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OPTIMIZING REINJECTION STRATEGY AT PALINPINON, PHILIPPINES BASED ON CHLORIDE DATA

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ABSTRACT

One of the guidelines established for the safe and efficient management of the Palinpinon Geothermal Field is to adopt a production and well utilization strategy such that the rapid rate and magnitude of reinjection fluid returns leading to premature thermal breakthrough would be minimized. To help achieve this goal, sodium fluorescein and radioactive tracer tests have been conducted to determine the rate and extent of communication between the reinjection and producing sectors of the field. The first objective of this paper is to show how the results of these tests, together with information on field geometry and operating conditions were used in algorithms developed in Operations Research to allocate production and reinjection rates among the different Palinpinon wells.

Due to operational and economic constraints, such tracer tests were very limited in number and scope. This prevents obtaining information on the explicit interaction between each reinjection well and the producing wells. Hence, the chloride value of the producing well, was tested to determine if use of this parameter would enable identifying fast reinjection paths among different production/reinjection well pairs. The second aim, therefore, of this paper is to show the different methods of using the chloride data of the producing wells and the injection flow rates of the reinjection wells to provide a ranking of the pair of wells and, thereby, optimize the reinjection strategy of the field.

INTRODUCTION

The Palinpinon Geothermal Field (Figure 1) is one of two producing steamfields currently operated by the Philippine National Oil Company (PNOC). The steam requirement of the 112.5 MWe commercial plant, known as Palinpinon 1 has been met by 21 production wells and 10 reinjection wells which accept wastewater by gravity flow. Figure 2 shows the surface reticulation system, the production and reinjection multi-wells pads, as well as the well tracks. The need to reinject waste liquid effluent has been primarily dictated by environmental constraint, which in the Philippines prohibit full disposal into the rivers that are used for field irrigation. In addition to this, the other benefits of injection, such as maintaining reservoir pressures and increasing thermal recovery from rocks have been recognized.

Although injection wells have been drilled at the periphery of the field, preferably at the identified outflows, initial chemical monitoring of the produced fluids showed increases in well reservoir chloride values (Figure 3). This has been interpreted as evidence of the return of reinjected fluids to the production sector. To maximize productivity of the reservoir and prolong the economic life of the field, guidelines for the safe and efficient management of the Palinpinon reservoir have been established. These include the requirements of:

1) minimizing fluid residence times in the surface and downhole piping while operating reinjection wells to prevent or minimize silica deposition of injected fluid that is supersaturated with respect to amorphous silica.

2) minimizing steam wastage due to varying steam demand and supply by prioritizing high enthalpy production wells during peak steam requirements and choosing injection wells with additional capacity.

3) adopting a production and reinjection well utilization strategy such that the rapid rate and magnitude of reinjection fluids returns leading to premature thermal breakthrough would be minimized, if not avoided.

Towards this objective, a comprehensive testing and monitoring programme was instituted. This programme includes fluorescein and radioactive tracer testing to determine interaction between the injecting and producing blocks.

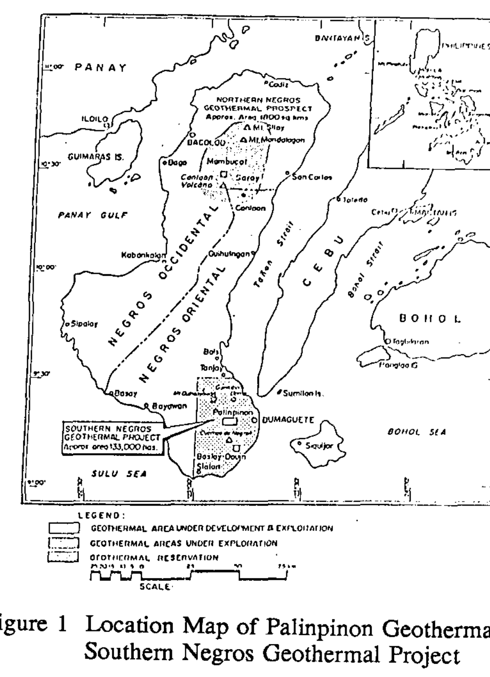

Figure 1 Location Map of Palinpinon Geothermal Field Southern Negros Geothermal Project

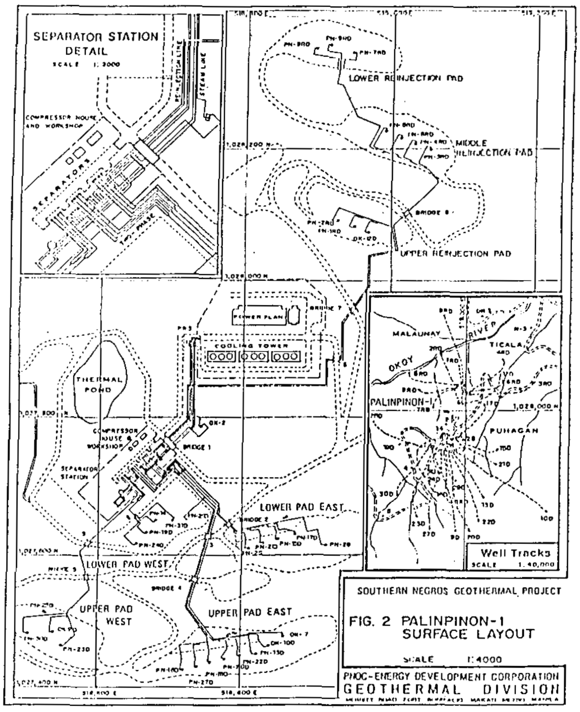

Figure 2 Palinpinon-1 Surface Layout

It is one aim of this paper to use the results of these tracer tests in algorithms of Operations Research to determine optimal production and reinjection rates among the different Palinpinon wells. However, since these tracer tests are limited, the other objective is to find another parameter that could be used in place of tracer return data in the optimization of production and reinjection strategy.

TRACER TESTS AT THE PALINPINON GEOTHERMAL FIELD

Table 1 shows the results of conducting fluorescein and radioactive tracer testing at Palinpinon 1. Sodium fluorescein dye was injected into OK-12RD, PN-1RD, and PN-9RD while radioactive Iodine-131 was injected into OK-12RD and PN-9RD. Amounts of the dye and radioactive tracer were increased with succeeding tests to expand the scope of the tests and overcome the limitations imposed by degradation of the tracers.

The results from Table 1 show that the eastern injection wells (OK-12RD, PN-1RD, and PN-6RD) communicate strongly with the eastern and central Puhagan wells such as PN-15D, PN-17D, PN-21D, PN-26, PN-28, and OK-7. The western injection well PN-9RD, likewise, interact with the western, southwestern, and central Puhagan wells such as PN-14, PN-19D, OK-9D, PN-23, PN-24D, PN-29D, PN-30D, PN-31D, OK-7, PN-26, PN-28, PN-16D, and PN-18D. Figure 4 shows the tracer breakthrough curve for OK-7 which had the earliest and strongest return during the PN-9RD tracer test. Coupled with interference testing and chemistry

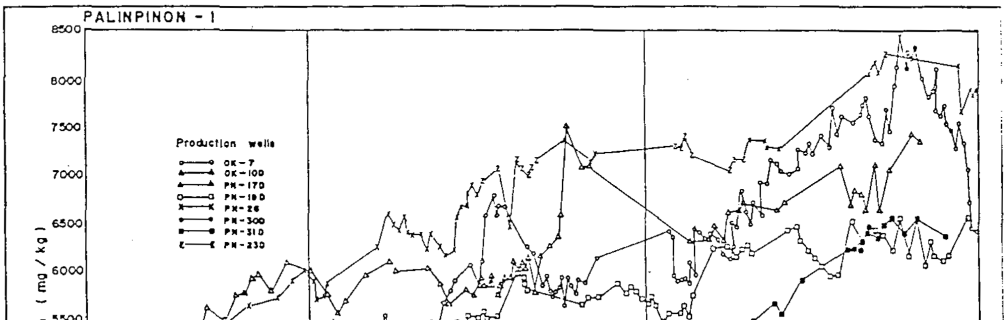

Figure 3 Reservoir Chloride vs Time

Table 1

Tracer Tests at the Palinpinon Geothermal Field

TRACER AMOUNT	RECIPIENT WELL (Inclusive Dates)	MONITORING WELLS, SPRINGS, RIVERS	RESULTS Positive Return	RESULTS Transit Time	RESULTS % Return
Iodine-131, 18.5 GBq (0.50 Ci)	OK-2 (15 Aug - 06 Sept 81)	OK-7, OK-12D, PN-13D PN-16D, OK-9D, OK-10D Ticala and Buhayan Springs	OK-7	16.0 days	0.23
			OK-12D	16.4 days	0.05
			PN-13D	16.2 days	0.10
Sodium Fluorescein 0.5 kg/test	OK-12RD (30 July - 02 Aug 83)	PN-6RD at different operating conditions	PN-6RD	.75-2.1 hours	8 - 55
Iodine-131, 20.2 GBq (0.545 Ci)	OK-12RD (03 Aug - 29 Aug 83)	OK-7, OK-10D, PN-15D, PN-17D, PN-21D, PN-26, PN-28, PN-29D, PN-3RD, PN-4RD, PN-6RD	OK-7	14.6 days	1.28
			OK-10D	13.8 days	1.35
			PN-15D	7.3 days	0.35
			PN-17D	3.9 days	8.22
				7.5 days	2.32
				10.5 days	2.52
			PN-28	6.0 days	0.58
			PN-21D	Traces on 4th and 9th day afte tracer injection	
			PN-26	Traces on 5th and 7th day afte tracer injection	
			PN-3RD	Very low traces	
			PN-4RD	Very low traces	
Sodium Fluorescein 2.0 kg	PN-1RD (28 Aug - 21 Sept 84)	OK-7, OK-9D, OK-10D, PN-15D, PN-16D, PN-17D, PN-18D, PN-19D, PN-23D, PN-24D, PN-29D, PN-30D, PN-31D, N-3, OK-2, RI 317/318, PN-3RD, PN-6RD, PN-9RD	PN-26	40.0 hours	
			PN-28	60.0 hours	
			OK-7	80.0 hours	
			OK-2	90.0 hours	
			PN-3RD	On downhole sample 27 hours after tracer injection	
			PN-6RD	On down hole sample 94 and 146 hours after injection	
			PN-9RD	On down hole sample 168 hours after injection	
Sodium fluorescein 10 kg Iodine-131, 67 GBq (1.81 Ci)	PN-9RD (26 Sept - 20 Oct 85)	OK-7, OK-9D, PN-16D, PN-17D, PN-18D, PN-19D, PN-23D, PN-26, PN-28, PN-29D, PN-30D, PN-31D RI 317/318	OK-7	5.7 days	29.20, 21.7*
			PN-29D	14.0 days	6.80, 4.6
			PN-26	11.0 days	3.90, 0.5
			PN-28	10.3 days	1.10, 0.3
			PN-18D	15.6 days	0.80, 1.6
			PN-30D	15.7 days	0.80, 1.6
			PN-23D	15.8 days	0.40, 1.6
			PN-31D	16.0 days	0.40, 1.6
			PN-16D	Tracer found in samples after 8-19 days	
			PN-19D	Tracer found in samples after 15-19 days	

*PNOC-EDC recalculated returns are in second column. Previous values for PN-26 and PN-28 believed to be erroneous due to innacurate flowrates used.

monitoring, results indicate fast interaction, too, of western injection wells PN-7RD and PN-8RD with the western and central Puhagan wells. Additional studies (PNOC-EDC, 1986) indicate that geological structures or faults are the preferred flowpaths of the reinjected fluids back to the producing wells.

From radioactive tracer testing, one can obtain the tracer breakthrough time, the peak tracer recovery time, the peak tracer concentration, and the fraction of tracer recovered. This presents an advantage over fluorescein testing where only breakthrough times and the quality (intensity) of the return were established during the test. This is why only the results of the radioactive tracer test were used for the algorithms in the optimization study as discussed later in this report.

Through this intensive chemical monitoring, tracer testing, as well as interference testing, injection and production wells with strong interactions have been identified; knowledge of which was employed to optimize the well utilization scheme. As an example, the northern and northeastern injection wells PN-2RD, PN-3RD, PN-4RD, and PN-5RD are considered "priority" in that they have exhibited minimal communications so far with the production wells. It is acknowledged that though almost all production wells produce reinjected fluid in varying proportions, the rate and magnitude of reinjection fluid returns are dependent on the combination of wells used for injection and production at any given time. It would be an advantage, therefore, to find a tool that would demonstrate or assess the interaction of a given injector/producer pair with time.

OPTIMIZATION STRATEGY

The results of the tracer tests, information on field geometry together with operating conditions were used to test algorithms in Operations Research to allocate reinjection and production rates in Palinpinon wells. These algorithms were modified by Lovekin (1987) to optimize injection scheduling in a geothermal field.

Essentially, under this strategy, the reservoir is idealized as a network of channels or arcs connecting each pair of wells in the field. The arc cost, c_{ij}, expresses the likelihood of thermal breakthrough resulting from the movement of a unit fluid from injection i to producer j. It consists of weighting factors which are taken from tracer return data, field geometry and field operating conditions as shown by Equation 1.

$$c_{ij} = \frac{1}{t_i} \frac{1}{t_p} C_p \cdot f \cdot \frac{1}{L^2} e^{sh} \cdot \frac{q_p}{q_{pt}} \frac{1}{q_{rt}} \qquad (1)$$

where

- t_i = initial tracer response, days
- t_p = peak tracer response, days
- C_p = peak tracer concentration, ℓ^{-1}
- f = fractional tracer recovery
- L = horizontal distance between wells, meters
- h = elevation difference between production and injection zones, meters
- s = scaling factor
- q_p = producing rate under operating conditions
- q_{rt} = injection rate during tracer testing

The results of the tracer tests demonstrate that the earlier the breakthrough or initial tracer response, the greater the tracer return, and the greater the likelihood for thermal breakthrough. Hence, the times of initial (t_i) and peak (t_p) tracer response are made to be inversely related to the arc cost c_{ij}. In contrast, the fraction of tracer recovered (f) and the peak tracer concentration (Cp) are made linear to the arc cost.

For a porous-media type of reservoir, the thermal recovery of injected fluid depends on the heat exchanged between the fluid and the rocks. Since this rock surface heat area is proportional to L^2, then the probability of thermal breakthrough is greater for smaller surface area. This means an inverse relationship between L^2 and the arc cost. The elevation difference (h) between the producing and injecting zone is made linear to the arc cost due to the fact that injected fluid, being cooler and denser would tend to sink down the reservoir. Hence, it is intuitive that a deep producing well would have a higher chance of communicating with an injection well, than a shallow producing well would. Since h could be positive (producing zone below the injection zone) or negative, it appears in the equation as an exponential term e^{sh}, with a scaling factor s to keep it from dominating the rest of the weighting factors.

In a similar manner, producing and injecting rates during the tracer tests (q_{pt} and q_{rt}), can also be made as weighting factors. A well which produces at a small rate and manifests positive tracer return would have a higher likelihood of being affected by injection returns than another well which is producing at a higher rate with similar returns. Therefore, q_{pt}, and with the same logic, q_{rt}, are inversely related to the arc cost.

It is to be emphasized that all the factors need not be used to get the arc costs. Some factors could be deleted, and others weighed or included depending on which ones the developer deem to be important on the basis of reservoir behavior and information.

The sum of the arc costs from a particular injection well to all the producing wells is its cost coefficient. The unknown or decision variable is the reinjection rate, q_{ri}, into injection well i. The product of the injection rate and the arc cost is the breakthrough index for the specific arc or injection/production pair of wells as expressed by Equation 2.

$$b_{ij} = c_{ij} q_{ri} \qquad (2)$$

The summation of breakthrough indices for all arcs is then the fieldwide breakthrough index B. Under the optimization strategy, it is this index which is the objective function that has to be minimized subject to well capacities and field operating constraints.

Two algorithms were used for optimization strategy:

1) linear programming which employs the simplex method, and
2) quadratic programming

Linear Programming

In the linear programming algorithm, the objective functions to be minimized are shown by Eqs. 3 and 4.

Minimize:

$$B_1 = \sum_{i=1}^{N_1} \sum_{j=1}^{N_2} c_{ij} q_{ri} \qquad (3)$$

subject to

$$q_{ri} \le q_{rimax}$$
$$\Sigma q_{ri} = Q_{rtot}$$
$$q_{ri} \ge 0 \qquad i = 1, N_1$$

Minimize:

$$B_2 = \sum_{i=1}^{N_1} \sum_{j=1}^{N_2} c_{ij} q_{pj} \qquad (4)$$

subject to

$$q_{pj} \le q_{pjmax}$$
$$\Sigma q_{pj} = Q_{ptot}$$
$$q_{pj} \ge 0 \qquad j = 1, N_2$$

where
N_1 = number of injectors
N_2 = number of producers
q_{ri} = injection rate into well i
q_{pj} = producing rate from well j
q_{rimax} = maximum permissible rate into well i
q_{pjmax} = maximum permissible rate from well j
Q_{rtot} = total required injection rate
Q_{ptot} = total required producing rate

In this algorithm, the mutual dependence of injection and production rates is accounted for by alternately exchanging their roles as decision variables and weighting factors.

Quadratic Programming:

On the other hand, the formulation for the second algorithm is shown by Equation 5.

Minimize:

$$B = \sum_{i=1}^{N_1} \sum_{j=1}^{N_2} c_{ij} q_{ri} q_{pj} \qquad (5)$$

where the variables and constraints are the same and combined as in the first formulation. In this approach, the interdependence of injection and production rates is explicitly acknowledged by treating both as decision variables and including them in the objective function as a product. Hence, the objective function becomes a quadratic and the problem is solved by a quadratic programming (QP) solver.

Preliminary Results Using Tracer Return Data

The results of the two radioactive tracer tests shown in Table 1 were used in the above algorithms. Specifically, the mean transit recovery time, the fraction recovered, the aerial and vertical separation between the injection and production pair of wells, the flowrates during the tracer tests, as well as the maximum flowrates of all the wells were used as input in the algorithms. In this test, it was assumed that only OK-12RD and PN-9RD are the reinjection wells. The problem calls for allocating the

Table 2

Allocation of Production Rates Among Palinpinon Wells Using Linear (LPAL) and Quadratic Programming (QPAL)

Qrtotal = 260 kg/s; Qptotal varies

L P A L 3						Q P A L		
Qptotal kg/s	Injectors	Qrinjected kg/s	Curtailed Producers	Qpcurtailed kg/s	Cost Coefficients	Injectors	Curtailed Producers	Qpcurtailed kg/s
930	OK-12RD	165	OK-7	Total	0.099200	OK-12RD	OK-7	Total
	PN-9RD	95	PN-17D	Total	0.046800	PN-9RD	PN-17D	Total
			PN-26	Total	0.013900		PN-26	Total
			PN-28	Total	0.009600		PN-28	Total
			PN-29D	Total	0.003900		PN-29D	Total
			PN-18D	3	0.003200		PN-18D	3
900	OK-12RD	165	OK-7	Total	0.099200	OK-12RD	OK-7	Total
	PN-9RD	95	PN-17D	Total	0.046800	PN-9RD	PN-17D	Total
			PN-26	Total	0.013900		PN-26	Total
			PN-28	Total	0.009600		PN-28	Total
			PN-29D	Total	0.003900		PN-29D	Total
			PN-18D	33	0.003200		PN-18D	33
850	OK-12RD	165	OK-7	Total	0.099200	OK-12RD	OK-7	Total
	PN-9RD	95	PN-17D	Total	0.046800	PN-9RD	PN-17D	Total
			PN-26	Total	0.013900		PN-26	Total
			PN-28	Total	0.009600		PN-28	Total
			PN-29D	Total	0.003900		PN-29D	Total
			PN-18D	Total	0.003200		PN-18D	Total
			OK-10D	19	0.001000		OK-10D	19
800	OK-12RD	165	OK-7	Total	0.099200	OK-12RD	OK-7	Total
	PN-9RD	95	PN-17D	Total	0.046800	PN-9RD	PN-17D	Total
			PN-26	Total	0.013900		PN-26	Total
			PN-28	Total	0.009600		PN-28	Total
			PN-29D	Total	0.003900		PN-29D	Total
			PN-18D	Total	0.003200		PN-18D	Total
			OK-10D	Total	0.001000		OK-10D	Total
			PN-31D	17	0.000640		PN-31D	17
750	OK-12RD	165	OK-7	Total	0.099200	OK-12RD	OK-7	Total
	PN-9RD	95	PN-17D	Total	0.046800	PN-9RD	PN-17D	Total
			PN-26	Total	0.013900		PN-26	Total
			PN-28	Total	0.009600		PN-28	Total
			PN-29D	Total	0.003900		PN-29D	Total
			PN-18D	Total	0.003200		PN-18D	Total
			OK-10D	Total	0.001000		OK-10D	Total
			PN-31D	Total	0.000640		PN-31D	Total
			PN-15D	2	0.000300		PN-15D	2
700	OK-12RD	165	OK-7	Total	0.099200	OK-12RD	OK-7	Total
	PN-9RD	95	PN-17D	Total	0.046800	PN-9RD	PN-17D	Total
			PN-26	Total	0.013900		PN-26	Total
			PN-28	Total	0.009600		PN-28	Total
			PN-29D	Total	0.003900		PN-29D	Total
			PN-18D	Total	0.003200		PN-18D	Total
			OK-10D	Total	0.001000		OK-10D	Total
			PN-31D	Total	0.000640		PN-31D	Total
			PN-15D	52	0.000300		PN-15D	52
650	OK-12RD	165	OK-7	Total	0.099200	OK-12RD	OK-7	Total
	PN-9RD	95	PN-17D	Total	0.046800	PN-9RD	PN-17D	Total
			PN-26	Total	0.013900		PN-26	Total
			PN-28	Total	0.009600		PN-28	Total
			PN-29D	Total	0.003900		PN-29D	Total
			PN-18D	Total	0.003200		PN-18D	Total
			OK-10D	Total	0.001000		OK-10D	Total
			PN-31D	Total	0.000640		PN-31D	Total
			PN-15D	Total	0.000300		PN-15D	Total
			PN-30D	30	0.000095		PN-30D	30

production rates among the different wells as the required total production rate decreases from 930 kg/s.

The results as shown by Table 2 indicate that the two approaches or algorithms give similar results. As the required total field load decreased, the producing rates was reduced and production wells were shut in one-by-one depending on its potential damage to the field as manifested by the injector/producer cost coefficient. The higher the cost coefficient, the more serious is the potential for thermal breakthrough. However, these cost coefficients which enable the explicit ranking of the wells are present only in the linear programming algorithm. Nevertheless, as seen from Table 2, the actual allocations provided by quadratic programming duplicate those of linear programming.

It can be concluded, therefore, that by knowing the arc costs, the programs obtain the optimal rate allocation for both injection and production wells.

USE OF CHLORIDE DATA

Due to economic and operational constraints, radioactive tracer cannot be injected into every reinjection well. Similarly, not all the production wells can be monitored during a tracer test. To find another parameter which can be used to optimize reinjection strategy, attention was turned to the reservoir chloride measurement of the production wells as shown by Figure 3. It has been established by the PNOC geochemists that the chloride values of a producing well can be used as an indication of the extent of reinjection returns to this well. The correlation or strength of the relationship between the chloride of a producing well and the flowrate of an injecting well was obtained in four different ways. Figure 4 shows in graphical form the different methods used to correlate the chloride values of a production well with the injection flowrates of an injection well. It should be remembered when comparing, that these numbers represent a relative assessment of the producer/injector pair potential for thermal breakthrough.

1. First, the correlation between the chloride value with time of a production well and the mass flowrate with time of an injection well was obtained (Figure 4a).

2. Second, the correlation between the chloride value with time of a production well and the total mass flowrate with time of an injection well was calculated (Figure 4b).

3. Third, the correlation between the deviation of the chloride value of a production well from the best fit line and the flowrate rate of an injection well was computed (Figure 4c).

4. Lastly, the chloride value with time of a production well was expressed as a linear combination of the mass flowrates of the injection wells.

The first method (Figure 4a) of chloride-flowrate correlation stems from the observation that the chloride values of a production well are affected when particular injection wells are disconnected from or hooked on line. If an injection well communicates strongly with a production well, then putting this injection well on line is usually followed by a substantial increase in the chloride measurements of the affected well. Once it is removed from service, there is an accompanying decrease in the chloride data of the producing well.

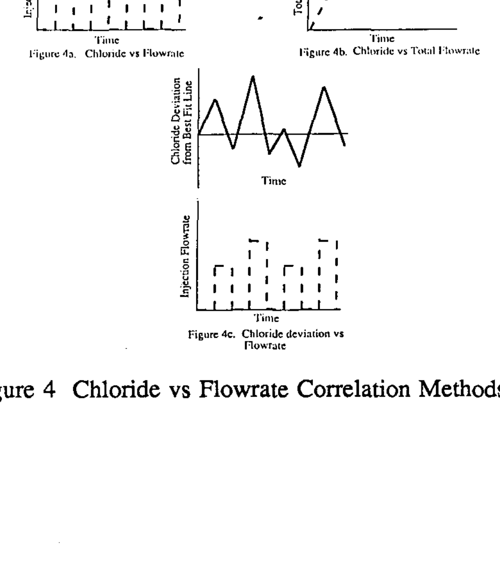

Figure 4 Chloride vs Flowrate Correlation Methods

In the second method (Figure 4b), what is examined is the relationship between chloride and the total flowrate. Since the chloride value of a production well at a particular time is the cumulative effect, it is reasonable to see the relationship between this chloride value and the total flowrate of the injection well. Given the hypothetical case of an injection well affecting strongly a production well, the plots of the two variables with time would be similar to Figure 4b.

On the other hand, it is also desirable to examine the relationship between the magnitude of the increases in chloride value of a production well with the flowrate of an injection well. Going back to the hypothetical case, it would be logical to expect that the effect of a high injection rate would be a greater step change in the chloride value of the production well. The magnitude of this change is measured by the deviation of the chloride value from the best fit line and this deviation is then correlated with the injection flowrate at that time (Figure 4c).

The effect of a particular injection well on a certain production well can be concluded unambiguously only when all other factors are held constant (such as injection flowrates of other injection wells and producing rates of all other wells are unchanged). This is complicated by the fact that a single injection well could interact with more than one production well. As a consequence, the net effect on a production well at a particular time interval would be due to the effects of the particular injection wells which were active in the same time interval. To take this into account, the last method seeks to express the chloride value of the production well as a linear combination of the injection flowrates of all the active reinjection wells at the concerned time. This is illustrated by Equation 6.

$$Cl_i = a_o + \sum_{j=1}^{n} a_j q_j \qquad (6)$$

where Cl_i = chloride value of well i at time t
a_o = initial chloride value at time t
a_j = correlation coefficient between production well i and injection well j
q_j = mass flowrate of injection well j
n = number of injection wells

The system of linear equations is put in matrix form and then solved simultaneously by a matrix solver like the Gauss-Jordan method of elimination.

<u>Results of the Chloride Data Methods</u>

The plots of the first three chloride methods are shown in Figures 5 to 12 using the wells OK-7, PN-9RD, PN-28 and PN-2RD. The first method is demonstrated by Figures 5 and 6, the second by Figures 7 and 8, and the third by Figures 9 and 10. Figures 11 and 12 have been included for comparison.

Figure 5a reflects the increase in monthly chloride values of well OK-7 and Figure 5b shows the monthly injection flowrates of PN-9RD. For an injector/producer pair with strong communication, it has been observed that the crests and troughs of the injection plot usually coincide with those of the producing well. This is reflected in high correlation coefficients during these times as demonstrated by Figure 6a. In this case, this would infer and confirm that there is good communication between OK-7 and PN-9RD. Figure 6b exhibits the effect if the correlation is calculated with a shift in time of the chloride values of OK-7. This was done to accommodate the reasoning that the increase in chloride value is an effect, and that there could be a lag or delay in the response of the producing well. In spite of the shift, the general trend of the correlation plot remains the same.

Figure 7b shows the plot of the cumulative flowrate with time of PN-9RD. The correlation with time of the chloride data with total rate shown in Figure 8 remain remarkably high throughout. The same pattern has been demonstrated by the rest of the OK-7/injection well pairs. The other plots of producing/injecting pairs show that the general trend for a particular production well remains the same with almost all the injection wells. This would indicate that this method can not be used to assess and differentiate the relationship between a producer and an injector.

Figure 9a is the same plot of OK-7 monthly chloride but with the dashed line representing the linearly regressed line to this curve. The deviations from this best fit line are plotted in Figure 9b and the correlation between the deviation and injection rate is shown in Figure 10. It can be seen that this plot of Figure 10 (Cldev-flowrate) and that of Figure 6 (Cl-flowrate) are similar.

Figures 11a and 11b show the chloride values of PN-28 and the flowrates of PN-2RD. These are correlated and the results plotted in Figure 12. One would note that the correlation values remain negative implying a lesser degree of interaction or communication between PN-28 and PN-2RD. When Figure 12 is compared with that of Figure 6, both being chloride-flowrate correlation, the immediate disparity in the relationship between OK-7/PN-9RD and PN-28/PN-2RD can be concluded.

Table 3 gives a tentative summary of the coefficients obtained from the four chloride methods. The method of chloride-total rate correlation (the second method) has been disregarded and, therefore, not included in this tabulation. For the linear combination method, the table only shows the correlation taken for the whole data set. For the chloride-rate correlations, the numbers chosen were either the average or those taken at the time the injection well has stopped injecting. The table shows:

1) In slightly more than half of the tabulated results, the calculated chloride-flowrate correlation is similar and very close to that of the chloride deviation-flowrate correlation. When only the signs of the correlation are compared, this increases to about 70%.

2) In general, the relationship shown by the linear combination coefficients agree with the observed relationships. For example, there is a high coefficient of correlation of OK-7 and PN-26 with PN-9RD, PN-8RD, and PN-1RD.

The limitation imposed by the two chloride-rate correlation methods (first and third) as shown by the dashed line is due to the fact that during the time considered the reinjection well was not injecting. Similarly, the linear combination method fails when the matrix is singular and no solution to the system of linear equations can be found.

A detailed study is ongoing and there is a need to examine the criteria for choosing which numbers best represent the relationship of injector/producer pair.

SUMMARY AND CONCLUSIONS

The tracer return data, together with field geometry and operating conditions have been used to allocate production and injection rates among the Palinpinon wells using algorithms in Operations Research.

The theory behind the optimization strategy is that the reservoir can be visualized as a network of arcs connecting injector to producer. Each arc has a potential for thermal breakthrough caused by fluid flow from injector to producer and this potential is measured by the arc cost. The methods for optimization make use of linear programming and quadratic programming where the objective function to be minimized is the fieldwide breakthrough index defined to be the product of the arc cost and the flowrate.

The results of allocation are the same for both linear and quadratic programming. However, cost coefficients which provide a ranking of the injector/producer pair according to the potential for thermal breakthrough is provided only in linear programming.

Chloride was examined as another parameter for optimization since it has been observed to be an indicator of the extent of reinjection returns to a producing well. Four different methods of finding the correlation between the chloride value and the flowrate were examined. In general, there has been agreement between the chloride-rate correlation and the chloride deviation-rate correlation. The linear combination method also shows encouraging signs. However, there is a need to examine the factors behind the disparities in the results. Nevertheless, the initial results of the study have been encouraging and points out that the correlation between chloride and flowrate can be used as arc costs in optimizing production and reinjection strategy.

REFERENCES

1. Lovekin, J., and Horne, R.N.: "Optimization of Injection Scheduling in Geothermal Fields," G.R.C. Transactions, 11, 1987.

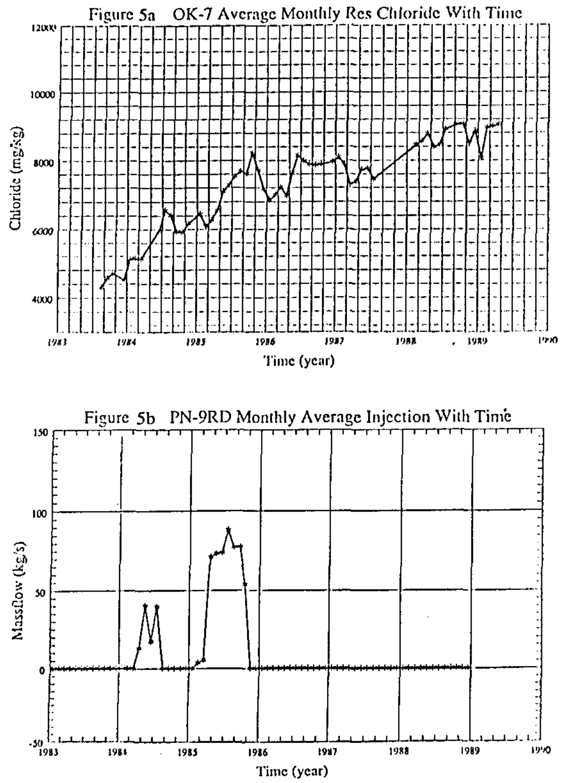

Figure 5 OK-7 Chloride and PN-9RD Flowrate

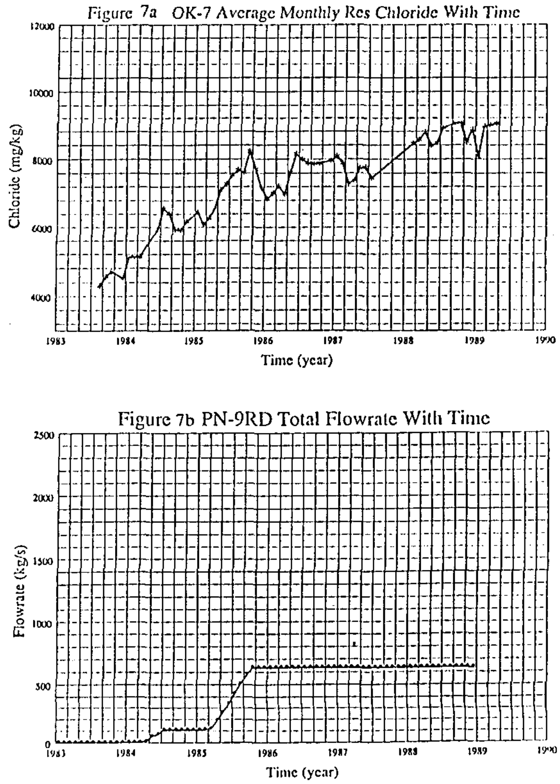

Figure 7 OK-7 Chloride and PN-9RD Total Flowrate

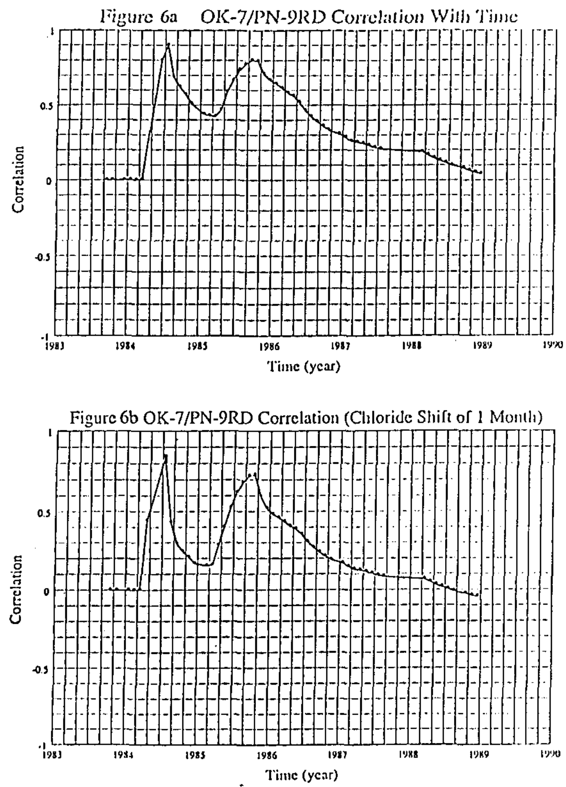

Figure 6 OK-7/PN-9RD Chloride-Flow Correlation

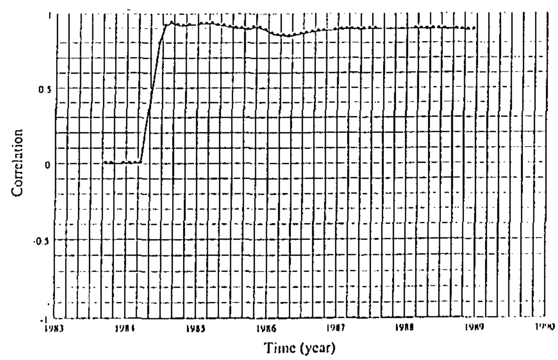

Figure 8 OK-7/PN-9RD Cl-Total Fow Correlation

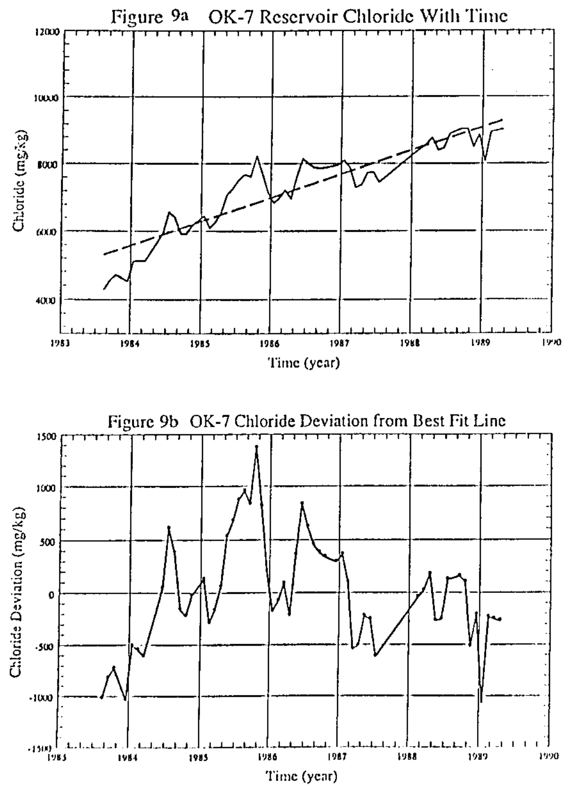

Figure 9 OK-7 Chloride and Deviation

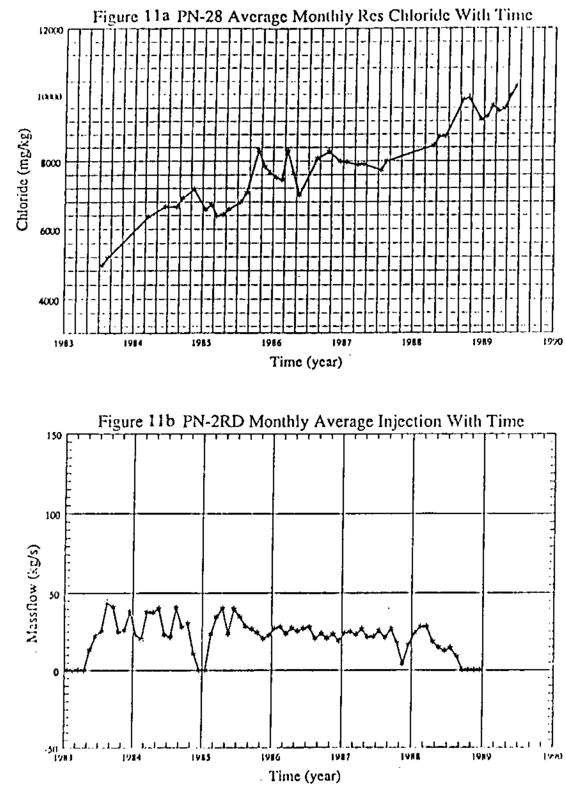

Figure 11 PN-28 Chloride and PN-2RD Flowrate

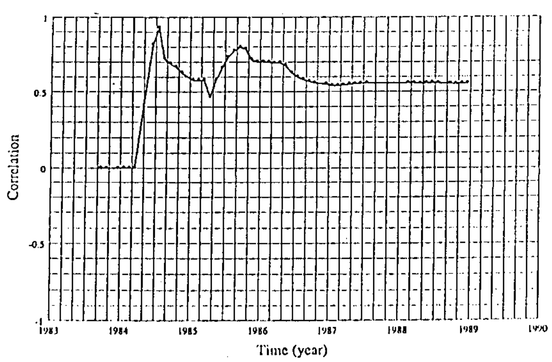

Figure 10 OK-7/PN-9RD Cldeviation-Flow Correlation

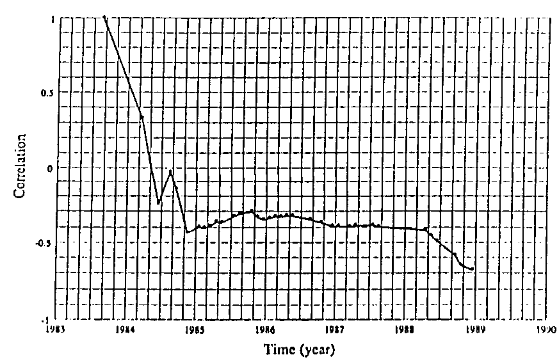

Figure 12 PN-28/PN-2RD Chloride-Flow Correlation

Table 3
Summary of Chloride - Flowrate Correlation

PRODUCTION WELL	METHOD	REINJECTION WELLS								
		PN-1RD	PN-2RD	PN-3RD	PN-4RD	PN-5RD	PN-6RD	PN-7RD	PN-8RD	PN-9RD
OK-10D	Cldev-Flow Corr	0.4320	-0.1310	-0.2740	-0.3800	-0.5690	0.3240	0.3590	-0.0330	-0.3910
	Cl-Flow Corr	0.3420	-0.2850	-0.0600	-0.3520	-0.4560	0.3320	0.4190	-0.0400	-0.3890
	Linear Comb Coeff	4.0440	-11.5100	1.7370	2.8710	-7.6590	4.1940	5.2960	2.6470	1.8320
OK-7	Cldev-Flow Corr	-0.1650	-0.1580	0.0270	0.4680	0.6140	-0.5050	0.9300	0.8160	0.9260
	Cl-Flow Corr	-0.4840	-0.4110	0.6370	0.4600	0.7790	-0.1310	0.9050	0.3730	0.9000
	Linear Comb Coeff	11.9300	-21.9200	28.5600	5.0000	11.2100	8.1530	-6.8300	20.9400	29.3800
PN-15D	Cldev-Flow Corr	0.2420	0.1510	-0.4720	-0.6670	-0.5340	0.3950	-0.4150	-0.5100	-0.7190
	Cl-Flow Corr	-0.2660	-0.5452	0.6250	0.5820	0.7840	0.3470	0.2620	0.5110	0.3040
	Linear Comb Coeff	12.9800	-19.0200	37.1400	-1.5330	-6.5890	5.3900	-0.2979	11.0600	0.2206
PN-26	Cldev-Flow Corr	0.0910	-0.1440	0.3050	0.3010	0.5460	-0.2830	0.7950	0.4000	0.5000
	Cl-Flow Corr	0.1150	-0.1260	0.7550	0.4520	0.5380	-0.3860	0.8010	0.1910	0.4730
	Linear Comb Coeff	*9.4090*	*-14.7200*	*25.2200*	*5.4490*	*5.4950*	*7.6020*	*-6.2060*	*21.3000*	*17.0900*
PN-28	Cldev-Flow Corr	0.4480	-0.1720	-0.0130	-0.0590	-0.0640	0.2230	0.5000	-0.2130	-
	Cl-Flow Corr	-0.0190	-0.4050	0.6790	0.5600	0.5320	0.2670	0.7470	-0.2010	-
	Linear Comb Coeff	9.7210	-8.9670	22.6100	-4.6030	15.1300	8.7520	-1.4170	-0.3865	-
PN-30D	Cldev-Flow Corr	-0.0840	-0.2100	-0.1630	0.0040	-0.1020	0.1720	-	-0.2130	-
	Cl-Flow Corr	-0.0900	-0.2470	-0.1620	-0.0640	-0.1020	0.1950	-	-0.2010	-
	Linear Comb Coeff	1.0040	-7.3590	4.7760	7.5970	-5.4280	1.7240	-	-0.3865	-