the advantages it has over the conventional interference tests. The pressure response from a pulse test can be easily detected from unknown trends in reservoir pressure.[1] Pulse test values are more sensitive to between-well formation properties; thus, a detailed reservoir description can be obtained from pulse testing.[1]

In all the work that has been reported on pulse testing, it was assumed that the flow disturbances at the pulsing well were generated by alternate periods of flow and shut in or injection and shut in. The pulsing period and shut-in period were always equal. There has been no study of pulse testing with unequal pulse and shut-in periods. Such a study might have indicated whether other pulse ratios will produce higher response amplitudes than the equal-period tests. The main purpose of this study is to determine the response of pulse testing to unequal pulse and shut-in periods and to find the optimum pulse ratio that gives the maximum response amplitude.

PULSE-TEST TERMINOLOGY

Fig. 1 shows the pulse-test terminology as used in this paper. In general, to analyze a pulse test, a

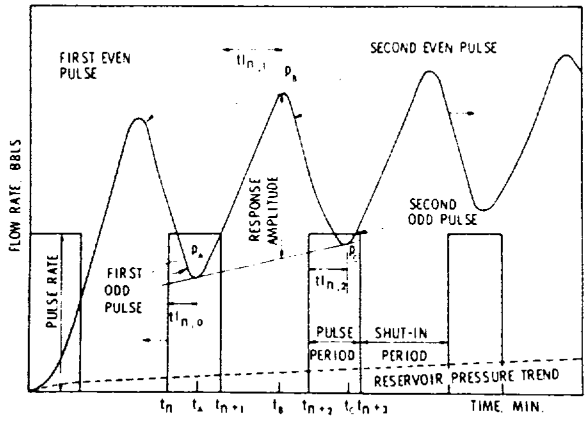

FIG. 1 — PULSE-TEST TERMINOLOGY.

Original manuscript received in Society of Petroleum Engineers office July 25, 1974. Revised manuscript received July 15, 1975. Paper (SPE 5053) was first presented at the SPE-AIME 49th Annual Fall Meeting, held in Houston, Oct. 6-9, 1974.

[1]References given at end of paper.

This paper will be included in the 1975 *Transactions* volume.

tangent is drawn between two consecutive "valleys" in the response curve and another parallel tangent is drawn at the "peak" between these valleys. Or conversely, a tangent can be drawn at the peaks and another at the valley between them. In Fig. 1, the flow disturbances at the pulsing well (the pulses) and the pressure response at the responding well are plotted vs time. The square wave at the bottom of the figure indicates the pulses, while the cyclic curve above indicates the pressure response at the responding well. To define the time lag and the response amplitude, let $p = p(t)$ represent the pressure response, if

1. The time elapsed from the beginning of the test until the end of the nth period is t_n.
2. $G_{n,1} = a_{n,1} + m_{n,1}t$ is the equation of the common tangent to p at t_A and t_C such that $t_n \le t_A \le t_{n+1}$ and $t_{n+2} \le t_C \le t_{n+3}$. (This is the equation of a straight line with a slope $m_{n,1}$ and an intercept of $a_{n,1}$ on the pressure axis.)
3. $G_{n,2} = a_{n,2} + m_{n,2}t$ is the equation of the tangent to p at t_B such that $t_{n+1} \le t_B \le t_{n+2}$ and $m_{n,1} = m_{n,2}$. (This is the equation of the straight line that has a slope of $m_{n,2}$ and an intercept of $a_{n,2}$ on the pressure axis. Since $m_{n,1} = m_{n,2}$ the straight lines defined in Definitions 2 and 3 are parallel.)

Then the response amplitude in the $n+1$st period is

$$\Delta p_{n+1} = a_{n,2} - a_{n,1} \; , \quad \ldots \ldots \ldots (1)$$

(Δp_{n+1} is the difference in the pressure between the two straight lines at any time, t.) There are three time lags that correspond to the equations above, defined as follows.

$$t\ell_{n,0} = t_A - t_n \quad \ldots \ldots \ldots (2)$$

$$t\ell_{n,1} = t_B - t_{n+1} \quad \ldots \ldots \ldots (3)$$

$$t\ell_{n,2} = t_C - t_{n+2} \quad \ldots \ldots \ldots (4)$$

Any one of these time lags *could* be used to define the test response; however, for convenience, the middle one (at t_B) is used because the response amplitude is measured at t_B.

The use of double subscripts for the time lags and of a single subscript for the response amplitude should not be confusing because there are three possible time lags in each period, whereas only one response amplitude is defined. This can be illustrated by Fig. 2. The three time lags in the nth period are $t\ell_{n-3,2}$, $t\ell_{n-2,1}$, and $t\ell_{n-1,0}$. In the nth period, $t\ell_{n-3,2}$ is the point of tangency of the straight line that is also a tangent to the pressure response curve at p_B. It is the third time lag when the three time lags lie in the $n-2$nd, $n-1$st, and nth periods. The point of tangency of the straight line that is parallel to the tangent at p_C and p_D is $t\ell_{n-2,1}$. It is the second time lag when the three time lags lie in the $n-1$st, nth, and $n+1$st periods. Finally, $t\ell_{n-1,0}$ is the point of tangency, in the nth period, of the straight line that is also a tangent to the pressure response curve at p_E. It is the first time lag when the three time lags lie in the nth, $n+1$st, and $n+2$nd periods. The only defined response amplitude is Δp_n, which is the response amplitude when the $n-1$st, nth, and $n+1$st periods are used. The double subscript of the time lag is used in this study instead of the single subscript that has been used in previous studies,[1,5-8] but it was necessary to clarify the fact that the three time lags in Eqs. 2 through 4 are not equal.

We should also mention that the pressure, P_E, in Fig. 2 is noticeably lower than one should expect in a pulse test. It was drawn this way so that the three time lags discussed above could be distinguished more easily in the figure.

COMPUTER PROGRAM

A computer program was written to find the three corresponding time lags and the response amplitude for any pulse in a given series of pulses. The program essentially uses the Newton-Raphson iterative technique[9] to solve the following three equations in the three unknowns — $t\ell_{n,0}$, $t\ell_{n,1}$, and $t\ell_{n,2}$. The derivation of these equations is shown in the Appendix.

$$f(t\ell_{n,0}) = q_1 \left\{ \frac{\exp\left[\frac{-t}{t_D t_A}\right]}{t_A} \right\} + \sum_{i=1}^{n} (q_{i+1} - q_i) \left\{ \frac{\exp\left[\frac{-t}{t_D (t_A - t_i)}\right]}{t_A - t_i} \right\}$$

$$- \frac{\mu}{kh(t_C - t_A)} \left\{ q_1 \left[Ei\left(\frac{-t}{t_D t_C}\right) - Ei\left(\frac{-t}{t_D t_A}\right) \right] \right.$$

$$+ \sum_{i=1}^{n+2} \{q_{i+1} - q_i\} \, Ei \left[\frac{-t}{t_D (t_C - t_i)}\right]$$

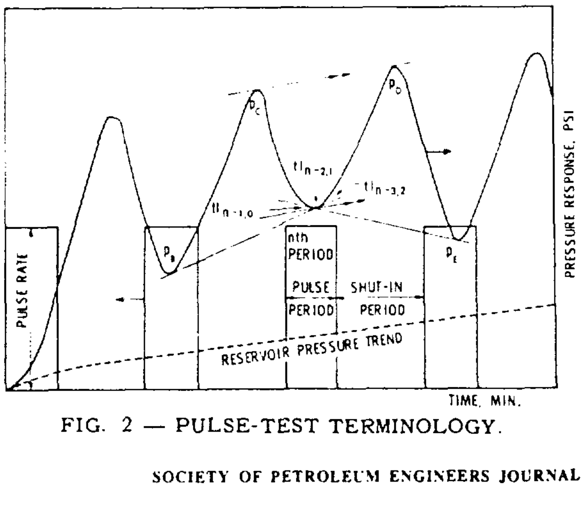

FIG. 2 — PULSE-TEST TERMINOLOGY.

$$- \sum_{i=1}^{n} \{q_{i+1} - q_i\} \, Ei \left[\frac{-t}{t_D(t_A - t_i)}\right] \Bigg\} \qquad \ldots\ldots (5)$$

$$f(t\ell_{n,1}) = q_1 \left\{ \frac{\exp\left[\frac{-t}{t_D \, t_A}\right]}{t_A} - \frac{\exp\left[\frac{-t}{t_D \, t_B}\right]}{t_B} \right\}$$

$$+ \sum_{i=1}^{n} \{q_{i+1} - q_i\} \left\{ \frac{\exp\left[\frac{-t}{t_D(t_A - t_i)}\right]}{t_A - t_i} \right\}$$

$$- \sum_{i=1}^{n+1} \{q_{i+1} - q_i\} \left\{ \frac{\exp\left[\frac{-t}{t_D(t_A - t_i)}\right]}{t_B - t_i} \right\} . \qquad \ldots\ldots (6)$$

$$f(t\ell_{n,2}) = q_1 \left\{ \frac{\exp\left[\frac{-t}{t_D \, t_A}\right]}{t_A} - \frac{\exp\left[\frac{-t}{t_D \, t_C}\right]}{t_C} \right\}$$

$$+ \sum_{i=1}^{n} \{q_{i+1} - q_i\} \left\{ \frac{\exp\left[\frac{-t}{t_D(t_A - t_i)}\right]}{t_A - t_i} \right\}$$

$$- \sum_{i=1}^{n+2} \{q_{i+1} - q_i\} \left\{ \frac{\exp\left[\frac{-t}{t_D(t_C - t_i)}\right]}{t_C - t_i} \right\} . \qquad \ldots\ldots (7)$$

At the correct solution, each of $f(t\ell_{n,0})$, $f(t\ell_{n,1})$, and $f(t\ell_{n,2})$ is equal to zero.

To solve for the three time lags, a value is assumed for $t\ell_{n,0}$ and, thus, for t_A, and the Newton-Raphson iteration method is used to find the corresponding value of $t\ell_{n,2}$ from Eq. 7. After the value of $t\ell_{n,2}$ that corresponds to the assumed value of $t\ell_{n,0}$ is found, the right side of Eq. 5 is evaluated. If it equals zero, the assumed value of $t\ell_{n,0}$ is the correct value. Otherwise, the Newton-Raphson iteration method is used on Eq. 5 to find a better value for $t\ell_{n,0}$. After each iteration on $t\ell_{n,0}$, the new value of $t\ell_{n,0}$ is used again in Eq. 7 to find the corresponding value of $t\ell_{n,2}$. This process of finding a new value of $t\ell_{n,0}$ and the corresponding value of $t\ell_{n,2}$ continues until the right side of Eq. 5 becomes zero.

After the correct values of $t\ell_{n,0}$ and $t\ell_{n,2}$ are found, Eq. 6 is solved using the Newton-Raphson iteration method to find the corresponding value of $t\ell_{n,1}$. The response amplitude is then calculated using Eq. A-7.

RESULTS AND DISCUSSION

The time lags and response amplitude were computed for a wide range of the values of the reservoir and pulse parameters. These ranges are beyond the normal values of the different parameters that should be encountered in practice.

Let R' denote the pulse ratio, Δt_{CYCD} denote the dimensionless cycle period, $t\ell_D$ denote the dimensionless time lag, and ΔP_D denote the dimensionless response amplitude as defined by the following equations.

$$R' = \frac{\text{The Pulse Period}}{\text{The Pulse Period + The Shut-In Period}} \; . \qquad \ldots\ldots (8)$$

$$R' = \frac{\Delta t}{\Delta t + R\Delta t} = \frac{1}{1 + R} \qquad \ldots\ldots (9)$$

$$\Delta t_{CYCD} = \frac{k\Delta t(1 + R)}{56900 \; \phi \; c_t \; \mu \; r_{bw}^2} \qquad \ldots\ldots (10)$$

$$t\ell_D = \frac{t\ell}{\Delta t_{CYC}} = \frac{t\ell}{\Delta t(1 + R)} \qquad \ldots\ldots (11)$$

$$\Delta p_D = \frac{kh \; \Delta p}{70.6 \; B\mu q} \qquad \ldots\ldots (12)$$

The definitions of Δt_{CYCD} and $t\ell_D$ are different from the conventional definitions of the dimensionless cycle period and the dimensionless time lag that have been presented previously in the literature. In all the previous work, the pulse period and the shut-in period were assumed to be equal, the pulse period (Δt) was used in the definitions of the dimensionless cycle period, and the dimensionless time lag was used instead of the total cycle period $[\Delta t(1 + R)]$, as in Eqs. 10 and 11. These previous definitions are not convenient in this study since the pulse period and the shut-in period are not equal. The most sensible time period to use appeared to be the full cycle period.

The values of the time lags and response amplitude of the first 10 pulses were calculated for pulse ratios ranging from 0.1 to 0.9 and for dimensionless cycle periods ranging from 0.44 to 7.04.

As mentioned before, there are three time lags associated with every pulse; for correlation purposes, one of them had to be chosen as the characteristic time lag. The value of $t\ell_{n,1}$ seemed most logical because the response amplitude is measured at time t_B, which is also the time at which $t\ell_{n,1}$ is measured.

It was found that the results can be divided into two different groups, those of the odd pulses (n odd) and those of the even pulses (n even). This classification of the pulses as odd and even pulses differs from that given by Brigham,[6] who considered the first pulse as the first odd pulse and the second pulse as the first even pulse. In this study, the first pulse is the first even pulse (since $n = 0$) and the second pulse is the first odd pulse (since $n = 1$). This means that the odd pulses in Brigham's study are termed even pulses here, and vice versa.

EVEN PULSES

RELATION BETWEEN TIME LAG AND CYCLE PERIOD

At fixed pulse ratio and dimensionless cycle period, the dimensionless time lag for all the even pulses, except the first one, are close enough to be considered one value. The differences among the time lags for all the even pulses, excluding the first one, is in the order of 1.5 percent. The dimensionless time lags for the first even pulse are shown in Fig. 3, and Fig. 4 shows the results for the remaining even pulses. The values of the dimensionless time lags in Fig. 4 are the arithmetic means of the dimensionless time lags of all the even pulses, excluding the first one. The product of the dimensionless cycle period and the dimensionless time lag is used as the dependent variable in these figures to reduce the range of variation so that more accurate plotting will be possible.

The dimensionless time lag decreases as the dimensionless cycle period increases at a given pulse ratio. This means that the time lag increases with an increase in the porosity, the distance between the test wells, the fluid compressibility, and viscosity, but it decreases as the permeability increases. These results are in agreement with those of Johnson *et al.*[1]

At any fixed value of the dimensionless cycle period, the dimensionless time lag and the time lag decrease as the pulse ratio increases. Since the time lag associated with any pulse is $t\ell_{n,1}$ and the first period is a pulsing period, the time lags for the even pulses are essentially the effects of the pulse periods. As the pulse ratio increases, the length of the pulse period increases, thus causing the decrease in the time lag with the pulse ratio.

RELATION BETWEEN TIME LAG AND RESPONSE AMPLITUDE

Figs. 5 and 6 show the relation between the dimensionless time lag and the dimensionless response amplitude for pulse ratios ranging from

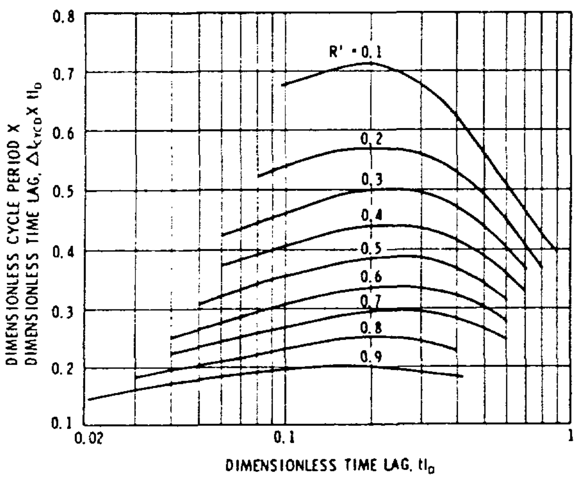

FIG. 3 — DIMENSIONLESS CYCLE PERIOD CORRELATION FOR THE FIRST EVEN PULSE.

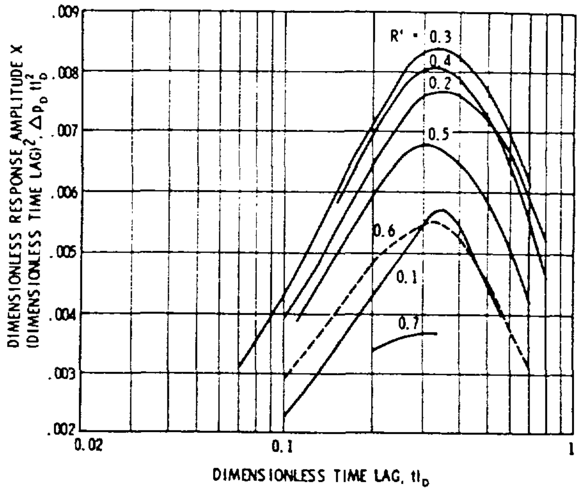

FIG. 5 — DIMENSIONLESS RESPONSE AMPLITUDE CORRELATION FOR THE FIRST EVEN PULSE.

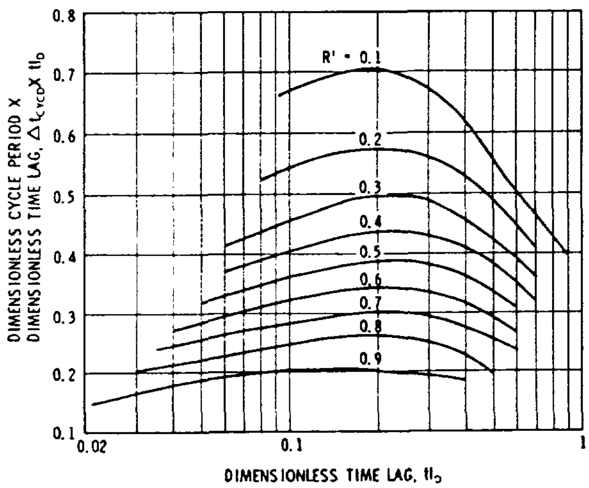

FIG. 4 — DIMENSIONLESS CYCLE PERIOD CORRELATION FOR LATER EVEN PULSES.

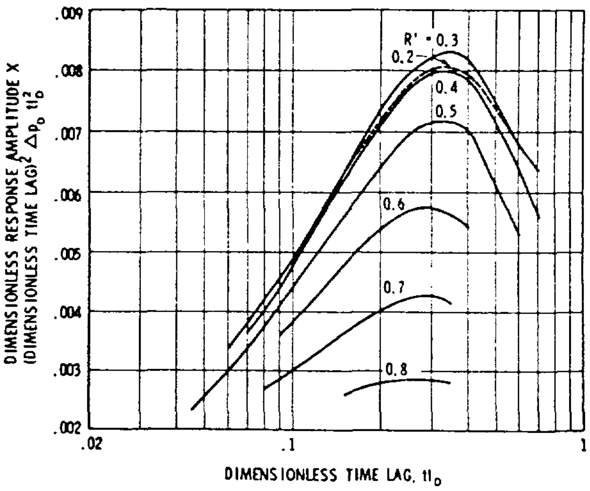

FIG. 6 — DIMENSIONLESS RESPONSE AMPLITUDE CORRELATION FOR LATER EVEN PULSES.

0.1 to 0.9. For R' values of 0.1 and for short cycle times (Δt_{CYCD} = 0.44), response amplitudes are too small to be easily interpreted on a pressure plot. Thus, small values of Δt_{CYCD} and R' should not be used; normally, if $R' > 0.2$ and $\Delta t_{CYCD} > 0.8$ this problem can be avoided. Generally, the differences among the response amplitudes of all the even pulses, except the first one, is in the order of 1.5 percent. To reduce the range of the dependent variable so that more accurate plotting can be achieved, the product of the dimensionless response amplitude and the square of the dimensionless time lag was used as the dependent variable in Figs. 5 and 6.

For any pulse ratio, the dimensionless response amplitude (the pressure response) increases as the dimensionless cycle period increases, or as the dimensionless time lag decreases. Using the definition of the dimensionless response amplitude, it can be seen that the response amplitude increases with the permeability, but decreases as the porosity, the distance between wells, the fluid viscosity, or the compressibility increases. Johnson *et al.*[1] reported the same behavior.

At the same dimensionless time lag, the dimensionless response amplitude increases as the pulse ratio increases from 0.1 to a value close to 0.3. As the pulse ratio increases from this value to 0.9, the dimensionless response amplitude decreases. Thus, when analyzing the even pulses, the maximum response will be obtained if the pulse ratio is chosen near 0.3.

THE ODD PULSES

RELATION BETWEEN TIME LAG AND CYCLE PERIOD

Except for the first odd pulse, the time lags are almost the same for all the odd pulses. As a result, the time lags could be correlated using only two figures. Fig. 7 shows the dimensionless cycle period as a function of the dimensionless time lag for the first odd pulse, and Fig. 8 is for the remaining odd pulses. As in the case of the even pulses, the dependent variable was modified to the product of the dimensionless time lag and the dimensionless cycle period to improve plotting accuracy. The differences among all the odd pulses, excluding the first one, are in the order of 1 percent. The values of the dimensionless time lag plotted in Fig. 8 are the arithmetic mean of all the odd pulses (through 10) except the first one.

For a given pulse ratio, the dimensionless time lag decreases as the dimensionless cycle period increases. This is the same as the result obtained with the even pulses; this means that the time lag is affected in the same manner by the rock and fluid properties.

For a given dimensionless cycle period, the dimensionless time lag and the time lag both increase with the pulse ratio. As in the case of the even pulses, this can be explained by realizing that the time lags for the odd pulses are essentially the effects of the shut-in periods. The length of the shut-in periods decreases with the pulsing ratio, causing the increase in the time lags.

RELATION BETWEEN TIME LAG AND RESPONSE AMPLITUDE

For the first odd pulse, the relation between the dimensionless time lag and the dimensionless response amplitude is presented in Fig. 9. The results for all the other odd pulses are presented in Fig. 10. The values of the dimensionless response amplitudes of the first pulse are different from those of all the other pulses and, thus, are plotted separately in Fig. 9. Generally, the differences among the response amplitudes of all the odd pulses except the first one do not exceed 2 percent. The dependent variable in Figs. 9 and 10 is the dimensionless response amplitude multiplied by the square of the dimensionless time lag. Again, this allowed more accurate plotting. The values of the dimensionless response amplitudes and the dimensionless time lags used in Fig. 10 are the arithmetic mean of the corresponding values of all but the first odd pulse.

As in the case of the even pulses, for any fixed pulse ratio the magnitude of the dimensionless

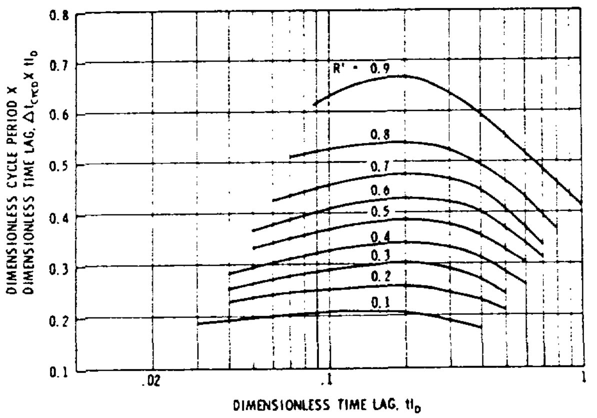

FIG. 7 — DIMENSIONLESS CYCLE PERIOD CORRELATION FOR THE FIRST ODD PULSE.

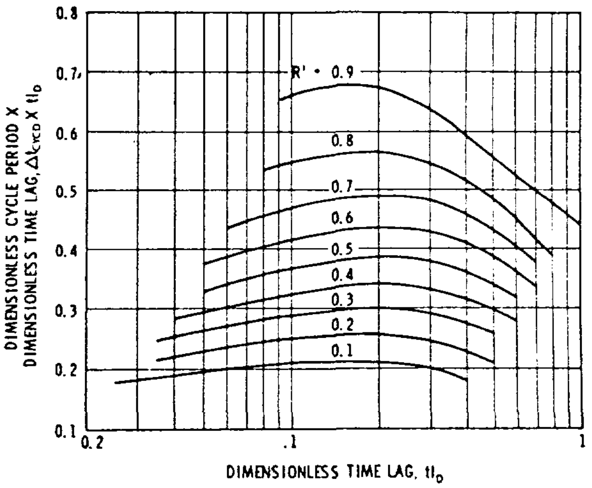

FIG. 8 — DIMENSIONLESS CYCLE PERIOD CORRELATION FOR LATER ODD PULSES.

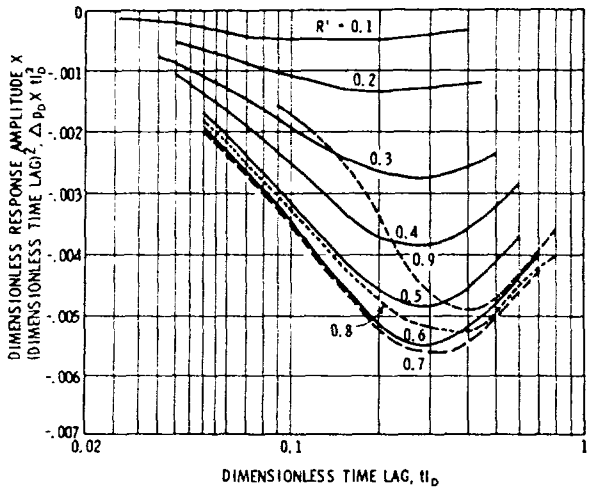

FIG. 9 — DIMENSIONLESS RESPONSE AMPLITUDE CORRELATION FOR THE FIRST ODD PULSE.

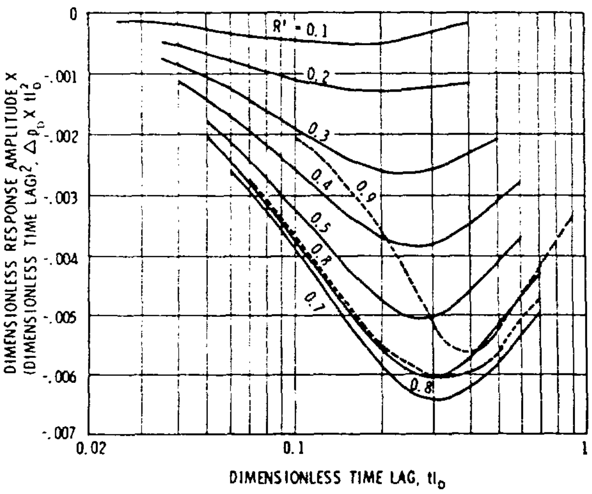

FIG. 10 — DIMENSIONLESS RESPONSE AMPLITUDE CORRELATION FOR LATER ODD PULSES.

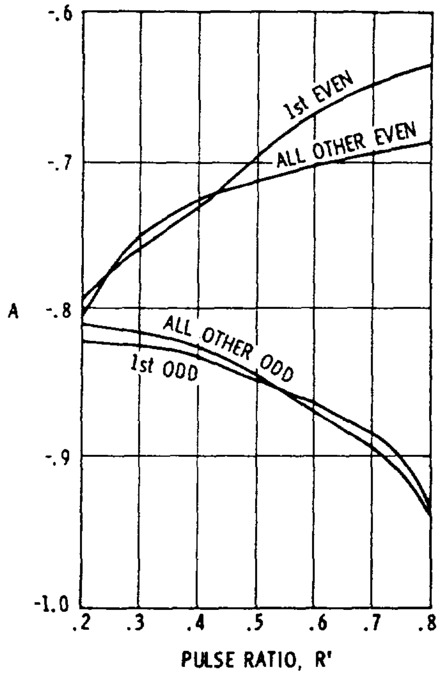

FIG. 11 — PARAMETER *A* AS A FUNCTION OF THE PULSE RATIO.

response amplitude increases as the dimensionless time lag decreases and, thus, the rock and fluid properties have the same effects.

At the same dimensionless time lag the magnitude of the dimensionless response amplitude increases as the pulse ratio increases from 0.1 to a value close to 0.7. As the pulse ratio increases from 0.7 to 0.9, the magnitude of the dimensionless response amplitude decreases. Since the dimensionless response amplitude is directly proportional to the pressure response, if the odd pulses are to be used for analysis, the pulse ratio may be chosen near 0.7 to obtain the maximum response.

RELATING TIME LAGS, CYCLE PERIODS, AND RESPONSE AMPLITUDES ANALYTICALLY

Figs. 3 through 10 graphically represent the relations among the dimensionless time lag, the dimensionless cycle period, and the dimensionless response amplitude. It would be desirable if relatively simple equations relating these three variables could be developed.

Several trials were made to find empirical equation forms and coefficients that give the best fit for the available values of the three variables. The results of these trials are presented as equations in the following two sections. Since it was noticed that the response amplitudes for pulse ratios as small as 0.1 or as large as 0.9 are too small to be easily interpreted on a pressure plot, the equations in the following two sections are developed only for pulse ratios ranging from 0.2 to 0.8.

RELATION BETWEEN DIMENSIONLESS TIME LAG AND DIMENSIONLESS CYCLE PERIOD

The equation found to relate the dimensionless cycle period to the dimensionless time lag is as follows.

$$\Delta t_{CYCD} = C\, t\ell_D^{A} + D \; , \quad . \; . \; . \; . \; . \; . \; . \; . \; (13)$$

where $D = -0.325$ for odd pulses and $D = -0.675$ for even pulses. *A* and *C* were found to be functions of the pulse ratio only. These functions are presented in Figs. 11 and 12, respectively.

RELATION BETWEEN DIMENSIONLESS TIME LAG AND DIMENSIONLESS RESPONSE AMPLITUDE

The equation that relates the dimensionless time lag, the dimensionless cycle period, and the dimensionless response amplitude is

$$\Delta p_D / \Delta t_{CYCD} = H\,[F \exp(E\, t\ell_D) + 0.01] \; , \quad . \; (14)$$

where $H = -1$ (odd pulses) and $H = 1$ (even pulses). *E* and *F* were found to be functions only of the pulse ratio. *E* is presented in Fig. 13 and *F* is presented in Fig. 14.

APPLICATION

The graphs and equations presented in this study can be used to design and analyze pulse tests with equal or unequal pulse and shut-in periods. The steps to be followed, together with numerical and field examples, are presented in Ref. 10.

EFFECT OF ASSUMING THE EQUALITY OF TIME LAGS WHEN PULSE AND SHUT-IN PERIODS ARE EQUAL

In an earlier study, Brigham[6] used the assumption that the three corresponding time lags are equal when the pulse period is equal to the shut-in period; that is, when the pulse ratio (R') is 0.5. His results are in good agreement with the results of this study, in which no such assumption was made. In this section, we discuss such an assumption and show the reason for the close agreement between the results of this study and those of Brigham's.

Because the definitions of the variables used in this study are different from those used by Brigham,[6] it was necessary to adjust the values of the different variables from the two studies before comparing them. The values of $t\ell'_D$ and $\Delta p_D t\ell_D^2$ in Brigham's study had to be divided by 2 and 4, respectively.

Fig. 15 shows an example of the correlation of the dimensionless cycle period in both studies. As can be easily seen from this figure, the results are very close. The following analysis shows the reason for this close agreement.

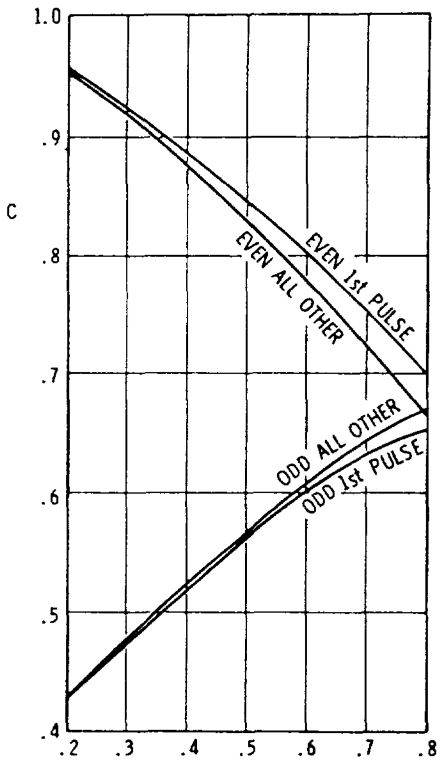

FIG. 12 — PARAMETER C AS A FUNCTION OF THE PULSE RATIO.

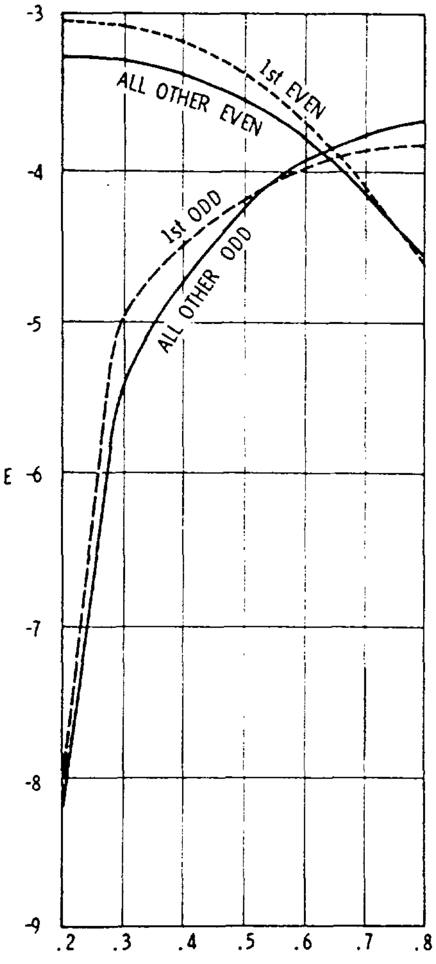

FIG. 13 — PARAMETER E AS A FUNCTION OF THE PULSE RATIO.

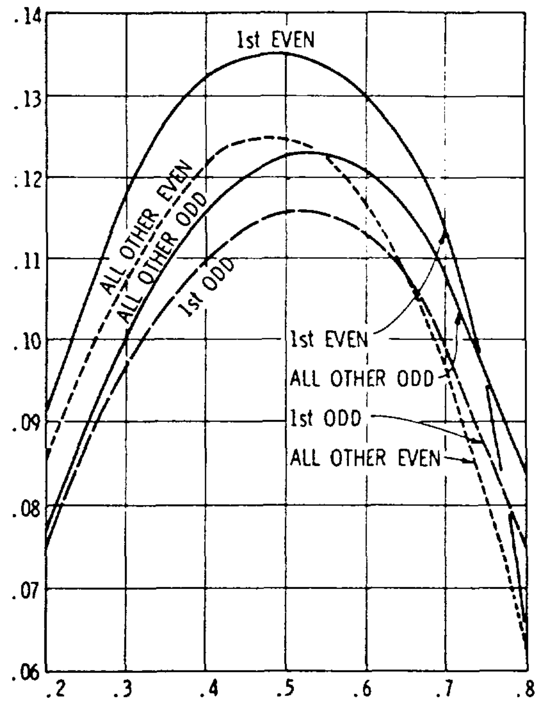

FIG. 14 — PARAMETER F AS A FUNCTION OF THE PULSE RATIO.

Let the values used by Brigham for $t\ell_{n,0}$, $t\ell_{n,1}$, and $t\ell_{n,2}$ be $t\ell_{n,0}'$, $t\ell_{n,1}'$, and $t\ell_{n,2}'$, respectively. Brigham assumed that both $t\ell_{n,0}'$ and $t\ell_{n,2}'$ equal $t\ell_{n,1}'$. Thus,

$$t\ell_{n,0} = t\ell_{n,0}' + \delta t\ell_{n,0} \quad \ldots \ldots (15)$$

$$t\ell_{n,1} = t\ell_{n,1}' \quad \ldots \ldots (16)$$

$$t\ell_{n,2} = t\ell_{n,2}' + \delta t\ell_{n,2} \quad \ldots \ldots (17)$$

Also, let the values used by Brigham for p_A, p_B, and p_C be p_A', p_B', and p_C', respectively. Thus,

$$p_A = p_A' + \delta p_A \quad \ldots \ldots (18)$$

$$p_B = p_B' \quad \ldots \ldots (19)$$

$$p_C = p_C' + \delta p_C \quad \ldots \ldots (20)$$

The equation for the slope of the correct tangent at (t_A, p_A) and (t_C, p_C) is

$$\left(\frac{dp}{dt}\right)_{actual} = \frac{p_C - p_A}{\Delta t(1+R) + t\ell_{n,2} - t\ell_{n,0}} \quad \ldots \ldots (21)$$

The equation for the slope of the same tangent used by Brigham is

$$\left(\frac{dp}{dt}\right)_{assumed} = \frac{(p_C - p_A) - (\delta p_C - \delta p_A)}{\Delta t(1+R) + t\ell_{n,2} - t\ell_{n,0} - (\delta t\ell_{n,2} - \delta t\ell_{n,0})} \quad \ldots \ldots (22)$$

Assuming a first-order approximation for δp_C, it follows that

$$\left(\frac{dp}{dt}\right)_{assumed} = \left(\frac{dp}{dt}\right)_{actual} \left[1 - \frac{[\delta t\ell_{n,2} - \delta t\ell_{n,0}]^2}{[\Delta t(1+R) + t\ell_{n,2} - t\ell_{n,0}]^2}\right] \quad \ldots \ldots (23)$$

Eq. 23 shows that the calculated slope using Brigham's assumptions is very close to the actual slope. First, $\delta t\ell$'s are small compared with $t\ell$'s. Second, the $\delta t\ell$'s are subtractive rather than additive in the second term (the error term) of the right side. Finally, the error is of the second order. This means that the slope of the tangent at (t_A, p_A) and (t_C, p_C) calculated using the equal-time-lags assumption is quite close to the actual slope. Therefore, the calculated time lag, $t\ell_{n,1}$, is quite close to correct and the calculated pressure, p_B, is quite close to correct, which explains the good agreement between the two studies shown in Fig. 15.

As for the response amplitude, Fig. 16 shows an example of the results given by both studies. The figure shows that the results of both studies are close; this can be explained using the following analysis.

The response amplitude in the $n+1$ period can be written as

$$\Delta p_{n+1} = p_B - p_A - (\Delta t - t\ell_{n,0} + t\ell_{n,1})\left(\frac{dp}{dt}\right)_{actual} \quad \ldots (24)$$

or

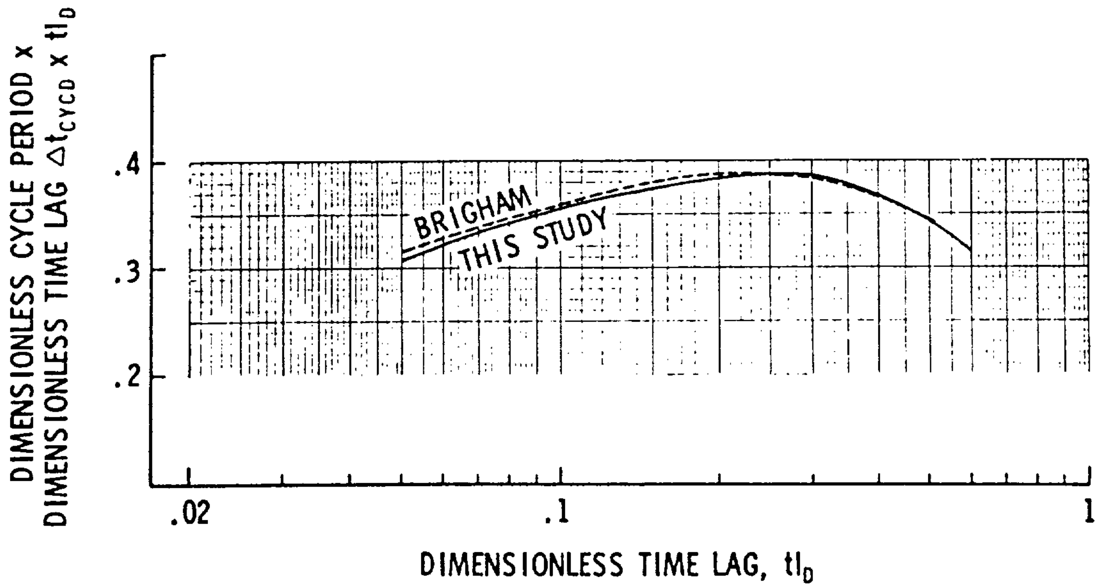

FIG. 15 — CYCLE PERIOD COMPARISON.

$$\Delta p_{n+1} = p_B - p_C + (\Delta t - t\ell_{n,1} + t\ell_{n,2}) \left(\frac{dp}{dt}\right)_{actual} \quad \ldots\ldots (25)$$

Adding Eqs. 24 and 25 and dividing the results by 2 yields

$$(\Delta p_{n+1})_{actual} = p_B - \frac{p_A + p_C}{2} + \left(\frac{\delta t\ell_{n,0} + \delta t\ell_{n,2}}{2}\right) \left(\frac{dp}{dt}\right)_{actual} \quad \ldots\ldots (26)$$

Brigham calculated the pressure response as

$$(\Delta p_{n+1})_{assumed} = p_B - \left(\frac{p'_A + p'_C}{2}\right). \quad \ldots\ldots (27)$$

Using a first-order approximation of δp_A and δp_C, we can write

$$(\Delta p_{n+1})_{actual} - (\Delta p_{n+1})_{assumed} = \left(\frac{\delta t\ell_{n,0} + \delta t\ell_{n,2}}{2}\right) \left[\left(\frac{dp}{dt}\right)_{actual} - \left(\frac{dp}{dt}\right)_{assumed} \right] \quad \ldots\ldots (28)$$

Eq. 28 shows that the error in calculating the response amplitude is first order on $[(dp/dt)_{actual} - (dp/dt)_{assumed}]$, which was shown by Eq. 23 to be of the second order. Thus, the error in calculating the response amplitude is also of the second order, which explains the close agreement between the two studies shown in Fig. 16.

CONCLUSIONS

The mathematical equations that relate the time lag, the cycle period, and the response amplitude for any pulse ratio were developed in this study. No assumptions were made other than those required for the validity of the line-source flow model. These equations were used to generate the time lags and response amplitudes for several cases with the dimensionless cycle period ranging from 0.44 to 7.04 and the pulse ratio ranging from 0.1 to 0.9.

From the results of this study the following conclusions have been made.

1. For a given dimensionless cycle period, the values of the time lags and the response amplitudes for all the even pulses, except the first one, are close enough to be considered one value. The same conclusion holds for the odd pulses.

2. At any dimensionless cycle period, a reasonable response amplitude can be obtained using a pulse ratio ranging from 0.3 to 0.7. If the pulse ratio is in the high range (near 0.7) it is better to use the odd pulses, and if the pulse ratio is in the low range (near 0.3), it is better to use the even pulses.

3. The relations among the dimensionless time lag, the dimensionless cycle period, and the

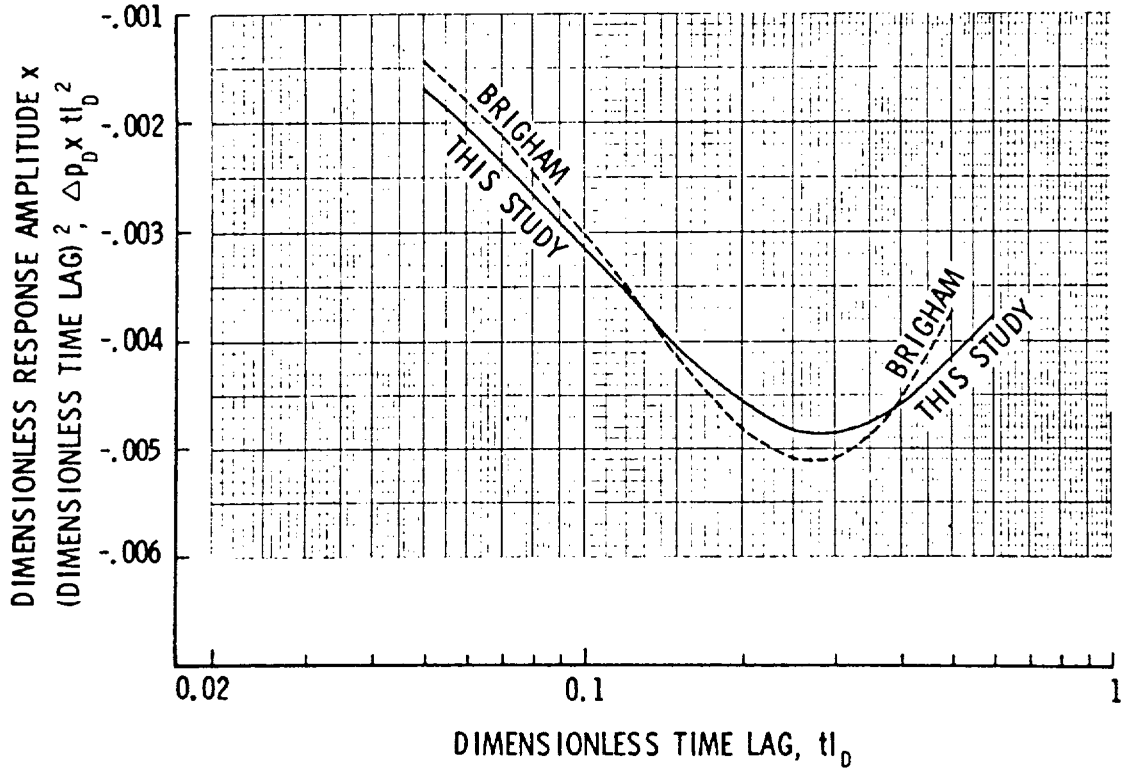

FIG. 16 — RESPONSE AMPLITUDE COMPARISON.

dimensionless response amplitude can be represented by two exponential equations (Eqs. 13 and 14). The coefficients of these relations are functions of the pulse ratio and the type of the pulse (odd or even).

4. For a pulse test with equal pulse and shut-in periods, assuming the equality of the three corresponding time lags is a reasonable approximation.

NOMENCLATURE

a = intercept on the pressure axis, psi
A = constant in the dimensionless cycle period equation
B = formation volume factor, res bbl/STB
C = constant in the dimensionless cycle period equation
c_t = isothermal coefficient of compressibility, psi^{-1}
D = constant in the dimensionless cycle period equation
E = constant in the dimensionless response amplitude equation
F = constant in the dimensionless response amplitude equation
G = pressure, psi
h = formation thickness, ft
H = constant in the dimensionless response amplitude equation
k = permeability, md
m = slope of the tangent at the time lag, psi/min
p = pressure, psi
p' = pressure, psi
q = flow rate, STB/D
q_i = flow rate in the ith period, STB/D
R = ratio between the pulse period and the shut-in period
R' = pulse ratio = $\Delta t/\Delta t_{CYC} = 1/1 + R'$
r = radial distance, ft
r_{bw} = distance between the pulsing and the responding wells, ft
r_{Dw} = dimensionless radial distance, r/r_w
r_w = well radius, ft
t = time, minutes
t_D = dimensionless time = $\dfrac{kt}{56{,}900\,\phi c_t\,\mu\,r_{bw}^2}$
t_n = time elapsed from the beginning of the test until the end of the nth period, minutes
$t\ell$ = time lag, minutes
$t\ell_D$ = dimensionless time lag = $t\ell/\Delta t_{CYC}$
$t\ell_{n,i}$ = the time lag after n periods, i = 1, 2 or 3, minutes
$t\ell'_{n,i}$ = approximate time lag after n periods, i = 1, 2, or 3, minutes
Δp = response amplitude, psi
Δp_D = dimensionless response amplitude = $kh\Delta p/70.6\,\mu\,Bq$
Δp_n = response amplitude in the nth period, psi
Δt = pulse period, minutes
Δt_{CYC} = cycle period = $\Delta t(1 + R)$, minutes
Δt_{CYCD} = dimensionless cycle period = $k\Delta t_{CYC}/56{,}900\,\phi c_t\,\mu\,r_{bw}^2$
μ = viscosity, cp
ϕ = porosity, fraction

ACKNOWLEDGMENTS

This work was done as a part of Kamal's PhD thesis at Stanford U. The financial support for this research was contributed by Stanford U., Amoco International Oil Co., and Amoco Production Co.

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APPENDIX

DERIVATION OF MATHEMATICAL MODEL

The reservoir considered in this study is assumed to be an infinite, homogeneous, and isotropic porous medium of uniform thickness filled with a single-phase fluid that has a small and constant compressibility and a constant viscosity. The porosity and permeability of the porous medium are assumed to be independent of pressure. The flow of the fluid through the porous medium is assumed to be isothermal radial flow into or out of a well open over the entire thickness of the porous medium. The flow rate is constant. Finally, the pressure gradient is assumed to be small and the gravity forces are assumed to be negligible.

The mathematical model describing the flow system consists of the diffusivity equation under the above conditions,[2]

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\,\frac{\partial p}{\partial r}\right) = \frac{\phi \mu c_t}{k}\,\frac{\partial p}{\partial t} \quad . \; . \; . \; . \quad (A\text{-}1)$$

and the boundary and initial conditions,

$$\text{(i)} \quad \left(r\,\frac{\partial p}{\partial r}\right)_{r_w} = \frac{q\mu}{2\pi kh} \qquad \text{for } t > 0$$

$$\text{(ii)} \quad p \rightarrow p_i \text{ as } r \rightarrow \infty \qquad \text{for all } t$$

$$\text{(iii)} \quad p = p_i \text{ at } t = 0 \qquad \text{for all } r$$

A solution to this problem using the line-source approximation of the first boundary condition has been well documented in the literature.[3,4]

$$p(r,t) = p_i + \frac{70.6\ B\ q\mu}{kh} \cdot \text{Ei}\left[\frac{-56900\ \phi\ c_t \mu\ r^2}{kt}\right] \quad . \; . \; . \quad (A\text{-}2)$$

In pulse testing, the flow disturbance at the pulsing well is generated by changing the flow rate periodically. The pressure response at the responding well at any time during the general *n*th period can be written by superposing the responses caused by the flow rate changes from the beginning of the test to the *n*th period. If we assume that all the odd periods are equal and all the even periods are equal, the pressure equation will be

$$p(r_{bw},t) = p_i + \frac{70.6\ B\mu}{kh} \cdot \left\{ q_1\ \text{Ei}\left[\frac{-56900\ \phi\ c_t\ \mu\ r_{bw}^2}{kt}\right] + \sum_{i=1}^{m-1} [q_{i+1} - q_i] \cdot \text{Ei}\left[\frac{-56900\ \phi\ c_t\ \mu\ r_{bw}^2}{k\{t - \frac{\Delta t}{2}(i[1+R] + \sum_{k=1}^{i} [(-1)^{k+1}(1-R)])\}}\right] \right\}$$

$$. \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (A\text{-}3)$$

The term $\sum_{k=1}^{i} [(-1)^{k+1}(1-R)]$ is zero when i is an even integer and is $(1-R)$ when i is an odd integer.

Let us consider three consecutive periods, the *n*th period, the $n + 1$st period, and the $n + 2$nd period (Fig. 1). Let t_A, t_B, and t_C denote the three points at $t\ell_{n,0}$, $t\ell_{n,1}$, and $t\ell_{n,2}$, respectively.

By the definition of the time lag, a tangent to the pressure response curve at (t_A, p_A) is also a tangent at (t_C, p_C) and is parallel to the tangent at (t_B, p_B). The slope of the straight line connecting the two points (t_A, p_A) and (t_C, p_C) is equal to the slope of the tangents at (t_A, p_A) and (t_C, p_C), since these three slopes are actually the slope of the same straight line. Equating the slopes of the tangent at (t_A, p_A), the tangent at (t_B, p_B), the tangent at (t_C, p_C) and the straight line connecting (t_A, p_A) and (t_C, p_C) yields three equations in the three unknowns $t\ell_{m,0}$, $t\ell_{m,1}$, and $t\ell_{m,2}$. These three equations are

$$f(t\ell_{m,0}) = q_1 \left\{ \frac{\exp[\frac{-t}{t_D t_A}]}{t_A} \right\} + \sum_{i=1}^{m} (q_{i+1} - q_i) \left\{ \frac{\exp[\frac{-t}{t_D(t_A - t_i)}]}{t_A - t_i} \right\}$$

$$- \frac{\mu}{kh(t_C - t_A)} \left\{ q_1 [\text{Ei}(\frac{-t}{t_D t_C}) - \text{Ei}(\frac{-t}{t_D t_A})] + \sum_{i=1}^{m+2} \{q_{i+1} - q_i\}\ \text{Ei}[\frac{-t}{t_D(t_C - t_i)}] - \sum_{i=1}^{m} \{q_{i+1} - q_i\}\ \text{Ei}[\frac{-t}{t_D(t_A - t_i)}] \right\} .$$

$$. \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (A\text{-}4)$$

$$f(t\ell_{m,1}) = q_1 \left\{ \frac{\exp[\frac{-t}{t_D t_A}]}{t_A} - \frac{\exp[\frac{-t}{t_D t_B}]}{t_B} \right\}$$

$$+\sum_{i=1}^{m}\{q_{i+1}-q_i\}\left\{\frac{\exp[\frac{-t}{t_D(t_A-t_i)}]}{t_A-t_i}\right\}$$

$$-\sum_{i=1}^{m+1}\{q_{i+1}-q_i\}\left\{\frac{\exp[\frac{-t}{t_D(t_B-t_i)}]}{t_B-t_i}\right\}$$

. . . . (A-5)

$$f(t\ell_{m,2})=q_1\left\{\frac{\exp[\frac{-t}{t_Dt_A}]}{t_A}-\frac{\exp[\frac{-t}{t_Dt_C}]}{t_D}\right\}$$

$$+\sum_{i=1}^{m}\{q_{i+1}-q_i\}\left\{\frac{\exp[\frac{-t}{t(t_A-t_i)}]}{t_A-t_i}\right\}$$

$$-\sum_{i=1}^{m+2}\{q_{i+1}-q_i\}\left\{\frac{\exp[\frac{-t}{t_D(t_C-t_i)}]}{t_C-t_i}\right\}$$

. . . . (A-6)

The Newton-Raphson iterative method[9] can be used to find the values of the three unknowns that satisfy these three equations simultaneously.

After the values of the three time lags are found, the response amplitude then can be calculated by subtracting p_B from the pressure on the straight line connecting (t_A, p_A) and (t_C, p_C) at time t_B. The equation of this response amplitude is

$$\Delta p =$$

$$\frac{70.6\ B(t_B-t_A)}{(t_C-t_A)}\left\{q_i[Ei(\frac{-1}{t_{DC}})-Ei(\frac{-1}{t_{DA}})]\right.$$

$$+\sum_{i=1}^{m+2}\{q_{i+1}-q_i\}\ Ei\left[\frac{-1}{t_{DC}(1-\frac{t_i}{t_C})}\right]$$

$$\left.-\sum_{i=1}^{m}\{q_{i+1}-q_i\}\ Ei\left[\frac{-1}{t_{DA}(1-\frac{t_i}{t_C})}\right]\right\}-p_B.$$

. . . . (A-7)

More details about the derivation of these equations are presented in Ref. 11.

* * *

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March 1, 1988

Mr. Michael E. Stogner
Oil Conservation Division
P. O. Box 2088
Santa Fe, New Mexico 87504

"Hand Delivered"

RECEIVED
MAR 1 1988
OIL CONSERVATION DIVISION

Re: Penroc Oil Corporation
NMOCD Case 9303
SWD Application

Dear Mr. Stogner:

At the conclusion of the examiner's hearing held on February 3, 1988 in the referenced case, you requested a draft order be submitted. Please find enclosed our proposed order.

Very truly yours,

W. Thomas Kellahin

WTK:ca

cc: M. Y. Merchant
William F. Carr, Esq.

STATE OF NEW MEXICO
ENERGY, MINERALS, AND NATURAL RESOURCES DEPARTMENT
OIL CONSERVATION DIVISION

IN THE MATTER OF THE HEARING CALLED BY THE OIL CONSERVATION DIVISION FOR THE PURPOSE OF CONSIDERING:

CASE NO. 9303
ORDER R-

APPLICATION OF PENROC OIL CORPORATION FOR SALT WATER DISPOSAL, LEA COUNTY, NEW MEXICO.

ORDER OF THE DIVISION

BY THE DIVISION:

This cause came on for hearing at 8:15 a.m. on February 3, 1988, at Santa Fe, New mexico, before Examiner Michael E. Stogner.

NOW, on this ____ day of __________, 1988, the Division Director, having considered the testimony, the record, and the recommendations of the Examiner, and having been fully advised in the premises,

FINDS THAT:

(1) Due public notice having been given as required by law, the Division has jurisdiction of this cause and the subject matter thereof.

(2) The applicant, Penroc Oil Corporation, is the owner and operator of the State "AF" Well No. 2 located 330 feet from the South line and 2130 feet from the East line (Unit O) of Section 8, Township 18 South, Range 35 East, NMPM, Lea County, New Mexico.

(3) The applicant proposes to utilize said well to dispose of produced salt water into the Undesignated Mid Vacuum-Devonian Pool with injection into the open interval from approximately 11,838 feet to 12,200 feet.

(4) Arco Oil & Gas Company ("Arco") is the operator of the Lea 4011 State No. 1 Well located 330 feet from the South line and 1650 feet from the West line of said Section 8 and appeared in opposition to the Penroc application.

(5) Arco agreed that Penroc Exhibit 11 was an accurate and reliable structural interpretation of the area and showed that the proposed Penroc SWD well was more than 250 feet down structure and on the opposite side of a fault from the Arco Lea 4011 State No. 1 Well.

(6) Arco speculates that because a Drill Stem Test conducted on the proposed Salt Water Disposal Well showed 928 feet of free oil that the fault between the Penroc Well and the Arco Well may not preclude communication between the two wells.

(7) Arco proposed that the Division require Penroc to conduct and pay for an expensive pulse test between the two wells in order to remove any doubt about communication.

(8) If Arco is correct concerning the potential for communication between the two wells, then Penroc should be able to complete the proposed Salt Water Disposal Well for commercial oil production; and if not, then the subject well should be suitable for Salt Water Disposal without adverse affect upon Arco.

(9) A reasonable inference from the testimony and evidence available is that the subject well is sufficient down structure and on the opposite side of a fault to not cause a violation of the correlative rights of Arco. However, in order to conclusively establish that fact, the subject well should be tested in the interval from 11,838 to 12,000_ to determine if said well is economic for oil production before said well is utilized as a salt water diposal well.

(10) The Division should require that Penroc first attempt to complete the subject well for oil production in the vertical interval from 11,837 to 11,850 with all such attempts being witnessed by the OCD staff and a representative of Arco, should they desire to participate.

(11) In the absence of production from the subject well, Penroc would be required to disposal of water below the depth of 12,000.

(12) Penroc, as operator, should give advanced notification to the supervisor of the Hobbs district office of the Division of the date and time of the testing of the well for production so that said test can be witnessed.

(13) The standard surface limitation pressure for a well at this depth is 2367.6 feet. However, in order to avoid any potential for migration of the disposal fluid across the fault as shown on Penroc Exhibit 11, a limitation pressure not to exceed 500 psi should be established.

(14) The foregoing provides a reliable means to prevent waste and protect correlative rights and subject to the foregoing the application should be granted.

(15) The injection should be accomplished through 2 7/8-inch plastic-lined tubing installed in a packer set at approximately 11,800 feet; the casing-tubing annulus should be filled with an inert fluid; and a pressure gauge or approved leak detection devise should be attached to ther annulus in order to determine leakage in the casing, tubing, or packer.

(16) Prior to commencing injection operations, the casing in the subject well should be pressure-tested throughout the interval from the surface down to the proposed packer-setting depth to assure the integrity of such casing.

(17) The injection well or system should be equipped with a pressure-limiting switch or other acceptable device which will limit the wellhead pressure on the injection well to no more than 500 psi.

(18) The Director of the Division should be authorized to administratively approve an increase in the injection pressure upon a proper showing by the operator that such higher pressure will not result in migration of the injected waters from the Wolfcamp formation.

(19) The operator should notify the supervisor of the Hobbs district office of the Division of the date and time of the installation of disposal equipment and of the mechanical integrity pressure test in order that the same may be witnessed.

(20) The operator should take all steps necessary to ensure that the injected water enters only the proposed injection interval and is not permitted to escape to other formations or onto the surface.

(21) Approval of the subject application will prevent the drilling of unnecessary wells and otherwise prevent waste and protect correlative rights.

IT IS THEREFORED ORDERED THAT:

(1) The applicant, Penroc Oil Corporation, is hereby authorized to, under supervision of the OCD District Office, attempt to complete the subject well for oil production in the interval from 11,838 to 11,850 and in the absence of said production is hereby authorized to utilize its State "AF" Well No. 2 located 330 feet from the South line and 2130 feet from the East line (Unit O) of Section 8, Township 18 South, Range 35 East, NMPM, Lea County, New Mexico, to dispose of produced salt water into the Mid Vacuum-Devonian Pool, injection to be accomplished through 2 7/8-inch tubing stalled in a packer set approximately 12,000 feet, with injection into the open hole interval from approximately 12,000 feet to 12,200 feet.

PROVIDED HOWEVER, THAT, the tubing shall be internally plastic-lined; the casing-tubing annulus shall be filled with an inert fluid; and a pressure gauge shall be attached to the annulus or the annulus shall be equipped with an approved leak-detection device in order to determine leakage in the casing, tubing, and/or packer.

PROVIDED FURTHER, THAT, prior to commencing injection operations, the casing in the subject well shall be pressure-tested to assure the integrity of such casing in a manner that is satisfactory to the supervisor of the Division's district office at Hobbs.

(2) The injection well or system shall be equipped with a pressure-limiting switch or other acceptable device which will limit the wellhead pressure on the injection well to no more than 500 psi.

(3) The Director of the Division may authorize an increase in injection pressure upon a proper showing by the operator of said well that such higher pressure will not result in migration of the injected fluid from the Devonian formation.

(4) The operator shall notify the supervisor of the Hobbs district office of the Division of the date and time of the installation of disposal equipment and of the mechanical integrity pressure test in order that the same may be witnessed.

(5) The operator, shall immediately notify the supervisor of the Division's Hobbs district office of the failure of the tubing, casing, or packer, in said well or the leakage of water from or around said well and shall take such steps as may be timely and necessary to correct such failure or leakage.

(6) The applicant shall conduct disposal operations and submit monthly reports in accordance with Rules 702, 703, 704, 705, 706, 708, and 1120 of the Division Rules and Regulations.

(7) Jurisdiction of this cause is retained for the entry of such further orders as the Division may deem necessary.

DONE at Santa Fe, New Mexico, on the day and year hereinabove designated.

STATE OF NEW MEXICO
OIL CONSERVATION DIVISION

WILLIAM J. LEMAY
Director

STATE OF NEW MEXICO

ENERGY AND MINERALS DEPARTMENT

OIL CONSERVATION DIVISION

September 28, 1988

GARREY CARRUTHERS
GOVERNOR

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Attorneys at Law
Post Office Box 2265
Santa Fe, New Mexico

Re: CASE NO. 9303
ORDER NO. R-8755

Applicant:

Penroc Oil Corporation

Dear Sir:

Enclosed herewith are two copies of the above-referenced Division order recently entered in the subject case.

Sincerely,

Florene Davidson

FLORENE DAVIDSON
OC Staff Specialist

Copy of order also sent to:

Hobbs OCD x
Artesia OCD x
Aztec OCD

Other William F. Carr