TID-4500, UC-51
Geology and Mineralogy

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UCRL-51303

**EXPLOSIVE STIMULATION
OF A GEOTHERMAL STEAM RESERVOIR**

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MS. date: November 1972

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EXPLOSIVE STIMULATION OF A GEOTHERMAL STEAM RESERVOIR

Abstract

A mineral deposition model is proposed to explain the production decline from geothermal wells producing dry (superheated) steam. The model is based on isothermal mineral deposition caused by a pressure gradient near the well. Using reasonable parameter values, the model approximates the pro-

duction behavior of a typical well at The Geysers field in California. The predicted effect of explosive fracturing on steam-well production and economics is discussed; the prediction shows that, in a well with a 4-ft fracture radius, the production of steam can be increased by a factor of 6 over 20 years.

Introduction

Geothermal reservoirs producing steam are much less common than hot-water systems, but steam reservoirs are commercially attractive for electrical power production. Geothermal energy has been recognized as a source of electrical power since the steam field at Lardarello, Italy, was tapped in 1904. Wairakei, New Zealand, began commercial production in 1958, and The Geysers, California, in 1960. There are plans for a large increase in utilization of this natural energy resource in the near future.

High explosives have been used successfully for many years in the petroleum industry to increase production from gas and oil reservoirs. Nuclear explosives show promise for stimulation of low-permeability gas reservoirs. The high temperatures of geothermal reservoirs have thus far discouraged the use of explosives; however, recent development of conventional explosives that are safe to handle and are stable at high temperatures

opens up the possibility of stimulating steam reservoirs with explosives.

Explosive fracturing increases the permeability of reservoir rock near the well-bore, in effect giving a larger well radius, which in turn permits increased fluid production. With a gas or oil well, it is possible to estimate the production increase from an enlarged well radius. Much less is known about the mechanism of fluid flow and reservoir depletion in a steam field. A complicating factor is the appreciable concentration of minerals dissolved in hot water or steam.

Mineral deposition is believed to affect steam-well production, sometimes causing plugging in the well-bore itself, or in the reservoir rock near the well.¹ The purpose of this report is to present a theory of mineral deposition in flowing steam wells, and to use the theory to predict the effect of explosive stimulation on steam-well production and economics.

Geothermal Resources

A recent comprehensive review by Grose^{2,3} surveys the geology, exploration, and utilization of worldwide geothermal resources. The proceedings of two United Nations conferences^{4,5} on geothermal energy contain much useful information. Volcanism, tectonism, and high heat flow are the regional geological conditions associated with geothermal systems. Most hot springs occur in districts with recognized volcanic activity nearby. Where this is not the case, the ultimate source of heat is believed to come from deeper magmatic intrusions.

The global average heat flow from the earth's surface is about 1.5×10^{-6} cal/cm²-sec. Geothermal regions may have heat fluxes several hundred times higher than average. In terms of present utilization, geothermal resources may be identified as hot-springs areas and wet or dry (superheated) steam fields.

Water from hot springs is most efficiently used for home and industrial heating, although water at 80°C is being used for power production in the USSR on a pilot scale.⁵

Steam fields are classified by White⁶ as composite hydrothermal systems. A convective system overlies a zone having an abnormally high conductive heat flux. The rock in the convective system can be of almost any type or age as long as it is

sufficiently porous and permeable to permit fluid movement. The near-surface rock layer has low permeability, forming a hydrothermal trap analogous to a gigantic steam boiler.

Wet steam fields vary greatly in temperature, depending on their dissolved salt content. In the geothermal brines of the Salton Sea in California, which contain 26% dissolved solids, the subsurface temperature exceeds 360°C at a depth of 2000 m.² About 20% of the brine flashes to steam at the wellhead. There are serious problems of corrosion, deposition, and waste disposal. Only New Zealand currently produces a significant amount of power (200 MW) from a wet steam field. Temperatures there are about 250-275°C with 15% steam content at the wellhead.

Dry steam fields yield most of the world's current geothermal power production of over 800 MW. The Geysers, California, produces 200 MW; expansion to 600 MW is planned by 1975. Estimates of reservoir capacity there range from 1200 to 4800 MW.³

Robinson *et al.*⁷ have estimated that the electrical energy potentially recoverable from steam reservoirs in the continental United States is 4×10^6 MW-years, which is appreciable when compared with the current annual energy consumption of about 3×10^5 MW.

Model for Mineral Deposition

Geothermal waters contain dissolved impurities, which may precipitate as temperature or pressure changes and

clog the pores and fissures of the host rock. Silica is the most important constituent for self-sealing^{8,9} at the

boundaries of geothermal systems, since SiO_2 is so abundant and its solubility increases so much with temperature. The Franciscan formation at The Geysers, California, has a high permeability due to fractures, yet there is little surface discharge from natural springs. Facca and Tonani⁹ believe that this is due to the deposition of silica as the hot fluid cools in passing towards the surface, and that the formation itself has no recognizable cap-rock in the usual petroleum-geology sense.

For the rest of this discussion we will focus on silica deposition in the vicinity of a well drilled into the main body of a dry (superheated) steam reservoir; we will use The Geysers field as an illustration.

According to White *et al.*,⁸ The Geysers is a vapor-dominated system with its temperature maintained nearly constant at 240°C by convection of steam in the permeable host rock, from a depth of 450 m to the water table at about 3000 m. We will assume then that steam-well production is not affected by silica deposition due to temperature changes, but is affected instead by the pressure gradient caused by steam flow in the reservoir near the well bore.

In the absence of deposition, isothermal steam flow would be similar in many respects to gas flow in a natural-gas reservoir. If this were the case, steam production from a single well would stabilize in time, after an initial transient period of high production, when the natural convection system was able to supply fresh steam at the radius of drainage of a given well.¹⁰ In fact, some of the original wells drilled at The Geysers in the 1920's did

produce steam for about 40 years.¹¹ The initial flow rates were an order of magnitude lower than production rates from recent wells, however, and the model proposed here suggests that long lifetimes are to be expected at low flow rates.

Production from a number of recent wells roughly follows an exponential decline curve with a half-life of about three years.¹² The Lardarello, Italy, steam field also has a vapor-dominated reservoir; a rough average half-life of typical wells there is about five years.¹³

DEPOSITION MODEL*

According to the data of Styrikovich *et al.*¹⁴ and Martynova,¹⁵ solubility isotherms for silica dissolved in water vapor may be represented by a simple power-law function of steam density. Steam density is proportional to pressure along an isotherm, although the proportionality "constant" varies slightly due to nonideal gas effects. At 240°C, after converting concentration and density units, their solubility-pressure correlation becomes

$$c = ap^\alpha, \quad (1)$$

where c is silica concentration in g/g H_2O , p is steam pressure in atmospheres, $a = 1.4 \times 10^{-7}$, and $\alpha = 0.5$. The constants in Eq. (1) are for amorphous SiO_2 . Quartz has a lower solubility but a stronger pressure dependence ($\alpha = 1.0$).

Assume that the concentration of silica in steam remains in equilibrium as

*Symbols used in this section are defined as they are introduced; they are also summarized for reference in a table of nomenclature on p. 10.

steam pressure changes, that nucleation and precipitation kinetics are fast, and that the particulate material formed is "filtered out" by the porous rock and deposited rapidly. The mass-conservation equation for silica in a volume element of reservoir rock is

$$\frac{\partial}{\partial t} (\phi \rho c) + \nabla \cdot n = R, \quad (2)$$

where ϕ is porosity (steam-filled void fraction), ρ is steam density in g/cm^3 , $\nabla \cdot n$ is the divergence of the silica flux n , n is in g/sec-cm^2 , and R is the silica deposition rate in g/sec-cm^3 .

The silica flux n is given by

$$n = cm + \rho D \nabla c, \quad (3)$$

where m is the steam flux in g/sec-cm^2 , and D is a silica-steam diffusion coefficient in cm^2/sec . Diffusion will be unimportant compared to the bulk flow of silica, and Eq. (3) reduces to

$$n = cm. \quad (4)$$

Assume a steady-state deposition rate, which implies that the mass flow rate of steam is constant. Steam flow rate can be expected to diminish with time as deposition gradually fills the porosity and lowers the permeability, but this assumption will be valid on a time scale of perhaps weeks or months.

The above assumption, with Eqs. (2) and (4), gives, for one-dimensional flow (cylindrical, spherical, or linear):

$$R = m \frac{dc}{dr}, \quad (5)$$

where $\frac{dc}{dr}$ is the concentration gradient at radius r . From Eq. (1):

$$\frac{dc}{dr} = a \alpha p^{\alpha-1} \frac{dp}{dr}. \quad (6)$$

The solubility "constant" a in the equation above is temperature dependent. The flow process may be closer to isenthalpic than isothermal, leading to a higher concentration gradient than that given by Eq. (6).

We will not include the refinement of isenthalpic flow, because of uncertainties in the solubility constant and other parameters of the model. The pressure gradient $\frac{dp}{dr}$ is related to the mass flux by Darcy's law:

$$\frac{dp}{dr} = \frac{m \mu}{\rho K}, \quad (7)$$

where μ is steam viscosity, K is the reservoir permeability, and steam density ρ is related to pressure by

$$\rho = \beta p, \quad (8)$$

where β is nearly constant along an isotherm. Putting Eqs. (6), (7), and (8) into Eq. (5) gives, for the deposition rate at radius r :

$$R = m^2 \frac{\mu}{K \beta} \frac{a \alpha}{p^{2-\alpha}}. \quad (9)$$

The mass fluxes for cylindrical and spherical flow are

$$\text{cylindrical: } m = \frac{M}{2\pi r h}, \quad (10a)$$

$$\text{spherical: } m = \frac{M}{4\pi r^2}, \quad (10b)$$

where M is steam flow rate in g/sec , and h is the height or producing thickness for radial flow.

We will assume cylindrical flow, although the deposition rate depends more strongly on radius in spherical flow. Equations (9) and (10a) give

$$R = \left(\frac{M}{2\pi rh} \right)^2 \frac{\mu}{K\beta} \frac{a\alpha}{p^{2-\alpha}} \quad (11)$$

Numerical values for the terms in Eq. (11) are chosen as follows:

$$M = 2.52 \times 10^4 \text{ g H}_2\text{O/sec (200,000 lb/hr)}$$

$$r = 11.1 \text{ cm}$$

$$h = 3.05 \times 10^3 \text{ cm (100 ft)}$$

$$K = 1 \text{ darcy}$$

$$\mu = 0.02 \text{ cp}$$

$$\beta = 4.91 \times 10^{-4} \text{ g/cm}^3\text{-atm}$$

$$p = 20.4 \text{ atm (300 psia)}$$

$$a = 1.4 \times 10^{-7} \text{ atm}^{-1/2}$$

$$\alpha = 0.5$$

The assumed steam flow rate is representative of a good producing well at The Geysers. The radius chosen is the well-bore radius for a conventional well diameter of 8-3/4 in. The permeability K and thickness h are somewhat arbitrary, but the Kh of 100 darcy-ft is representative of the reservoir.¹² A well-bore pressure of 300 psia is intermediate between the surface pressure of 100 psia and a reservoir pressure of 485 psia (saturated steam at 240°C), and allows 200 psi for pressure drop to the surface. The above numbers give a deposition rate at the well radius of:

$$R = 4.4 \times 10^{-10} \text{ g silica/sec-cm}^3.$$

The overall deposition rate can be calculated by integrating Eq. (11) from the

well radius out to the drainage radius. A radius of drainage of 200 ft is consistent with the steam flow rate and other parameters chosen. A simpler method of calculation is to multiply the steam flow rate by the change in silica concentration between the reservoir and well pressures. By either method, the result is 380 g of silica per day, most of which, according to Eq. (11), will be deposited close to the well bore.

It should be recognized that the deposition rate calculated above is based on the well radius as drilled. If natural fractures with significant hydraulic capacity intersect the drill hole, a radial flow model might still be used as an approximation, but with a larger effective well radius and therefore a smaller deposition rate. Ramey¹⁶ has inferred from a short-time test of a steam well at The Geysers that fractures or cavities with appreciable void volume were present.

PLUGGING TIME ESTIMATE

Rock porosity is void (steam-filled) volume divided by total volume. If the deposition rate were constant, the porosity at time t would be

$$\phi(t) = \phi_0 - \frac{Rt}{\rho_s} \quad (12)$$

where ϕ_0 is the initial porosity and ρ_s is the density of the deposited silica. A crude estimate of the time to plug the well would be when $\phi = 0$ at the well radius, i. e.,

$$t \approx \frac{\phi_0 \rho_s}{R}.$$

Using the deposition rate just calculated, with $\rho_s = 2.2 \text{ g/cm}^3$ and $\phi_0 = 0.05$, plugging time is about 8 years.

EFFECT OF DEPOSITION ON MASS FLOW RATE

The plugging time calculated above assumes a constant deposition rate. In fact, the permeability decreases as the porosity is filled, causing the steam flow rate to decrease, which in turn leads to a lower deposition rate.

Assume that we have reached the condition of stabilized flow¹⁰ where a pressure gradient has been established in the reservoir between the well radius r_w and the radius of drainage r_d . Then the mass flow rate M is constant and proportional to the average permeability over that region:

$$M = \frac{\pi \bar{K} h \beta (p_d^2 - p_w^2)}{\mu \ln \frac{r_d}{r_w}}, \quad (13)$$

where p_d and p_w are the steam pressures at r_d and r_w , respectively.

The correct average permeability in cylindrical flow is

$$\frac{1}{\bar{K}} = \frac{\int_{r_w}^{r_d} \frac{dr}{rK(r)}}{\ln \frac{r_d}{r_w}}, \quad (14)$$

where $K(r)$ is permeability at radius r . Inspection of Eq. (14) shows that

$$\bar{K} \approx K(r_w), \quad (15)$$

since the harmonic-type averaging favors the smallest value of $K(r)$, which will be at the well radius where deposition is greatest. Also the radial weighing factor r favors the smallest radius. From Eq. (13), which expresses the proportionality between mass flow rate and average permeability,

$$\frac{M(t)}{M_0} = \frac{\bar{K}(t)}{K_0}, \quad (16)$$

where $\bar{K}(t)$, by Eq. (15), is the permeability at the well radius at time t and K_0 and M_0 are initial permeability and mass flow rate values before deposition.

According to the Kozeny equation,¹⁷ permeability is proportional to porosity cubed for low porosities, and therefore:

$$\frac{M(t)}{M_0} = \left[\frac{\phi(t)}{\phi_0} \right]^3. \quad (17)$$

Rewriting Eq. (12) for variable deposition rate gives:

$$\frac{\phi(t)}{\phi_0} = 1 - \int_0^t \frac{R(t) dt}{\phi_0 \rho_s}. \quad (18)$$

From Eqs. (11) and (16),

$$R(t) = R_0 \frac{M(t)}{M_0}. \quad (19)$$

Substituting Eqs. (17) and (19) into Eq. (18) gives:

$$\left[\frac{M(t)}{M_0} \right]^{1/3} = 1 - \frac{R_0}{\phi_0 \rho_s} \int_0^t \frac{M(t)}{M_0} dt. \quad (20)$$

Fig. 1. Predicted decline in production rate (Eq. (21)) compared with a three-year-half-life exponential decline.

Solving the integral equation for $M(t)/M_0$ gives:

$$\frac{M(t)}{M_0} = \frac{1}{\left(1 + \frac{2R_0 t}{\phi_0 \rho_s}\right)^{3/2}}. \quad (21)$$

This predicted production-rate decline curve is plotted on Fig. 1 and compared with a three-year-half-life exponential decline. The agreement is quite good, considering that the exponential decline gives only a rough indication of the flow rate of a Geysers well and is not a close fit to measured data.

CUMULATIVE STEAM PRODUCTION

The total or cumulative amount of steam produced up to some given time can be calculated by integrating Eq. (21):

$$I(t) = \int_0^t M(t) dt, \quad (22)$$

which gives

$$I(t) = \frac{M_0 \phi_0 \rho_s}{R_0} \left[1 - \left(1 + \frac{2R_0 t}{\phi_0 \rho_s}\right)^{-1/2} \right]. \quad (23)$$

If time t is very small or very large, Eq. (23) reduces to

$$I(t \rightarrow 0) = M_0 t, \quad (24a)$$

$$I(t \rightarrow \infty) = \frac{M_0 \phi_0 \rho_s}{R_0}. \quad (24b)$$

In other words, at early times the total steam production is proportional to time and the initial flow rate, but as minerals deposit, production approaches an upper limit determined by initial flow and deposition rate.

EXPLOSIVE STIMULATION

For a steam reservoir with fixed physical properties such as initial permeability, porosity, etc., total steam production might be increased either by drilling more wells or by explosive fracturing to increase the effective well radius of individual wells. It takes a large increase in well radius to significantly increase the initial mass flowrate, since, from Eq. (13),

$$M_0 \propto \left(\ln \frac{r_d}{r_w}\right)^{-1}. \quad (25)$$

For steam flow with mineral deposition, a modest increase in well radius by

Fig. 2. Cumulative steam production from wells of various radii. The physical properties of the reservoir are given in the text.

explosive fracturing may have a very significant effect on production, since production at late times is proportional to the ratio M_0/R_0 according to Eq. (24b), and

$$\frac{M_0}{R_0} \propto r_w^2 \ln \frac{r_d}{r_w} \quad (26)$$

Figure 2 shows the cumulative steam production for a steam reservoir with the physical properties previously chosen.

The lowest production curve is based on the original drill-hole radius. Increasing the effective well radius to 4 ft by explosive fracturing gives about a factor-of-6 increase in steam production over 20 years.

An effective fracture radius of only 1 ft shows a production increase by about a factor of 3.

Effective fracture radius means the radius within which the rock is sufficiently fractured to have very high permeability. Very high permeability implies no pressure gradient, therefore no silica concentration gradient, and therefore no silica deposition.

Economics of Steam Production

Geothermal steam fields produce low-cost electrical power. According to Bowen and Groh,¹⁸ total costs are 4.9 mills/kWh, compared with 6.2, 6.5, and 7.6 mills/kWh for hydroelectric, nuclear, and coal plants, respectively. Grose³ cites slightly different figures for nongeothermal power costs, but

geothermal still makes the lowest-cost power, mainly because of the low power-plant investment and the high utilization factor. The geothermal costs cited here are based on The Geysers field in California; the steam fields at Lardarello, Italy, and Matsukawa, Japan, have somewhat lower costs.

WELLHEAD STEAM VALUE

At The Geysers, Pacific Gas and Electric Company owns and operates the power station and buys the necessary steam at about 2.7 mills/kWh of generating-unit output from a combine of Union Oil Company, Magma Power, and Thermal Power Company. Union Oil operates the steam field, drills new wells as needed, pipes the steam to the power plant, and disposes of the waste condensate by reinjection.

It is expected that the price paid for steam could rise by as much as 1.5 mills/kWh because of the cost advantage of geothermal power relative to other methods.³ The value of steam at the wellhead must be reduced, however, by the cost of steam transmission lines, amortization of exploration costs, royalty payments to landowners, and waste-water disposal costs. These costs are estimated to be about 0.7 mill/kWh.¹⁸ Assume then, that steam at the wellhead is currently worth about 2 mills/kWh.

One kW is equivalent to 20 lb/hr of steam (at 1200 BTU/lb and 14% conversion efficiency). At 2 mills/kWh, steam is worth $\$10^{-4}$ /lb ($8\text{¢}/10^6$ BTU) and a steam well flowing at 100,000 lb/hr produces \$90,000/yr in revenue [$\$0.9/\text{yr})/(\text{lb/hr})$].

DISCOUNTED VALUE OF STEAM-WELL PRODUCTION

Steam-well drilling costs at The Geysers run between \$50,000 and \$250,000 depending on depth; about \$150,000 is an average cost.^{18,19} This cost variation is consistent with figures quoted for other parts

of the world,⁵ where a 3000 to 4000-ft well runs between \$15 and \$40/ft. Since steam flow persists for perhaps 20 years or more, future revenues should be discounted back to the present, using an appropriate rate of return, and compared with the investment cost of the well.

The present dollar value P of future steam flow is

$$P = V \int_0^t M(t)e^{-it} dt, \quad (27)$$

where $V = (\$0.9/\text{yr})/(\text{lb/hr})$ as mentioned above, i is the rate of return, and t is time in years. Introducing Eq. (21) for mass flow rate $M(t)$ into Eq. (27) and integrating leads to a rather complicated expression; we will pass to the calculated results.

The present values of discounted future steam revenues are given in Table 1 for a conventional well of 8-3/4-in. diameter (0.365-ft radius) and for wells with fracture radii of 1, 2, and 4 ft. Initial steam flow rates are based on Eq. (13), steam production is based on Eq. (23) using the reservoir parameters previously discussed, and a 20% rate of return has been used to discount future steam revenues. If a lower rate of return were acceptable, the present value of 20-year steam production would be larger. The present value of \$400,000 for the conventional well compares favorably with a \$150,000 average well cost, or in other words the rate of return on investment is higher than 20%. The calculated increase in present value for the explosively fractured wells is substantial, and would appear to justify a reasonable investment in explosive stimulation. A 4-ft fracture radius

Table 1. Values of discounted future steam revenues for wells of various radii.

Well radius (ft)	Initial steam flow rate (10 ⁵ lb/hr)	20-year steam production (10 ¹⁰ lb)	Present value, i = 0.20 (\$10 ⁶)
0.365	2.0	0.8	0.4
1.0	2.4	2.5	0.8
2.0	2.7	3.9	1.1
4.0	3.2	5.2	1.4

shows a \$1-million increase in present value over the conventional well.

Development of an appropriate low-cost explosive for a geothermal environment presents both problems and opportunities. Attention must be given to questions of thermal stability, chemical compatibility, safety, and ease of handling, emplacement, and detonation under field conditions.

A fluid explosive may provide better coupling to the host rock and allow displacement of the explosive into existing fractures before detonation. There are opportunities here, as well as in formulation of the explosive to enhance fracturing by matching detonation characteristics to the mechanical properties of the host rock.

Conclusion

A simplified theoretical model has been developed to explain the decline in production from geothermal steam wells. The model is based on isothermal mineral deposition caused by a pressure gradient near the well. This mechanism is in contrast to a natural gas well, where late-time production decline is related to reservoir depletion.

The mechanics of flow in a geothermal steam reservoir are not yet well understood. The proposed mineral deposition model needs to be tested by a field experiment in a well where flow rate is not initially fracture-controlled. The implication of the model is that a small amount of explosive fracturing may be very beneficial.

Nomenclature

a	constant in Eq. (1), atm ^{-1/2}	$\bar{K}$	permeability, average, darcies
c	silica concentration, g/g H ₂ O	K(r)	permeability at radius r, darcies
h	reservoir thickness, cm	K ₀	permeability, initial before deposition, darcies
I(t)	cumulative steam production, g	m	mass flux, g/sec-cm ²
K	permeability of reservoir, darcies		

M	mass flow rate, g/sec	R_0	silica deposition rate, initial near well radius, g/sec-cm ³
M(t)	mass flow rate at time t, g/sec	t	time, sec
M_0	mass flow rate, initial before deposition, g/sec	α	exponent in Eq. (1)
n	dissolved silica flux, g/sec-cm ²	β	constant, $\beta = \frac{\rho}{p}$, g/cm ³ -atm
p	pressure, atm	μ	viscosity, cp = 10 ⁻² poise = 10 ⁻² g/cm-sec
r	radius, cm	ρ	density of steam, g/cm ³
r_d	radius of drainage, cm	ρ_s	density of amorphous silica, g/cm ³
r_w	radius of well, cm	ϕ	porosity
R	silica deposition rate, g/sec-cm ³	ϕ_0	porosity, initial before deposition near well radius
R(t)	silica deposition rate at time t near well radius, g/sec-cm ³	$\phi(t)$	porosity, at time t near well radius

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