PHYSICAL MODELS OF STIMULATED GEOTHERMAL RESERVOIRS

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As part of the geothermal energy program at Stanford University, physical models have been developed to evaluate optimum performance of fracture-stimulated geothermal reservoirs. Three such efforts reported in this summary are: laboratory simulation of an explosion-produced rubble chimney to obtain experimental data on the extractability of heat from hot rock by in-place boiling; heat and mass transfer transients with individual porous rock fragments to compare their relative importance in stimulated systems; and measurement of radon emanation from geothermal reservoirs as a tracer for reservoir engineering studies. Definitive progress has been achieved with each of these physical models.

Hunsbedt, Kruger, and London (1975a) reported the progress on the construction and operation of a 19-ft.^{3} laboratory model of an explosion-produced rubble chimney (shown in the production mode in Fig. 1.b) to study the processes of in-place boiling, moving flash fronts, and two-phase flow in porous and fractured hydrothermal reservoirs, It had been noted by Ramey, Kruger, and Raghavan (1973) that although considerable energy is available from hydrothermal resources, most of this energy is stored in the aquifer host rock. Production by some nonisothermal process, such as in-place boiling or colder fluid recirculation, might be valuable for increasing heat extraction from natural or stimulated hydrothermal or hot rock geothermal resources.

Recent results by Hunsbedt, Kruger, and London (1975b) show that heat extraction obtained by pressure reduction which allows boiling to occur in the rubble chimney resulted in rock energy extraction fractions in excess of 0.75 under various experimental conditions. The degree of rock energy extracted depended on such parameters as height of liquid level, extent of condensed steam reflux, rate and temperature of cooler-water recharge, and rock to steam temperature difference which in turn depends on rock particle size and cooldown rate. In this high-permeability fractured rock system, recovery of available thermal energy ranged from 1.25 to 2.58 times the energy extractable by flashing the initial in-place fluid alone. Parameters noted to affect the extent of heat recovery included the external heat transfer parameter, rock porosity, initial reservoir conditions and enthalpy of the recharge fluid. Predictive models were developed for the laboratory model system based on mass-energy balance for comparison with the experimental data. Agreement was satisfactory for these experiments, other than recharge with cool water which produced non-uniformity in the axial temperature distribution. Evaluation of the results from the laboratory model are underway to scale the parameters to real-size stimulated reservoirs.

A second physical model was developed to examine microscale processes of mass and heat transfer in fracture stimulated reservoirs, based on two types of void space: macropores, defined as void volume between rock fragments; and micropores, defined as pore space inside individual rock fragments. The importance of mass transfer between hot geofluid in micropores and colder circulating fluids in macropores on heat extraction rates from fractured geothermal reservoirs was investigated. In the physical model, both mass transfer, using HTO as a tracer for the micropore water, and heat transfer, using a sensitive quartz thermometer, from artificial porous spheres were measured under similar experimental conditions.

Kuo, Brigham, and Kruger (1975) compared the molecular diffusivity associated with mass transfer as a function of porosity with the thermal diffusivity associated with heat transfer as a function of mixing rate. They noted that the ratio of the effective molecular diffusion and thermal diffusion coefficients was about 3×10^{-4}, indicating that even for very porous fragments heat transfer is a much more rapid process than mass transfer. Analytical models for the heat and mass transfer transients for spherical rocks agree with these indications, but suggest that a film coefficient in the model is desirable. Efforts are underway to investigate heat transfer transients for irregular shaped rocks.

Radon has been shown by Stoker and Kruger (1975) and Kruger and Umana (1975) to have potential as an internal tracer for reservoir engineering studies because of a unique combination of nuclear, chemical, and physical properties, its emanating power in geothermal reservoirs, and its transport characteristics in hydrothermal fluids. Interest in radon in geothermal reservoirs developed as a potential means to evaluate the creation of new surface area by reservoir stimulation techniques, such as hydraulic, thermal-stress, and explosive fracturing, and concern about the environmental release of radon and its short-lived radioactive products. However, since stimulated reservoirs are not available for testing, studies were concentrated on the emanation properties of radon in existing production geothermal wells as a function of steady-state and transient flow rate.

Radon concentration in geothermal fluids is noted to vary not only by resource type but also within individual wells in a given geotherma field. Temporal variations at steady flow rate are within useful limits. Models have been initiated to examine the dependence of radon concentration on flow rate, with a vertically linear model for vapor dominated systems and a horizontal radial model for liquid dominated systems. An initial test at the Geysers steam field, shown in Figure **2**, indicates a transient reduction in radon concentration to about half value over the three-week period following an instantaneous reduction in flow rate to half value. An excursion in radon concentration was noted during the onset of a period of seismic activity in the region. Additional tests at this field and similar tests at other steam fields and some hot water fields are being planned to evaluate the relationship of radon concentration under reservoir transient conditions.

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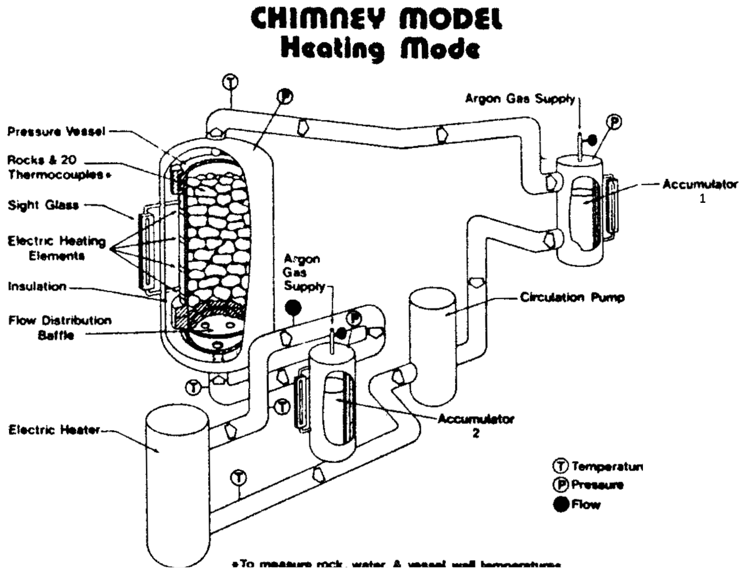

Figure 1.a Diagram of Chimney Model System - Heating Mode Operation

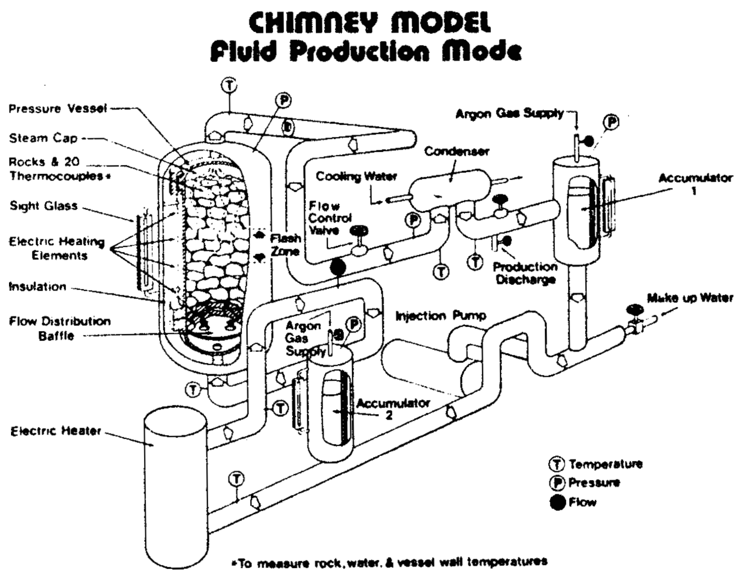

Figure 1.b Diagram of Chimney Model System - Fluid Production Mode Operation

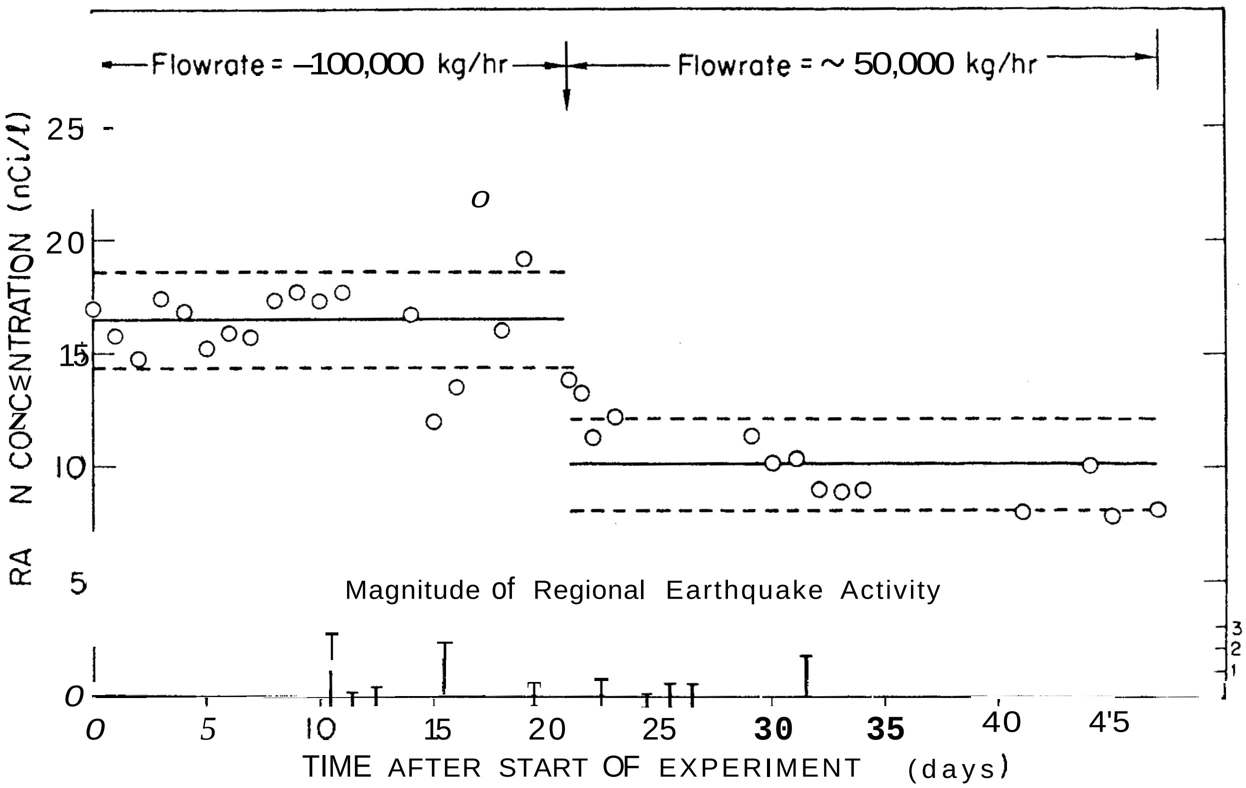

Figure 2 Radon concentration as a function of flow rate. Solid lines are the mean values over the flow rate period. Broken lines represent one standard deviation. Also shown is the magnitude of regional earthquake activity on the Richter scale.