AQUIFER BOILING MAY BE NORMAL IN EXPLOITED HIGH-TEMPERATURE GEOTHERMAL SYSTEMS

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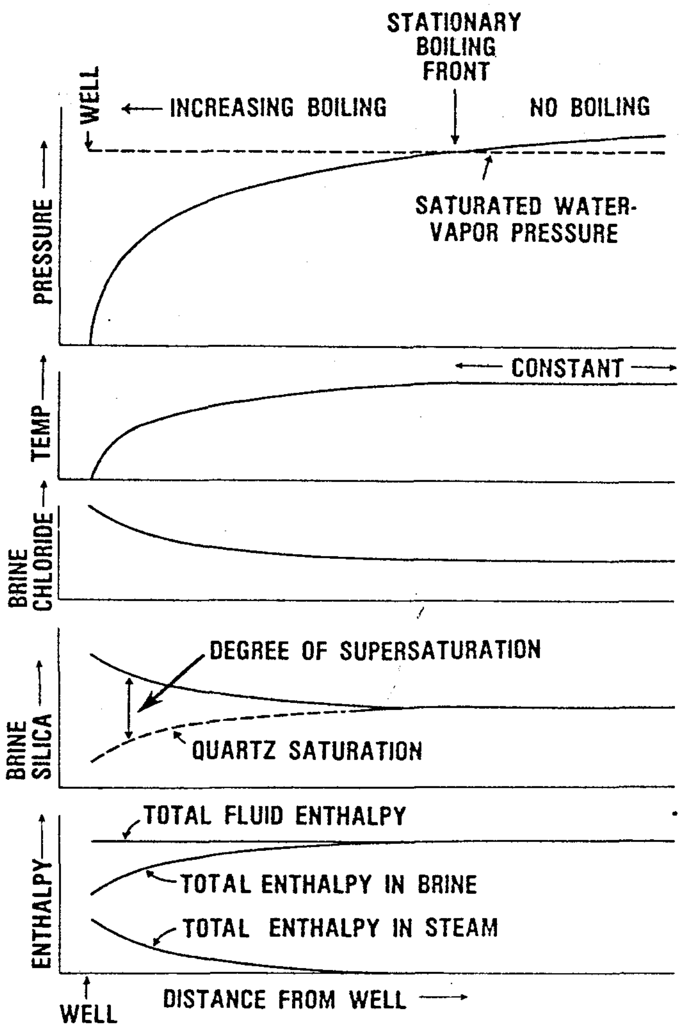
The Wairakei, New Zealand geothermal system has been extensively studied as the first major hot-water system to be exploited for the generation of electricity. There is a temptation to assume that other high-temperature geothermal systems will respond to exploitation in the same way; however, Wairakei is probably an atypical geothermal system. Although some shallow drillholes now produce only wet steam, unusually high fracture permeability at Wairakei allows most drillholes to tap large flows of liquid water which flash to steam-water mixtures only in the wellbores and cyclone separators. This high permeability is not found in vapor-dominated systems or in most wells of Cerro Prieto or Broadlands, the two other extensively studied hot-water geothermal systems.

In these more normal systems typically all or part of the liquid water in the aquifer boils in response to pressure decrease before it enters the well. Boiling can occur throughout the aquifer with more or less gravity separation of steam and water, or boiling can occur locally to each well or to a group of wells. Local boiling is unlikely to produce phase separation because the large pressure gradient in the boiling zone forces all steam and residual water to move to the well. When the boiling front expands into fresh rock, heat is transferred from the rock to the fluid which has been cooled by boiling; when the front is stationary, rocks and fluids are in thermal equilibrium and no heat transfer occurs. The rate of expansion of the boiling front is influenced by the relative mobility of steam and water, the well bottom and aquifer pressures, and the water/rock ratio. Extreme examples of expanding boiling fronts occur in vapor-dominated systems in which the liquid is essentially immobile and the water/rock ratio so low that all liquid is vaporized by heat transferred from the rock. In other systems liquid water is more mobile but aquifer boiling occurs when the liquid water cannot flow to the well fast enough to prevent pressure dropping below the saturated water vapor pressure (S.W.V.P.) for the aquifer temperature (fig. 1).

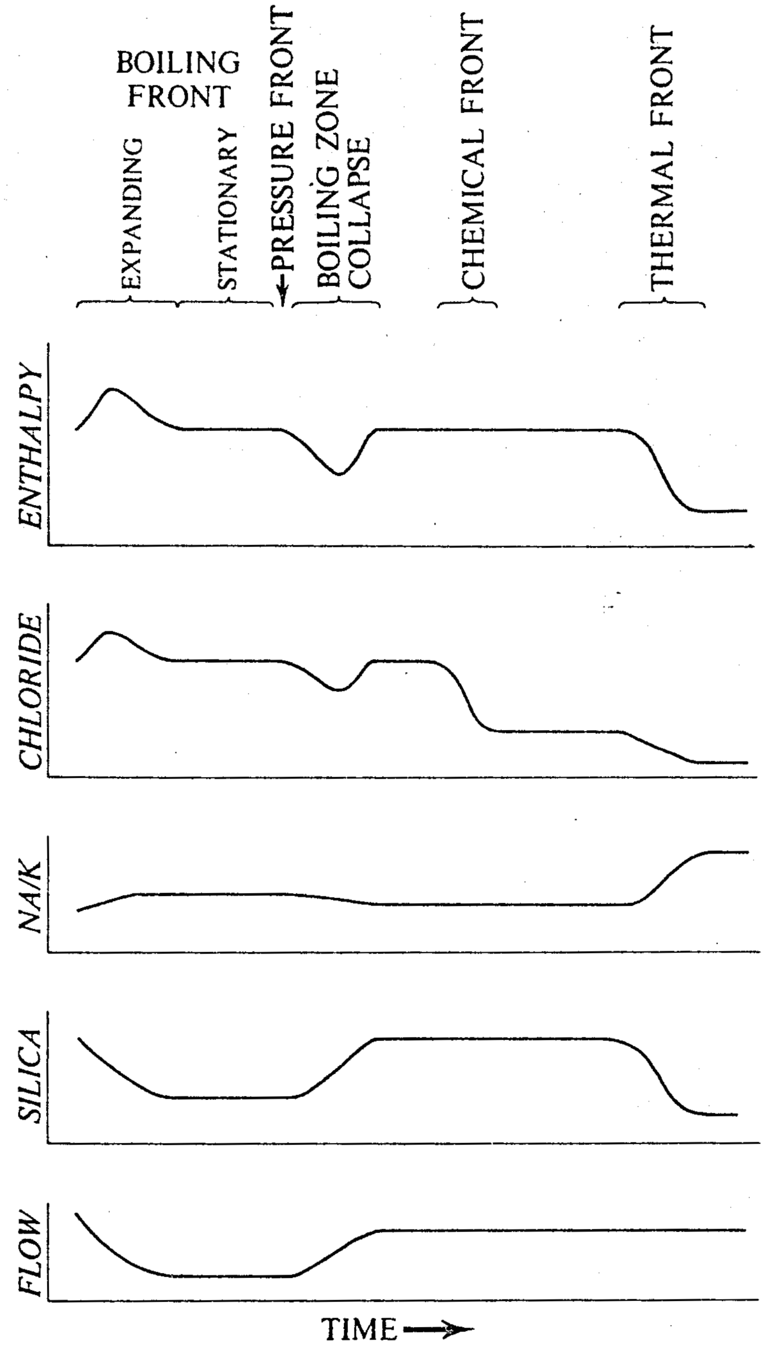
During flow toward the well fluid velocities increase and fluid pressures decrease. The amount of boiling is therefore greatest near the well and decreases away from it to some point where the pressure decrease is not sufficient to cause boiling. At greater distances from the well pressures will be lower than original values but greater than the S.W.V.P., and boiling will not occur.

FLUID PROPERTIES AFFECTED BY AQUIFER BOILING



A boiling front may become essentially stationary if pressures at a distance from the well are controlled by a constant pressure recharge boundary. The schematic changes in fluid pressure, temperature, and enthalpy and in brine chloride and silica concentrations from outside a stationary boiling front to the well are shown in figure 1. Since no additional heat is added once the front is stationary, there is no change in total enthalpy nor in total chemical concentrations, although there is separation of heat into steam and separation of solutes into residual water. Wellhead fluid enthalpies and chloride concentrations will be identical in wells producing from the same aquifer fluid regardless of the presence or absence of boiling in the aquifer provided that the separators are operated at the same pressure. Silica concentrations, Na/K ratios, and other temperature indices, however, may be affected. Boiling lowers fluid temperatures and therefore lowers the solubility of quartz. At the same time boiling increases actual silica concentrations in residual water because part of the original water is changed to steam. This results in substantial quartz supersaturation throughout the boiling zone with the degree of supersaturation increasing toward the well. Although metastable supersaturation with quartz occurs at low to moderate temperatures and is necessary to the operation of the silica geothermometer, equilibration rates increase with temperature, and at 260-300°C quartz probably approaches equilibrium in a few hours. Thus quartz deposition is likely in all parts of the boiling zone. In the outer parts where supersaturation is moderate, fluid velocities are also moderate and time is available for precipitation; close to the well where flow is rapid, the water is highly supersaturated favoring rapid precipitation. Other geothermometer indices such as the Na/K ratio may also be affected by the cooling effect of boiling but are not affected by concentration due to steam formation. These geothermometer indices generally appear to equilibrate more slowly than does quartz saturation although exact data are not available. Because of slower reaction rates and less disequilibrium there may be comparatively little effect from local boiling on these geothermometers, and chemically indicated temperatures may be nearly equal to original aquifer temperatures.

During the initial flow of a well, boiling may expand outwards into new rock and heat will be transferred to the fluids to produce excess enthalpy. These fluids will also contain excess chloride because a greater proportion of the water will be vaporized. As the boiling front moves outward and becomes stationary the excess enthalpy and chloride will decrease and disappear. These enthalpy and chloride "humps" have been observed at Cerro Prieto (CFE unpublished data) and Broadlands (Mahon and Findlayson, 1972). At Cerro Prieto boiling in the reservoir was accompanied by a "breakthrough" of lower temperature, lower chloride water from a shallower aquifer. This breakthough may have been triggered by a tectonic event, or it may represent the enlargement of a pre-existing minor pathway by hydraulic channeling. This breakthrough produced (1) a pressure front which in mid-1975 reversed the previous steep declines in water levels of shut-in wells within the field (Mercado, in press); and (2) a chemical front indicated by 1975-77



SCHEMATIC CHANGES IN FLUID CHARACTER

declines in aquifer chloride of more than 2000 ppm in the central part of the field (Truesdell et al., 1979). These changes should eventually be followed by a thermal front but this has not yet appeared. After 1975 fluid silica concentrations increased substantially as boiling zones collapsed and near-well temperatures rose (Alfredo Mañon unpub. data). The expected changes in fluid wellhead properties caused by aquifer boiling and subsequent fluid breakthrough are shown schematically in figure 2. The hypothesized changes in enthalpy and chemical variables are based on the arguments presented above; the flow changes are based only on the relative mobilities of single and two-phase fluids in porous media and do not reflect the pressure increase upon breakthrough or changes in the postulated inter-aquifer channel.

Monitoring of silica, Na/K (NaKCa), and enthalpy-derived temperatures can indicate the existence of expanding, stationary, or collapsing boiling fronts; and changes in chloride can indicate breakthrough of water from other aquifers. These chemical changes are more specific indicators of reservoir processes than are changes in wellhead pressure, flow, or downhole temperature.

References

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