PREDICTING THE RATE BY WHICH SUSPENDED SOLIDS PLUG GEOTHERMAL INJECTION WELLS

L. B. Owen, P. W. Kasameyer, R. Netherton, and L. Thorson
University of California
Lawrence Livermore Laboratory
P. O. Box 808
Livermore, California 94550

Standard membrane filtration tests have been used by the oil industry for more than 20 years to evaluate injection well performance. Published analytical models are also available for relating filtration data to injector lifetimes. We have utilized these techniques to evaluate injection at the Salton Sea Geothermal Field, Southern California. Results indicate that direct injection into reservoir zones with primary porosity is not feasible unless 1 μm or larger particulates formed during or after the energy conversion process are removed.

Injection Rationale

Commercialization of geothermal resources in the United States will require injection as the preferred means of waste effluent disposal. Prevention of surface and groundwater pollution is an obvious rationale for waste injection. Reservoir pressure- and temperature-maintenance and subsidence control may also, in many instances, mandate subsurface disposal. When evaluating geothermal injection systems, advantage can be taken of the extensive experience gained by the oil industry during the last 20 years in the design and operation of massive waterflood operations.

Potential injection problems can be grouped with respect to well completion techniques, casing corrosion and waste effluent chemistry (Jordan et al., 1969). This paper deals with evaluation of injection problems at the Salton Sea Geothermal Field (SSGF) caused by suspended solids formed during or after the energy conversion process.

WORK PERFORMED UNDER THE AUSPICES OF THE U.S. DEPARTMENT OF ENERGY, CONTRACT NO. W-7405-ENG-48.

The work was carried out as part of the Lawrence Livermore Laboratory Industrial Support Program which provides technological support for the joint Magma Power-San Diego Gas and Electric Company-DOE 10 mw Geothermal Loop Experimental Facility (GLEF) located in the SSGF (Austin et al., 1977; Quong et al., 1977).

Analytical Method

Barkman and Davidson (1972) developed quasi-steady-state analytical solutions for calculating the effect of suspended solids on a porous medium. The models require injection well geometry, formation characteristics, suspended solids concentration and filter cake permeability as input data. We used the open-hole solution for injector failure by filter cake build-up on the porous formation surface (no invasion) to arrive at a conservative estimate of injector half-life:

$$t_{1/2} = \frac{3\pi r_w^2 h \quad (\rho_c/\rho_w)}{i_o w} \left(\frac{k_c}{k_f}\right) \ln\left(\frac{r_e}{r_w}\right) \quad \text{for} \quad \frac{k_c}{k_f} \leq 0.05$$

where:

i_o = injection rate (m^3/sec)

r_w = wellbore radius (m)

h = injection interval (m)

r_e = effective radius (m)

k_f = formation permeability (mD)

k_c = filter cake permeability (mD)

(ρ_c/ρ_w) = density ratio: filter cake/brine

$t_{1/2}$ = half-life of injector (sec)

w = suspended solids concentration (ppm)

For a single well at the SSGF operating at an injection rate of 0.04 m^3/sec (Figure 1), the injection rate-permeability product $(i_o/h)\ k_f$ ranges between 4000 and 100,000 (B/D-FT) mD. To insure injectivity with a half-life greater than one year, the water quality ratio w/k_c must be $\ll 1$. For a perforated completion, the half-life estimate is reduced by a factor proportional to the perforated area.

Membrane filtration tests were used to measure the ratio w/k_c. A plot of cumulative filter throughput as a function of time approaches a straight line provided a filter cake forms.

$$\frac{w}{k_c} = \frac{2000}{S^2/60} \left[\frac{\left(\frac{\rho_c}{\rho_w}\right) A_c^{\ 2} \quad \Delta p_t}{\mu} \right]$$

S= slope of linear portion of filtration curve (ml/$\sqrt{\text{min}}$)
A= area of filter exposed to brine (cm^2)
ΔP_t= pressure drop across filter (Atm)
μ= brine viscosity (cp)

The intercept of the linear portion of the filtration curve, if negative, indicates plugging without filter invasion, or, if positive, plugging with filter invasion. Examples of both types of filtration curves for effluents from the SSGF are shown in Figure 1.

Membrane Filtration Apparatus

A schematic diagram of the filtration apparatus is shown in Figure 2. 47 mm Nuclepore polycarbonate membrane filters were mounted in Nuclepore stainless steel in-line holders. Temperature drops in the system were minimized by insulating all lines and bypassing most of the flow at the filter holder. All runs were made at a differential pressure of 50 psig and temperatures of $\sim$ 80°C. Suspended solids concentrations were measured in accordance with procedures outlined by Doscher and Weber (1957).

A novel brine-tolerant flow metering system was employed. The volume measuring system consisted of a 23 kgm load cell and associated power supply, digital voltmeter and elapsed timer. This system produced accurate average flow rates and total volume throughputs. Linear calibration curves were obtained by transferring known volumes of brine to the storage container and recording load cell output in millivolts.

Results

Filtration tests were performed with three types of brine effluents: One experiment was run adjacent to the injector (Magmamax No. 3) and two experiments were run in conjunction with the LLL test unit located adjacent to the producing well (Magmamax No. 1).

The effect of process chemistry on filtration characteristics is summarized in Table 1. None of the effluents were suitable for direct injection into a porous medium as indicated by relatively high values of w/k_c.

Magmamax No. 3 Wellhead

Tests run at the injection wellhead were carried out during a period when acidified condensate was remixed with brine effluents (∿110°C) from the GLEF at a point upstream of the injection pump. Dilution of brine by acidified condensate significantly reduced scaling in the injection line and improved long-term performance of the injection pump. Suspended solids (lead sulfide) concentrations were also reduced to <50 ppm with respect to nominal solids levels of ∿150 ppm (mostly silica) during injection without condensate recombination. Most of the PbS particles were between 5-10 μm in diameter.

LLL Test Unit

Filtration characteristics of acidified and unmodified effluents from the LLL four-stage flash system were also determined. The flash system is a model of the GLEF and is being used to assess scale control, by chemical modification (primarily acidification), and corrosion. During acidification runs, hydrochloric acid was injected into the brine input line of the second-stage separator (190-210°C). Filtered solids were composed of iron-rich amorphous silica. The concentration of particulates in brine prior to filtration was 14 ppm for acidified effluent and 150 ppm for unmodified effluent. The order of magnitude decrease in suspended solids in acidified brine demonstrates the effect of reduced pH on silica precipitation kinetics. The diameter of deposited solids varied from collodial to about 10 μm. Low permeability filter cakes formed because dissolved silica effectively sealed interstices between deposited solids.

Discussion

Data from membrane filtration tests indicated that silica solids, ranging in size from<1μm to 10μm, are present in SSGF effluents. These solids form low permeability filter cakes (0.4 to 10^{-5} mD). The analytical model was used to compute the half-life of the Magmamax No. 3 injection well. Our measured values of water quality ratio lead to a short predicted lifetime for injection into porous formations in Magmamax No. 3 ($t_{1/2}$ < 0.01 years). However, brine has been successfully injected into Magmamax No. 3 on an intermittent basis from March of 1976, to the present, far longer than expected for a porous medium. This contridiction is resolved by results of a spinner survey reported by Nugent and Vick (1977) which indicated plugging of all but four feet of the 458-foot slotted liner during the initial eight months of intermittent injection. Subsequently, the well was worked over and injection resumed. One week later, all porous zones were plugged again as predicted by the model. The four-foot interval, which is interpreted as a fracture zone, continues to accept fluid at rates up to 800 gal/min.

The analytical model was also used to evaluate injection data presented by Mathias (1975) for East Mesa well 5-1. The observed half-life of 0.0002 years is in good agreement with our calculated half-life of less than 0.002 years (assuming w = 92 ppm, k_f = 69 mD, h $\leq$301 m, open hole completion, and k_c $\leq$ 1 mD.)

Brine Treatment Requirements for Injection

Removal of solids from brine prior to injection may require some form of final filtration. Knowledge of effective pore size of the formation is required for establishment of minimum filtration requirements. Since core samples of reservoir rocks from Magmamax No. 3 were not available, absolute filtration requirements were estimated on the basis of filter tests and calculations of mean reservoir pore diameter.

Formation pore size can be estimated to be less than 20 μm since a 20 μm filter does not plug, but the formation does. The Carman-Kozeny equation can be used to estimate mean pore diameter for given values of porosity and permeability (Champlin et al., 1977). Using values of average porosity 20% (Tewhey, 1977) and average permeability 500 mD (Morse, 1977) estimated mean pore diameter are about 11 μm. The largest particle that can pass through pores is conservatively estimated to be 10% of the average pore diameter (Barkman and Davidson, 1972) suggesting that absolute filtration to 1 μm or less will be required to insure injectivity in porous zones.

Formation damage may occur even after absolute filtration. Harrar et al. (1977) found that solids continue to precipitate from SSGF effluents held at 90°C at rates controlled by brine pH or degree of dilution with water prior to incubation. The effect of delayed precipitation away from the well is difficult to forecast, and successful injection may require hold-up time prior to filtration. Chemical reactions between formation rock and filtered effluents must be understood. To that end, cores flushing experiments with filtered brine will be continued at the SSGF.

Conclusions

Membrane filter tests are useful in evaluating injectivity of geothermal effluents. Techniques are available for estimating injector half-life utilizing filtration data. Injection of brine with suspended solids is not feasible in reservoir zones with primary porosity. However, long-term injection of brine and suspended solids can apparently be achieved in fracture zones.

Table 1. Filtration Characteristics of SSGF Effluents (80°C)

Process Chemistry	Filter Pore Size (μm)	Slope (ml/$\sqrt{min}$)	w/k_c (ppm/mD)	w (ppm)	Solids
Acidified Condensate Recombination	0.4	1010	448	24	5-10 μm PbS
	0.4	190	12,655	27	
	1.0	210	10,360	32	
Brine pH ∿5.5	5.0	169	15,996	46	
	10.0	95	50,621	10	
Unmodified Brine pH 5.8	0.4	32	123,464	150	<1-10 μm Amorphous SiO_2
	2.0	540	434	150	
	5.0	147	5,851	150	
	10.0	44	65,303	150	
Acidified Brine pH ≤4.6	1.0	50	50,629	14	<1-10 μm Amorphous SiO_2
	5.0	12	878,972	14	
	10.0	21	287,011	14	

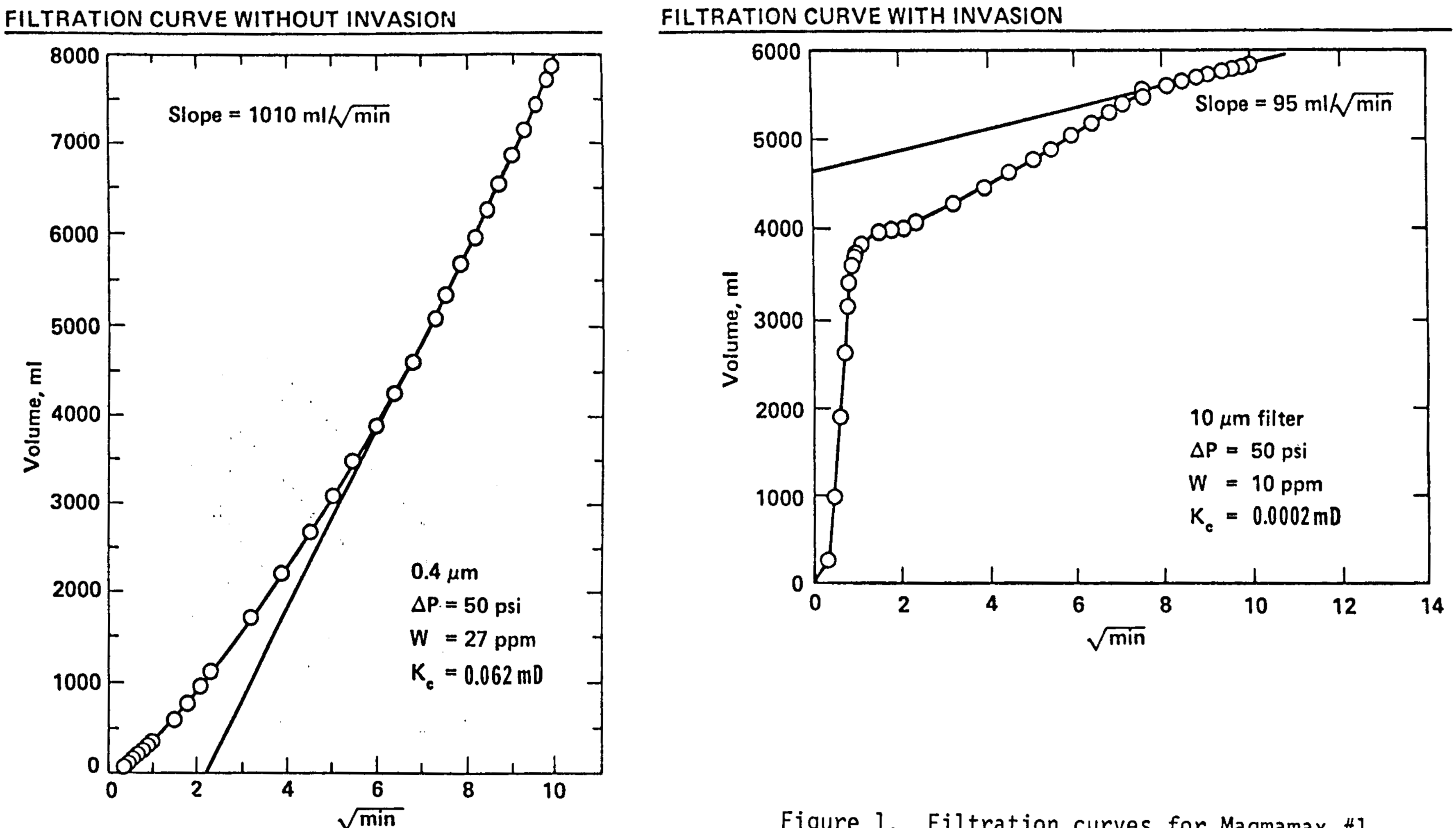

Figure 1. Filtration curves for Magmamax #1 brine, measured at the injection wellhead.

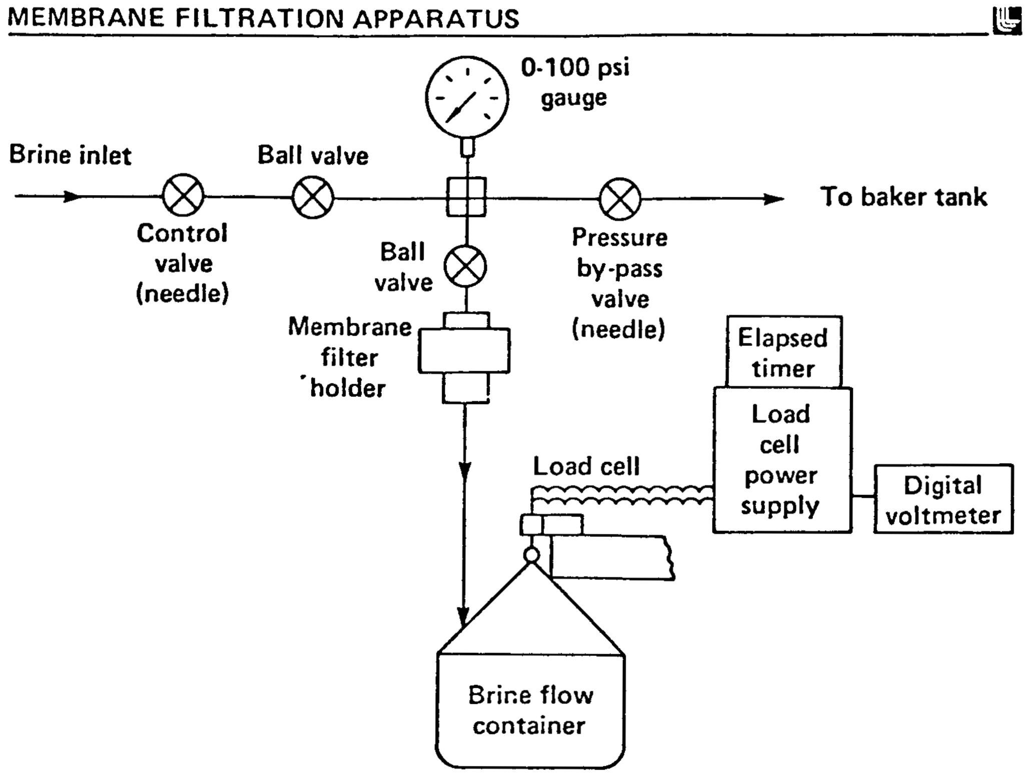

Figure 2. Membrane filtration apparatus.

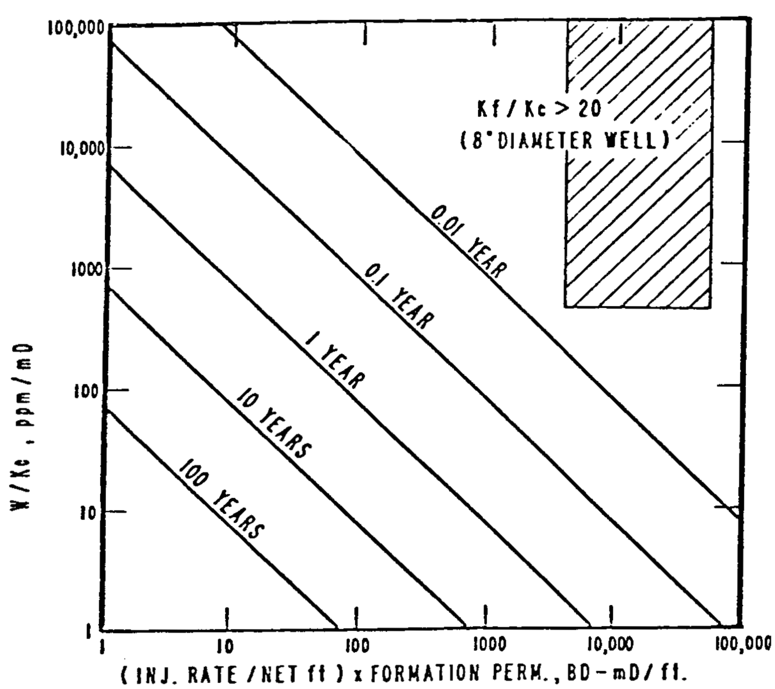

Figure 3. Calculated injection half-lives for porous formations (after Barkman and Davidson, 1972). The shaded area indicates the range of values assumed for Magmamax #3. (k_f=100-300 mD, i_0=0.04 m^3/sec., h=100-500 feet, and the measured water quality ratios are 450-100,000 ppm/mD.)

References

Austin, A. L., Lundberg, A. W., Owen, L. B., and Tardiff, G. E., (1977), the LLL Geothermal Energy Program Status Report January 1976-January 1977: Lawrence Livermore Laboratory Report UCRL-50046-76.

Barkman, J. H., and Davidson, D. H., (1972), Measuring Water Quality and Predicting Well Impairment: Jour. Petroleum Technology, p. 865-873.

Champlin, J. B. F., Thomas, R. D., and Brownlow, A. D., (1967), Laboratory Testing and Evaluation of Porous Permeable Rock for Nuclear Waste disposal: U.S. Bureau of Mines Report of Investigations No. 6926.

Doscher, T. M., and Weber, L. (1957), The Use of the Membrane Filter in Determining Quality of Water for Subsurface Injection: Drilling and Production Practice, (API), p. 169-179.

Harrar, J. E., Otto, C. H., Jr., Hill, J. H., Morris, C. J., Lim R., and Deutscher, S. B., (1977) Determination of the Rate of Formation of Solids from Hypersaline Geothermal Brine: Lawrence Livermore Laboratory Report UCID-17596.

Johnston, K. H., and Castagno, J. L., (1964), Evaluation by Filter Methods of the Quality of Waters Injected in Waterfloods: U.S. Bureau of Mines Report of Investigations No. 6426, 14 pgs.

Jordan, C. A., Edmondson, T. A., and Jeffries-Harris, M. J., (1969), The Bay Marchand Pressure Maintenance Project-Unique Challenges of an Offshore Sea-Water Injection System: Jour. Petroleum Technology, p. 389-396.

Mathias, K. E., 1975, The Mesa Geothermal Field - A Preliminary Evaluation of Five Geothermal Wells: Second U.N. Symposium on the Development and Utilization of Geothermal Resources, V. 3, p. 1741-1747.

Morse, J. G., (1977), Well Interference Study of the Multi-layered Salton Sea Geothermal Reservoir: Third Annual Workshop on Geothermal Reservoir Engineering, Stanford University.

Nugent, J. M., and Vick, L. R., (1977) Well Operations - Salton Sea Geothermal Field: Geothermal Resources Council, Transactions, V. 1, p. 233-234.

Quong, R., Bishop, H. K., and Hill, J. H., (1977), Scale and Solids Deposition in the SDG&E/U.S. ERDA Geothermal Loop Experimental Facility at Niland, California: Geothermal Resources Council, Transactions, V. 1, p. 249-250.

Tewhey, J. D., (1977), Geologic Characteristics of a Portion of the Salton Sea Geothermal Field: Lawrence Livermore Laboratory Report UCRL-52267.