Title

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Publication Date

1978-06-01

Presented at the Geothermal Resources
Council 1978 Annual Meeting, Hilo, Hawaii,
July 25-28, 1978

LBL-7064

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June 1978

Prepared for the Division of Geothermal Energy of the
U. S. Department of Energy under Contract W-7405-ENG-48

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INTRODUCTION

It has become generally accepted that reinjection will be necessary for optimizing the exploitation of a geothermal field. Not only does this afford a way to solve the problem of disposal of cooled geothermal brine, but it also serves the purpose of maintaining reservoir pressure, thus reducing possible subsidence effects, and sustaining production flow rates. In addition, reinjection enhances thermal energy extraction from the reservoir rocks.

However, reinjection creates a zone of relatively cold water around each injection well that will grow with time and eventually reach the production wells. When the cold water appears ("breaks through") in the producing wells, the efficiency of the operation may be drastically reduced. It is therefore important to design the system of injection wells to prevent cold water breakthrough before a specified time. For a given production field, it is essential that both the location and flow rates of the injection wells be optimized.

In the present paper the results of an initial study of possible reinjection patterns for the Cerro Prieto geothermal field, Baja California, Mexico are discussed. First, the numerical model and assumptions made are described, then the various cases we studied are presented. The resulting data indicate what may be expected from different reinjection schemes and may provide useful guidelines for future reinjection operations at Cerro Prieto and other liquid-dominated geothermal fields.

Analytic Model Used

In this study a single two-dimensional steady-state flow model based on the work of Gringarten and Sauty[1] has been used. This model, which assumes constant fluid property parameters, is capable of simulating a system of many production and injection wells in a horizontal aquifer system. In such a system, steady-state fluid flow is expected within a relatively short time. Then the fluid velocity may be written down explicitly as a sum of contributions from each well. Natural regional flow in the reservoir can also be included very simply. Along each flow line thus constructed, the temperature is evaluated by considering heat transfer with bedrock and caprock, and by assuming instantaneous local thermal equilibrium between fluid and rock matrix. It is true that more sophisticated numerical models are available; but due to their complexity, nearly all of these are limited to the study of a small number of wells, or wells arranged in a highly symmetrical pattern. The simpler model adopted for the present work has the great advantage of being able to readily handle a system of many production and injection wells located throughout the field.

Calculations and Results

At Cerro Prieto around sixteen production wells are directing steam to the power plant and the separated brine is disposed to a large evaporation pond. This study explores the effect of reinjecting part of the produced water into the reservoir. At the present time a total of about 2,750 m^3/hr of brine-steam mixture is being produced.

In our calculations we assumed that 50% of the produced fluids, i.e., 1,375 m^3/hr, will be reinjected into 3 or 4 wells. The thickness of the actual aquifer varies from place to place. We do not have sufficient data to obtain a typical average thickness. However, we assume a reasonable value of 250m. The breakthrough time at the production wells, i.e., the time it takes for cold water to reach the production wells, is simply proportional to this thickness. Further field tests are now being performed at Cerro Prieto to establish the characteristics of this geothermal system. As more data come in and as the geological model of the field is improved, a more detailed analysis will be made.

Figure 1 shows the positions of all the wells used in the study. A well label beginning with M represents a currently existing well. A well label beginning with X represents a hypothetical reinjection well yet to be drilled and tested for injection. Only three or four of the wells are used for injection in any particular case. Thus not all the wells indicated are used at the same time. The production wells indicated in the figure are those currently used to supply steam to the Cerro Prieto power plant. They are located toward the northeast next to the railroad. Note that wells M-11 and M-42 are somewhat separated from the rest of the producing wells M-3 and M-7. This will have certain implications if M-3 and M-7 are used for reinjection, as is shown below.

Altogether 13 alternative reinjection schemes have been studied. Eight of these assume that we basically use the presently available wells outside the production region for reinjection. The other five cases assume a line of four injection wells southwest of the production area. The parameters assumed in these calculations are listed in Table 1, and the results are summarized in Table 2. The first and second breakthrough times shown in Table 2 are the earliest times required for cold water to break through at any two production wells the numbers of which are indicated in brackets. A brief description of these runs is given as follows:

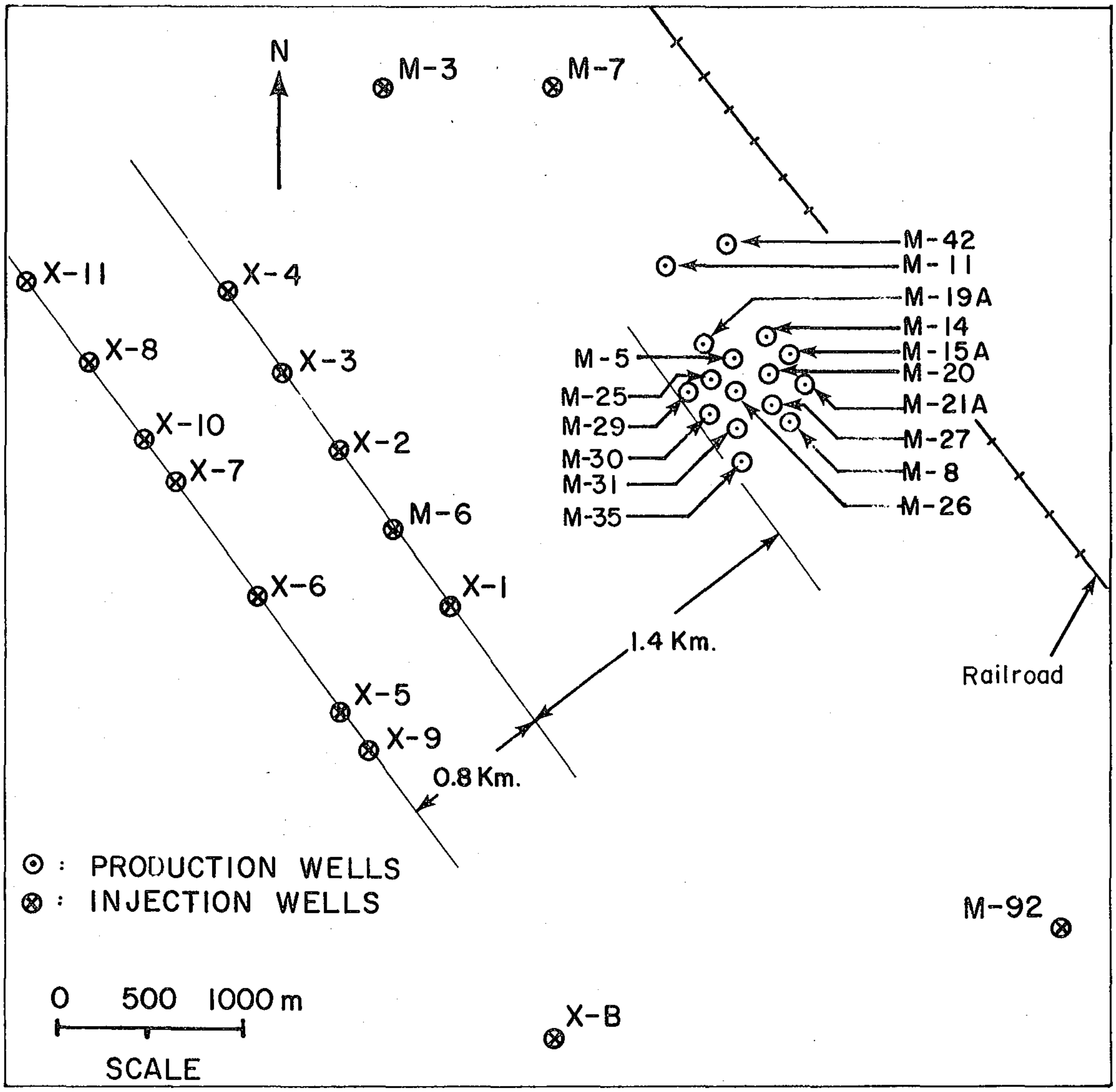

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Figure 1: Relative locations of the production and injection wells used.

Table 1

CONSTANTS USED

Rock thermal conductivity = 0.006 cal/cm/sec/°C

Initial reservoir temperature = 300°C

Injected water temperature = 100°C

Aquifer thickness = 250m

Aquifer porosity = 19%

Rock volumetric heat capacity = 0.5 cal/cm^3/°C

Density of brine = 1 g/cm^3

Table 2

SUMMARY OF REINJECTION STUDIES FOR THE CERRO PRIETO GEOTHERMAL FIELD

RUN	INJ. WELLS	INJECTION RATE (m^3/hr)		NO. PROD. WELLS	PRODUCTION RATE (m^3/hr)		BREAKTHROUGH TIME (years)		COMMENTS
		each	total		each	total	1st (well)	2nd (well)	
1	M-3	343.75	1,375	16	171.88	2,750	82 (M-19A)	107 (M-5)	
	M-6	343.75					60 (M-30)	61 (M-29)	
	M-7	343.75					32 (M-11)	32 (M-42)	
	M-92	343.75					169 (M-25)	170 (M-8)	
2	M-3	343.75	1,375	16	171.88	2,750	79 (M-11)	84 (M-19A)	
	M-6	250.00					62 (M-29)	64 (M-25)	
	M-7	187.50					37 (M-11)	56 (M-5)	
	M-92	593.75					140 (M-8)	140 (M-27)	
3	M-3	343.75	1,375	16	171.88	2,750	73 (M-11)	92 (M-19A)	
	M-6	343.75					56 (M-29)	60 (M-25)	
	M-92	687.50					131 (M-8)	133 (M-27)	
4	M-3	250.00	1,375	16	171.88	2,750	80 (M-11)	101 (M-19A)	New injection well introduced, X-B
	M-6	187.50					62 (M-29)	69 (M-25)	
	X-B	375.00					143 (M-31)	146 (M-35)	
	M-92	562.50					137 (M-8)	138 (M-27)	
5	M-3	343.75	1,375	16	171.88	2,750	74 (M-11)	89 (M-19A)	
	X-B	468.75					134 (M-31)	143 (M-35)	
	M-92	562.50					133 (M-8)	136 (M-27)	
6	M-3	250.00	1,375	16	171.88	2,750	80 (M-11)	97 (M-19A)	
	X-B	562.50					126 (M-31)	132 (M-35)	
	M-92	562.50					131 (M-8)	136 (M-27)	
7	M-3	343.75	1,375	14	196.43	2,750	85 (M-19A)	89 (M-25)	M-11, M-42 not used for production
	M-6	343.75					56 (M-30)	61 (M-26)	
	M-7	343.75					47 (M-19A)	48 (M-5)	
	M-92	343.75					163 (M-8)	164 (M-27)	
8	M-3	343.75	1,375	15	183.33	2,750	86 (M-19A)	102 (M-25)	M-11 not used for production
	X-B	468.75					132 (M-31)	137 (M-35)	
	M-92	562.50					131 (M-8)	134 (M-27)	
9	X-1	343.75	1,375	16	171.88	2,750	45 (M-30)	47 (M-25)	New injection wells introduced X-1, X-2, X-3
	M-6	343.75					45 (M-29)	51 (M-26)	
	X-2	343.75					55 (M-25)	56 (M-29)	
	X-3	343.75					81 (M-19A)	>200 (----)	
10	X-1	187.50	1,375	16	171.88	2,750	53 (M-30)	56 (M-26)	
	M-6	187.50					50 (M-30)	54 (M-26)	
	X-2	437.50					49 (M-29)	53 (M-25)	
	X-3	562.50					68 (M-19A)	78 (M-20)	
11	M-6	187.50	1,375	16	171.88	2,750	54 (M-30)	87 (M-26)	New injection well introduced, X-4
	X-2	187.50					54 (M-29)	60 (M-25)	
	X-3	437.50					63 (M-25)	64 (M-29)	
	X-4	562.50					87 (M-19A)	97 (M-11)	
12	X-5	343.75	1,375	16	171.88	2,750	90 (M-30)	95 (M-31)	New injection wells introduced X-5, X-6, X-7, X-8
	X-6	343.75					88 (M-29)	90 (M-25)	
	X-7	343.75					110 (M-25)	112 (M-20)	
	X-8	343.75					168 (M-19A)	>200 (----)	
13	X-9	343.75	1,375	16	171.88	2,750	93 (M-30)	95 (M-31)	New injection wells introduced X-9, X-10, X-11
	X-6	343.75					91 (M-29)	93 (M-25)	
	X-10	343.75					125 (M-25)	144 (M-20)	
	X-11	343.75					>200 (----)	>200 (----)	

Run #1: Water is injected into the existing wells, M-3, M-6, M-7, and M-92, at the rate of 343.75 m^3/hr at each one. On the other hand the 16 production wells, operating at the same rate, produce a total of 2,750 m^3/hr. The results indicate that the first breakthrough of cold water will occur at well M-11 after about 32 years, due to cold water from well M-7. Note that the second breakthrough does not occur until 18 years later. Thus, if M-11 is discarded as an active production well after approximately 32 years, production from the other wells remains undisturbed for an additional 18 years. During these 18 years, M-11 will serve as a screening well[2].

Run #2: In this run the injection rates in wells M-7 and M-6 are smaller than in run #1, but the total injection rate of 1,375 m^3/hr is maintained. As expected, this variation improves the breakthrough times from wells M-7 and M-6, but only by 5 and 2 years respectively.

Run #3 (Figure 2): In the first two runs, injection well M-7 was determined to be the critical well with respect to breakthrough times. Therefore, M-7 is omitted in this run and the total injection rate is maintained by doubling the injection rate at M-92. The results obtained show considerable improvement, as breakthrough occurs at well M-29 after 56 years.

Run #4 (Figure 3): For this run, a fourth injection well X-B is added to the three employed in run #3. The injection rates are unequally distributed, and the total injection rate is unchanged. Again, the first breakthrough occurs at M-29 as brine injected at M-6 arrives 62 years after injection began. Secondary breakthrough of brine from well M-6 arrives at M-25 7 years later.

Run #5: In this run, well M-6 is not used, and the brine is injected into M-3, X-B and M-92 at rates of 343.75, 468.75 and 562.50 m^3/hr, respectively. The first breakthrough occurs at well M-11 after a 74 year period of injection, and the second occurs 15 years later at M-19A. Both breakthroughs are due to the injection at well M-3.

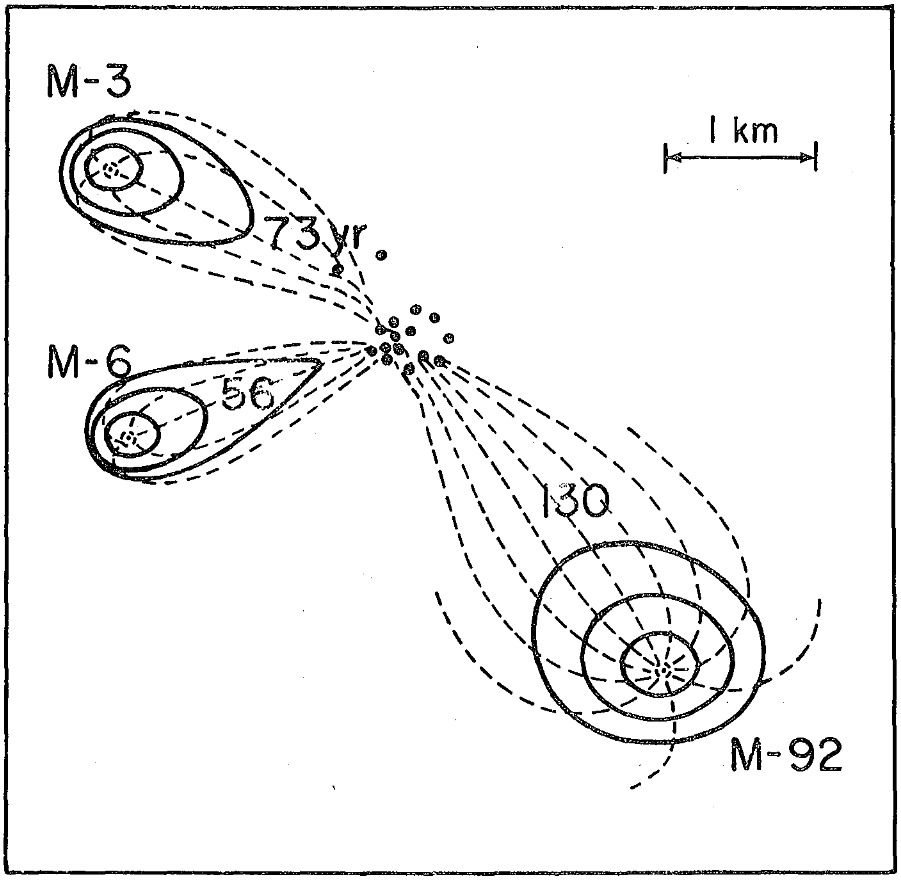

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Figure 2: The brine flow characteristics for run #3. The dotted lines are streamlines and the solid lines are the thermal fronts, after 5, 20 and 50 years of injection. The numbers indicate the first breakthrough time in years.

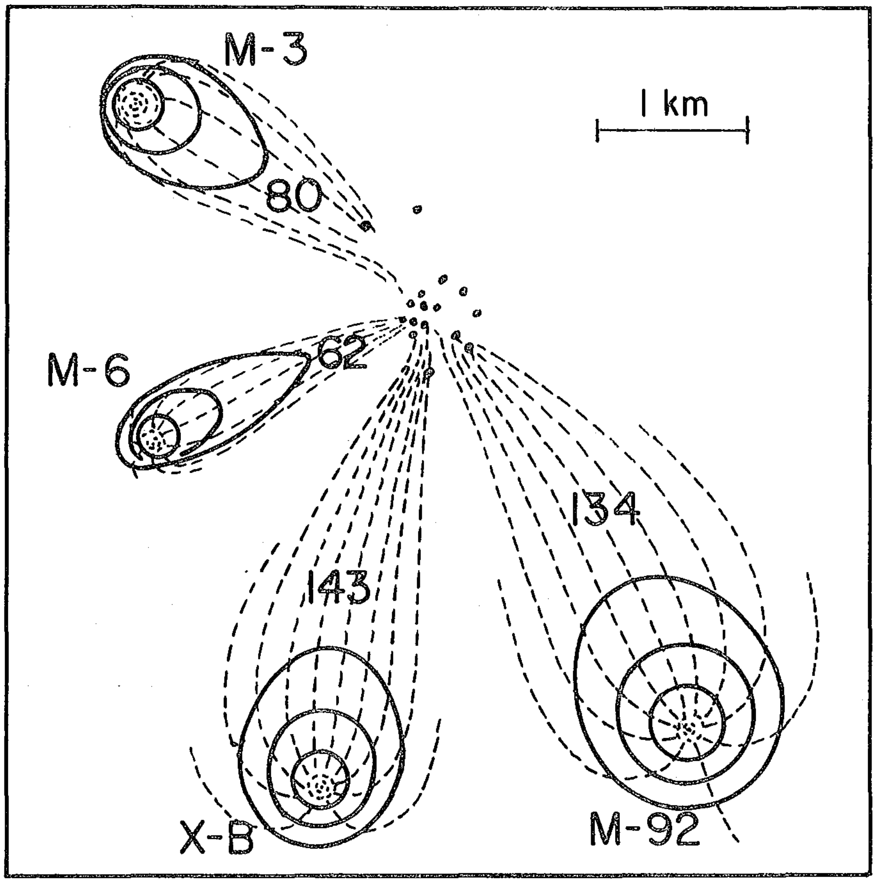

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Figure 3: The brine flow characteristics for run #4.

Run #6: For this run, the same injection-production scheme as in the previous run, is used. The only difference is the decrease of the injection rate at M-3. In this case, the breakthrough occurs at M-11, 80 years after injection begins, thus indicating some improvement in the breakthrough times.

Run #7: In this run, only 14 production wells are employed, the wells M-11 and M-42, are considerably closer to injection well M-7 than are the other 14 (see Figure 1) and have been omitted in this run to avoid early breakthrough times. However, the total production rate of 2,750 m^3/hr remains unchanged. In all other aspects this run is identical to run #1. In a comparison between the two runs (#'s 1 and 7), the earliest breakthrough time is increased from 32 to 47 years.

Run #8: This run is identical to run #5, except that M-11 is omitted as a production well. Comparison with run #5 shows a 12 year improvement in the first breakthrough time, resulting in 86 years of undisturbed production.

Run #9: This case is in the first of a series of runs in which injection is made along a line of wells southwest of the present production area. In this run wells X-1, M-6, X-2 and X-3 are injected at equal rates. The 16 production wells operate at a total rate of 2,750 m^3/hr. Breakthrough occurs after 45 years of injection, as brine from wells X-1 and M-6 arrives at wells M-29 znd M-30.

Run #10: The well pattern used in the previous run is repeated here. The injection rates at X-1 and M-6 are decreased, but increased at X-2 and X-3. However, the total injection rate is maintained. In this run there is minor improvement (5 years) in the breakthrough time.

Run #11: For this run, a new injection well, X-4, is introduced (see Figure 1), and injection well X-1 is dropped. Otherwise, run #11 is identical to run #10. The breakthrough occurs after 54 years, so only minor improvement is found in the breakthrough time (by 4 years).

Run #12 (Figure 4): In this run the use of injection wells X-5, X-6, X-7, and X-8, which are positioned farther from the production area than those of the last runs is considered. The breakthrough times are consequently longer, with the shortest breakthrough occuring 90 years after injection began.

Run #13: For this run, the conditions are the same as those of run #12, but different spacings are used between the injection wells. The results indicate minimal change in breakthrough times when compared with run #12.

Summary and Conclusions

Under the assumptions adopted in these studies, the preliminary results suggest that reinjection of cold brines into the Cerro Prieto reservoir can be safely accomplished without a premature reduction in the temperature of the produced fluids. If the presently available wells, M-3, M-6, and M-7, and M-92, are used for injection, the productive life of the field is strongly dependent upon well M-7. The use of M-7 would probably limit undisturbed production to approximately 30 years; whereas, replacing M-7 by an injection well further away from the production area would lengthen the productive life of the field to over 50 years.

The results from the runs involving brine injection into wells placed along a straight line southwest of the production area (including well M-6) indicate that breakthrough of cold water should not occur for at least 50 years. When the injection line is moved farther away from the production area, the productive life of the geothermal field is significantly increased. In general, cold water breakthrough time is strongly dependent on the distance of the production wells from the closest injection well. On the other hand, varying the relative flow rates among the injection wells does not change the breakthrough times by more than a few years. One point to note is that, as colder water is injected into the reservoir, it is heated by the rock-matrix through which it passes. Thus the hydrodynamic front, corresponding to the mass of injected water,

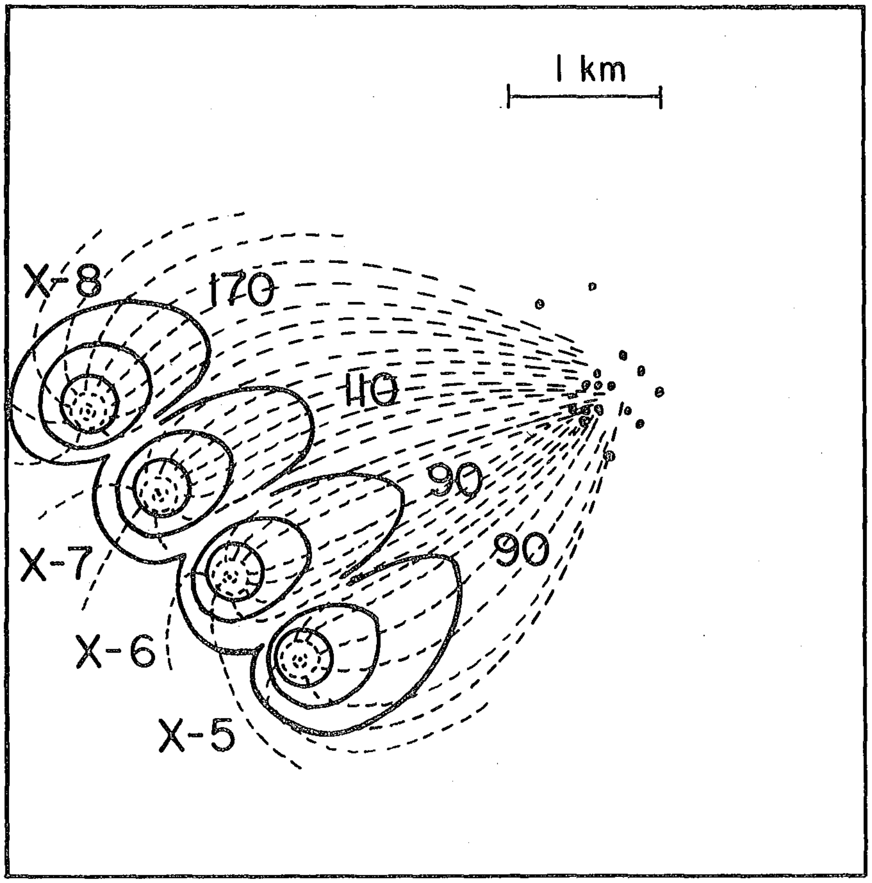

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Figure 4: The brine flow characteristics for run #12.

precedes the thermal front across which the change of water temperature occurs. (The lag of the temperature fron behind the injected fluid front depends on well distribution and reservoir properties.) Since the molecules of injected brine follow the hydrodynamic front, if one tags the injected fluid with a tracer, the approach of the cold front may then be predicted by periodic chemical analysis of the produced waters. This would provide time for remedial actions if necessary.

The results presented in this paper should be regarded as rough estimates, since they are based on the assumption that the Cerro Prieto reservoir can be simulated by an homogeneous horizontal 250 meter-thick aquifer. They will be updated as a better understanding of the field is achieved. Furthermore, in practical cases, we need to consider (a) the injectibility of the reinjection wells, i.e. whether they are able to accept a given flow rate; and (b) the chemical compatibility of injected and native waters. Research to address these problems is underway.

References

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+ Work performed under the auspices of the U.S. Department of Energy