PROCEEDINGS, TOUGH Symposium 2006
Lawrence Berkeley National Laboratory, Berkeley, California, May 15–17, 2006

EVALUATION OF C-14 AS A NATURAL TRACER FOR INJECTED FLUIDS AT THE AIDLIN SECTOR OF THE GEYSERS GEOTHERMAL SYSTEM THROUGH MODELING OF MINERAL-WATER-GAS REACTIONS

Patrick Dobson, Eric Sonnenthal, Jennifer Lewicki, and Mack Kennedy

Lawrence Berkeley National Laboratory
Earth Sciences Division
Berkeley, CA, 94720, USA
e-mail: pfdobson@lbl.gov

ABSTRACT

A reactive-transport model for ^{14}C was developed to test its applicability to the Aidlin geothermal system. Using TOUGHREACT, we developed a 1-D grid to evaluate the effects of water injection and subsequent water-rock-gas interaction on the compositions of the produced fluids. A dual-permeability model of the fracture-matrix system was used to describe reaction-transport processes in which the permeability of the fractures is many orders of magnitude higher than that of the rock matrix. The geochemical system included the principal minerals (K-feldspar, plagioclase, calcite, silica polymorphs) of the metagraywackes that comprise the geothermal reservoir rocks. Initial simulation results predict that the gas-phase CO_2 in the reservoir will become more enriched in ^{14}C as air-equilibrated injectate water (with a modern carbon signature) is incorporated into the system, and that these changes will precede accompanying decreases in reservoir temperature. The effects of injection on ^{14}C in the rock matrix will be lessened somewhat because of the dissolution of matrix calcite with “dead” carbon.

INTRODUCTION

The Aidlin Geothermal Field (Figure 1) is located within the northwestern portion of The Geysers geothermal system, California. This portion of The Geysers steamfield is characterized by higher reservoir temperatures (260–290°C) and elevated noncondensable gas contents (Klein and Chase, 1995; Hulen et al., 2001).

Since production began in the Aidlin field in 1989, injection has consisted primarily of relatively limited volumes at rates of ~750 L/min of steam condensate, with variable seasonal contributions of creek and well waters. During 2004 and 2005, nearly all injection at Aidlin was condensate (J. Beall, pers. comm., 2006). Beginning in November 2005, more extensive injection utilizing reclaimed water from the Santa Rosa–Geysers Recharge Project (SRGRP; Stark et al., 2005) was initiated at the Aidlin area, with the goal of increasing steam production and reducing problems associated with the high gas contents of the produced fluids. The reclaimed water contains natural tracers, such as ^{14}C (modern carbon), that can be potentially monitored to evaluate the movement of injectate throughout the Aidlin field. The purpose of this preliminary study is to evaluate the feasibility of using ^{14}C as a tracer for the movement of reclaimed water injectate within the Aidlin reservoir.

Field sampling of produced fluids from the Aidlin steam field was conducted prior to the initiation of reclaimed water injection to establish a baseline for the geothermal reservoir fluid chemistry. Subsequent sampling will evaluate changes that result from injection of larger volumes of water that are distinctly different in chemical composition from reservoir fluids and previously injected condensate.

RESERVOIR PROPERTIES

The Aidlin reservoir rocks consist of fractured argillites and metagraywackes of the Franciscan Assemblage (Hulen et al., 2001). These rocks typically contain a matrix mineralogy consisting of 45% quartz, 30% plagioclase, 20% sheet silicates (mixed-layer illite-smectite, chlorite, phengite and biotite), and 5% potassium feldspar (Moore and Gunderson, 1995). These metamorphosed sediments also contain abundant (commonly >10%) veins of calcite and quartz. Hydrothermal vein minerals encountered within the reservoir rocks at Aidlin include quartz, K-feldspar, actinolite, chlorite, and minor amounts of epidote, axinite, pyrite, chalcopyrite, and sphalerite (Hulen et al., 2001).

Fluid flow within the Geysers reservoir is strongly controlled by fractures, as the argillite and metagraywacke reservoir rocks have extremely low matrix permeability. Persoff and Hulen (2001) reported matrix permeability values ranging from 3×10^{-21} to 4×10^{-20} m^2 for metagraywacke core samples obtained from The Geysers steam reservoir. Hydrothermal mineralization associated with an earlier liquid-dominated geothermal system at The Geysers is concentrated along fractures (Hulen et al., 2001). The steeply dipping Mercuryville strike-slip fault bounds the Aidin reservoir to the southwest.

MODELING APPROACH

Reactive transport modeling can be used to evaluate heat and mass transfer and chemical reactions between rocks and fluids in geothermal systems. Reactive transport modeling provides a powerful tool to evaluate the integrated effects of injection on reservoir performance (e.g., Xu et al., 2004). Heat transfer in fractured geothermal reservoirs is controlled by the effective surface area between fractures and the rock matrix, as well as mass transfer occurring at these interfaces. Changes in fluid chemistry within the geothermal reservoir are controlled by a variety of processes, including boiling, mixing of reservoir and injected fluids, and mineral-fluid reactions.

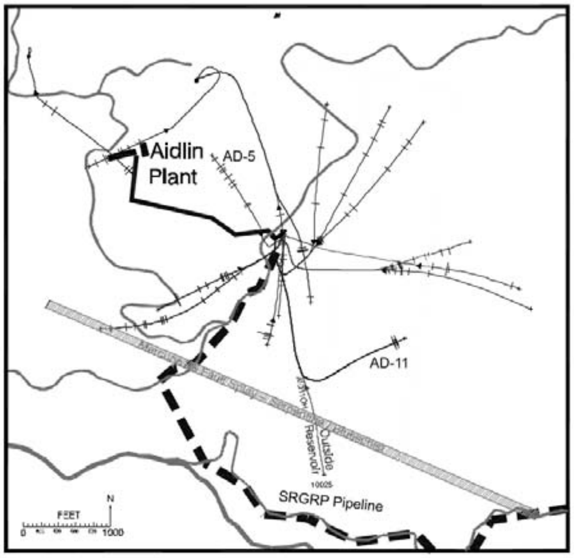

Figure 1. Location of wells at Aidlin. Condensate from the Aidlin power plant and reclaimed water from the SRGRP are injected into wells AD-11 and AD-5.

The TOUGHREACT simulator couples the flow of water, gas, and heat to reactive chemistry and transport for multiphase, multicomponent systems (Xu et al., 2006). The code uses a sequential iteration approach that solves the transport and reaction equations separately. Aqueous and gaseous species are transported by advection and diffusion. Reactions between mineral, gas, and aqueous species can be modeled under either equilibrium or kinetic conditions. Porosity, permeability, and capillary pressure changes are coupled to mineral precipitation and dissolution. TOUGHREACT has also been used to model stable isotopic fractionation and the use of isotopes as tracers (e.g., Singleton et al., 2004).

We have incorporated ^{14}C into the model as a separate component, so that for each C-bearing phase in the system (i.e., calcite, bicarbonate, and CO_2), there is a corresponding ^{14}C-bearing equivalent that is assigned the identical thermodynamic properties as its "normal" C counterpart. For this modeling work, there is no isotopic exchange between the "normal" C phases and the ^{14}C phases, and all changes take place through precipitation/dissolution (for minerals) and gas exsolution/dissolution (for aqueous and gaseous species).

Previous modeling studies have assessed the potential geochemical effects resulting from injecting treated Santa Rosa waste water at The Geysers (Crecraft and Koenig, 1989). The goal of our study is to evaluate the use of ^{14}C as a potential tracer for Santa Rosa reclaimed water that is currently being injected into the Aidlin reservoir.

Model Conditions

A simplified 530 m 1-D horizontal grid with dual permeability (fracture-matrix continua) was developed to represent the flow path between an injection well and a production well. The different mineral and chemical components used in this model are listed in Table 1. All calcite in the rock matrix was assumed to be old (no ^{14}C). The reservoir water was assumed to have 1% modern ^{14}C, and the injection water was assumed to have 100% modern ^{14}C. The reservoir conditions were set at T = 240°C and P = 4 MPa. As a first approximation, the injection rate was fixed at 86 L/day at a temperature of 25°C. Flow through the system was driven by a small pressure gradient induced by injection and production at the ends of the 1-D grid.

Table 1. Mineral and Chemical Model Components.

Primary Mineralogy	Aqueous Species	Gases
Silica polymorphs	H^+	CO_2
Plagioclase	Ca^{2+}	$^{14}CO_2$
K-feldspar	Na^+	Air
Calcite (absent in fractures)	K^+	Water vapor
	Al^{3+}	
	SiO_2	
	HCO_3^-	
	$H^{14}CO_3^-$	

MODELING RESULTS

The 1-D model system was simulated for a total of four years. Over time, the CO_2 gas in the reservoir becomes more ^{14}C-rich upon interaction with the injectate water, which contains 100% modern carbon (Figure 2). For the extremely low injection rates used in this simulation, the effects only extend out to a distance of ~80 m away from the injection well at the end of four years of injection. This effect is reduced in the matrix relative to the fractures. Calcite (with no ^{14}C) in the matrix blocks dissolves slowly, producing both ^{14}C-free bicarbonate and CO_2, thus diluting the effect of the ^{14}C in the injectate as it enters the matrix portion of the reservoir system.

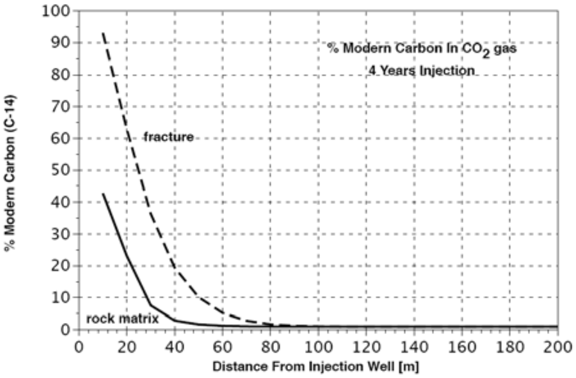

Figure 2. Variation in percent modern carbon in CO_2 gas as a function of distance from the injection well. Reduced effect in rock matrix results from contribution of "dead" carbon from calcite.

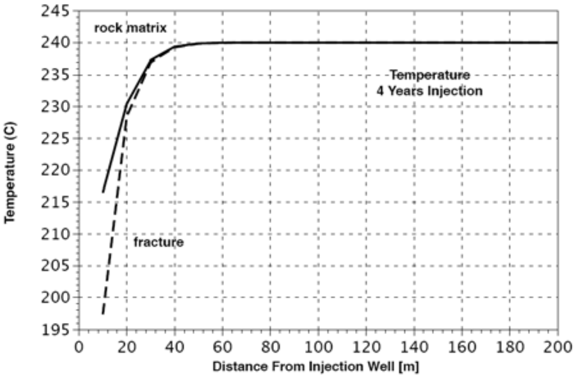

Figure 3. Variation in temperature as a function of distance from the injection well. Lower temperatures in the fracture blocks near the injection well reflect the higher permeability of the fracture system.

The thermal impact of injection (Figure 3) is less pronounced than the chemical changes, because the thermal effect extends out only about half the distance away from the injection well (~40 m) as the change in the ^{14}C signal in fracture CO_2 gas. The slower migration of the thermal front through the system is consistent with the relative rates of tracer and thermal breakthrough observed in geothermal systems (e.g., Shook, 2001). The thermal effect near the injection well is more pronounced in the fracture blocks, owing to the higher permeability and correspondingly larger advective heat transfer in the fracture network.

Future Modeling Refinements

Further development of our model will incorporate reservoir, production, and injection conditions that more closely represent those found at Aidlin. Future models will utilize reservoir conditions of 275°C and 3 MPa, an injection fluid temperature of 40°C, and injection rates ranging between 750 and 3500 L/min. Representative matrix hydrologic properties obtained by Persoff and Hulen (2001) from measurements of Geysers core samples, as well as injectate fluid composition from Crecraft and Koenig (1989), will also be incorporated into future modeling efforts.

Analysis of Aidlin gas and condensed steam well samples will provide information on the abundance of ^{14}C and the composition of isotopic tracers such as $^{13}C/^{12}C$, $^{18}O/^{16}O$, and D/H. These data will be used to constrain future TOUGHREACT simulations of the interactions between injectate water and the mineral, gas, and steam phases present in the geothermal reservoir and the resulting changes in composition and enthalpy of the produced fluids over time.

CONCLUSIONS

Initial reactive transport modeling results suggest that ^{14}C could serve as an effective tracer for the injection of reclaimed water within the Aidlin geothermal reservoir. With injection, the movement of ^{14}C occurs more rapidly through the simulated reservoir than does the drop in temperature that accompanies injection. Forthcoming analytical results from field sampling conducted prior and subsequent to initiation of injection of reclaimed water at Aidlin will be used to constrain and refine future models.

ACKNOWLEDGMENT

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Geothermal Technologies Program, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. We thank Joe Beall for his assistance in the field and Calpine for their support in conducting this study. We also thank Curt Oldenburg, Marcelo Lippmann, and Dan Hawkes for their constructive reviews.

REFERENCES

Crecraft. H.R., and B.A. Koenig, Geochemical consequences of treated waste water injection at The Geysers, USA geothermal field, *Geothermics, 18*, 65–72, 1989.

Hulen, J.B., D.L. Norton, J.N. Moore, J.J. Beall, and M.A. Walters, Initial insights into the nature, origin, configuration, and thermal-chemical evolution of the Aidlin steam reservoir, Northwest Geysers steam field, California, *Geotherm. Resour. Coun. Trans.*, *25*, 345–352, 2001.

Klein, C.W., and D. Chase, Chemical transients during production of high gas wells at the northern Geysers steam field, California, USA, *Geotherm. Resour. Coun. Trans.*, *19*, 513–519, 1995.

Moore, J.N., and R.P. Gunderson, Fluid inclusion and isotopic systematics of an evolving magmatic-hydrothermal system, *Geochim. Cosmochim. Acta*, *59*, 3887–3907, 1995.

Persoff, P., and J.B. Hulen, Hydrologic characterization of reservoir metagraywacke from shallow and deep levels of The Geysers vapor-dominated geothermal system, California, USA, *Geothermics*, *30*, 169–192, 2001.

Shook, G.M., Predicting thermal breakthough in heterogeneous media from tracer tests, *Geothermics*, *30*, 573-589, 2001.

Singleton, M.J., E.L. Sonnenthal, M.E. Conrad, D.J. DePaolo, and G.W. Gee, Multiphase reactive transport modeling of seasonal infiltration events and stable isotope fractionation in unsaturated zone pore water and vapor at the Hanford Site, *Vadose Zone Jour.*, *3*, 775–785, 2004.

Stark, M.A., W.T. Box Jr., J.J. Beall, K.P. Goyal, and A.S. Pingol, The Santa Rosa – Geysers recharge project, Geysers geothermal field, California, USA, *Proc. World Geotherm. Cong. 2005*, paper 2420, 2005.

Xu, T., Y. Ontoy, P. Molling, N. Spycher, M. Parini, and K. Pruess, Reactive transport modeling of injection well scaling and acidizing at Tiwi field, Philippines, *Geothermics*, 33, 477–491, 2004.

Xu, T., E. Sonnenthal, N. Spycher, and K. Pruess, TOUGHREACT—A simulation program for non-isothermal multiphase reactive geochemical transport in variably saturated geologic media: Applications to geothermal injectivity and CO_2 geological sequestration, *Computers & Geosciences*, 32, 145–165, 2006.