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Production of Superheated Steam from Vapor-Dominated Geothermal Reservoirs

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ABSTRACT

Vapor-dominated geothermal systems such as Larderello, Italy, The Geysers, California, and Matsukawa, Japan yield dry or superheated steam when exploited. Models for these systems are examined along with production data and the thermodynamic properties of water, steam and rock. It is concluded that these systems initially consist of a water and steam filled reservoir, a water-saturated cap rock, and a water or brine-saturated deep reservoir below a water table. Most liquid water in all parts of the system is relatively immobilized in small pores and crevices; steam dominates the large fractures and voids of the reservoir and is the continuous, pressure-controlling phase. With production, the pressure is lowered and the liquid water boils, causing massive transfer of heat from the rock and its eventual drying. Passage of steam through already dried rock produces superheating. After an initial vaporization of liquid water in the reservoir, the decrease in pressure produces increased boiling below the deep water table. With heavy exploitation, boiling extends deeper into hotter rock and the temperature of the steam increases. This model explains most features of the published production behavior of these systems and can be used to guide exploitation policies.

Introduction

A few important geothermal systems, including the Larderello fields of Italy, The Geysers of California, and Matsukawa, Japan, produce dry or superheated steam with little or no associated liquid. The physical and production characteristics of these fields contrast strikingly with the more numerous geothermal fields that produce fluids consisting largely of hot water in which the proportion of « flashed » steam depends on initial temperature of the hot water and the well-head (separation) pressure. Many models have been published to explain these differences.

We review here the principal models that have been proposed to explain vapor-dominated systems; we emphasize the available well-test and production data from these systems; we review thermodynamic data on the phases present in the reservoirs; and we suggest that the model of White et al. (1971) provides a satisfactory basis for explaining the origin and initial characteristics of these systems, and the changing physical properties and flow rates of steam produced from exploited fields.

Production and well-test data

Production and well-test data for vapor-dominated systems have not been plentiful. Widely scattered fragmentary data were published before 1970 (Allen and Day 1927, Penta 1959; Burgassi 1964; Di Mario 1964; Chierici 1964; Bruce 1964; Nencetti 1964; Cataldi 1967; Otte and Dondanville 1968; and Ramey 1970) but many more have become available from the 1970 *United Nations Symposium on Geothermal Energy in Pisa, Italy* (Baba, Takaki, Matsuo and Katagiri; Corti, Di Mario and Mondolfi; Fabbri and Vidali; Ferrara, Panichi and Stefani; Rumi; Nakamura, Sumi, Katagiri and Iwata; Koenig; Mori; and Sestini, all 1970). Sestini's paper contains detailed data not previously available of flow rates, temperatures, pressures and gas contents of the individual wells in four regions of Larderello.

Reservoir pressures, temperatures

Measured static in-hole temperatures and shut-in pressures at Larderello, The Geysers, and Matsukawa indicate approximate saturation of water and steam before production. Reservoirs that occur at and below a depth of about 350 m tend to have relatively uniform initial temperatures near 235° to 240 °C and pressures from 32 to 35 kg/cm^2 (Penta 1959; Burgassi 1964; Otte and Dondanville 1968; Ramey 1970; Baba et al. 1970; Nakamura et al. 1970; and Koenig 1970). The initial temperatures and pressures are evidently strongly influenced by the maximum enthalpy of saturated steam (669.7 cal/g at 236 °C and 31.8 kg/cm^2; James 1968; Sestini 1970). If the gas content of the vapor exceeds a few percent, these physical characteristics can change considerably (White et al. 1971). Pressures in these vapor-dominated reservoirs are much below those of water-saturated rocks and are increasingly deficient with increasing depth (Figure 1).

The most complete data on in-hole temperatures and shut-in pressures are for parts of The Geysers. Wells in the old « Big Geysers » field were drilled in 1922-1925 (Allen and Day 1927). Initial shut-in pressures and flowing temperatures (Figure 2, after White et al. 1971) in general indicated rock saturated with boiling water. Well G6 was erratic. Initial pressures were successively too high (possibly due to high initial gas content) and too low for liquid saturation. Later measurements by McNitt (1963) and a meas-

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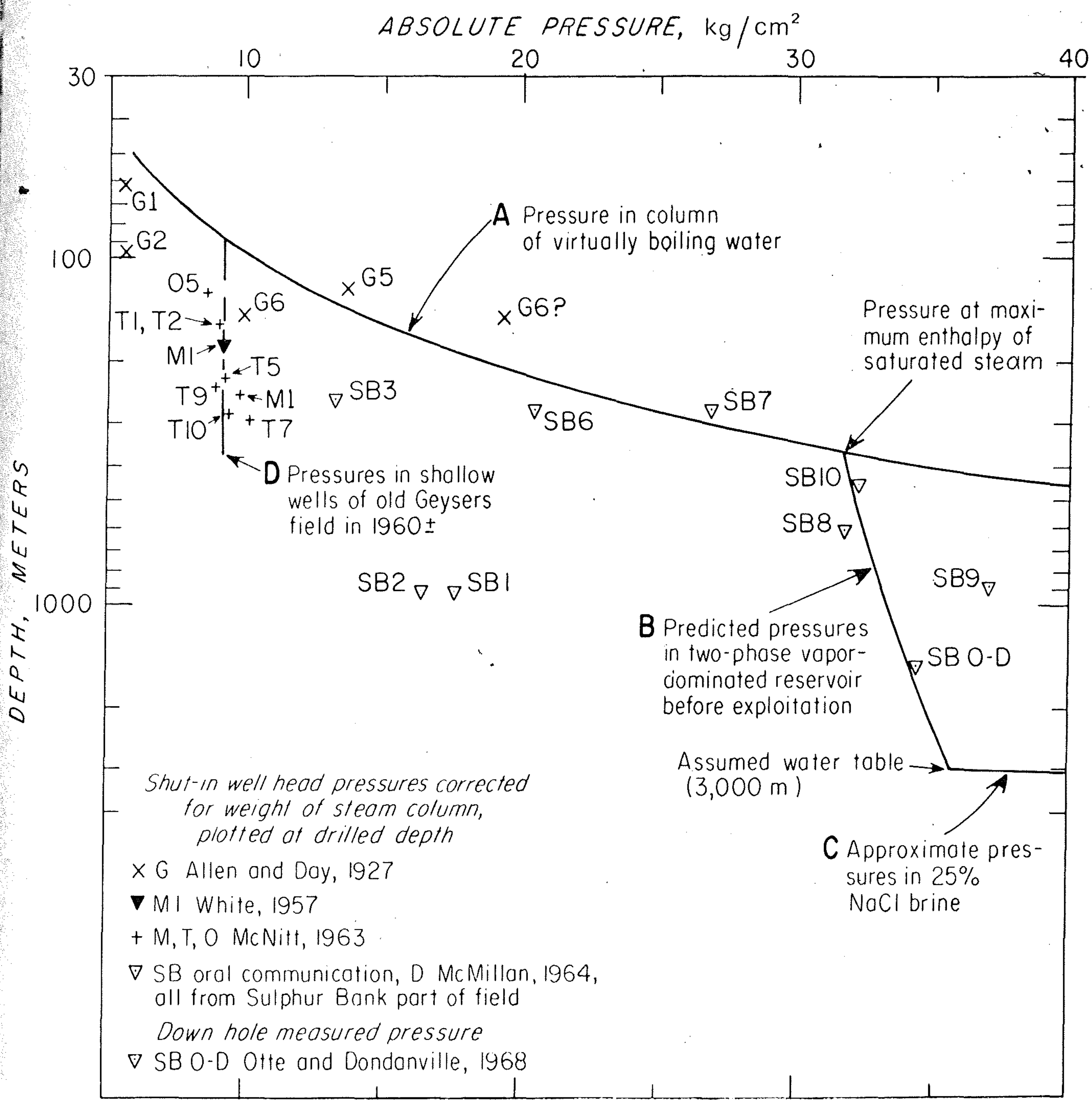

FIG. 1. — *Pressure-depth relations of early-drilled wells at The Geysers, California, with respect to the reference boiling-pressure curve for pure water and hypothetical relations in and below a vapor-dominated reservoir.*

urement by WHITE (1957) showed that temperatures were in general unchanged and still in rough correspondence with the reference boiling curve for liquid water but that the pressures had decreased markedly. This demonstrates depletion of liquid water due to 30 years of production with a resulting drop in pressure but with the temperature buffered by heat contained in the rock.

The deeper wells in the Sulfur Bank area of The Geysers have shut-in pressures (Figure 1) that indicate control of pressure by liquid water to a depth of 380 meters (curve A), where the pressure (32 kg/cm²) is equal to that of the maximum enthalpy of steam (see discussion in JAMES 1968 and SESTINI 1970). Below 380 meters most pressures indicate control by the weight of saturated steam (curve B). Pressures in a hypothetical 25% NaCl deep brine shown in Figure 1, curve C, are suggested in the models of CRAIG (1966) and WHITE ET AL. (1971). Similar but less detailed temperature-depth and pressure- depth data are given for The

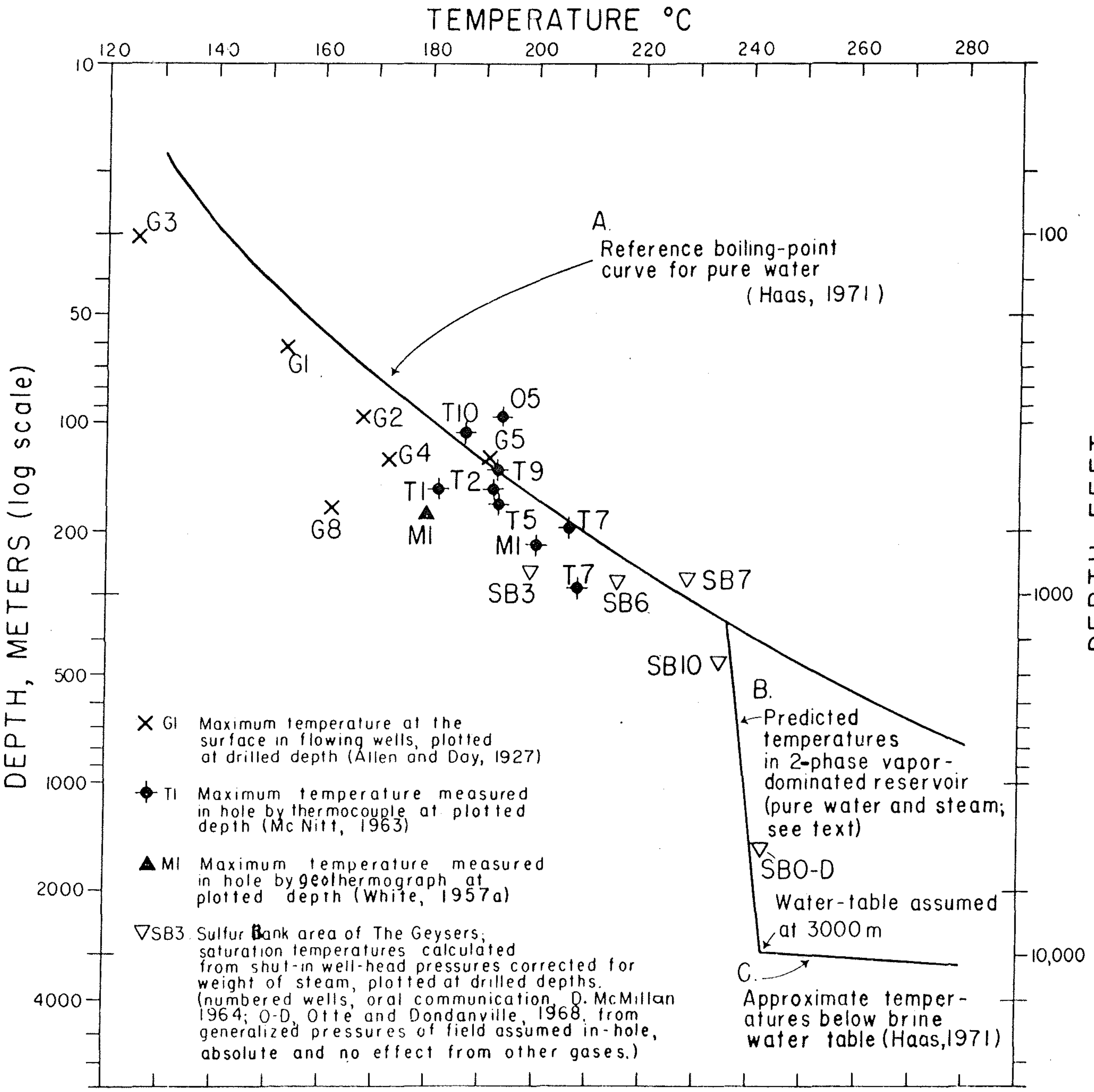

FIG. 2. — *Temperature-depth relations at The Geysers from* WHITE ET AL. (1971).

Geysers by RAMEY (1970). Temperature-depth data in newly exploited reservoirs is also available for Matsukawa (NAKAMURA ET AL. 1970; BABA ET AL. 1970) and rather crudely, for Larderello (ELDER 1966 after PENTA 1954).

In-hole temperatures and shut-in pressures in other vapor dominated fields seem to be quite different. Bagnore wells (Monte Amiata, Italy) had initial shut-in pressures of 20-22 kg/cm^{2}G and temperatures of 140-150°C at a delivery pressure of 4-5 atmospheres; Piancastagnaio wells (Monte Amiata) showed initial shut-in pressures of 35-42 kg/cm^{2}G and temperatures of 150-180°C at a delivery pressure of 4-5 at. (CATALDI 1967; ENEL, written commun., 1974). In these areas the shut-in pressures were high due to high gas content and decreased rapidly as the gas content decreased. These changes have been discussed briefly by WHITE (1973). The Travale 22 well initially had a shut-in pressure of 62 kg/cm^{2}G and a temperature near 260°C (A. ROSSI, oral commun., 1973).

NATURE OF FLUIDS PRODUCED

Most production wells of vapor-dominated systems produce only steam with various degrees of superheat;

liquid water occurs in some non-commercial wells on the borders of reservoirs and in some production wells that change eventually from wet steam with a little water to dry steam (FACCA and TONANI 1964; SESTINI 1970; and NAKAMURA ET AL. 1970). Most shut-in wells contain vapor as the only identifiable fluid, but liquid water flows into some Larderello wells that have been shut in (SESTINI 1970).

The enthalpy of steam from deep wells at The Geysers seems to have been fairly constant since the drilling of the first deep wells in 1957-59. Production enthalpies then were 666-670 cal/g (MC NITT 1963). BRUCE (1964) quoted 669 cal/g; later (1970), 667 to 669 cal/g and RAMEY (1970), 661 to 672 cal/g. The steam at The Geysers is slightly superheated at the usual production pressures.

It is not unusual at The Geysers for a well to yield wet steam for a considerable period of time before the discharge dries (H. C. RAMEY, oral commun., 1972). Whether this is due to incomplete casing of the near-surface liquid saturated zone or to liquid water in the reservoir is not certain. However, some wells at Monte Amiata initially produced 10-30 times as much liquid water as had been lost during drilling (R. CATALDI, oral commun., 1973).

The wells of Larderello, Monte Amiata and Travale, Italy show great variations in discharge enthalpy. Average enthalpies in the Larderello central zone were 682 cal/g in the early 1960's (BURGASSI 1964) but have risen to 694 cal/g since (SESTINI 1970). Other zones have lower fluid enthalpies (Serrazzano about 676 cal/g; Prata about 691, etc.). Exceptional wells have high fluid temperatures (> 240 °C) and enthalpies (VC-10, 259 °C and 709 cal/g; Larderello 89, 255 °C and 709 cal/g) but these wells are few in number and have been drilled recently (SESTINI 1970). Temperature increases at Larderello are considered later.

Discharges from the Monte Amiata wells were initially so high in gas content that the fluid enthalpy could not be determined by pressure and temperature measurements. The steam produced at Monte Amiata had high initial gas contents (85-95% at Bagnore) which decreased in 4 to 5 years to about 9% (CATALDI 1967). This field produces at present (November 1973) nearly saturated steam with following average characteristics: wellhead temperature 135-150°C; delivery pressure 3-3.6 kg/cm^{2}G; gas content 7.5%. Present flow at Travale 22 has an enthalpy of about 683 cal/g, a temperature of 200°C, and a gas content of 11% (ENEL, written commun. 1974).

INCREASE IN STEAM TEMPERATURE WITH TIME AT LARDERELLO

The average and maximum steam temperatures of the Larderello zones have increased with time up to 1966 as detailed by SESTINI (1970). From 1950 to 1966 in the central zone the average temperature of steam from wells of good flow has increased from about 210° to above 235°C (BURGASSI 1964; SESTINI 1970), and a maximum steam temperature of 255 °C was measured in well 89. In the Prata zone the well VC10 (also near Serrazzano) reached 259 °C in 1966 and the average steam temperature increased from 190° to 220 °C (SESTINI 1970). In other zones the increases have been as great but the average and maximum temperatures are lower. Wells that are close together may have quite different temperatures. It is significant that the highest average and maximum temperatures have occurred in heavily exploited zones. A general decline in temperature may have occurred since 1966, but more data is needed to confirm this.

DECREASE IN FLOW WITH TIME

Rapid declines in flow with time in the wells of Larderello are well documented. Data for individual wells have been given by PENTA (1954), DI MARIO (1964) and in more detail by BURGASSI (1964) and by FERRARA ET AL. (1970). Flow declines for all wells of the Valle del Secolo zone have been described by CHIERICI (1964) and for most wells of four Larderello zones by SESTINI (1970). New drilling at Larderello has tended to offset the flow declines, the total production remaining nearly constant at about 3000 metric t/h since 1951 (SESTINI 1970). New wells may produce more than 100 t/h but most wells decline ∾ 50 percent of their initial production in 5 years and to 30 percent in 10 years (CHIERICI 1964, SESTINI 1970). Notably, new wells in heavily exploited fields may show substantially the same rapid decline as wells in unexploited fields (data in SESTINI 1970). Although specific data are not available, new high-flowing wells are said to have been drilled in already heavily exploited zones near producing wells (SESTINI 1970, p. 627). Similar flow declines of 50 percent in 5 years are also observed at The Geysers (BUDD 1973).

FLOW-PRESSURE-TEMPERATURE MEASUREMENTS

Well-head flow-pressure relations are routinely determined in order to optimize production conditions (RUMI 1970, 1972). For some wells, well-head flow-pressure-temperature data have also been published (NENCETTI 1964; FERRARA, PANICHI and STEFANI 1970: SESTINI 1970). These data show that temperature attains a maximum at intermediate flow rates, with pressure near the shut-in value; with even lower flows, heat losses in the upper parts of wells cause lowering of temperature unrelated to the reservoir properties. Usually the produced steam under these conditions is nearly saturated with water. With higher rates of flow, well-head temperature and pressure decrease and the degree of superheating increases. The time required to stabilize a well after a change in flow rate ranges from days

(RUMI 1972) to months (NENCETTI 1964; ELDER 1966). Calculations by MANUEL NATHENSON (written commun. 1973) demonstrate that over a range of flow rates with a large variation in well-head pressures and temperatures, the well-bottom temperature remains constant. For moderate flow rates (< 80 t/h) typical of Larderello producing wells the decrease in temperatures and pressures from well bottom to well head is small ($< 8\,^{\circ}$C and 3 kg/cm^2). For higher flows of 130 t/h the temperature and pressure drops reach $\sim 15\,^{\circ}$C and $\sim$ 7 kg/cm^2. For these flows the pressure drop calculations agree with those of RUMI (1967).

GAS CONTENTS

The vapor-dominated systems of Italy that have no natural vent areas (Bagnore, Piancastagnaio, and Alfina) all have gas contents of 80-100% when first produced, and if produced long enough have shown a rapid evolution to contents near 7-10% (CATALDI 1967; CATALDI, pers. commun. 1973). Systems with vent areas have lower initial contents of gas. The data for Larderello show increases and decreases of gas with time for individual wells (SESTINI 1970) but overall the gas content is about 5 ± 1% (CORTI, DI MARIO and MONDOLFI 1970). At The Geysers, production is from a more homogeneous reservoir and gas contents in steam vary from 0.2 to 1.8% (BRUCE 1970). The average content seems to have decreased from about 2% to less than 1% from 1925 to 1969 (ALLEN and DAY 1927; BRUCE 1964, 1970). The composition of the gas has also changed with time, showing an increase in content of the more water-soluble gases (H_2S, H_2, NH_3) and a decrease in the less water soluble gases (CO_2) (ALLEN and DAY 1927; BRUCE 1964, 1970; KOZINTSEVA 1964). Similar gas composition differences were observed in producing layers of a Larderello well (FERRARA ET AL. 1970).

Models of vapor-dominated systems

NATURE OF THE RESERVOIR FLUID

Wide disagreement exists among earlier workers concerning the nature of the reservoir fluid(s) of vapor-dominated systems. FACCA and TONANI (1964), MARINELLI (1969), and FERRARA, PANICHI and STEFANI (1970) consider the initial fluid to be entirely liquid water. CHIERICI (1964), JAMES (1968), and probably ELDER (1965) and RAMEY (1970) consider the initial fluid of the main reservoir to be entirely saturated steam. CRAIG (1966) and OTTE and DONDANVILLE (1968) assume or imply superheated steam. WHITE, MUFFLER, and TRUESDELL (1971) and less clearly GOGUEL (1953) and SESTINI (1970) advocate a reservoir that contains both steam and water in its natural state prior to production.

We will consider the proposed models for the reservoir and possible mechanisms for superheating the steam, limiting our discussion to models based on relatively comprehensive consideration of available data.

Goguel (1953)

Perhaps the earliest model of the Larderello system that considered the thermodynamic behaviour of water was that of GOGUEL (1953). He considered a body of magma emplaced at $\sim$ 5000 meters depth to generate convection of overlying meteoric water, with a dispersed down flowing cold current and a channeled rising hot current. The hot current, at depth a supercritical fluid ($> 374\,^{\circ}$C, with salts not involved), becomes subcritical as it ascends along large, open fissures. The loss of heat to the rock causes condensation of liquid water on the fissure walls; the condensate percolates downward, presumably to be revaporized again at greater depths. Some of the saturated vapor thus produced escapes at the surface but the greater part is condensed.

When the system is produced, the vapor diverted into the bores takes heat from the rock (whereas before it had given heat to the rock) and, following an isothermal rather than an adiabatic decompression path, becomes superheated.

This model assumes that vapor removed by production can be replaced by increased recharge of meteoric water via the cold convection current and that the limit on longevity of production is the store of heat rather than fluid. The observed declines in flow, the prevalence of temperatures near 240 °C, and the lack of filling of the underpressured reservoirs by meteoric inflow are not explained. There is no near-surface liquid-saturated layer and no deep water table, but diverse features of GOGUEL'S model are found in most later models, including those of ELDER (1965), JAMES (1968), SESTINI (1970), FERRARA ET AL. (1970), and WHITE ET AL. (1971).

Facca and Tonani (1964)

This model assumes a permeable reservoir filled with convecting liquid water at about 260 °C and capped by an impermeable layer. Initial production from the reservoir includes some liquid water but soon a decompression volume is established adjacent ($\sim$ 1 meter) to the well bore, which is fed by hot water from the reservoir. In this volume a flashing steam-water mixture is accelerated to hypersonic velocities and the water separates by gravity from the steam. The excess translational energy of the steam causes superheating upon deceleration on entering the bore. JAMES (1968) criticized this hypothesis on the grounds that (1) hypersonic velocities could not be attained; (2) mineral deposition from evaporation of the liquid fraction adjacent to the well would choke off flow; (3) the turbulent steam-water mixture could not separate by gravity

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and (4) for many years the water-filled Wairakei system did not yield dry steam. We would add that an initial water-filled reservoir cannot have the observed nearly constant pressure with depth, and that disposal of the residual liquid fraction after steam separation in the decompression volume seems impossible—where can the liquid go except along paths of decreasing pressure to the well?

Elder (1966)

As part of a larger study of the physics of hydrothermal systems, Elder (1966) proposed a model for the Larderello system. Elder considered that the reservoir contains slightly superheated steam and is bounded by a perched water table from the surface to 400 m and by a deep water table below 2.4 km. In the natural state boiling from the deep water table produces steam which becomes slightly superheated. Heat carried by upward steam flow is conducted through the perched water layer; however, in the reservoir neither the condensation of this steam nor the fate of the resulting liquid is considered. Upon production the evaporation at the deep water table would increase due to decreased pressure. In Elder's scheme, this evaporation at the deep water table is considered essentially the same as the production of vapor below steaming ground in a hot-water system. It is thus necessary to have movement of hotter liquid up beneath the evaporation zone and of cooler liquid to the side and away. Heat transfer from the solid phases to the fluid is not considered. Elder rejects a supercritical magmatic steam source because of conflicting isotopic evidence and because without storage the total heat flux could not increase upon production over the steady state (unexploited) value. Elder's model does not consider why the natural reservoir has not become water filled nor does it explain the observed initial production of hot water and wet steam or the decline of production with time. The convection of liquid past a deep water table, as required by this model for the production of steam, probably could not keep up with the increased steam flow upon exploitation and wet steam and eventually liquid would result.

James (1968)

James (1968), in a model which is a well reasoned extension of Elder's concept, has included most of the features that are important to the heavily exploited central zone of Larderello. James argued against a steam-only system as requiring an unreasonable reservoir thickness to explain the production from this zone. He also rejected a water-filled reservoir as incapable of producing superheated steam. He adopted, in general, Elder's steam-filled, water-bounded reservoir and demonstrated from the thermodynamics of water why steam-filled reservoirs should exist at about 30 atm and 240 °C with their upper bounds at about - 400 meters. His mechanism for production of superheat differs from Elder's and follows that of Goguel (1953) in utilizing heat transfer from the rock. This results in nearly isothermal flow from the water table to the bore, with pressure dropping from $\sim$30 atm to 20 atm, thus producing superheated steam with observed enthalpy near 685 cal/g. An isoenthalpic pressure decrease of 15 atm in the bore, with a corresponding temperature decrease of 35 °C as assumed by James (1968), does not agree with the calculations and measurements of Rumi (1967, 1970) or the calculations (except for unusually large flows) of Nathenson (pers. commun. 1973) who found for average wells decreases of only 0.2 to 6 atm and 4 to 8 °C, depending on flow, bore length, and diameter. James rejects Craig's (1966) suggestion of a brine water table because of a consideration of the effect of mineral deposition on flow. James also rejects Elder's (1966) mechanism for the superheating of steam because it does not involve heat transfer from the rock but he accepts Elder's hypothesis of water table decline to explain the decreasing flow with time. This hypothesis predicts a 1 percent decrease in flow each year, with all wells of a field showing the same decrease. The observed decreases in flow of individual wells are much greater, however, a 50 percent decrease usually observed within 5 years (Sestini 1970; and others). This mechanism also fails to account for the independent decreases in newly drilled wells. James' model like Elder's requires unreasonably increased convection of liquid water below the deep water table to maintain steam production during exploitation. James' model also does not explain the early wet discharges from some wells. The arguments of James for a temperature- controlling mechanism at the water-steam interface below the reservoir and for the necessity of heat transfer from the rocks to the fluids during production are, however, particularly useful and convincing.

Sestini (1970)

Along with a wealth of production data, Sestini (1970) proposed a model of the Larderello system similar to that of Goguel (1953). Supercritical steam is assumed to originate at depth and flow up into the permeable reservoir along large fractures. Superheating of the steam is attributed to heat conduction through the rock from depth and transfer to the steam after it had decompressed and lost liquid to attain its maximum enthalpy. In the unexploited state, this steam condenses in the reservoir due to heat loss by conduction and the condensate along with some new meteoric water circulates in the permeable reservoir. This « disturbance » water initially saturates the reservoir and accounts for the wet steam and water of some new wells; water can also partly fill a shut-in well. As local concentrations of liquid are discharged or evaporated and as the reservoir pressure decreases with production, a greater proportion of superheated steam from the deep high-temperature source enters the well and the production temperature therefore rises. The claimed recent stabilization of total flow from the system and of well-head temperatures is assumed to indicate that the maximum rate of flow of deep superheated steam has been reached.

If the reservoir is water saturated, the near-constant pressures are not explained, nor are the initial high flows of new wells in exploited fields. In addition it is not reasonable that higher steam temperatures result from heat transport into the reservoir by conduction.

The significant differences between this model and that of WHITE ET AL. (1971) lie in the origin and circulation of the « disturbance » water, the dispersion of water in all porous rocks to supply new steam, the explanation for superheat in produced steam, and the existence of a deep water table. The difference between stored heat and fluid and SESTINI's assumed continuous supply at production rates is obviously extremely important to the ultimate fate of the resource.

Ferrara, Panichi and Stefani (1970)

This model, developed in connection with the study of an experimental well, assumes a reservoir originally filled with convecting liquid water; the drilling of a well produces an evaporation space which enlarges with steam production. The lengthening flow path decreases the flow until it equals the rate of water inflow to that part of the reservoir, at which time the size of the evaporation volume and the flow rate stabilize. With time further inflow of hotter water from depth is assumed to produce increased temperature of the steam. Some features of actual production behavior seem satisfactorily explained by this model, such as the initial production of water and wet steam, the declines in flow, and increase in steam temperature, but this model does not agree with the observed nearly constant pressure with depth prior to production. Also, the model as stated is thermodynamically impossible if, in the evaporation volume, water with an enthalpy of 250 to 500 cal/g is considered to evaporate to steam of 700 cal/g by extraction of heat from rocks originally at 240 °C. This cannot be done with a stabilized position of the water-steam interface which would rapidly exhaust heat stored in the rocks. This model has several basic similarities to that of WHITE ET AL. (1971), which is discussed next.

White, Muffler and Truesdell (1971)

The relatively rare geothermal systems that produce dry or superheated steam are called vapor-dominated systems. These systems develop initially from hot-water systems when the heat supply is large relative to the heat-transfer ability of the convecting liquid water in the system. This situation is caused primarily by low permeability of the rocks bounding the sides of the reservoir, with resulting low rates of recharge. When, due to increasing heat or decreasing permeability from self-sealing, more water is boiled off than is replaced by recharge, a vapor-dominated system begins to form. Discharge from the top of the reservoir is required for systems of the Larderello type; these cannot form under a truly impermeable cap (WHITE 1973). Thus, concealed reservoirs of the Larderello type are not to be expected. The excess of discharge over recharge is supplied from water in the larger fractures and pores; additional water in small pores and downward-terminating spaces is retained in the reservoir, whereas vapor occupies large pores and fractures and becomes the pressure-controlling phase.

Conductive heat losses from the margins of a high-temperature reservoir must be high, with actual conductive heat flows being of the order of 10 to 30 HFU (1 HFU = 10^{-6} cal/cm^{2}s), depending on depth and thermal conductivity of the rocks. Such heat flows cannot be explained by thermal conduction through the reservoir where temperatures are nearly uniform; the high conductive heat flows from the reservoir margin must be explained by condensation of steam. WHITE (1970) has calculated that a conductive heat flow of 20 HFU requires the heat from 20 kg of condensing steam per km^2 of surface area per minute. Such condensate being supplied at the upper surface of a reservoir already gravity drained is excess water not retainable by gravity; it must drain downward, thus ensuring the coexistence of liquid and vapor in the natural systems prior to exploitation. Vapor, however, is the continuous, pressure-controlling phase in large pores and open channels; thereby accounting for the nearly uniform pressures and, in turn, the nearly uniform temperatures; a pressure of 32 kg/cm^2 is less than the pressure of a column of standing water greater than about 1/3 km; thus the deep reservoirs must be underpressured with respect to a hydrostatic gradient (Figure 1).

The model of WHITE ET AL. (1971) requires a water-saturated zone below the uniform reservoir, as in Figure 1, curve C; the low temperature and pressure gradients within the reservoir cannot continue indefinitely downward because magmatic temperatures (and lithostatic pressures) must eventually be attained. The deep water-saturated zone is supplied by returning condensate and by any new recharge that enters the system through its margins. These margins must be characterized by low permeabilities; if highly permeable, more water would flow into the system than could be vaporized by available heat causing flooding of the reservoir resulting in a normal hot-water convection system.

Another consequence of this model is that, with time, the water body below the deep water table evolves to a brine of high salinity. All recharging water contains chlorides that are highly soluble in liquid but have volatilities too low to be carried in escaping steam. Chlorides volatile in low pressure steam (NH_4Cl, HCl, $HgCl_2$) are too rare to account for significant loss from the deep water body.

We emphasize that critical aspects of this model have not yet been confirmed. These include identification of a deep water table and an underlying liquid-saturated zone; the saline character of this water, if present; temperature and fluid pressure gradients that increase abruptly below the uniform reservoir; and higher permeabilities in the reservoir rocks than in the bordering rocks.

We will show that available thermodynamic and production data from vapor-dominated geothermal systems are consistent with our model and can be explained by the following processes:

(1) New wells of high flow drilled in unexploited parts of a vapor-dominated reservoir may first produce small quantities of water and wet steam and then dry steam from coexisting steam and liquid water stored in the reservoir adjacent to each well. The proportion of liquid water in the unexploited reservoir is estimated from experiments of gravity draining and from consideration of production enthalpies and temperatures.

(2) As pressures decrease toward a producing well, the liquid of an outer zone of reservoir rocks is evaporating, and the resultant steam is then superheated by transfer of heat from the rocks of an inner, previously dried zone. This process occurs initially in the reservoir and later involves the rocks and liquid below the initial deep water table.

(3) The local storage of water and steam adjacent to a well allows large initial rates of flow that decrease rapidly as the length of the fluid path increases, thus possibly explaining the characteristic flow-time curves of these wells.

(4) With intensive exploitation, production from the deep water body becomes increasingly important; the top of this zone of saturation declines into hotter rocks and the residual water increases in salinity; consequently, the produced steam increases in temperature and enthalpy.

(5) The recent (1966) attainment of maximum flow temperatures at Larderello, followed by declines, may indicate decreasing available fluid from the deep water table and possible approaching exhaustion of the resource.

Physical and thermodynamic properties of phases in a vapor-dominated reservoir

PURE WATER AND STEAM

The thermodynamic properties of greatest importance to geothermal systems — the temperature and density of water and steam as functions of pressure and enthalpy — are shown in Table 1 and Figure 3 (data from KEENAN ET AL. 1969).

EFFECTS OF SALTS AND GASES

The addition of salts to pure water affects most of the properties but the data are much less abundant. For the fluids present before exploitation within the vapor-dominated reservoir of our model, this is not a serious drawback because the common salts are not significantly soluble in low-pressure steam. Water in the vapor-dominated reservoir is largely replenished by condensation of steam (WHITE ET AL. 1971), so the condensate is dilute and has properties that do not differ much from those of pure water.

The fluids below the deep water table inferred to underlie the vapor-dominated reservoir (WHITE ET AL. 1971, Fig. 7) are probably saline. In general, the effect of adding salt is to increase the temperature required for vapor and liquid to coexist at a given pressure. The effect of dissolved NaCl on the position of the 2-phase region is shown in Figure 4, (data from HAAS, written commun., 1970). If the initial temperature and pressures of vapor-dominated systems are controlled by the maximum enthalpy of saturated steam (JAMES 1968; SESTINI 1970), the presence of salt could raise these values considerably (Figure 4).

TABLE 1. — *Viscosity, density, and enthalpy of water and saturated steam and surface tension and vapor pressure of water at temperatures of 0 to 350 °C.*

	Water (1)				Steam (1)			Water-steam
Temp °C	Vapor press. kg/cm²	Viscosity poise × 10⁴	Density g/cm³	Enthalpy cal/g	Viscosity poise × 10⁴	Density g/cm³	Enthalpy cal/g	Surface tension (2) dynes/cm
0	0.006	175	1.00	0	—	5×10^{-6}	597.4	75
50	0.126	54.4	0.988	50	—	8×10^{-5}	619.1	68
100	1.033	27.9	0.958	100	1.2	0.0006	639.2	58
150	4.852	18.1	0.917	151	1.4	0.0025	656.0	49
200	15.84	13.4	0.864	204	1.6	0.0079	667.1	40
250	40.51	10.7	0.799	259	1.8	0.020	669.1	32
300	87.50	9.0	0.71	321	2.0	0.046	656.6	25
350	168.4	7.3	0.57	399	2.2	0.11	612.4	16

(1) Data other than surface tension from KEENAN ET AL. (1969).

(2) Calculated from the relation of surface tension to viscosity proposed by SCHOENHORN (1967); viscosity data from DORSEY (1940) and KEENAN ET AL. (1969). Data below 100 °C refer to air-water interfaces; those above 100 °C to steam-water interfaces. Calculated values fit experimental values (available only to 130 °C, SIGWART in DORSEY 1940).

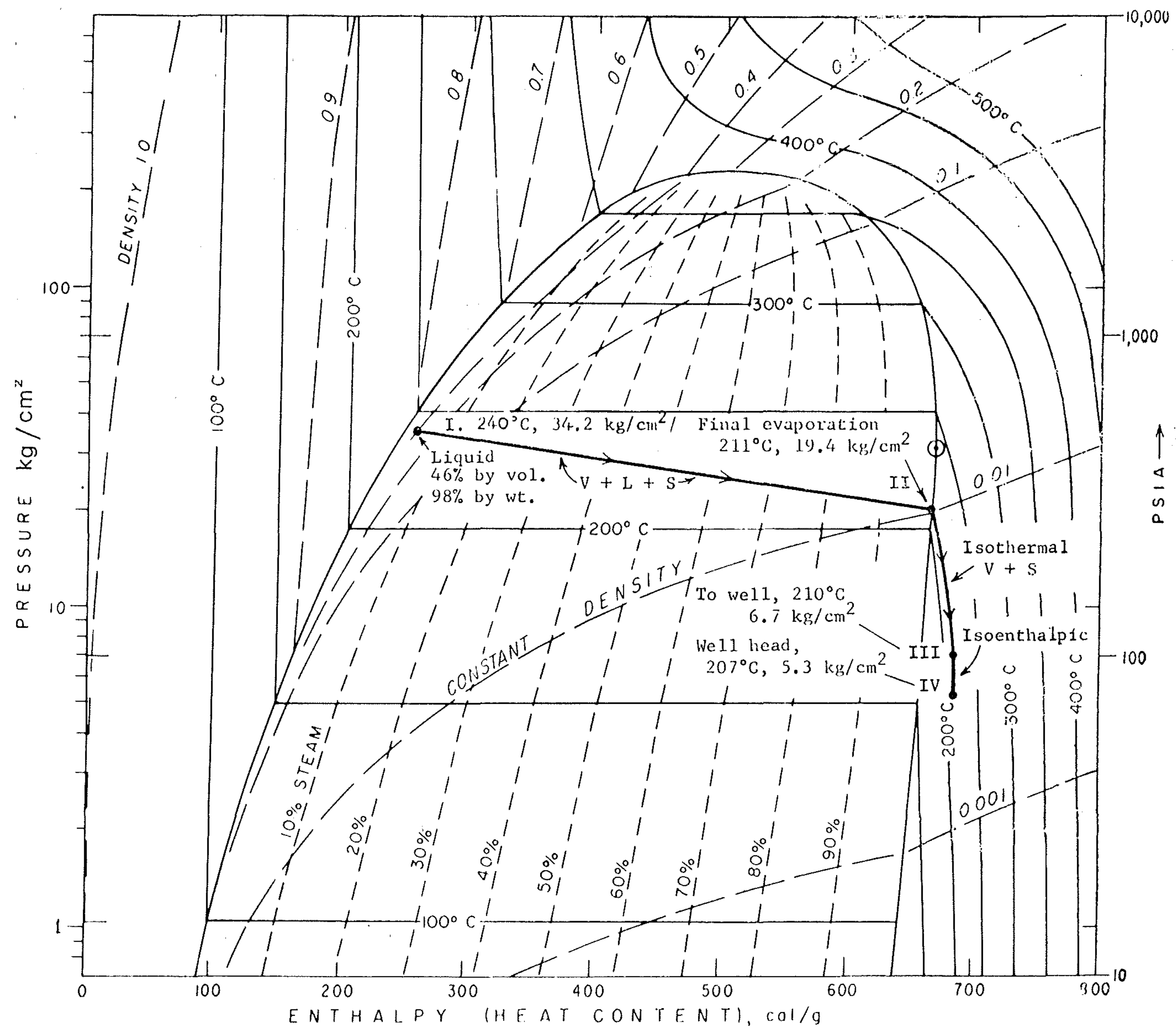

FIG. 3. — *Pressure-enthalpy-temperature diagram for pure water and vapor (modified from* WHITE ET AL. 1971), *showing a typical path for production of superheated steam (see text).*

Few data are available on the effects of KCl and $CaCl_2$, the other chlorides are likely to be of major importance at high temperatures and at extreme salinities. The solubility of NaCl increases only slightly with increasing temperature, but brines high in $CaCl_2$ and KCl can exist as liquids up to magmatic temperatures.

CO_2, H_2S and other gases in solution also significantly modify the thermodynamic properties of a liquid coexisting with a vapor phase. The effect of adding a gas such as CO_2 is opposite to that of adding a salt; i.e., the temperature required for liquid and vapor to coexist at a given pressure decreases with increasing CO_2 content (TAKENOUCHI and KENNEDY 1964, 1965; WHITE ET AL. 1971, Tables 5 and 6). Presence of gases thus has a marked effect on the behavior of the vapor phase in the two-phase reservoir, with the effect differing depending on the individual gases and the partial pressure of each.

EFFECTS OF SOLID PHASES AND SURFACE TENSION

Deviations from the normal physical properties of H_2O are also caused by surface effects between fluid and solid phases that come into play when the water is finely dispersed. In natural geothermal systems this becomes critical when water and vapor coexist in a porous rock. In wettable porous media the interfaces between water and vapor are concave toward the vapor. Accordingly, any transfer of mass from liquid to vapor (i.e. boiling) increases the area of the interface and is opposed by surface tension, leading to an increased stability of liquid relative to vapor. This increased

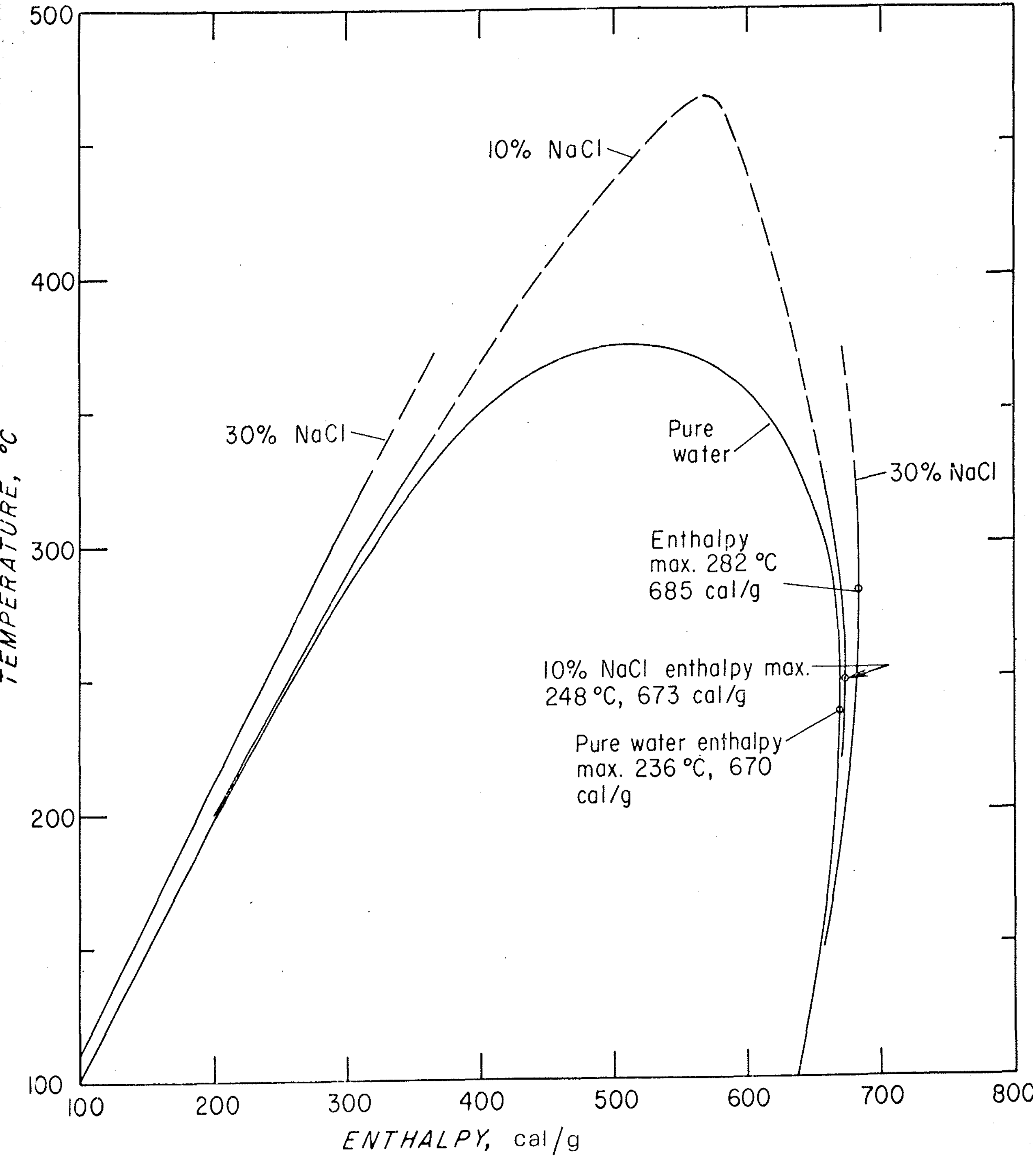

FIG. 4. — *Temperature-enthalpy diagram for H_2O-NaCl, showing fields of coexisting vapor and liquid at different salinities (data from* HAAS, *written communication,* 1970).

stability is expressed in lower vapor pressure of the liquid, with consequent higher boiling temperature than for bulk water.

These effects have been extensively studied for soil-water systems. Data exist for relatively permeable rocks, unconsolidated sands, and artificially consolidated sands up to 100 °C (MARSHALL 1959; SMITH 1961; CALHOUN ET AL. 1949). These studies show that the vapor pressure of water in a porous solid is a function of the state of saturation. When the solid is saturated with liquid water the vapor pressure of the contained water is nearly equal to that of bulk water. With decreased water contents the vapor pressure of the remaining water decreases. At low water contents (less than five volume percent of saturation) in the artificially consolidated sands studied by CALHOUN ET AL. (1949), the vapor pressure at 97 °C was from 50 to 12 percent of that of bulk water at the same temperature.

Data on these effects at higher temperatures and for rocks with smaller pores are not available. The surface tension of water with steam has not been measured above 130 °C but can be estimated from Schoenhorn's (1967) empirical relation between surface tension and viscosity (Table 1). These calculations show that the surface tension of water at 236 °C is near 35 dynes/cm, or about half of its value at 25 °C. The surface tension of pure water decreases rapidly above 300 °C but that of brine is probably significant to much higher temperatures (the surface tension of molten NaCl is higher than that of water at 25 °C).

The effect of surface tension on water dispersed in very small pores of a vapor-dominated reservoir rock is to raise the boiling point, thus permitting the liquid to be in equilibrium with nominally superheated steam. If boiling occurs in brine below a deep water table, soluble salts will concentrate in the residual water as boiling continues, and contribute additionally to its stability. Thus, liquid in tiny pores may coexist with steam that is superheated with respect to bulk water. We have no data on the magnitude of these effects in vapor-dominated systems relative to pore diameter and salinity of remaining liquid; such data are not essential to our initial model, but are likely to be critical in understanding the detailed physical behavior of an exploited reservoir.

HEAT CAPACITIES OF RESERVOIR ROCKS

In this paper we emphasize the critical role of heat contained in the reservoir rocks in converting pore liquid into steam that is first saturated and then superheated. Heat capacities of sandstone, shale and limestone as functions of temperature have been measured by Somerton (1958). In our reservoir calculations (Table 2), we assume the heat capacity of sandstone. The heat capacity of a limestone reservoir rock such as Larderello's may be about 5 percent greater than the sandstone assumed here, and shale and arkose of low porosity may be similarly high.

PRODUCTION OF SUPERHEATED STEAM FROM A RESERVOIR CONTAINING SOME LIQUID WATER

Data on pressures and temperatures from newly exploited systems (The Geysers, Matsukawa) and fragmentary early data from Larderello as well as theoretical arguments (James 1968) indicate that *in the unexploited state* vapor-dominated reservoirs are characterized by temperatures near 240 °C and pressures near 32 kg/cm². Thus it is of great interest to examine the flowing temperatures of steam produced from these systems, particularly temperatures of steam from the first production wells drilled into the reservoir itself (not into the near-surface liquid water zone). Drilling in the various zones of Larderello exceeded 400 meters depth in the mid 1940's (Penta 1954), at which time a maximum temperature of 241 °C was recorded. Most of the field, however, produced steam of much lower temperature, the average being about 200 °C (Burgassi 1964). Steam temperatures were at a maximum for wells at 300 to 600 meters in depth and were 20° to 70 °C lower for deeper wells (Penta 1954).

Table 2. — *Heat content above 0 °C in calories per cm³ of saturated steam, water, and rock at various temperatures.*

Temperature °C	Steam	Water	Rock (1)
100	0.38	95.9	50.8
150	1.67	138.5	81.4
200	5.24	176.1	115.0
240	11.21	201.6	143.6
250	13.75	208.7	150.9
300	31.16	230.2	188.3

(1) Assumed density of rock 2.5; heat content of dry rock from Somerton (1958).

At The Geysers the shut-in pressures of the deep wells of the Sulfur Bank area (Figures 1, 2) indicate a reservoir temperature near 240 °C, assuming saturated steam with a low gas content. Although the downhole temperatures are not very accurate (Ramey 1970), in general they confirm this temperature. If superheated steam existed in the reservoir, the temperature would be higher than saturation at prevailing pressures rather than lower (liquid water saturation would allow lower temperatures but not the observed constant pressure with depth). However, the temperatures of flowing steam are only 175 to 182 °C (calculated from Bruce 1964, 1970).

Thus both at Larderello and The Geysers large differences are observed between the flowing temperatures of the wells and the reservoir temperatures. Temperature losses in the well bore have been studied by Rumi (1967, 1970, 1972) and Nathenson (written commun. 1973). For wells of very small flow (< 10 metric tons per hour), heat loss in the well can explain these differences; conversion of heat to translational energy in wells of very large flows (> 150 t/h) can produce similar losses. However, most wells at The Geysers and Larderello have neither very large nor very small flows (Budd 1973; Sestini 1970) and the losses in the well bore are not enough to explain the observed differences.

James (1968) suggested that heat was extracted from the rocks in superheating existing saturated steam. But the superheating of steam contained in rock of 0.1 porosity initially at 240 °C from 670 cal/g to 700 cal/g would decrease the temperature of the system by only 0.1 °C. Wells drilled into a totally dry reservoir of steam at 240 °C should yield superheated steam of 239.9 °C at the well bottom. This steam, flowing at 80 t/h, would lose only about 8 °C in traveling up the well bore to a well-head pressure of 5 kg/cm². Thus, steam of 230 °C and $\sim$697 cal/g should be commonly observed. In fact, however, steam of this temperature and enthalpy is still rare in Larderello in spite of recent temperature increases, and is not known to exist at The Geysers.

We believe that the observed temperature differences result from evaporation of liquid water in and below the reservoir. Most water in vapor-dominated systems is stored as liquid, initially in small pores throughout the reservoir and in a saturated zone below a deep water table; after extensive production, largely limited to deep liquid-saturated rock with the reservoir rocks mostly dried. The evaporation of this liquid water to form steam absorbs large amounts of heat and explains the difference between initial reservoir temperatures and flowing well temperatures.

The thermodynamics of this process are easy to calculate. The total heat of even a water-saturated system is mostly contained in the solid phases (Table 3). If the pressure is reduced in a system containing steam, liquid water, and rock the water will boil and its temperature will decrease. If the water is dispersed in small pores in the rock, heat will be transferred from the rock to the water as boiling occurs, either until the entire system is at saturation temperature for the new pressure or until all local water is exhausted. Depending on the temperature, the water/rock ratio, and the pressure decrease, this process can produce a steam-water mixture, just-saturated steam, or superheated steam.

TABLE 3. — *Contributions of steam, water and rock to the total heat content in calories above 0°C of one cm^3 of rock at 240°C with 0.1 porosity.*

Volume fraction steam in pores (1)	Steam	Water	Rock (2)	Ratio of heat in rock to heat in fluid
0.0	0	20.2	129.3	6.4
0.2	.22	16.1	129.3	7.9
0.4	.45	12.1	129.3	10.3
0.6	.67	8.1	129.3	14.7
0.8	.90	4.0	129.3	26.4
1.0	1.12	0	129.3	115.4

(1) Remainder of pore space filled with liquid.

(2) Assuming 90 percent of heat content of SOMERTON'S (1958) sandstone at 240°C.

Some calculations of these drying paths are given in Table 4 and Figure 5 and a single drying path has been superimposed on the enthalpy-pressure diagram of water in Figure 3. The zones of co-existence of vapor, liquid, and rock, and of vapor and rock are also shown for simplified reservoir geometries in Figure 6. Outside of surface I (Figure 6, both models), the reservoir has its original temperature and pressure. Between surfaces I and II (Figures 3 and 6), the proportion of liquid decreases as the temperature and pressure decrease and as heat is transferred to the fluid. Along surface II the last liquid water disappears and the steam is just saturated. Further passage through the rock from surface II to the well (III) is nearly isothermal but a small amount of additional heat is transferred as the steam becomes more superheated. As may be seen on Figure 3, the steam would become superheated without ad-

TABLE 4. — *Drying effects and superheat of produced steam as functions of porosity and pore water for an initial vapor-dominated reservoir with steam and water coexisting at 240°C and 34 kg/cm^2* (1).

Original reservoir			Becomes saturated steam at		Well-bottom temperature (Pressure about 6.7 kg/cm^2) (1) °C	Well-head (p = 5.3 kg/cm^2)		
Porosity	Volume percent of water in		Temperature °C	Pressure kg/cm^2		Temperature °C	Enthalpy cal/g	°C superheat (3)
	Pores	Total rock						
0.05	10	0.5	237.1	32.4	236.9	233.9	698.9	80.5
	30	1.5	231.3	29.2	230.7	227.7	695.8	74.3
	50	2.5	225.3	26.1	224.5	221.5	692.6	68.1
	70	3.5	219.2	23.3	218.2	215.2	689.3	61.8
	100	5	209.9	19.4	208.8	205.8	684.6	52.4
0.1	10	1	233.9	30.6	233.5	230.5	697.3	77.1
	30	3	221.3	24.2	220.3	217.3	690.3	63.9
	46 (2)	4.6	210.8	19.4	209.5	206.5	685.0	52.8
	50	5	208.2	18.7	207.0	204.0	683.7	50.6
	70	7	194.3	14.0	193.2	190.2	676.7	37.2
	100	10	172.8	8.6	172.2	169.2	665.4	15.8
0.2	10	2	226.0	26.5	225.3	222.3	691.4	68.9
	30	6	196.0	14.6	194.8	191.8	677.5	38.4
	50	10	163.4	6.9	163.3	160.3	660.5	7.1
0.3	10	3	215.6	21.7	214.6	211.6	687.6	58.2
	20	6	189.0	12.5	188.0	185.0	674.0	31.6
	30	9	160.8	6.6	160.8	157.8	659.3	4.4

(1) Well-head pressure assumed 5.3 kg/cm^2; temperature and pressure changes within the well from calculations by RUMI (1967) for a fluid at 233°C; approximate for other temperatures.

(2) « Typical » trend of drying and production of superheat plotted in Figure 1.

(3) Temperature of saturated steam at 5.3 kg/cm^2 pressure = 153.4°C under static conditions; dynamic effects neglected.

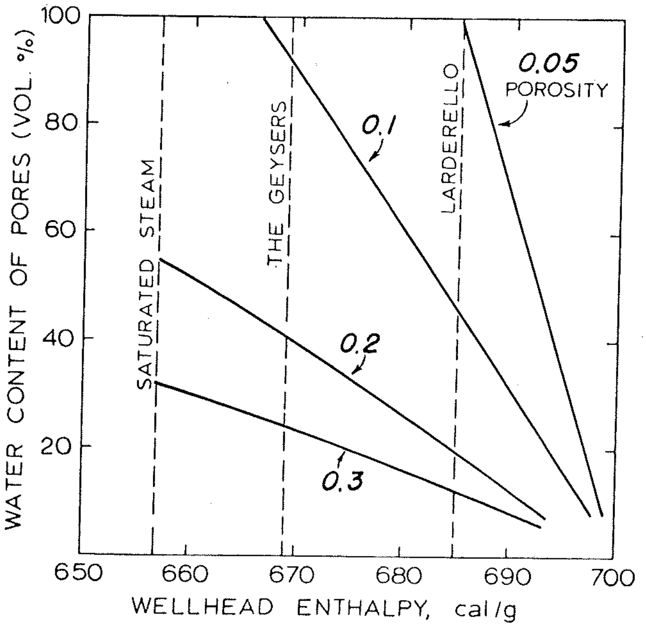

FIG. 5. — *Enthalpy at well-head relative to porosity and initial water content of pores, assuming a vapor-dominated reservoir at 240 °C and 34 kg/cm² producing steam at well-head pressure of 5.3 kg/cm² (data from Table 4).*

ditional heat transfer, but only to 670 cal/g maximum enthalpy. Passage up the well is adiabatic (except for very small flows as noted) and a small decrease in temperature occurs.

The final temperature and enthalpy depend in part on the original rock/water ratio, which may vary greatly throughout the reservoir. With a porosity of 0.1 and an initial temperature of 240 °C, a water-saturated zone would produce (at 5.3 kg/cm² wellhead pressure) steam of 169 °C and 665 cal/g. In contrast, a liquid-free zone under otherwise similar conditions would produce steam of about 237° C and 700 cal/g. Thus, differing flowing temperatures of adjacent wells may be explained.

DECOMPRESSION VOLUME

Production of vapor from a new well creates a volume around the well in which pressure is lower than that of the original reservoir. This volume, called the decompression volume, can have many configurations, two idealized extremes of which are shown diagrammatically as models A and B of Figure 6. Surface I, the outer margin of the decompression volume, is probably far more complex than shown in either model A or model B, but these idealized models allow visualization of changes in length of effective flow path as the decompression volume increases with production of steam.

The outer margin of the decompression volume is the surface within which water is vaporizing to steam in response to decreasing pressure. The pressure gradient is toward the well, with a resultant decrease in temperature and liquid content inward to surface II; between II and the well (III) liquid is absent, the temperature gradient is slight, but the pressure gradient is large.

With time and continuing production of fluid, both zones of the decompression volume expand and the volumes of adjacent wells encroach upon each other and eventually merge.

Depending on the permeabilities of fractures and interstices, the spacing of fractures, and the distance to the deep water table, the influence of a well may extend to the water table while volumes of rock in the initial vapor-dominated reservoir are still near their original pressure. This may result in a double source of fluid, as illustrated in Figure 7 (after a sketch by IAN DONALDSON, written commun., 1972). Double sources of produced steam are indicated in heavily exploited parts of the Larderello fields, as discussed below. In this drawing, the pressure front has just reached the water table, where the pressure is almost the original one. Continued production will locally depress the water table and cause flow of liquid along permeable channels but removal of liquid and vapor from small pores below the water table will proceed by the drying process described.

Water content of a vapor-dominated reservoir

PRODUCTION ENTHALPY LIMITATIONS

During production from a vapor-dominated reservoir, heat stored in the reservoir rock is transferred to the fluid. Most of the transferred heat is used in vaporizing water to steam, and only a minor amount is used in superheating the steam. For any given rock/water ratio, the degree of superheat at the well head depends on the initial temperature, heat capacity, and porosity of the rock, the depth and diameter of the well, the flow rate, and the well-head pressure. We can make reasonable assumptions for all these factors, and thus use the observed production enthalpy to evaluate the rock/water ratio in a vapor-dominated reservoir.

In Table 4 and Figure 5, production enthalpy is related to volume percent of liquid in the pores at four porosities. These curves are calculated assuming a rock heat capacity of 0.24 cal/g °C, an original temperature of 240 °C, a well depth of 600 m, a diameter of 0.33 m, a flow rate of 70 t/h, and a production well-head pressure of 5.3 kg/cm² absolute. These values are typical of Larderello (BURGASSI 1964, RUMI 1967, SESTINI 1970). The fluid is assumed to be pure H_2O. Steam flow within the well is assumed to be adiabatic with pressure and enthalpy changes typical of Larderello and calculated by RUMI (1967) and NATHENSON (written commun. 1973).

Steam near the average production enthalpy of Larderello (about 685 cal/g) can be produced from reservoir rock having a wide range in porosity (Figure 5) but with liquid content of about 5 volume percent

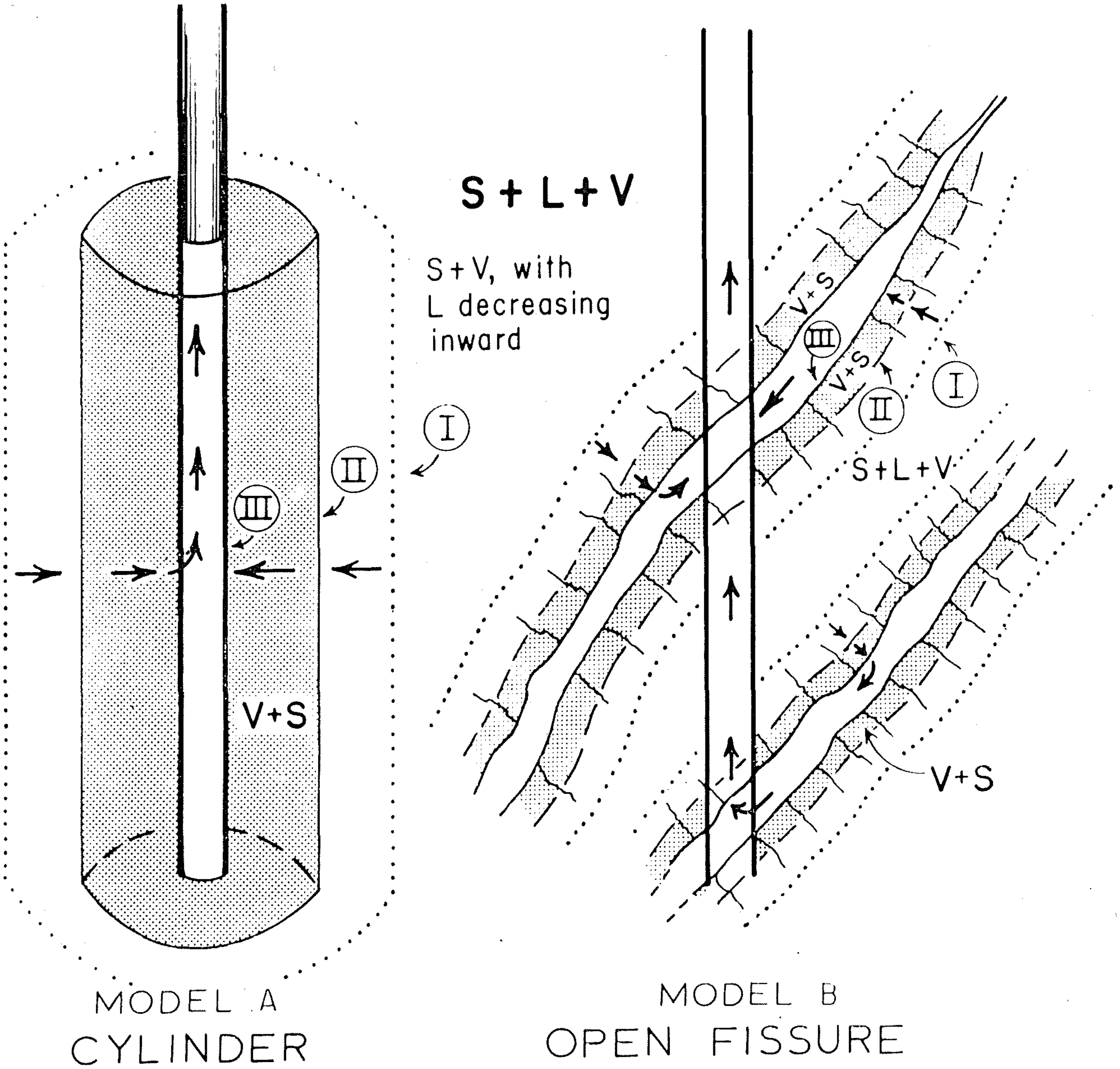

FIG. 6. — *Idealized decompression models of vapor-dominated systems, numbered points correspond to those of Figure 3. Model A is for a homogeneous reservoir of initially uniform pressure, temperature, and water content; model B assumes control by large permeable fractures in porous rock of low permeabilities.*

of the rock. Porosity at Larderello seems likely to range from 0.1 to 0.2, which corresponds to a volume of water in the pores of 20 to 50 percent; porosity in the reservoir cannot be as low as 0.05 requiring saturation with liquid, because water is not the hydraulically dominant phase; initial pressures in the reservoir were nearly constant, indicating that steam was the continuous phase. However, continued production from below a deep water table may require lower porosity values. Wells with high enthalpy (near 700 cal/g) may come from zones with low contents of liquid, whereas low enthalpy wells may be in wetter or more permeable zones.

The production enthalpy at The Geysers generally ranges from 667 to 669 cal/g (BRUCE 1970) but a maximum of 681 cal/g was noted by MCNITT (1963). BRUCE's average (Figure 5) implies either a high porosity (> 0.09) for the reservoir rocks or much production from below a deep water table where 100 percent of pore volume is filled with liquid.

DRAINAGE LIMITATIONS

As we have seen, the local liquid water content of the reservoir rock is related to specific characteristics that affect gravity draining. The effectiveness of drainage varies with size, shape, and interconnections of interstices (e.g., sand vs. clay; isolated vesicles in volcanic rocks). A given material has a well defined content of liquid water under gravity drainage at a given temperature.

The theory of gravity draining of a uniform sand (well sorted, with nearly spherical grains) has been discussed by SMITH (1961). In a water-saturated sand of uniform properties the process of draining is characterized by a water level in the material, somewhat higher than the free water surface in an open well due to capillary rise. If this water level declines, small bodies of water remain behind, held by capillarity to pairs or groups of sand grains. Immediately after draining of such a sand, the water content is about 0.10 to 0.14 of the total pore volume, depending on the packing, porosity, and grain diameter. A parallel theory has been developed for soils by CHILDS and POULOVASSILIS (1962), in which recharge on a gravity-drained soil is shown to maintain a constant water content with depth. This content is slightly higher than the gravity-drained minimum, with the excess depending on rate of recharge. This corresponds to our suggested recharge of a vapor-dominated reservoir, in important part by steam condensing at all margins where heat is flowing outward by conduction.

The application of these principles to the gravity draining of vapor-dominated reservoirs is necessarily qualitative; quantitative application to vapor-dominated systems depends upon better experimental and production data. Surface tension effects in porous rocks at high temperatures have not been studied; the poorly sorted and highly fractured materials of the reservoirs at Larderello and The Geysers must differ substantially in water retention, relative to uniform sands and soils.

Significance of our model to exploitation

VAPOR-DOMINATED CAPS OF EXPLOITED HOT-WATER RESERVOIRS

The importance of the water/rock ratio and the influence of the pressure-controlling fluid phase on production characteristics has been convincingly demonstrated at Wairakei, New Zealand where vapor-dominated caps of coexisting liquid and vapor have been artificially produced in a system that was initially a

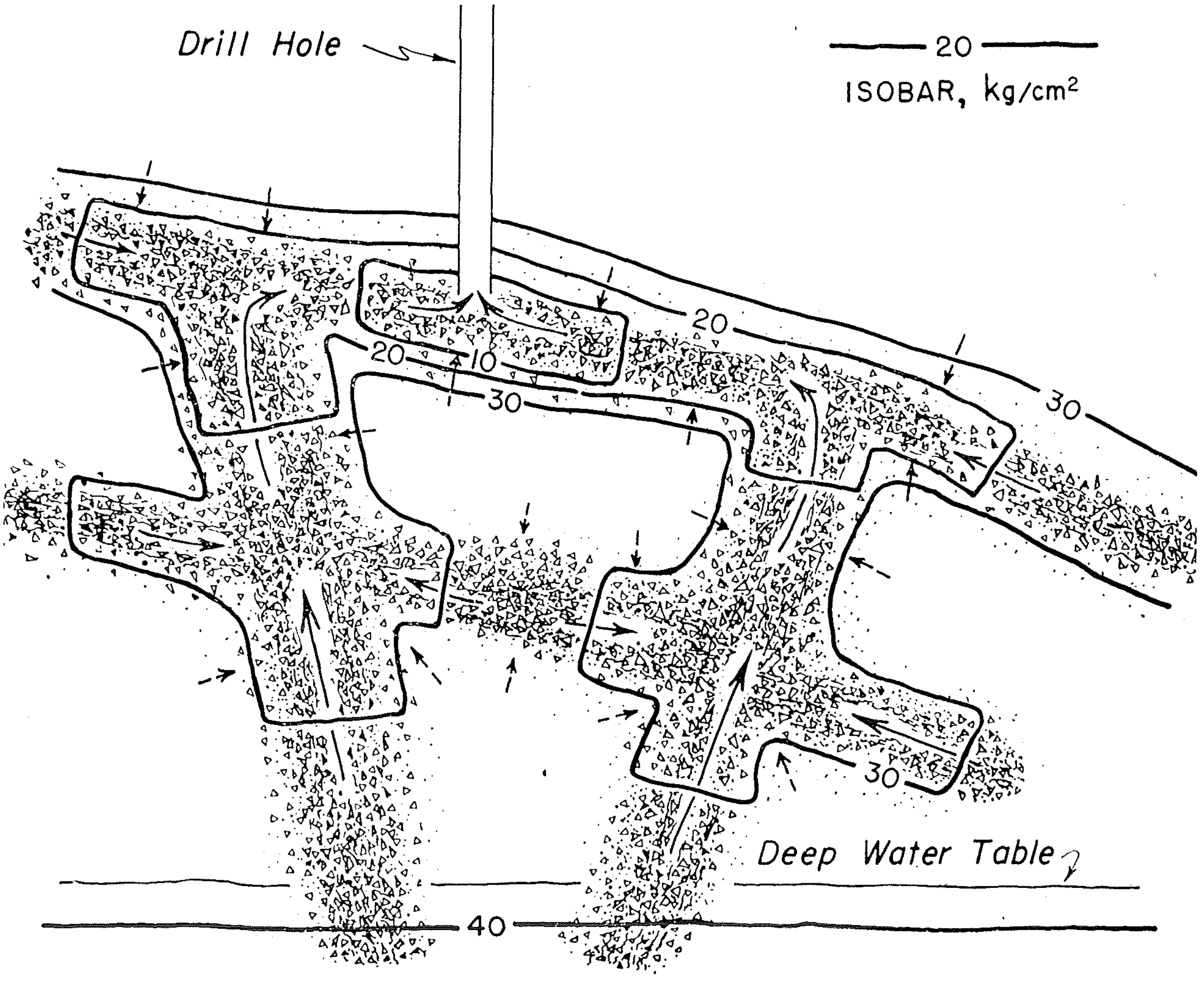

FIG. 7. — *Schematic pressure relations in a fractured reservoir with production first affecting pressures (and temperatures) below the initial deep water table.*

classic example of the hot-water type (JAMES 1968; GLOVER 1970; MAHON 1970). The change was produced by the discharge of fluids from drilled wells at rates that exceeded the local recharge capacity of the system in supplying new water. Production of total fluid during exploitation from about 1961 to 1967 has exceeded the former natural discharge by about five times, according to STUDT and THOMPSON (1969) and HUNT (1970). As a consequence, reservoir pressures declined and locally crude interfaces developed, separating underlying water-dominated zones from overlying gravity-drained caps dominated by vapor. The interface is presumably similar to the deep water table of our model of a vapor-dominated system. As reservoir pressures and this interface declined, the fluids produced by individual wells changed from dominantly water with normal « flashed » steam to wet steam with variable but low water contents, and then eventually to dry steam. This steam even becomes superheated by a few degrees (data of GRINDLEY 1965, p. 120, well 40) or more, for reasons discussed previously. This process is not entirely analogous to production of steam by boiling from a deep declining water table because the water table at Wairakei was artificially lowered by production of liquid from deep wells.

During the rather rapid gravity draining of the Wairakei caps, much liquid water was no doubt retained in isolated vesicles in tuffs and tuffaceous sediments, on mineral surfaces, in small pore spaces, and in pores of highest salt content. Actual contents of retained liquid have not been measured directly, but probably differ in various parts of the reservoir. The water contents were probably somewhat higher than for similar rocks in natural vapor-dominated systems because of the short time (up to a few years, at most) available for drainage. Water contents of the order of 10 to 15 percent of rock volume seem likely for the gravity drained Wairakei caps judged by relations shown in Figure 5 and the relative scarcity of superheated steam in the wells tabulated by GRINDLEY (1965, p. 112-121). The measured enthalpy of produced fluid from an individual well first attained 668 cal/g in 1961, but by 1965 six wells were producing steam of this enthalpy.

DECREASE IN FLOW RATES WITH TIME

Individual steam wells at Larderello, although having productive lives that average about 20 years (CHIERICI 1964), show relatively rapid decreases in flow with time. These decreases have been summarized for single wells by PENTA (1954), DI MARIO (1964) and in more detail by BURGASSI (1964, Table 5) and SESTINI (1970). Decreases for the entire field are considered by CHIERICI (1964). Similar decreases have been described at The Geysers (BUDD 1973).

Nearly all Larderello wells are similar in showing an initial steep decline, that seems to be independent of production from adjacent wells (SESTINI 1970). We interpret this to mean that the source of steam is initially local to each well.

TABLE 5. — *Production of a « typical » well at Larderello* (BURGASSI *1964*).

Year	Well-head conditions			Flow	
	Temp., °C	Pressure kg/cm²	Enthalpy cal/g	Metric t/h	Percent of 1951
1951	199	5.2	681.3	138.2	100
1952	208	5.1	686.1	90.5	65.5
1953	208	5.6	685.5	65.5	47.4
1954	208	5.5	685.6	51.8	37.5
1955	206	4.9	685.3	42.7	30.9
1956	200	4.2	683.1	37.7	27.3
1957	198	4.1	682.2	35.5	25.7
1958	196	3.9	681.5	33.6	24.3
1959	195	3.6	681.4	31.8	23.0
1960	190	3.5	679.0	30.9	22.4

The simplest explanation for a rapid decline in flow rate is that the initial path from the source to the well is short, with the path lengthening rapidly with production. This can be seen in a quantitative way from a consideration of Darcy's law (MARSHALL 1959, for example) which for horizontal flow can be written,

$$V = -\frac{k\partial p}{\mu\partial S}$$

in which V is the volumetric flow per unit area in the S direction, k is the permeability, μ the viscosity of the fluid and $\partial P/\partial S$ the pressure gradient. If the pressure in the reservoir is fixed at the outer margin of a decompression volume and the well bottom pressure is held constant, then the average pressure gradient is equal to the pressure difference ΔP between the unexploited reservoir and the well bore divided by the effective path length, l. As more steam is produced from a well, the decompression volume increases, the effective path length increases, and the average pressure gradient decreases, resulting in a decrease in flow with time. The mathematic analysis of flow in model vapor-dominated systems requires detailed reservoir data not available in the published literature.

TEMPERATURE INCREASE WITH TIME IN HEAVILY EXPLOITED FIELDS

The drying paths discussed in a preceding section were calculated for dilute liquid water in part of the pore spaces of a reservoir initially near 240 °C. This water is likely to be the dominant source of steam from a borehole in a vapor-dominated system during its early years of exploitation. In later production from part of a heavily exploited system that has exhausted most of its initial liquid H_2O, a mechanism similar to that proposed by JAMES (1968) and CRAIG (1966) probably becomes dominant. This consists of boiling from and below a brine water table that may be relatively dilute near the interface but that becomes increasingly saline with depth. The existence of this brine below a vapor-dominated system is inferred from the required hydrostatic and thermal continuity around the reservoir, as discussed in an earlier paper (WHITE ET AL. 1971) and reviewed here.

In the highly exploited steam fields of Larderello, the maximum temperature observed during each year has increased continuously from about 1930 to 1966, with especially clear convincing evidence since 1950. Beginning about 1966 in several fields, temperatures then started to decline (SESTINI 1970). The maximum recorded by SESTINI (p. 638) was 259 °C and several wells have exceeded the well-head temperatures calculated in Table 5 for a model reservoir initially at 240 °C. Although a part of this increase could be due to deeper drilling and higher initial temperatures, most of the temperature increase is probably due to an increasing involvement of boiling brine.

The maximum well-head temperature of each Larderello well occurs after its flow has decreased to a small fraction of initial flow, indicating a source of steam distant from the well. After long production of a well, the impedance of the flow paths of steam from evaporating liquid in remote parts of the initial reservoir becomes equivalent to that of paths to the underlying water table (Figure 7). Boiling from the water table then supplies an increasing portion of the produced steam. As accelerated boiling continues, the deep water table declines and dissolved salts are concentrated in residual water in deeper rocks of higher initial temperature. The resulting steam is higher in both temperature and enthalpy than initial steam of the vapor-dominated reservoir. Data for H_2O-NaCl are shown in Figure 4. Much higher temperatures and enthalpies of steam are probably attainable in brines high in $CaCl_2$ and KCl, where salinities can exceed 60 percent (ROEDDER 1970), but quantitative data are lacking. Significantly, in the most intensely exploited zone of Larderello, steam has reached the highest temperatures and is observed to contain up to 30 ppm Cl (C. PANICHI, oral commun. 1973). Although the form of the Cl is unknown, this may indicate boiling from a concentrated brine with a high activity of Cl.

Production from the central 10 km^2 of Larderello has averaged about 1500 t/h for the past 20 years (SESTINI 1970), for a total of 2.6×10^8 tons. Earlier production may add another 1.3×10^8 tons. Production of this quantity of steam, if originally contained as liquid in rock of porosity 0.1 under the 10 km^2 area of production would lower the deep water table by 500 meters. If the liquid below the deep water table were pure water everywhere at its boiling point with a temperature of 240°C at the water table, then the temperature of the rock and water 500 meters below the water table would be 289°C. If the liquid were 25% NaCl brine under the same conditions the temperature 500 meters below the water table would be 308°C (HAAS 1971). The temperature of steam produced by boiling of this deep liquid would be less than the original rock temperature by about the amounts calculated in Table 4 for 100% water saturation. Thus, if the rock porosity is 0.05 production of steam with temperatures above 240 °C would require original temperatures above 280°C. The water-table decline would be greater if the porosity were less than 0.1. Decreasing porosities with depth may be expected in such a system due to mineral deposition.

SESTINI (1970) suggests an increasing involvement of super-critical steam from a deep unspecified source, presumably volcanic. Volcanic steam is not essential, and its implied source is not consistent with the demonstrated dominance of meteoric water in Larderello steam (CRAIG 1963); moreover, the ore fluids of many fossil geothermal systems of close volcanic association are not dilute water but brines of high salinity.

DECOMPRESSION VOLUMES, ENLARGEMENT AND INTERFERENCE

As production from each well is initiated in a new field, the first fluid consists of vapor already present in large pores and fractures adjacent to the well, along with some « ponded » water perched in cavities where free drainage was prevented by downward closures. Already-existing vapor is almost immediately supplemented and then dominated by new vapor from boiling of pore liquid as the zone of drying (Figure 6) expands into previously unaffected ground. Eventually, depending on the spacing of wells, their structural interconnections, and the previous production history of the field, the enlarging decompression volume of each well starts to interfere with the decompression volumes of adjacent wells. Evidence for interference may be long delayed in porous rocks of homogeneous reservoirs (model A of Figure 6) with widely spaced wells, but may be almost instantaneous for two or more wells that intersect a single open fissure (model B, Figure 6).

CALCULATION OF RESERVES

Total production of steam per unit of reservoir volume perhaps can be established for the main vapor-dominated reservoirs from detailed records of production vs. time, where breaks in slope toward lower productivity may first indicate interference between adjacent wells. In the absence of well interference data, reserves may be estimated from a water content of 5 to 7 vol % of the total rock (Table 4) which seems reasonable for known vapor-dominated systems. These water contents for a reservoir initially at 240 °C produced to 5 kg/cm^2 well-head pressure will yield 4-5.7 × 10^7 metric tons of steam per km^3. This is equal to 4.9 to 6.8 megawatt-centuries of power at a consumption rate of 8 kg/kW. Table 4 and Figure 5 should be useful in calculating more precise initial water contents of a new field, but are not applicable to an old exploited field for which adequate data are lacking. After initial production of steam of nearly constant properties, gradual increases in temperature and enthalpy indicate production of steam from a deep brine water table.

Evidence for exhaustion of natural fluids

Vapor-dominated geothermal fields are still so little understood and their production histories are so short that premonitory indications of exhaustion are not yet generally recognized. Sestini (1970) concludes that present production of about 3000 tons of steam per hour from the Larderello fields is approaching a steady state and can be maintained for many years. However, our previous discussion implies that nearly all fluids of the initial reservoir have already been produced as steam and that the water of the deep brine water body may also be approaching exhaustion. Declining production rates of average wells and apparent attainment of maximum temperatures and enthalpy in 1966 (Sestini 1970) with subsequent declines suggest the possibility of approaching exhaustion.

Possibilities for recharging dried but still-hot reservoirs

Assuming the validity of our reservoir model and the previous discussion, decompression and the resulting conversion of all original liquid to steam (neglecting surface tension and salt effects) will eventually result in a large volume of dried rock that still retains much heat, but lacks sufficient fluids for effective transfer of the heat to a power plant. Production of low-pressure steam at a rate that is controlled by natural recharge of water could presumably continue indefinitely, but actual rates and pressures of the produced steam are not likely to be economic. Much of the dried rock of the original reservoir may be at 200 ± 20 °C, but parts that are adjacent to upflow channels from the deep brine water body may be considerably higher in temperature.

Injection of water into the still-hot reservoir is certain to yield some additional steam. If water could be introduced uniformly throughout the reservoir to attain a liquid content and dispersion similar to that of the original reservoir, a « second crop » of steam could be withdrawn at temperatures and pressures that can be calculated. The major problem is to obtain a uniform dispersion of liquid throughout the reservoir. Most injected water is likely to flow down to the deep water body (or its residue), utilizing available permeable channels and favoring the nearly vertical channels nearest injection wells. Injecting water at low rates into numerous relatively shallow wells of small diameter would be much more effective in dispersing new water throughout the dried hot reservoir than using a few large deep wells originally drilled for production. Whether economic « multiple crops » of steam can be harvested from water-depleted vapor-dominated reservoirs can only be determined by study and experimentation.

Conclusions

The model previously described by White et al. (1971) explains the physical and chemical characteristics and origin of natural unexploited vapor-dominated geothermal systems, and compares such systems to the abundant water-dominated systems.

In this paper we review previously proposed models of vapor-dominated geothermal systems, with particular emphasis on explaining the thermodynamics and production characteristics of such systems undergoing exploitation. In this effort we are hampered considerably by the lack of adequate data during the early years of development of the Larderello fields of Italy prior to their extensive production and by the fact that only scanty data have been released for The Geysers field of California. Production characteristics that require satisfactory explanation include:

1. Superheated (unsaturated) steam is produced.
2. Total mass of steam produced is very great. If originally as steam in the reservoir, total production from the central zone of Larderello requires a reservoir of its known area and a depth extending to the mantle (James 1968).
3. Temperatures and pressures within reservoirs at depths greater than about 350 m seem to be remarkably uniform prior to exploitation, with pressures near 32 kg/cm^2 and temperatures near 240 °C; with increasing depth below 350 m, the pressure is increasingly deficient in comparison to a hydrostatic gradient.
4. The gas contents of produced steam tend initially to be several percent, consisting largely of CO_2, H_2S, CH_4, and N_2; with production, the gas content tends to decrease and gas compositions shift toward the more water soluble gases, especially H_2S.
5. Some liquid water initially accompanies the dominant steam in some production wells, but the « wet » fluids tend to dry with time and then become superheated.
6. Natural superheated steam may occur in the old shallow reservoir of The Geysers, or old wells permitted to flow for more than 30 years may account for the superheating; we suspect the former as a characteristic of a major natural vent.
7. Initial steam produced from a virgin area has well-head temperatures from 180° to 220°C at production pressures near 5 kg/cm^2; the enthalpy of produced steam is generally from 670 to 680 cal/g. Steam initially saturated at 240 °C but decompressing through an already dried reservoir also at 240 °C should flow into the well at temperatures and enthalpies above those actually observed during early years of exploitation.
8. Initial physical characteristics of Larderello's produced steam have been changing rather consistently, at least since

1950 when better records became available. Most wells have increased in well-head temperature and enthalpy, with maxima reportedly attained about 1966; the recorded maximum for a single well was 259 °C, and most individual production zones then started to decrease. Similar trends have not yet been described from The Geysers or Matsukawa, Japan.

9. Most wells at Larderello show a decrease in rate of flow of about 50 percent of initial flow over a production interval of 5 years. The same general rate of decrease has been observed at The Geysers (Budd 1973). Newly-drilled wells tend to have a high rate of initial production, with independent decreases with time. Presumably after extreme exploitation and as the field approaches exhaustion, initial high production rates are no longer characteristic; Larderello seems to have achieved a maximum total production of about 3000 t/h regardless of the number of new wells drilled; however, several spectacular new producers have been discovered recently on the borders of old producing fields.
10. Production of fluids from Wairakei, New Zealand (a high-temperature hot-water system) at a rate about 5 times that of its natural recharge, has resulted in a man-made vapor-dominated cap remarkably similar in production characteristics to a vapor-dominated geothermal system.

Our analysis of these characteristics suggests initial intimate coexistence of liquid and vapor in the reservoir rocks. Vapor is the dominant pressure-controlling phase in large fractures and pores, but liquid water is the major phase by mass and is held in small pores and fractures by surface tension. Low permeability boundaries have permitted the under-pressured reservoir to develop in the rare circumstances where heat supply is high enough to vaporize all new recharge, with the difference being supplied by pore water from former water-saturated rocks. Vent areas are also required to permit the loss of the excess water and also to flush out gases other than steam that might otherwise accumulate.

The superheat of produced steam is explained by decompression adjacent to each new well, with at least 85 percent of initial total heat being contained in the solid phases. With decompression and the consequent decrease in boiling temperature, the heat of the rocks is first utilized in vaporizing any available liquid, up to a maximum of about 10 percent liquid by volume (with higher contents, liquid becomes the dominant pressure-controlling phase and the system is not vapor-dominated). After drying and cooling the rocks through an outer evaporating zone, the vapor then decompresses further in flowing to the well through an inner zone of already dried but still hot rocks. A slight transfer of heat from the rocks to the decompressing vapor produces nearly isothermal expansion that accounts for the superheat.

Thus, the supply of newly produced steam is from liquid water in the immediate rocks of the reservoir and the pore volumes required for an all-vapor reservoir are not necessary. The initial water content of some wells when first produced is accounted for by inadequate casing-off of high-level water-dominated aquifers; by wells too near the reservoir margins; and by local perched water bodies. Normal production temperatures, pressures, and enthalpies seem to demand the intimate coexistence of vapor and liquid that our model provides.

The changing characteristics of Larderello production with time seem best explained by the tapping of fluids in a deep brine-saturated zone below the initial vapor-dominated reservoir. This hypothesized deep zone, not yet identified by deep drilling and physical measurements, is necessary to explain the transfer of heat to the base of the homogeneous reservoir, to account for the flow of steam required for the natural vents, and to supply the heat required for the high conductive heat flow from the reservoir margins. The high temperature gradients and the high liquid salinity of the deep water body become even higher with decompression and production from this deep zone as the vapor boiling from this deep brine increases in temperature and enthalpy with time.

The decrease in flow rates of wells, and the relative independence of individual wells through early and middle stages of exploitation are also compatible with our model.

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