

Chemistry and Geothermometry of Brine Produced From the Salton Sea Scientific Drill Hole, Imperial Valley, California

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The December 29–30, 1985, flow test of the State 2-14 well, also known as the Salton Sea Scientific drill hole, produced fluid from a depth of 1865–1877 m at a reservoir temperature of $305^{\circ} \pm 5^{\circ}\text{C}$. Another flow test at a depth of 3170 m produced brine contaminated by drilling fluid and diesel oil. Therefore we focus on the first flow test. Samples were collected at five different flashing pressures. The brines are Na-Ca-K-Cl-type waters with very high metal and low SO_4 and HCO_3 contents. Compositions of the flashed brines were normalized relative to the 25°C densities of the solutions, and an ionic charge balance was achieved by adjusting the Na concentration. The composition of the preflashed reservoir fluid was calculated using enthalpy-chloride relations applied to the normalized and charge-balanced brines. The calculated total dissolved solids in the preflashed reservoir fluid ranges from about 24.8 wt %, assuming insignificant thermal losses from the erupting fluid before sampling, to 26.0 wt %, assuming a 10% enthalpy loss by conduction of thermal energy through casing and surface piping. The preferred total dissolved solids of the reservoir fluid is 25.05 wt %. The calculated specific density of the preflashed reservoir fluid at 305°C and 1870 m depth ranges from 0.9980 (no thermal loss prior to sampling) to $1.0107 \pm 0.0023 \text{ g cm}^{-3}$ (10% thermal loss). Of the various cation geothermometers that are now in common use, the Na-K-Ca method gives a temperature (310°C) closest to the measured temperature (305°C) in the production horizon. Calculated Na/K geothermometer temperatures, using equations suggested by different investigators, range from 326° to 364°C . The Mg/K² method gives a temperature of about 350°C , Mg/Li² about 282° , and Na/Li 395° – 418°C .

INTRODUCTION

To date, two flow tests have been conducted to characterize the reservoir conditions and fluids encountered by the State 2-14 well, the Salton Sea Scientific drill hole (SSSDH). This hole was drilled with funds administered by the Department of Energy on land controlled by the Kennecott Copper Corporation. The first flow test was conducted on December 29–30, 1985, when the total depth was 1898 m and the estimated formation temperature at the bottom of the hole was $305^{\circ} \pm 5^{\circ}\text{C}$ [Sass *et al.*, 1987]. Brine was produced from the first permeable zone (about 1865–1877 m) that was encountered after setting casing to a depth of 1829 m. Little drilling fluid had been lost to the portion of the formation that was flow tested, and the produced liquid was clear with no visual trace of drilling mud 2 hours after the start of the flow test. The second flow test, March 20–21, 1986, was conducted under much less favorable conditions when the hole had a depth of 3170 m and a liner was suspended to a depth of 3089 m. Brine, contaminated by drilling fluid and diesel oil, was produced during this flow test, and the test had to be terminated before the contamination was flushed from the system. Therefore we focus on the first flow test. The results presented here differ from those previously presented [Thompson and Fournier, 1987] because of an inadvertent comingling of data in milligrams per liter and milligrams per kilogram.

PHYSICAL CONDITIONS AT THE TIME OF SAMPLING

The apparatus used for collecting liquid and gas samples at different flashing pressures during flow testing of the SSSDH has been described by Michels [1986a] and is shown schematically in Figure 1. The sampling spool, shown in Figure 1, was located several tens of meters downstream from the well-

head. A mixture of brine and steam flowed from the wellhead through the sampling spool where it passed through a series of pressure-reducing orifice plates into sections of pipe equipped with traps and sampling ports (SP3–SP6) designed to sample brine or steam (Figure 1). Brine samples were collected at successively lower pressures and temperatures (greater fractions of flashed steam) from all the regularly available sampling ports (SP3, SP4, SP5, and SP6). In addition, the Kennecott Copper Corporation kindly allowed us to sample brine from a sampling port (SP2) that they had installed near the wellhead. We used a small, portable cyclone separator to ensure complete separation of brine and steam while sampling at port 2.

Approximate locations of pressure gauges (P1–P8) and thermal wells for in-line temperature measurements (T1–T8) are shown in Figure 1. The temperatures and pressures at which samples were collected are given in Table 1 and shown in Figure 2. For reference, boiling-point curves for pure water and aqueous solutions containing 25 and 30 wt % NaCl also are shown. Note that the temperature-pressure conditions measured near SP3–SP6 are within the expected range for boiling brines containing 25–30 wt % dissolved salt and small partial pressures of noncondensable gas, mainly CO_2 (calculated maximum about 1.2 bars at SP3 and 0.2 bars at SP6), in the steam fractions. In contrast, the temperature-pressure condition at SP2, measured during the December 29, 1985, flow test, plots slightly to the high-pressure side of the boiling-point curve of pure water. This result cannot be ascribed to instrumental error because different pressure and temperature measuring instruments installed upstream (wellhead and P1, T1) and downstream (P8, T8) from SP2 also gave the same readings, about 235°C and 32.5 Bars (S. S. Priest, written communication, 1987).

The pressure readings at the various ports give the sums of the partial pressures of steam plus all other gases (predominantly CO_2) at those measurement points. Therefore the pressure measured at a given temperature is expected to be some-

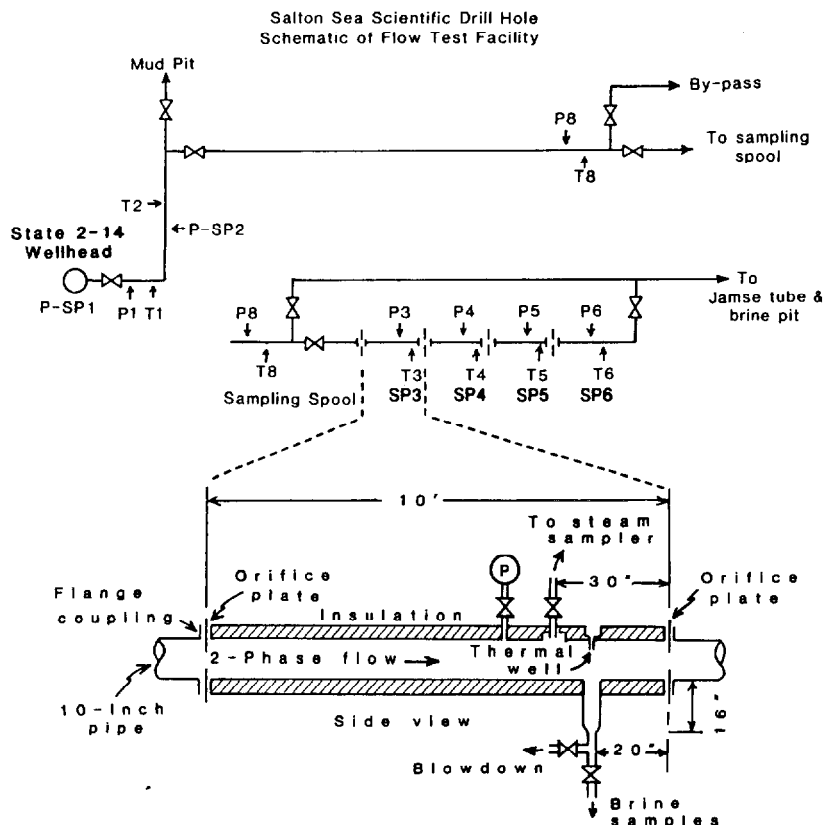


Fig. 1. Schematic diagram of surface piping, pressure and temperature measurement points (P1-P8 and T1-T8, respectively), fluid and gas sampling spool, and sampling ports (SP2-SP6) used during the December 29-30, 1985, and March 21, 1986, flow tests of the State 2-14 scientific drill hole.

what higher than the vapor pressure of water for the particular salinity of the solution. However, this effect is not large enough to explain the observed pressures between the wellhead and the sampling spool. For an initial concentration of 0.1664 wt % CO_2 dissolved in the reservoir fluid prior to flashing [Michels, 1986b] and taking account of CO_2 salting-out effects owing to the high salinity [Ellis and Golding, 1963], the calculated initial partial pressure of CO_2 at 305°C prior to flashing is 37.1 bars. During movement of the fluid up the well, the mass fraction of steam increased, the volume of the gas phase expanded, and the $\text{CO}_2/\text{H}_2\text{O}$ ratio in the steam decreased markedly. After flashing to the temperature measured at P2, the calculated partial pressure of CO_2 is only 1.9 bars. Subtracting 1.9 bars from the measured pressure yields a corrected steam pressure of 30.6 bars, which is equal to the vapor pressure of pure water at 235°C [Keenan *et al.*, 1969]. In contrast, the expected vapor pressure of a 25 wt % brine at 235°C is less than 23 bars (Figure 2). One of us [Fournier, 1987a] concluded that nonequilibrium three-phase flow (brine plus dilute water plus steam) occurred within the piping up to the point of entry into the sampling spool. Others have come to the same conclusion (GeothermEx, written communication, 1986). Evidently, small thermal losses during flow of the fluid up the well and along the surface piping resulted in condensation of a small amount of steam. The resulting very dilute condensate water tended to float on top of the brine, rather than mix with it, because of the significantly different specific densities of the two liquids (about 0.82 g cm^{-3} for the condensate and $>1.00 \text{ g cm}^{-3}$ for the brine). Therefore the liquid sample collected from port 2 could have been a mixture

of brine and a small amount of dilute liquid water. The dilute liquid water fraction appears to have disappeared (probably by flashing) when the fluid passed through the orifice plate at the inlet to the port 3 sampling chamber. In contrast to the above, during the March 21, 1986, flow test when the well was discharged at a greater flow rate than during the December 29-30, 1985, flow test, the measured pressure and temperature near port 2 were appropriate for brine-steam equilibrium (shown by the triangle in Figure 2) with no indication of a dilute liquid water phase.

SAMPLING AND ANALYTICAL PROCEDURES

Five samples of brine were collected at each sampling port: (1) a raw, unfiltered sample (500 mL), (2) a diluted (1:5), raw, unfiltered sample (500 mL), (3) a raw unfiltered, acidified sample (250 mL), (4) a diluted (1:4), raw, unfiltered, acidified sample (250 mL), and (5) a diluted (1:3), raw, unfiltered sample for the determination of silica. The brine samples that were acidified were collected directly into bottles containing acid, without filtration of the sample prior to acidification. This was done to prevent loss of calcium that might have precipitated as a carbonate during the lengthy collection process and to minimize precipitation of iron that occurred as a result of oxidation. To prevent separation of steam from brine after a sample emerged from the sampling port, each sample was passed through a stainless steel tube immersed in an ice bath so that it was chilled to less than 80°C before emerging at atmospheric pressure. Determinations for alkalinity, specific gravity, and total dissolved solids (TDS) were made immedi-

TABLE 1. Analytical Results for Brines Collected During the December 29, 1985, Flow Test of the State 2-14 Well

	Port 2	Port 3	Port 4	Port 5	Port 6
Hour	~1930	1600-1610	1626-1633	1805-1815	1640-1650
Temperature, °C	235	221	189	164	154
Pressure, bars	32.5	19	9.5	5	3.5
Density (weight)	1.222	1.236	1.245	1.252	1.261
Density (hydrometer)	1.225	1.241	1.246	1.252	1.263
pH	5.47	5.44	5.06	3.08	3.89
SiO ₂ *	322	340	428	251	236
Fe*	1,430	1,640	1,630	1,890	...
Mn*	1,730	1,830	2,050	2,150	...
Ca*	36,100	38,600	40,900	42,500	43,200
Mg*	42.6	46.5	49.5	52.6	51.9
Sr*	495	545	580	586	590
Ba*	234	271	187	219	184
Na*	57,100	62,300	60,300	62,700	69,500
K*	18,800	20,000	20,300	21,800	22,600
Li*	241	250	270	286	281
Rb*	132	139	156	155	161
Cs*	42	43	49	46	47
Zn*	547	610	625	614	634
Cu*	6.0	8.2	8.6	8.7	9.4
HCO ₃ *	217	187	78	0	0
SO ₄ *	0	0	0	0	0
Cl*	170,800	186,200	185,100	190,000	196,800
F*	17	15	19	12	15
B*	530	411	420	437	528
Sum, wt %	28.84	31.32	31.30	32.36	33.44
TDS (measured), wt %	29.23	30.27	34.00(?)	32.22	33.33
Sum anions, equivalents	4.75	5.15	5.18	5.40	5.76
Sum cations, equivalents	4.81	5.25	5.22	5.36	5.55
Cl/Na†	2.99	2.99	3.07	3.03	2.83
Cl/K†	9.09	9.31	9.12	8.72	8.71
Cl/Ca†	4.73	4.82	4.53	4.47	4.56
Cl/Mg†	4,010	4,000	3,740	3,610	3,790
Cl/Li†	708	744	685	664	700
Ca/Na†	0.63	0.62	0.68	0.68	0.62
Ca/K†	1.92	1.92	2.01	1.95	1.91
Ca/Mg†	847	830	826	808	832
Ca/Li†	149	154	151	148	153

*In milligrams per kilogram.

†By weight.

ately upon return to Menlo Park, California. The TDS were determined by evaporation of a known volume and weight of brine at 180°C, using the method described by *Fishman and Friedman* [1985]; chloride was determined by the mercurimetric method [*Fishman and Friedman*, 1985]. Copper and lead were determined by atomic absorption spectrometry in an air-acetylene flame at 325 and 217 nm, respectively. Specific gravity (density) was determined by two methods, by weighing of a known volume of liquid and by hydrometer. For the weight method we modified the procedure reported by *Fishman and Friedman* [1985]: 25 mL of distilled water were transferred into a preweighed evaporating dish and weighed to calibrate the pipet volume; then, using the same pipet, 25 mL of each brine were transferred into a separate preweighed evaporating dish and weighed. The specific gravity was calculated from weight of brine/weight of distilled water, assuming equal volumes. ERTCO ASTM Specific Gravity, plain form hydrometers were used, having subdivisions of 0.0005 g cm⁻³ and a range of 0.050 g cm⁻³. All other constituents were determined using the methods reported by *Thompson* [1985].

ANALYTICAL RESULTS AND BALANCING OF CHARGES

The results of the chemical analyses are shown in Table 1. The differences between the sums of the cation and anion charges shown in Table 1 are not large, considering the many potential sources of error that are present in the collection and analysis of dissolved constituents in brines containing over 25 wt % TDS. The brines are Na-Ca-K-Cl-type waters with extremely high metal contents (Fe, Mn, Zn, Pb) and very low SO₄ and HCO₃. During the flow test some dissolved silica precipitated in the flow line as a consequence of flashing of steam and cooling, but no indication of salt precipitation was found upstream or within the sampling apparatus after the flow test. The variations in the ratios of dissolved constituents shown in Table 1 appear to be mainly the result of analytical uncertainty and not precipitation of salts before or after sampling, as there are no systematic changes going from the most dilute to the most concentrated samples (port 2 to port 6).

The first step in calculating the composition of the pre-flashed reservoir fluid was to derive an internally consistent

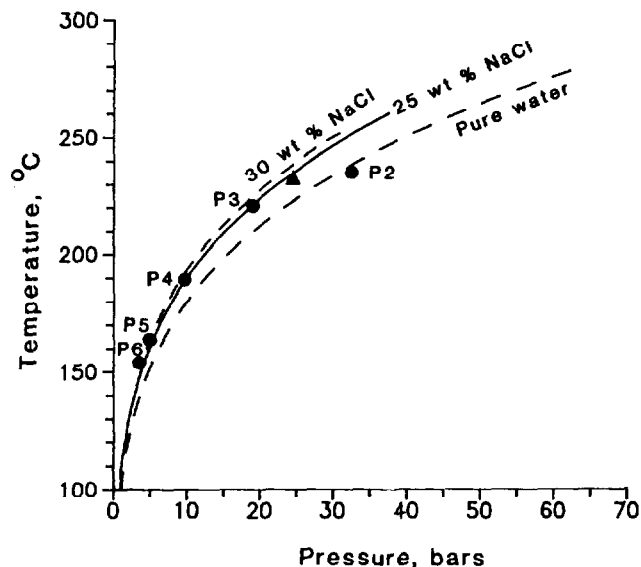


Fig. 2. Temperature-pressure diagram showing conditions at the sampling ports (numbered circles) during the December 29, 1985, flow test. The triangle is for port 2 during the March 21, 1986, flow test. Also shown are the boiling-point curves for pure water and for 25 and 30 wt % NaCl solutions.

data set of brine compositions obtained from the various sampling ports that were also consistent with the densities of these brines cooled to 25°C. The analytically determined values for dissolved Ca and K systematically increase with increasing density of the solution, but those for Na and Cl do not (Table 1). Also, ratios of calcium to other dissolved constituents were found to be generally more consistent than ratios involving other elements, and cation ratios involving sodium were found to be the least consistent of those calculated. Therefore the analytical results for K, Mg, Li, and Cl were normalized relative to Ca, and then the concentration of Na required to balance the ionic charges was calculated. The next step was to calculate the densities of the normalized and charge-balanced compositions for comparison with the measured densities at 25°C.

The densities of the brines at 25°C were calculated using a model that is applicable for brines that are composed predominantly of NaCl, KCl, and CaCl₂ [Potter and Haas, 1978]. In that model the measured density of the brine, d_b , is related to the composition of the brine as follows:

$$d_b = d_N + (d_K - d_N)f_K + (d_C - d_N)f_C \quad (1)$$

where d_N , d_K , and d_C are the densities of pure solutions of NaCl, KCl, and CaCl₂, respectively, at the molality of the total chloride in solution, and f_K and f_C are the mole fractions of chloride present in the brine as KCl and CaCl₂, respectively. Densities of the pure chloride solutions of the three salts were taken from Potter and Brown [1976, 1977] and Potter and Clyme [1976]. Density data for KCl at 25°C extend only to about 5 m solutions, so densities of more concentrated solutions in the range 5.0-5.8 m were obtained by extrapolation, using a plot of chloride molality versus the difference in density between KCl and NaCl for solutions of the same molality with respect to chloride. Above 4 m chloride that plot is close to a straight line, and a straight-line extrapolation was used (Figure 3). Departure of the KCl curve in Figure 3 from a straight line in the 5-6 molal chloride range

should affect the final calculated density of the Salton Sea brine by less than 0.0002 g cm⁻³. The calculated densities of the normalized and charge-balanced brines at 25°C from the sampling ports SP2-SP6 are 1.221, 1.237, 1.252, 1.262, and 1.266, respectively. The agreement with measured densities (Table 1) is generally good. The exclusion of iron and other dissolved constituents from the density model is not likely to have made a significant difference, even though they constitute about 2 wt % of the brine, because extra sodium compensated in great part for their not being included in the computations. This compensation was accomplished by using sodium to bring the cation charges into balance with the anion charge.

Finally, complete agreement between the measured and calculated densities was obtained by making minor adjustments to the calcium concentrations and renormalizing other ions relative to calcium until a charge-balanced solution was obtained with a calculated density that agreed with measured densities. The final preferred brine compositions are shown in Table 2. The results are only slightly different from the analytical values shown in Table 1.

CALCULATED COMPOSITION OF RESERVOIR FLUID PRIOR TO FLASHING

The preflashed composition of a fluid can be determined graphically using enthalpy-dissolved constituent diagrams [Fournier, 1979a]. The method requires knowledge of the initial fluid enthalpy in the reservoir (obtained from the reservoir temperature and approximate initial TDS of the fluid), the enthalpies of the boiling liquids at the point of collection, and the brine composition after flashing at a given pressure. Initial reservoir fluid compositions can be estimated with or without assumed thermal losses by conduction prior to sampling. In contrast, Michels [1986a, b] used a method based on chloride and CO₂ in coexisting brine and steam at different confining pressures to determine steam quality and the preflashed composition of the reservoir fluid without assuming an initial reservoir temperature. It will be seen subsequently that our cal-

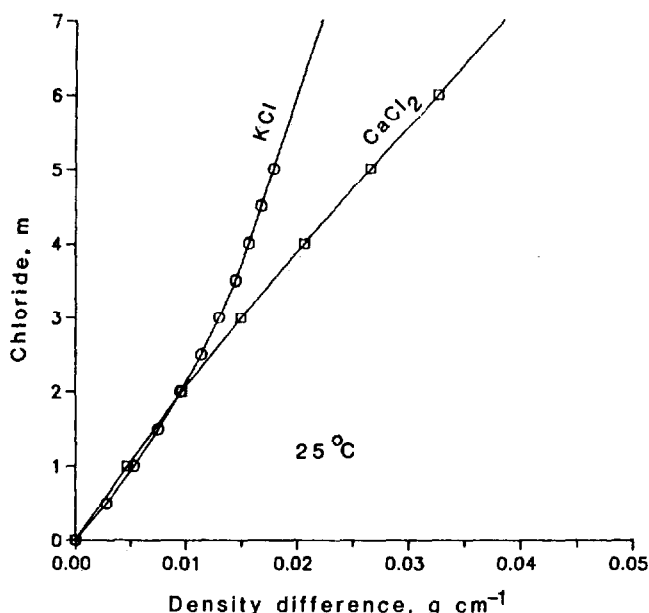


Fig. 3. Molal chloride versus the density difference between CaCl₂ and NaCl at 25°C, with data points shown by squares, and between KCl and NaCl, with data points shown by circles.

TABLE 2. Smoothed and Charge-Balanced Compositions of Brines Collected During the December 29, 1985, Flow Test of the State 2-14 Well

	Port 2	Port 3	Port 4	Port 5	Port 6
Calculated density, g cm ⁻³	1.221	1.237	1.252	1.262	1.266
Ca, mg/kg	36,100	38,200	39,800	41,000	42,400
Mg, mg/kg	44.6	47.3	49.2	50.7	52.4
Na, mg/kg	54,400	57,600	60,000	61,700	63,900
K, mg/kg	18,900	20,000	20,800	21,400	22,200
Li, mg/kg	241	255	265	273	283
Cl, mg/kg	165,000	174,500	181,800	187,000	193,600
Total wt %*	27.5	29.0	30.2	31.1	32.2

*Total dissolved solids may be as much as about 0.5 wt % greater owing to other dissolved constituents.

culated results and those of Michels [1986a, b] are in good agreement.

The fractures supplying fluid during the December 29–30, 1985, flow test were close to the bottom of the well where the formation temperature is estimated to be $305 \pm 5^\circ\text{C}$ [Sass *et al.*, 1987]. According to Michels [1986a] the enthalpy, HB, of a brine (in Btu/lb of brine) at its boiling point is given by

$$HB = 0.36(F)^{1.16}[\exp_{10}(-0.006Nn)] \quad (2)$$

where F is temperature in Fahrenheit, N is the wt % NaCl in a simple brine, and n is the multiplier that relates a mixed brine of N wt % TDS and a simple brine with the same N value. For the simple system NaCl-water in which $n = 1$, equation (1) becomes

$$H = 0.837(1.8t + 32)^{1.16} \times 10^{-0.006N} \quad (3)$$

where H is enthalpy in joules per gram and t is temperature in degrees Celsius. Using (3), the calculated enthalpies of 20–30 wt % NaCl solutions at $150^\circ\text{--}225^\circ\text{C}$ range from about 9 to 0% higher than corresponding enthalpies of a synthetic Salton Sea brine published by Helgeson [1968].

Figure 4 is an enthalpy-chloride diagram constructed using enthalpies derived from equation (3) and chloride values (shown as circles) from Table 2. Data points representing brines collected from the various sampling ports are labeled P2–P6. The range in enthalpies of the steam phases coexisting with the brines sampled at the various sampling ports is shown by points S2 and S6 in Figure 4. These estimated enthalpies of steam coexisting with the brine range from about 70 to 80 J/g higher than those of steam in equilibrium with pure water at the same temperature. The chloride of the initial unflashed reservoir fluid should lie along the line connecting a particular flashed liquid with its coexisting steam, such as line P6–S6 in Figure 4. However, because the Salton Sea brine contains significant amounts of salts other than NaCl, the value of n in (2) is not unity, and (3) gives calculated enthalpies of Salton Sea brines that are slightly in error, with the largest errors at higher salinities (most flashed brines). If corrections had been made for the differences in enthalpy of the actual brines compared to NaCl solutions with the same TDS, the positions of the brines and steam-brine tie lines, such as P6–S6 in Figure 4, would be very slightly rotated using the enthalpy of the coexisting steam as a focal point. The difference in enthalpy of steam in equilibrium with the actual brine compared to a NaCl solution with the same TDS is likely to be small. The net result of calculating enthalpies of Salton Sea

brines using a NaCl-H₂O model is that the calculated enthalpy of the initial reservoir fluid is likely to be slightly in error, but the calculated chloride value for the preflashed reservoir fluid is likely to be about the same.

The calculated enthalpy of a 305°C solution that contains NaCl in the expected range, about 24.4–26.0 wt % (14.8–15.8 wt % chloride) varies from about 962 to 943 J/g. For the P6–S6 tie line in Figure 4 the initial reservoir fluid plots at 955 J/g and 14.96 wt % Cl (point R6) when insignificant thermal losses prior to sampling are assumed. Except for P2, other flashed chloride-steam pairs give initial reservoir chloride concentrations ranging from about 14.7 to 15.0 wt % and average 14.89. Point P2 yields a calculated reservoir chloride of 14.52 wt %. That value appears to be anomalously low, probably because of incorporation of dilute water during sampling (nonequilibrium three-phase flow, as previously discussed). The calculated composition of the initial preflashed reservoir fluid with 14.89 wt % Cl is given in Table 3, sample A.

At the time of sampling, temperatures and pressures measured at the surface had attained a steady state, and the above calculations were made with the assumption that thermal losses during flow up the well and through the surface piping prior to entering the sampling spool were not significant. However, if the interpretation is correct that condensation of steam during flow up the well and through the surface piping resulted in nonequilibrium three-phase flow involving a small amount of dilute condensate water that did not readily mix

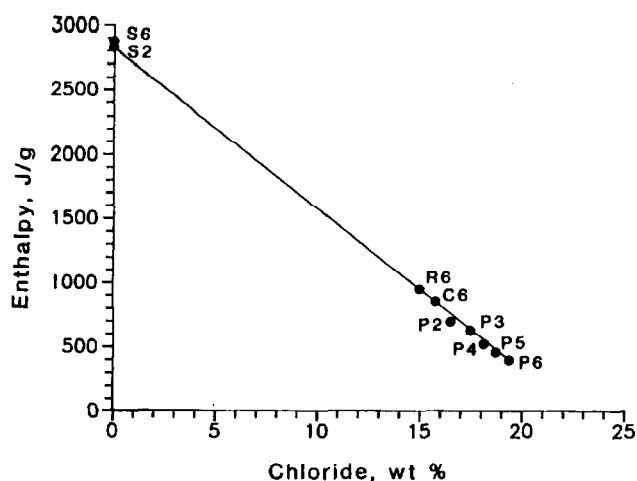


Fig. 4. Enthalpy-chloride relations for fluids produced from the State 2-14 well. Additional explanation in text.

TABLE 3. Calculated Preflash Concentrations of Selected Elements in Brine From a Depth of 1829–1898 m in the State 2-14 Well, December 1985 Flow Test

	Sample				
	A Dec. 29	B Dec. 29	C Dec. 29	D Dec. 29	E Dec. 30
SiO ₂ ,* mg/kg	808	776	803	793	795
Ca, mg/kg	31,600	33,200	31,900	27,100	26,500
Mg, mg/kg	39.1	41.0	39.4	37	36
Na, mg/kg	50,600	53,100	50,900	52,800	52,700
K, mg/kg	16,500	17,300	16,700	16,700	16,500
Li, mg/kg	211	221	212	193	190
Cl, mg/kg	148,900	156,100	150,000	153,400	153,700
Total dissolved solids, wt %	24.86†	26.25†	25.05†	25.54	25.46

A, this study, assumed no thermal losses; B, this study, assumed 10% thermal losses; C, this study, reservoir fluid with density = 1 g cm⁻³; D, reported by *Michels* [1986b]; E, reported by *Michels* [1986b].

*Calculated by the method of *Fournier* [1983].

†TDS may be as much as about 0.5 wt % greater owing to other dissolved constituents.

with the much denser brine, effects of thermal losses must be considered. The effect of a conductive loss of enthalpy on the relations shown in an enthalpy-chloride diagram (e.g., Figure 4) is to move the calculated preflashed reservoir chloride to a lower concentration. We have calculated the effect of a 10% decrease in enthalpy (95.5 J/g) within the erupting fluid by conduction of heat through the casing and surface piping, although it is unlikely that this large a thermal loss occurred during the interval when sampling occurred. For the P6-S6 tie line in Figure 4 the initial chloride in the reservoir fluid plots at C6 for an assumed 10% enthalpy loss by conduction. For all the brines sampled, with 10% assumed thermal loss by conduction, the calculated chloride concentrations in the preflashed reservoir fluid range from about 15.5 to 15.7 wt %, and average 15.61 wt %. The calculated composition of this average initial preflashed reservoir fluid with 15.61 wt % Cl is given in Table 3, sample B.

The uncertainty in TDS for the compositions shown for samples A and B in Table 3 is about ± 1 wt %. In addition, the TDS could be as much as 0.5 wt % greater than the totals shown because of the presence of other dissolved constituents that are not listed, such as iron, manganese, and zinc. However, as previously discussed, adding in these ionic species requires a corresponding decrease in sodium. According to our analyses and calculations the actual composition of the preflashed reservoir fluid should be between those given by samples A and B, and probably closer to A. The agreement with the reservoir fluid composition calculated by *Michels* [1986b] is very good.

DENSITY OF BRINE IN THE RESERVOIR AT 305°C

The density of the brine in the reservoir prior to flashing is of considerable interest in regard to developing models of heat and mass transfer within the hydrothermal system. During drilling, the mud weight required to just balance the pore fluid pressure at a depth of 1879 m indicated a pore fluid density very close to 1 g cm⁻³ (J. H. Sass, personal communication, 1986). No downhole pressure measurements were made at that depth, and downhole fluid sampling was unsuccessful, so the only available check on the pore fluid density is by calculation, using the preflashed composition of the brine sampled at

the surface. This calculation was carried out using the density model of *Potter and Haas* [1978], densities of the pure chloride solutions of the three salts from *Potter and Brown* [1976, 1977] and *Potter and Clyne* [1976], and the brine compositions shown in Table 3. In that calculation, however, corrections had to be made for conditions slightly beyond the range of the available density data for the pure salts. Densities of aqueous solutions of KCl at temperatures in the 200°–400°C range extend only to about 4 m, so densities of more concentrated solutions in the range 4.0–5.8 m were obtained by extrapolation, using a plot of chloride molality versus the difference in density of KCl and NaCl for solutions of the same molality with respect to chloride, as was described previously for the calculation carried out at 25°C. At 300°C that plot and a similar plot for CaCl₂, instead of KCl, yield straight lines (Figure 5). Also, density data for both KCl and CaCl₂ are available only at the vapor pressures of the solutions, and density data for CaCl₂ are not available above 300°C. Therefore densities of the preflashed reservoir fluid were calculated at 300°C and the vapor pressure of the solution, and those results were then multiplied by factors to correct for the slightly increased temperature and pressure actually present in the reservoir. The correction factors were obtained by assuming that the changes in density caused by increased temperature and pressure were proportional to the changes in density caused by similar increases in temperature and pressure in the pure NaCl system. The temperature correction factor that was used required multiplication of the density calculated at 300°C and the vapor pressure of the solution by 0.995, and the pressure correction factor required multiplication by 1.019. These corrections for temperature and pressure act in opposite directions, and the combined correction factor requires multiplication by 1.014. The exclusion of iron and other dissolved constituents from the density model is not likely to have made a significant difference for reasons previously discussed.

Calculated densities of preflashed reservoir fluids produced from the SSSDH at a depth of 1865–1877 m and a temperature of 305°C are shown in Table 4. The reservoir fluids published by *Michels* [1986b] yield densities very close to 1 g cm⁻³. Our average reservoir fluid, calculated with the assumption that there was insignificant thermal loss prior to

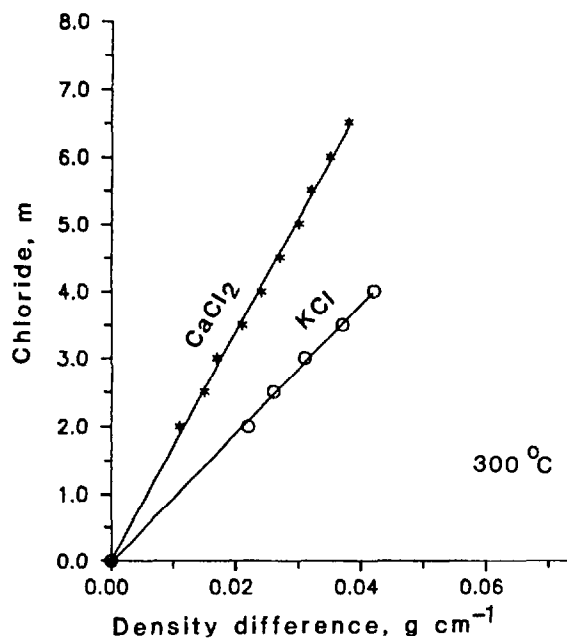


Fig. 5. Molal chloride versus the density difference between CaCl_2 and NaCl at 300°C , with data points shown by stars, and between KCl and NaCl , with data points shown by circles.

sampling, yields a density of $0.9980 \pm 0.0023 \text{ g cm}^{-3}$, and the average reservoir fluid calculated with the assumption of 10% thermal loss yields a density of $1.0107 \pm 0.0023 \text{ g cm}^{-3}$. The errors associated with not taking account of small amounts of other constituents in the brines, such as iron and manganese, and assuming a model based on pure NaCl to correct for pressures greater than the vapor pressure of the solution and a temperature of 305°C instead of 300°C , will cause the calculated density to be slightly on the low side. Therefore the chemical data favor reservoir fluid densities of about 1 g cm^{-3} or greater at a depth of 1870 m.

If isochemical conditions prevailed above about 2 km and the brine at a depth of 1.8 km had a density of 1 g cm^{-3} , the brine at the top of the system at a depth of 1 km and a

temperature of 275°C would have a specific density of about $1.02\text{--}1.03 \text{ g cm}^{-3}$. That high a fluid density in the shallow part of the system would not be consistent with free convection driven by the influx of cold dilute water at the sides of the system. However, a fluid density of 1 g cm^{-3} at a depth of 1.8 km is consistent with a double-diffusive model that provides a mechanism for efficiently transferring heat by convection from the bottom to the top of the hydrothermal system while maintaining vertical and horizontal salinity gradients [Fournier, 1987b, 1988]. In the double-diffusive model of the Salton Sea geothermal system a series of thin convection cells are present that contain hot brines at slightly different temperatures and salinities but having similar densities that are close to unity [Fournier, 1987b, 1988]. These convection cells are in approximate pressure equilibrium with cold water at the sides of the hydrothermal system. Our calculated composition of the reservoir fluid having a density of 1 g cm^{-3} at 305°C at a depth of 1.8 km is given in Table 3, sample C.

The fluid mechanical behavior resulting in double-diffusive convection was first studied experimentally by Stommel [1962] and described by Turner and Stommel [1964]. Huppert and Turner [1981] provided an excellent summary of double-diffusive convective processes within bodies of liquid, and experiments by Griffiths [1981] have shown that double-diffusive convection cells may develop in porous media when hot saline waters underlie more dilute cooler waters. The important parameters that lead to the establishment of a double-diffusive convection system are the contrasting rates of transport of heat and salt across a boundary layer separating cooler less saline water above from hotter more saline water below. Both heat and salt are transported through the interface solely by molecular diffusion. Thermal input from below into the deeper more saline water causes it to become less dense than the overlying less saline water and convection is initiated. Upward movement of the more saline water continues until a slight cooling increases its density to the point when buoyancy is no longer a driving force. When the thermal boundary layer ahead of the convecting region reaches a critical Rayleigh number, it too becomes unstable, and a second layer forms above the first. Eventually, many individual salinity layers form and convection is sustained by a more rapid vertical

TABLE 4. Calculation of Specific Density of Preflashed Brine at 305°C at a Depth of 1865–1877 m in the State 2-14 Well

	Sample			
	A Dec. 29	B Dec. 29	C Dec. 29	D Dec. 30
$d_K - d_N$	0.0590	0.0629	0.0603	0.0602
$d_C - d_N$	0.0328	0.0350	0.0335	0.0335
f_K	0.101	0.101	0.0987	0.0973
f_C	0.376	0.376	0.3125	0.3050
d_N	0.9660	0.9774	0.9698	0.9696
$(d_K - d_N)f_K$	0.0060	0.0064	0.0060	0.0059
$(d_C - d_N)f_C$	0.0123	0.0132	0.1047	0.1022
Sum	0.9843	0.9970	0.9862	0.9857
PT correction	$\times 1.0139$	$\times 1.0139$	$\times 1.0139$	$\times 1.0139$
Density at 305°C	0.9980	1.0108	0.9999	0.9994

The notation is the same as in the text. A, this study, assumed no thermal losses; B, this study, assumed 10% thermal losses; C, reported by Michels [1986b]; D, reported by Michels [1986b].

TABLE 5. Calculated Temperatures of Last Water-Rock Equilibrium, Using Various Cation Geothermometers

Geothermometer	Reference	Dec. 29*	Dec. 29†	Dec. 30†
Na/K	Arnórsson <i>et al.</i> [1983]	331°C	327°C	326°C
Na/K	Fournier [1979b]	345	341	339
Na/K	Giggenbach [1986]	349	345	345
Na/K	Truesdell [1976]	364	358	355
Na-K-Ca	Fournier and Truesdell [1973]	310	311	310
Na/Li	Fouillac and Michard [1981]	418	396	395
Mg/Li ²	Kharaka and Mariner [1988]	285	281	281
Mg/K ²	Giggenbach [1986]	348	351	350

*This study.

†Reported by Michels [1986b].

transport of heat relative to salt. For the situation in which there are horizontal as well as vertical temperature and salinity gradients, individual double-diffusive convection cells should be bounded on the sides by other convection cells that have slightly different salinities and temperatures.

GEOOTHERMOMETRY OF THE RESERVOIR FLUID

Temperatures of brine-rock chemical equilibration prior to flashing were calculated using a variety of cation geothermometers. The results are shown in Table 5. The temperatures calculated using our preferred reservoir fluid, sample C, Table 3, give essentially the same results as the data reported by Michels [1986b]. The Na-K-Ca method of Fournier and Truesdell [1973] appears to give the most reliable results, 310°–311°C compared to a measured temperature of 305° ± 5°C. Calculated Na/K temperatures range from 326° to 364°C, depending on the equation that is used [Arnórsson *et al.*, 1983; Fournier, 1979b; Giggenbach, 1986; Truesdell, 1976], the Mg/K² method [Giggenbach, 1986] gives about 350°C, and the Mg/Li² method [Kharaka and Mariner, 1988] gives 281°–285°C. The Na/Li method [Fouillac and Michard, 1981] gives results that are much too high, 395°–418°C. Silica geothermometry is not appropriate because of loss of significant amounts of silica from solution prior to sampling. The calculated concentration of silica in the reservoir fluid prior to flashing is 790–800 mg/kg, using the method of Fournier [1983], and TDS ranging from 25.2 to 25.7, and fluid density equal to 1 g/cm³ at 305°C.

CONCLUSIONS

The preflashed reservoir fluid, according to this study, contains about 24.8 wt % TDS if calculated with the assumption that there was insignificant thermal loss before sampling and about 26.0 wt % TDS if there was 10% thermal loss. Our preferred value for the TDS of the reservoir fluid is about 25.0 wt % (sample C, Table 3). These values might be increased by up to 0.5 wt %, depending on adjustments for various trace elements, such as iron and manganese, that were not included in the charge-balancing and density models. Our calculated preflashed reservoir fluid is in good agreement with that reported by Michels [1988b]. The main difference between the two studies is that slightly less Na and more Ca were found in the present study than were reported by Michels [1986b]. Of the various cation geothermometers, the Na-K-Ca method gives temperatures closest to the apparent temperature of the reservoir supplying brine during the December 1985 flow test of the State 2-14 well. Accurately determined densities of

brines composed predominantly of NaCl-CaCl₂-KCl can be used to check analytical results and resolve inconsistencies in ionic charge balances.

Acknowledgments. D. E. Michels designed the sampling apparatus and coordinated the sampling efforts of many groups before and during the flow test. His enthusiastic help is gratefully acknowledged. We also thank the Kennecott Copper Corporation for kindly allowing us to use their sampling port to obtain a fluid sample at a higher temperature and pressure than was possible at the regular sampling ports. The manuscript was critically reviewed by Yousif K. Kharaka, Donald E. White, A. F. White, and Donald E. Michels.

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(Received August 10, 1988;
accepted February 16, 1988.)