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INJECTION TESTING IN GEOTHERMAL WELLS.

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ABSTRACT.

Transient pressure analysis methods were applied to analyze the results of injection tests carried out in a recently completed geothermal well in Los Azufres Geothermal field in Mexico. Potential use of those methods (employing injection, two rate injection and fall off tests) is ilustrated in obtaining important well and reservoir parameters at the well completion stage and in predicting future well performance. Also, based on the experience obtained with this well and other similar wells, suggestions are made on the type of analysis which is most applicable.

INTRODUCTION.

Injection tests are carried out as a part of completion procedures of geothermal wells in the Los Azufres Geothermal Field, Michoacan,Mexico. The main purpose of these tests is to obtain early information about the well and reservoir parameters in order to predict future well performance. Injection tests are considered especially useful to achieve this objective, as the problems associated with two phase flow conditions observed during draw-down and build-up tests are avoided, making the eventual analysis simpler.

Moreover, injection tests are easier to carry out than the drawdown and build-up tests.

In this paper the application of different pressure analysis methods to the results of several injection tests carried out in a geothermal well in Los Azufres is illustrated; and the potential of these methods in reaching the above objective, even with incomplete data, is demonstrated.

GENERAL BACKGROUND.

Los Azufres Geothermal Field is located in the State of Michoacan in Central Mexico. It is on the E-W oriented neo-volcanic axis and is covered by neo-quaternary volcanic deposits overlying a basement of lutites and sands. Microgranular andesites form the lower part of the volcanic formations and are overlaid at places by riolites and pyroclastics.

Alteration zones and thermal manifestations are clearly related to tectonic activity and are located near faults and fracture zones. The wells so far drilled in this area are sited near the known major faults in order to encounter secondary permeability associated with them.

The main production is thought to come through fractures.

The completion of the well is shown in Fig. 1 which also includes the data on circulation fluid losses and percentage core recovery.

It was drilled almost completeley in fractured andesitas. The fractures were usually filed with silica, chlorite and epidote. The portion of the well below 2200 m was highly fractured and fragmented as was observed from the last two cores taken and as confirmed by very poor core recoveries.

The well was drilled using bentonitic mud from surface up to 1500 m and with water from 1500 m downwards.

The circulation was totally lost at 2224 m for one hour, then partially recovered and was lost again completeley at about 2332 m. The last part of the well was drilled with total loss of circulation.

The first series of tests were carried out when the well was at 2404 m, after a core had been taken at this level. Here when the first attempt was made to core, it was found that there was an accumulation of cuttings 50 m thick at the bottom, and after several trials these cuttings were cleaned with a batch of mud.

The second series of tests were run after deepening the well to 2450 m and putting a liner as shown in Fig. 1. The well was stopped at this depth for reasons of well safety, problems with water supply and materials.

TEST PROCEDURE.

Before the injection tests were run two temperature surveys had been carried out (5 and 7 hours after circulation stopped) to determine the distribution of the permeable

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Type Curve Matching Using the Curves of Earlougher and Kersch. (3).

The results of the analysis with this method are also presented in tables II and III.

Although two or three different matches could be made for earch test, an average of the parameters obtained with different matches give a reasonable indication of the order of values sought. One can also observe that the average values obtained by this method compare reasonably well with the average values obtained by the log-log method.

With Semi-Log Method.

In order the confirm the conclusions obtained by the log-log analysis semi-log standard plots of data were also made.

It was found that wellbore storage effects were dominating almost all or a very large portion of the data; and either the semi-log straight line data were lost completely (because of not having sufficient clock time) or only the beginning of the required data were recorded. Therefore, it was impossible to analyse the data by this method.

However, the semi-log plot of the results of the first test (the longest recorded test) are presented in Fig. 13 as an example. It can be seen that towards the end of the data semi-log straight line conditions are being reached, and the slope of the drawn lines may give an idea about the lower limit of the transmissivity value. One can also observe a high skin effect.

Other methods of analysis were also tried. In Figure 14 one can see the results of the conventional two rate analysis (2) of the second test. It will be noted that the proper straight line portion of the data had not been reached.

The method suggested by Gladfelter et al. (4) for the data dominated by wellbore storage effects, was also applied to the results of some of the tests.

Although it was possible to obtain reason ably good semi-log straight lines in every case, the transmissivity obtained was very low (in the order of 1.60 d.m./cp) compared to the values shown in tables II and III. However, in plotting the graphs, a figure of 0.0351 m^3/m (0.0672 bbl/ft) was used (as calculated using the actual hole, casing and pipe dimensions during the tests) for casing capacity. This figure gives a C value of 0.1551 bbl/psi. On the other hand the tests results indicate a C value of about 0.250 bbl/psi.

When a correction was made to the casing capacity using this latter value, it was found that the slope of the semi-log straight line diminished giving transmissivity values slightly smaller than those obtained by type curve matching methods. Also it has been observed with the method that unless one uses very small time intervals (one or two minutes) one gets a large dispersion of points.

It was also found that with this type of wells one can not use methods of analysis employing logarithmic pressure change versus time. This is probably because the late time transients are short and the early time transient data are masked by wellbore storage effects. Therefore, it is very difficult to select the plot which gives the right straight line for the evaluation of the parameters sought.

In the case of the five tests considered usually there were not any late time transient data, and when they were recorded either they were not sufficient or they could not be used for analysis for the above reasons.

DISCUSSION.

Although the results obtained by the type curve matching methods vary from match to match and from one method to other, they are all of the same order and give a good indication in what range the actual values lie. In fact the average values obtained by both type curves agree very well and give a very good idea about the parameters sought.

It seems the log-log method gives results with less dispersion and for the data used appears to be superior to the other as it also enables us to calculate the storitivity. ($\emptyset h c_t$).

It will be noted that the second series of tests indicate a transmissivity 10% higher than the value obtained by the first series of tests. This is quite logical as the additional drilling of 40 m after the first series of tests, through an obviously fractured formation, must have increased the transmissivity by increasing the h.

The skin damage appears to be high, but understandable when it is remembered that almost 220 m were drilled with no return of the circulation fluid and the cuttings were obviously pushed into the fractures, causing a skin damage. It clearly lies between 5 and 10.

The storage coefficient indicated by both series of tests is about 0.250 bbl/psi which is about twice as high as the value calculated taking into account the profile of the well (0.1578 bbl/psi). The discrepency may be due to the fractured nature of the tested formation, with the fractures acting as a part of the well storage.

This may be supported by the increase in storitivity after the deepening of the well by40 m. It will be noted that the storitivity is nearly doubled after this zones along the well depth. The results of these tests are plotted in Figure 2. It can be noted that although the formations below 2200 m were generally permeable, several well defined zones had higher permeability and might be associated with fractures and/or fractured zones. The best permeable feature appears to be the zone where the first total loss of circulation was observed (at about 2224 m).

Also a pressure-depth survey was made to determine the standing water level in the well. It was found to be at about 672 m.

The tests were carried out using a Kuster pressure gauge to monitor the pressure changes. Three-hour clocks were used as clocks of larger capacities were not available.

The first series of testing consisted of three tests as follows:

I.- With the pressure gauge at 1472 m, injection at the rate of 500 litres/min., for 370 minutes, then recovery for 236 minutes.

II.- With the pressure gauge at 1472 m, injection at a rate of 1000 litres/min for 75 minutes and then raising the injection rate to 1500 litres/min and injection at this rate for 45 minutes. At the end of this period water was injected at a rate of 2050 litres/min and there was a partial return of water after about 4 minutes.

III.-With the pressure gauge at 1500 m, injection at the rate of 800 litres/min for 136 minutes.

The second series of tests were carried out as follows:

I.- With the pressure gauge at 2000 m, injection at 800 litres/min for 258 minutes, and then recovery for 140 minutes.

II.-With the pressure gauge at the same level, injection at 1000 litres/min. (Data monitored for 124 minutes). During this test, the injection could not be kept constant.

The results of these tests are plotted in Figures 3 through 7.

ANALYSIS OF THE RESULTS.

With Log-Log Method.

Although, almost always the tendency is to analyze the results by means of the semi-Log method, it has been found with similar tests that in almost all cases the wellbore storage effects dominate and mask a large part of the data, and it is difficult to define the proper semi-log straight line.

Therefore, the results were first plotted in a log-log form, and analysed by means of the"Type Curve Matching" technique using the type curves of Ramey et al (1), enlarged versions of the curves presented as Fig. C.6 in monogram Vol. 5 of the SPE (2).

The matching procedure for four tests using the log-log plots is illustrated in Figures 8 through 12. The well and reservoir parameters were calculated using the formulae for dimensionless pressure, dimensionless time and dimensionless storage coefficient, as shown in apendix A. The results of the analysis are presented in tables II and III.

The results of the last test were not analyzed for the reason that the injection rate during this test was not constant.

With the results of some tests one could obtain more than one good match. In these cases the best match was selected by comparing the value of the storage coefficient obtained by the formula 3 in Apendix A with the value obtained by using the data on the unit slope parts of the log-log graphs and the formula 4 in Apendix A. In some cases, however, it was difficult to select the best match amongst two matches and the parameters obtained by both matches were presented in tables II and III.

In the case of the analysis of the recovery part of the first test the differences between the C values indicated that the beginning of the recovery was perhaps 3.7 minutes later than assumed. The data were adjusted taking this time difference into account and a new match was obtained. The results of the new match are not significantly different from the previous match.

The results calculated by this method indicated that with the data used, semi-log straight line should start about 3 hours after the beginning of the test. It was clear that in some tests the useful part of the data for semi-log analysis was lost during the period when the Kuster gauge was raised and relowered, after re-winding or changing the clock; and in others only the beginning of the semi-log data was recorded within the first 3 hours of clock time.

It is well known that the "Type Curve Matching Techniques" are especially useful when the wellbore storage effects last a long time and early time transient data exist, as it was the case with the tests carried out. However under these circumstances the methods give only aproximate values.

Therefore, the results were analyzed by means of another"Type Curve Matching" technique, using the type curves of Earlougher and Kersch (3). (Larger scale versions of the curves presented as Fig. C.7 in Monograph Vol. 5 of the SPE (3).

additional drilling, indicating that the additional 40 m were highly fractured forming a psuedo-porous medium.

The storitivity value obtained from the first series of tests is quite acceptable, because if one assumes $\emptyset = 0.1$ and $c_t = 5.7 \times 10^{-5}$ $(Kg/cm^2)^{-1}$ one gets $h = 298$ m which is very close to the permeable interval observed (2410 - 2200 = 210 m).

The tests during which late data were registered do not show the typical fractured reservoir behaviour, indicating that the formations are behaving like porous. However, typical semi-log curves of fractured formations were observed with the data of another well in the same field.

Finally, if the flow efficiency is calulated using the results of first and fourth test, a value between 0.51 and 0.52 is obtained. When one takes into account that when the well was eventually induced, it produced 63 t/h, it indicates that if the skin damage can be removed the well will produce about 123 t/h.

CONCLUSIONS.

I.- Injection tests can be successfully used to determine well and reservoir parameters at the completion stage of a well and the results can be analysed with the established methods.

II.- They are easy to perform and Kuster pressure gauges are sufficient to record the pressure changes. However clocks of at least 6 hours period are required to register all the necessary data.

III.- Injection data are usually dominated by well bore storage effects and the parts which can be analysed by semi-log methods are short. For this reason it is absolutely necessary to make log-log plots to define the data which can be analyzed by the semi-log methods.

IV.- In cases where a large part of the semi-log straight line data is missing, or too short to be identified, the type curve matching techniques using the type curves of Ramey et al and Earlougher and Kersch can be successfully used to analyse the early time transient data. Although the results obtained are approximate when several tests are carried out reasonably reliable average values can be determined.

The log-log analysis with the type curves of Ramey et al are likely to give more consistent results.

V.- Experience with this and other wells indicate that the methods of analysis using log pressure-time plots are not recommendable for these wells.

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The authors also state that the opinions expressed are their own and not necessarily of their respective organizations.

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TABLE I

NOMENCLATURE

Symbol	Meaning	Units: Conventional	Units: Metric
K	Effective average permeability	millidarcy	darcy
h	Net formation pay thickness	ft.	m
p	Pressure	psi	kg/cm^2
q	Injection Rate	SBD	
W			t/h
μ	Viscosity	centipoise	centipoise
t	time	hour	hour
B	Formation volume factor (reservair volume/standard volume = $\frac{Vr}{Vsc}$)		
ø	porosity	fraction of bulk volume	
c_t	Total system effective isothermal compressibility	$(psi)^{-1}$	$(Kg/cm^2)^{-1}$
r_w	welbore radius	ft	m
c	Wellbore sturage coefficient	bbl/psi (1 bbl/psi = 2.2615 $m^3/Kg/cm^2$)	$m^3/Kg/cm^2$
P_D	Dimensionless pressure		
t_D	Dimensionless time		
C_D	Dimensionless storage coefficient		
ΔP	Pressure change	psi	Kg/cm^2
Δt	Time change	hour	hour
m	Slope of Semi-log Straight line	psi/log cycle	Kg/cm^2/log cycle
Vsc	Specific Volume at standard conditions		m^3/t
Vr	Specific volume at reservoir conditions near the injection (assumed to be 1.0435 m^3/t in all calculations)		m^3/t
s	Skin effect (dimensionless)		
Δps	See equation 7.		
$\bar{p}$	Volumetric average plessure within drainage volume	psi	Kg/cm^2

TABLE II

RESULTS OF THE ANALYSIS OF THE TESTS

WITH THE WELL AT 2,404 M .

Type of Test	Analysis Method	$\frac{Kh}{\mu}$ d.m/cp	mdft/cp	$\phi h c_t$ m/Kg/cm^2	ft/psi	C bbl/psi	S
Injection 500 litres/min	Semi-log	There are not enough data.					
	Log-Log	14.34 ?	49018 ?	7.46×10^{-3} ?	1.72×10^{-3} ?	0.251+ 0.241	20 ?
	(Ramey)	8.72	28620	7.37×10^{-3}	1.70×10^{-3}	0.236	10
	E-K	7.65	25088			0.290	12.39
		7.02	23027			0.290	3.18
		7.33	24057			0.290	7.79
Recovery after injection with 500 litres/min	Semi-log	5.49 ?	18013 ?				
		4.12 ?	13518 ?			0.350+	
	Log-Log	8.01	26281	8.32×10^{-3}	1.92×10^{-3}	0.269	10
	(Ramey)	8.01	26281	7.00×10^{-3}	1.61×10^{-3}	0.280+	10
						0.235	
	E - K	No good match					
Injection with 1,000 litres/min	Semi-log	There are enough data.				0.246+	
	Log-Log (Ramey)	8.58	28151	6.10×10^{-3}	1.41×10^{-3}	0.198	10
	E - K	4.63	15193			0.190	3.39
		11.23	36860			0.199	14.88
		7.93	26026			0.195	3.14
Injection with 800 litres/min	Semi-Log	There are not enough data.				0.298+	
	Log-Log	6.31	20703	8.4×10^{-3}	1.94×10^{-3}	0.272	5
	(Ramey)	9.38	30776	8.0×10^{-3}	1.84×10^{-3}	0.261	10
	E - K	9.81	32193			0.254	10.15
		5.34	17510			0.248	4.41
		7.57	24852			0.251	7.28
Average Representative Values		8.00	26248	7.36×10^{-3}	1.70×10^{-3}	0.250	8.82

+ Calculated using the data on the unit slope part of the log-log plots.

NOTES : 1 E-K stand for analysis using Earlougher + Kersch curves (2). Skin values were obtained by assuming $\phi = 0.1$ and $c_t = 5.7 \times 10^{-3}$ $(Kg/cm^2)^{-1}$. h = 910 m.

2 Figures underlined are the average values obtained using Earlougher + Kersch curves.

TABLE III

RESULTS OF THE ANALYSIS OF THE TESTS

WITH THE WELL AT 2430 M.

Test	Analysis Method	Kh/μ d.m./cp	Kh/μ md.ft/cp	Ø hc$_t$ m/kg/cm2	Ø hc$_t$ ft/psi	C bbl/psi	S
Injection with 800 litres/min	Semi-log	There are not enough data					
						0.262	
	Log-log (Ramey)	9.38	30776	13.66×10^{-3}	3.15×10^{-3}	0.256	10
	E - K	6.20	20351			0.210	3.55
		15.25	50151			0.230	18.45
		8.53	27577			0.220	6.96
		10.00	32826			0.220	8.87
Recovery after injection with 800 litres/min	Semi-log	There are not enough data					
						0.269*	
	Log-log (Ramey)	6.75	22147	15.52×10^{-3}	3.58×10^{-3}	0.267	5
	E - K	9.14	30000			0.255	5.73
		8.99	29500			0.236	5.77
		9.07	29750			0.246	5.75
Injection with 1000 litres/min	E -K	9.32 ?	30590 ?			0.345 ?	4.78?
						0.370 ?	
Average Representative Values		8.80	28856	14.59×10^{-3}	3.37×10^{-3}	0.248	7.31

* Calculated using the data on the unit slope part of the log-log **plots.**

NOTES: 1. E-K stand for analysis using Earlougher + Kersh curves (2). Skin values were obtained by assuming $\phi = 0.1$ and $c_t = 5.7 \times 10^{-5}$ $(Kg/cm^2)^{-1}$, h = 250 m.

2. Figures underlined are the average values obtained using Earlougher + Kersch curves.

FIGURE 1

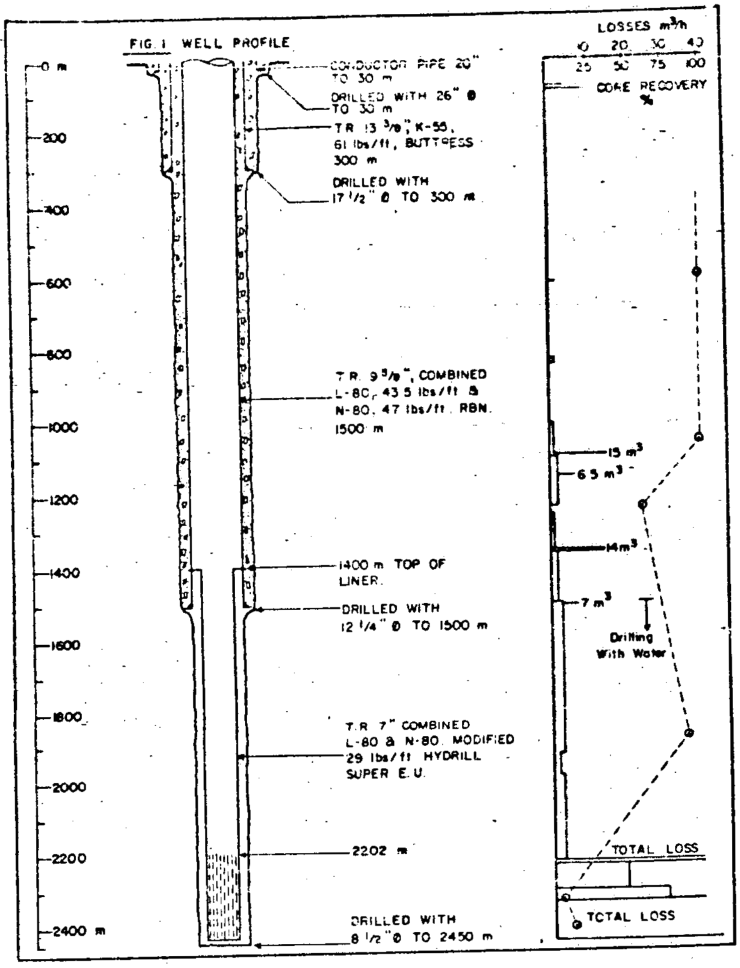


FIGURE 2

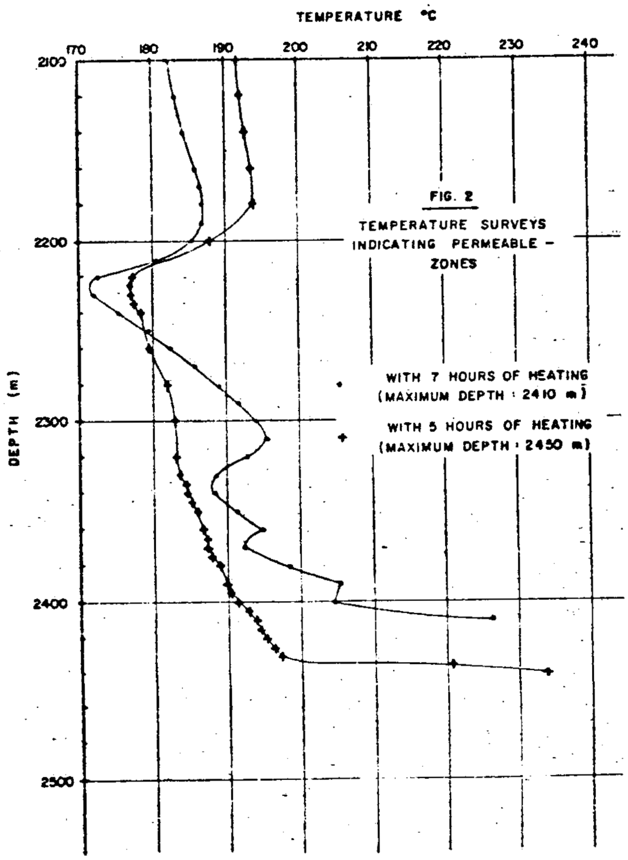
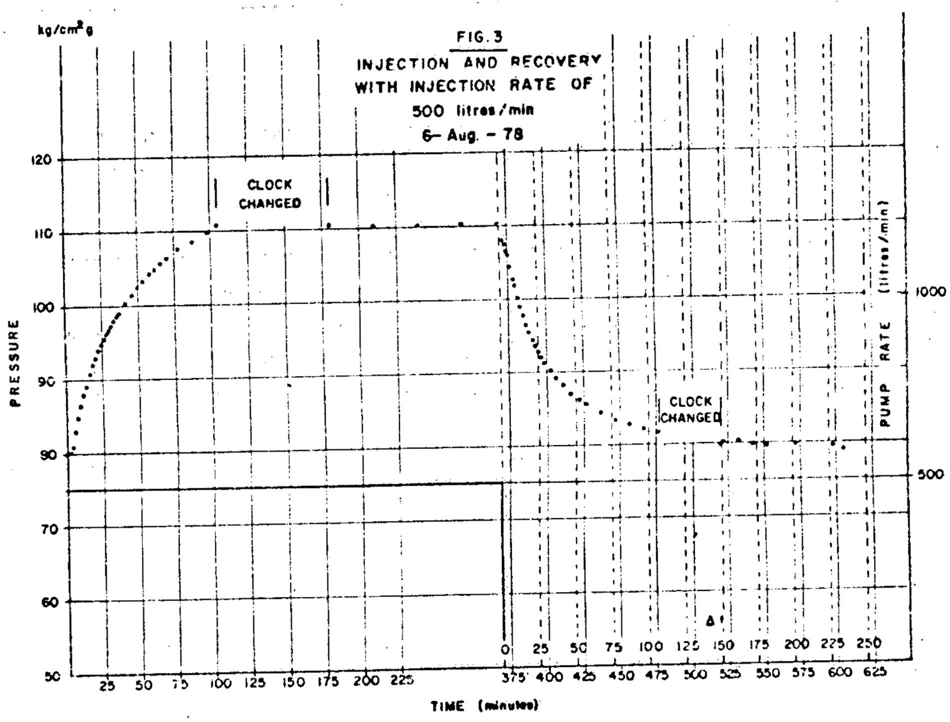


FIGURE 3



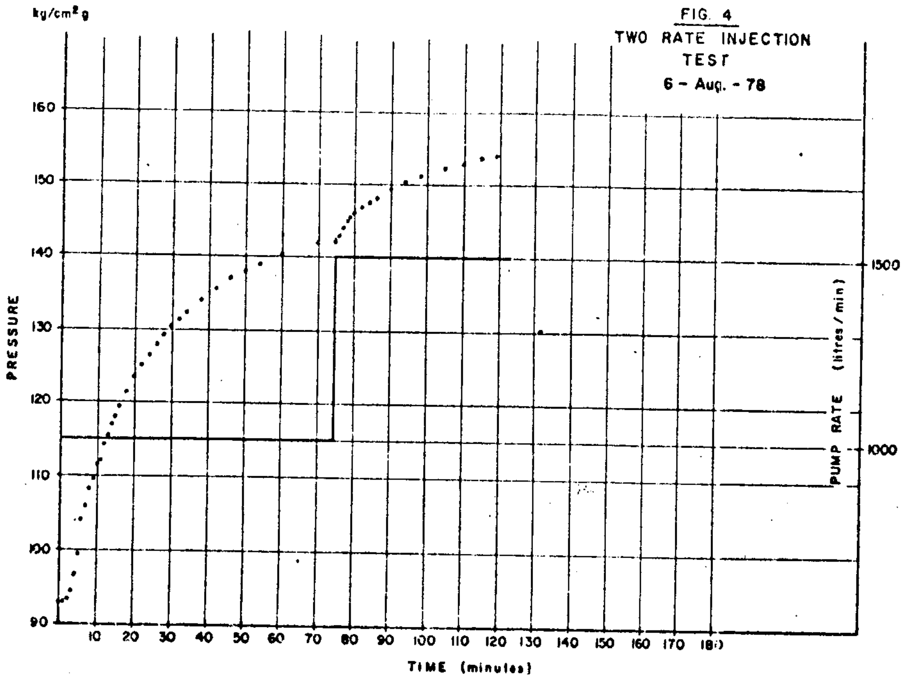


FIG. 4
TWO RATE INJECTION TEST
6 - Aug. - 78

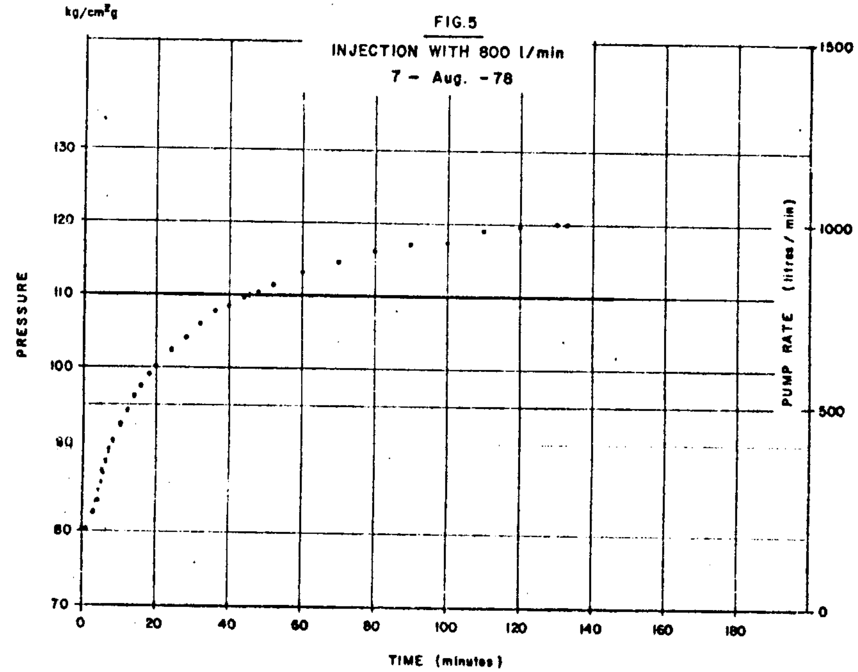


FIG.5
INJECTION WITH 800 l/min
7 - Aug. - 78

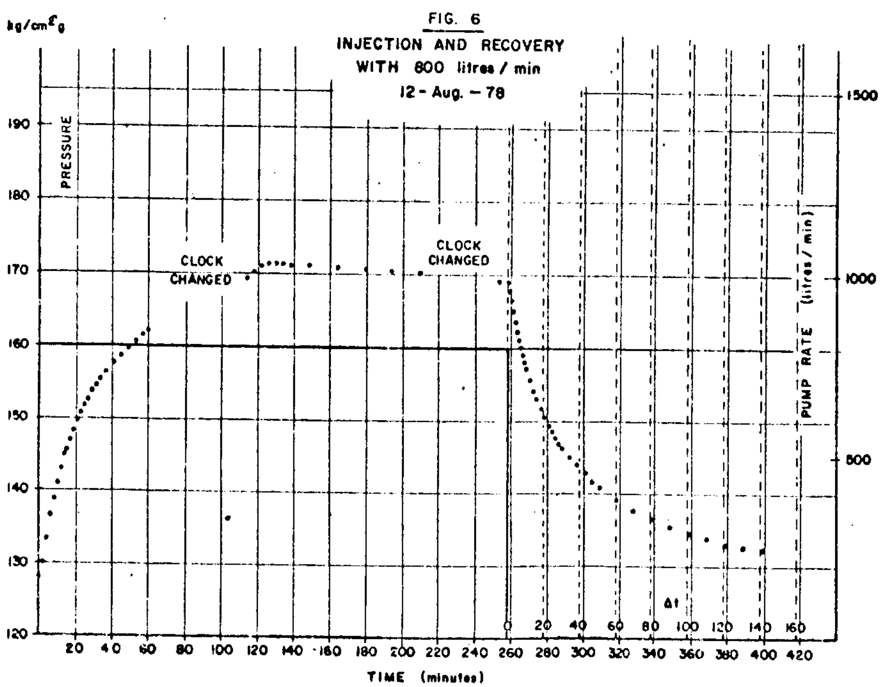


FIG. 6
INJECTION AND RECOVERY WITH 800 litres / min
12 - Aug. - 78

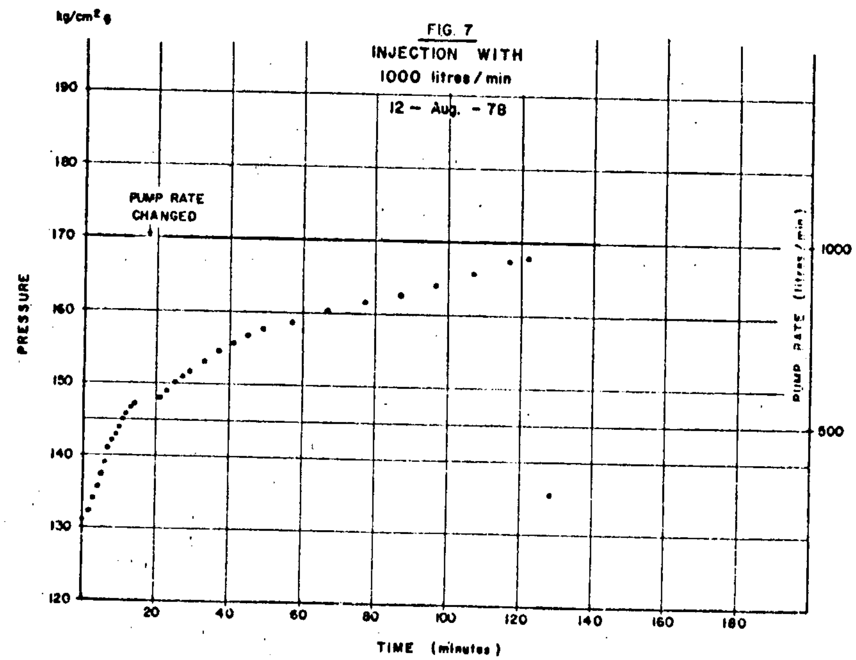


FIG. 7
INJECTION WITH 1000 litres / min
12 - Aug. - 78

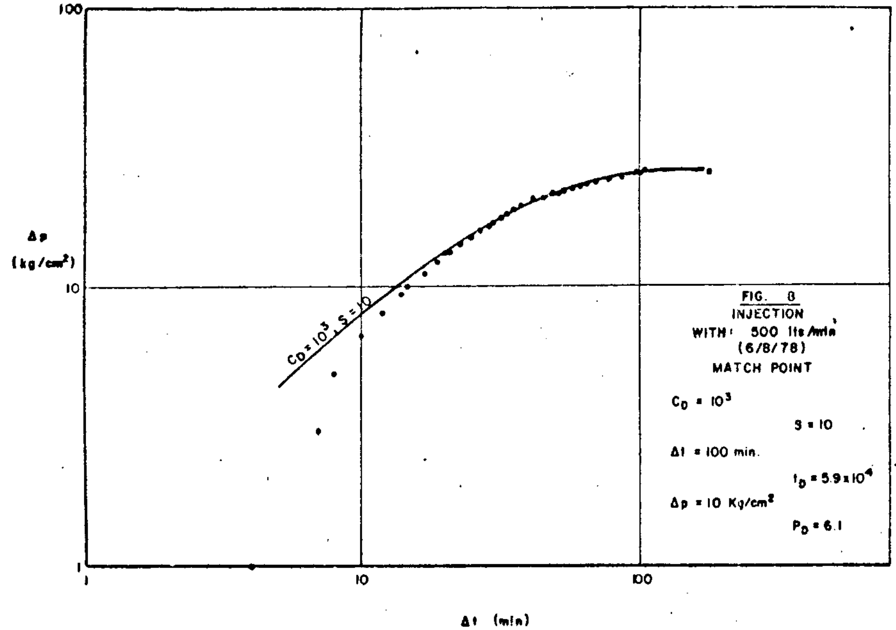


FIG. 8
INJECTION
WITH: 500 lts/min
(6/8/78)
MATCH POINT
$C_D = 10^3$ S = 10
Δt = 100 min. $t_D = 5.9 \times 10^4$
Δp = 10 Kg/cm² $P_D = 6.1$

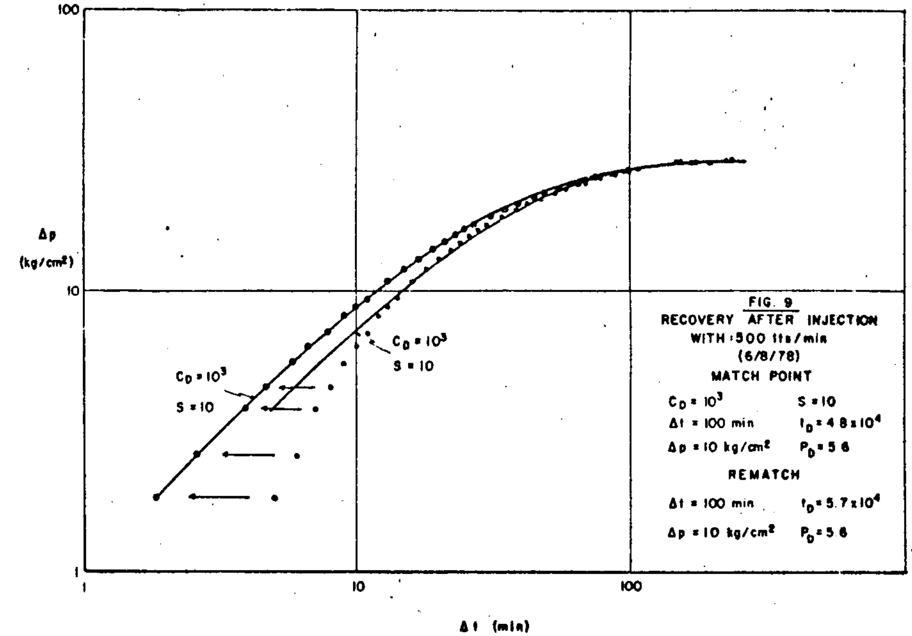


FIG. 9
RECOVERY AFTER INJECTION
WITH: 500 lts/min
(6/8/78)
MATCH POINT
$C_D = 10^3$ S = 10
Δt = 100 min $t_D = 4.8 \times 10^4$
Δp = 10 kg/cm² $P_D = 5.6$
REMATCH
Δt = 100 min $t_D = 5.7 \times 10^4$
Δp = 10 kg/cm² $P_D = 5.6$

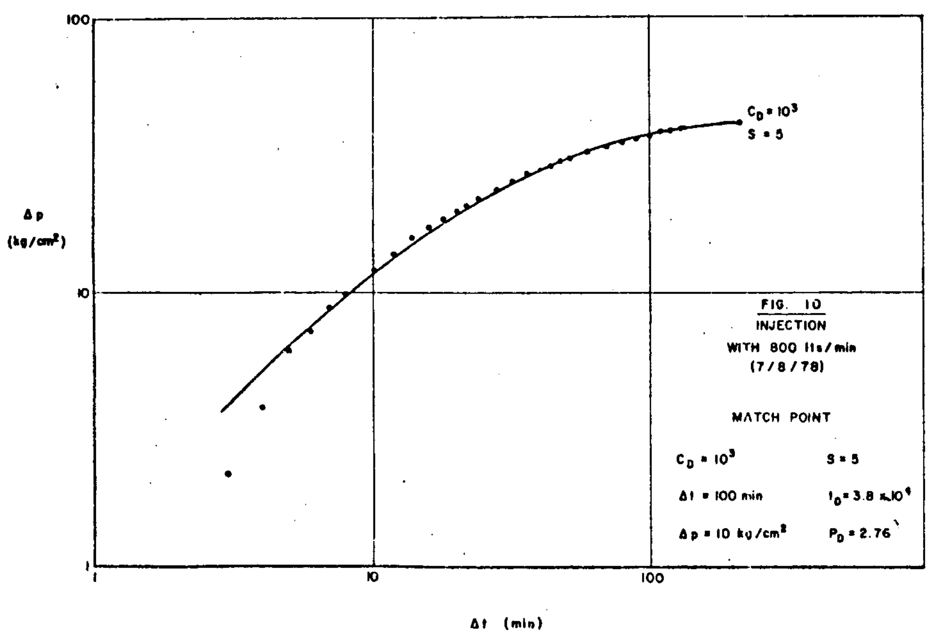


FIG. 10
INJECTION
WITH 800 lts/min
(7/8/78)
MATCH POINT
$C_D = 10^3$ S = 5
Δt = 100 min $t_D = 3.8 \times 10^4$
Δp = 10 kg/cm² $P_D = 2.76$

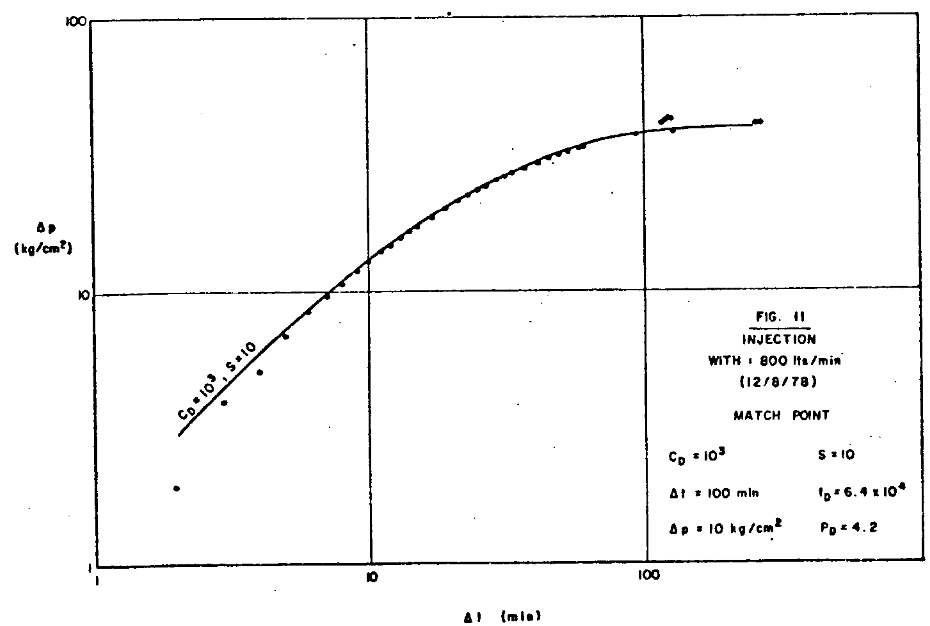


FIG. 11
INJECTION
WITH: 800 lts/min
(12/8/78)
MATCH POINT
$C_D = 10^3$ S = 10
Δt = 100 min $t_D = 6.4 \times 10^4$
Δp = 10 kg/cm² $P_D = 4.2$

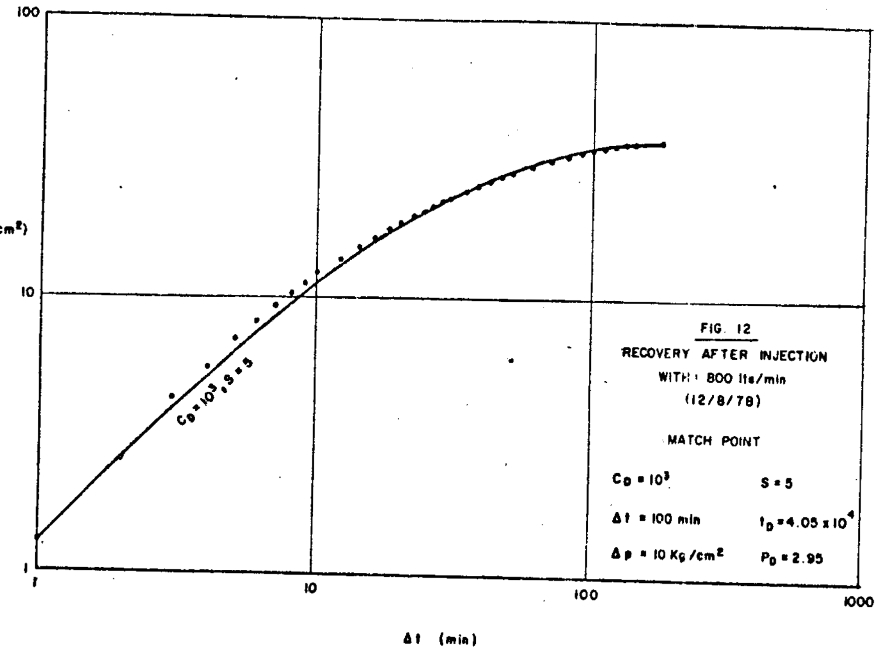


FIG. 12
RECOVERY AFTER INJECTION
WITH : 800 lts/min
(12/8/78)

FIG. 13
INJECTION AND RECOVERY
WITH 500 litres/min
6-Aug.-78

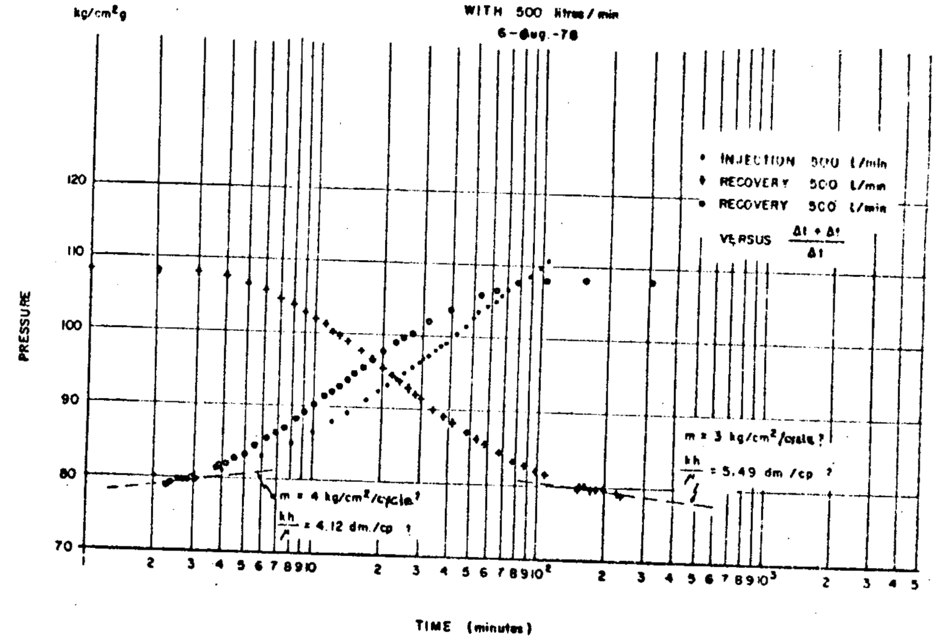
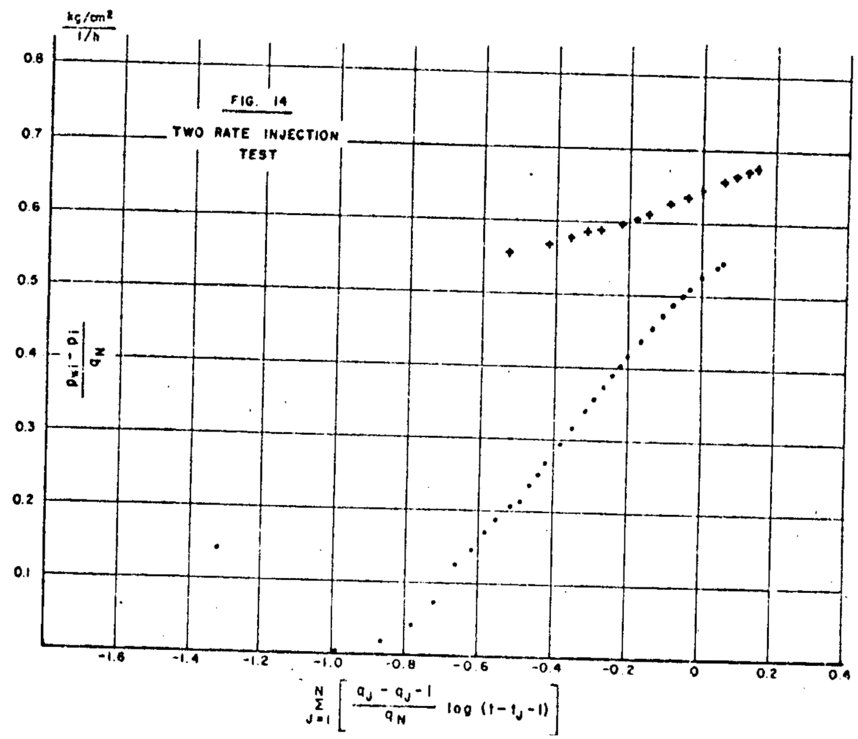


FIG. 14
TWO RATE INJECTION TEST



Appendix A:

Formulae Used :

Conventional Reservoir Engineering Units		Metric Units
$P_D = \dfrac{\Delta pkh}{141.2\ q\ B\mu}$	(1)	$P_D = \dfrac{2.1891\ \Delta pkh}{sc\ W\ B\mu}$
$t_D = \dfrac{0{,}0002637\ kt}{\emptyset\mu c_t\ h\ r^2_w}$	(2)	$t_D = \dfrac{0{,}3485\ kt}{\emptyset\mu c_t r_w^2}$
$C_D = \dfrac{5.6146\ C}{2\ \emptyset\ C_t\ h\ r^2_w}$	(3)	$C_D = \dfrac{C}{2\pi\emptyset\ c_t h\ r^2_w}$
$C = \dfrac{qB\ \Delta t}{24\ Ap}$	(4)	$C = \dfrac{W\ Vsc\ B\ \Delta t}{\Delta p}$
$m = \dfrac{162.6\ q\mu B}{Kh}$	(5)	$m = \dfrac{0.5258\ Vsc\ q\ B\mu}{Kh}$
$t = \dfrac{(200000 + 12000\ s)}{(kh/\mu)}$	(6)	$t = \dfrac{(200000 + 12000\ s)}{3281\ (kh/\mu)}$

$$\text{Flow efficiency} = \frac{\bar{p} - pwf - \Delta ps}{\bar{p} - pwf} = 1 - \frac{\Delta ps}{\bar{P} - pwf}$$

$\Delta p_s = 0.87$ m.s. (7)