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ASSESSMENT OF CALCITE AND AMORPHOUS SILICA SCALING POTENTIAL FROM PRODUCTION WELLS IN THE MUTNOVSKY GEOTHERMAL FIELD, KAMCHATKA, RUSSIA

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ABSTRACT

The Mutnovsky geothermal power plant, Kamchatka, Far East Russia was commissioned in 2002. Troublesome scaling of amorphous silica has been experienced in one well and one of the steam separators. In this report, calcite and amorphous silica scaling potential has been assessed for individual well discharges and the mixed discharge of two wells, nos. 5E and 26. Calcite scaling is not expected. Amorphous silica scaling for individual wells with liquid enthalpy is only expected at temperatures below about 150°C. The silica scaling from well 26 is thought to be due to evaporation to dryness of the small amount of water discharged from this well. This scaling can be eliminated by mixing together the discharges of wells 5E and 26.

1. INTRODUCTION

The problems generally of most concern in geothermal reservoirs for power production are reservoir pressure decline and recharge of cooler waters into the reservoir that tend to cause a decline in the temperatures of producing aquifers. Formation of scales in wells, separators and other surface equipment is a common operational problem (Moskalev, 2005a).

The Mutnovsky power plant has experienced both pressure decline and scaling problems. Deposition of amorphous silica was observed in surface constructions of the Mutnovsky geothermal power plant (GeoPP-1) after three months of operation. Observable deposition only occurs within separator 2 of the first stage and in the pipeline of well 26. No scale formation has been observed in separator 1 of the first stage (Moskalev, 2005b).

One solution to the silica scaling problem, which has been considered, involves the mixing of water from well 5E with the discharge of well 26. The idea is that such mixing will prevent excessive evaporation of the small water fraction in the discharge of well 26 and, in this way, maintain the water from well 26 amorphous silica under-saturated at the temperature in the steam separator (Moskalev, 2005a).

In this report the emphasis is on the potential formation of scales of calcite and amorphous silica from individual production wells, and evaluating the likely success of the solution described above. The results of the WATCH speciation program indicate that waters from individual liquid enthalpy production wells are amorphous silica under-saturated above 150°C so deposition of this phase is not expected in production wells and steam separators since their temperatures are above 150°C. Also, amorphous silica scaling is not expected to occur from the mixed discharge of wells 5E and 26 although it occurs in the unmixed discharge of well 26. Calcite scaling is not expected.

2. GEOLOGICAL FEATURES AND POWER PRODUCTION AT MUTNOVSKY GEOTHERMAL FIELD

2.1 Geographical setting and geothermal activity of Mutnovsky geothermal field

The Mutnovsky geothermal field is a high-temperature geothermal area, located in the Kamchatka peninsula in the far eastern part of Russia (Figure 1). The Mutnovsky field is located within the Southern Kamchatka volcanic zone. It is linked with the Mutnovsky (Vilyuchinsky) centre of volcano-magmatic activity. The size of the geothermal area is approximately 30 km^2, which is characterized by abundant active thermal manifestations. This system is associated with a volcanic graben in a zone crossed by deep, regional fractures sited to the northeast and below the meridian (Taran et al., 1992).

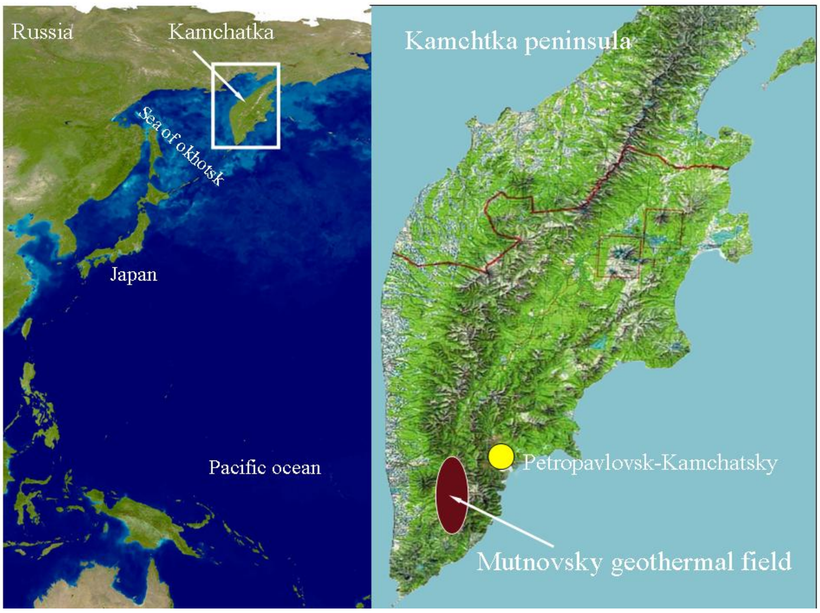

FIGURE 1: Location of Kamchatka Peninsula and the Mutnovsky

The Mutnovsky geothermal area is within a region of very intense volcanic activity. There are two active volcanoes, Mutnovsky and Gorely, and one extinct and eroded volcano, Zhirovskoy, in the vicinity of the geothermal field. The area of the Mutnovsky field is characterized by volcanogenic and volcanogenic-sedimentary rocks, recent volcanic formations, numerous hot springs, and steam manifestations (Kiryukhin and Sugrobov, 1987; Assaulov, 1994). The Mutnovsky geothermal system is liquid-dominated with fluid temperatures of 235-270°C (Kiryukhin and Pruess, 2000). Geothermal exploration of the field was carried out during 1978-1990. More than 80 wells have been drilled covering an area of about 25 km^2. Well depth ranges from 1000 to 2500 m. The drilling identified prospect sites within the Mutnovsky area.

The field is connected with the city of Petropavlovsk-Kamchatsky by a 125 km long road. Climate conditions at the Mutnovsky geothermal field are unique owing to its situation at a high northern latitude and high elevation. The mean annual air temperature is -1.5°C. For 8 months of the year, the daily mean temperature is below -5°C. The climatic condition condensation temperatures for the power cycle are as low as 10°C leading to high efficiency in electric power output compared to the geothermal power plants located in areas of moderate or hot climates. Access to the field is very difficult during the winter time due to heavy snowfall, requiring snow removal for access (Kiryukhin and Pruess, 2000).

The Mutnovsky geothermal area of Kamchatka can be considered one of the largest areas of heat from the Earth's interior (Kiryukhin and Pruess, 2000).

2.2 The Mutnovsky geothermal power plant (Mutnovsky GeoPP-1)

Two geothermal power plants are in operation in the Mutnovsky geothermal area, the Mutnovsky and the Verkhne-Mutnovsky power plants. Construction of the Verkhne-Mutnovsky power plant was proposed as early as in the middle 1970's, but these plans were not realized until in the 1990's. In 1999, Verkhne-Mutnovsky power plant was put into operation with a total capacity 12 MWe. There are 3 production wells, 3 injection wells, one monitoring well and one well for production of cold water.

The first stage of the Mutnovsky power plant, which has a total installed capacity of 50 MWe (two 25 MW units) was commissioned in 2002. This power station was built specially to cope with operation in difficult climatic, geological and geographical conditions (Figure 2).

FIGURE 2: Outward appearance of Mutnovsky geothermal power plant

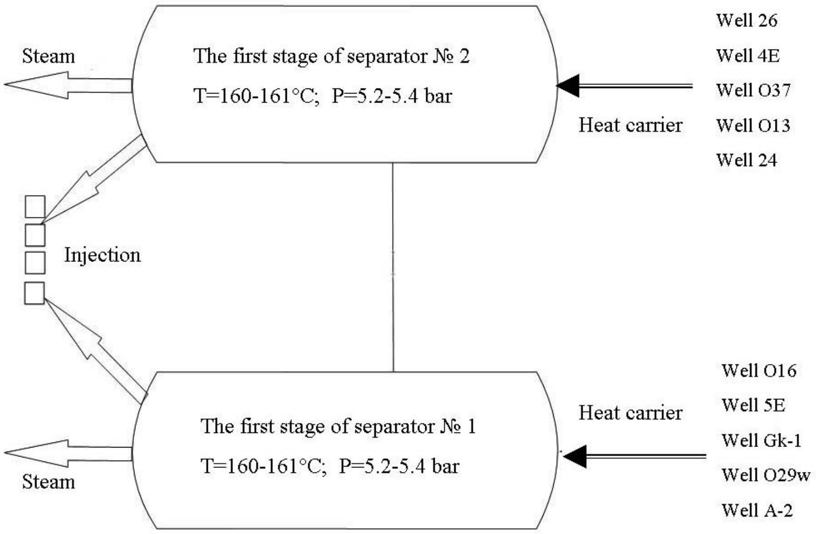

FIGURE 3: The technological scheme of the heat carrier's collection from Mutnovsky geothermal field (Moskalev, 2005a)

Mutnovsky power plant is located in the central part of the Mutnovsky geothermal field. It has 13 production, 5 injection and 5 monitoring wells. At present, there are ten production wells in operation. A schematic layout of the steam supply system is presented in Figure 3. The average extraction of geothermal fluid in 2004 was 1,000,000 tons per month. Of this, 36% is vapour, which is used for power production. The remaining 64% of the geothermal fluid discharged from the production wells is liquid water with a temperature of 160°C. This water is injected back into the reservoir. Plans are under way to utilize this water to drive a binary power plant unit in the near future. Utilization of the liquid water for extraction of silica is also of interest (Moskalev, 2005b).

The problems generally of most concern in exploitation of geothermal fields for power production are reservoir pressure decline, recharge of cooler waters leading to declining temperatures and scaling and corrosion. The Mutnovsky power plant has experienced all these problems. Here, the emphasis is on the formation of amorphous silica scaling in surface equipment of the power plant (Moskalev, 2005b).

2.3 The theory of silica scale formation

Geothermal systems are one of the alternative sources of energy which have economic and ecological advantages. However, in spite of these advantages, there are some problems that can make it difficult to utilize geothermal resources. All geothermal fluids contain dissolved minerals. These minerals are deposited at different points during the operation, adversely influencing the operation of power plant. Silica scaling is usually the largest problem and one that is displayed practically in all geothermal fields, especially at high-temperatures. The solubility of silica minerals decreases when temperature decreases. Opposed to carbonate, amorphous silica deposition is controlled by kinetics and can begin on the surface in several minutes or hours after reaching supersaturation. Silica scales are hard to remove mechanically.

Formation of silica scales is a physical-chemical process. It is controlled by the following factors: amorphous silica solubility, temperature, composition, pH of solution, rate of growth, dimension, concentration of colloidal particles, and hydrodynamic conditions in brine flow. Depending on the degree of supersaturation processes of nucleation and colloidal particles, growth develops as a result of the interaction of silaneous groups (polymerization reaction, Iler, 1979) and the aggregation of particles. Colloidal particles are moved to the surface by mass transfer in a flow and silica precipitates finely as a solid amorphous matter. An increase in alkalinity to $pH>8.0$ speeds up the aggregation of particles (Kashpura, V.N., and Potapov, V.V., 2000).

2.4 Scaling problems in Mutnovsky GeoPP-1 and possible solutions

The formation of scales is one of the most difficult technical problems encountered in the exploitation of high-temperature geothermal resources. Changes in water temperature, pressure, pH and mineral saturation are unavoidable when fluid is tapped from geothermal reservoirs by production wells drilled into such reservoirs. As a consequence, minerals may deposit in producing aquifers, within the wells, in pipelines, steam separators and other surface equipment and in injection wells. The most common scales consist of calcium carbonate and amorphous silica but scales of various oxide and metal-sulphide phases are also known. At Mutnovsky the main scaling problem is due to deposition of amorphous silica, which possesses high mechanical strength and is therefore difficult to remove (Moskalev, 2005a).

The deposition of silica inside the equipment of Mutnovsky GeoPP-1 was observed after three months of operation. Observable deposition only occurs within separator 2 of the first stage and in the pipeline of well 26. No scale formation could be seen in separator 1 of the first stage. The temperature in both separators of the first stage is 160-161°C and pressure 5.2-5.4 bars. According to experimental data of Marshall on amorphous silica solubility, saturation is attained at a concentration of 700 mg/kg dissolved silica (as SiO_2). The silica concentration in the steam separators is around 600 mg/kg which corresponds to amorphous silica saturation at about 150°C (Moskalev, 2005a).

The observed silica scale in separator 2 has been explained by deposition from water from well 26. The discharge enthalpy of this well is very close to that of dry steam. Pressure drop below about 10

TABLE 1: Data on the production wells of the Mutnovsky power plant (Moskalev, 2005a)

Well	**Wellhead pressure (bar-g)**	**Mineralization of heat carrier (g/l)**	**Pressure of heat carrier (bar-g)**	**Wellhead temperature (°C)**	**Rate parameters (kg/s)**			**Enthalpy of fluid (kcal/kg)**	**SiO_2 (mg/l)**
					Total fluid	**Steam**	**Water**		
26	6.2	0.036 – 0.045	4.9 – 5.6	169	16	16	0	660	0.1 – 1.3
4-E	8.0	1.4 – 1.6	7.7 – 8.7	173	33.4	6.2	27.2	267	550 - 630
O37	9.2	1.4 – 1.7	7.6 – 8.8	178	32.8	6.8	26	284	550 - 830
013	7.0			168	21.5	10.5	11	409	
24	8.4	0.6 – 1.1	5.7 – 6.1	175	22.9	1.9	21	218	450 - 500
016	7.0	0.2 – 0.4	5.2 – 6.9	165	14	14	0	661	80 - 100
5-E	6.2	1.5 – 1.6	8.3 – 8.7	165	33	8.0	25	248	640 - 650
Gk-1	7.0			166	20.0	4.0	16	268	
029W	8.0	1.3 – 1.5	7.1 – 8.1	167	66	16	50	293	640 - 670
A-2	6.5	1.5 – 2.0	8.4 – 8.6	160	27.2	7.2	20	298	750 - 770

bar-a may lead to evaporation to dryness of this water, the consequence of falling enthalpy of steam with decreasing temperature below this pressure. The scale formed is depicted in Figure 4. Information about production wells of Mutnovsky GeoPP-1 given in Table 1.

FIGURE 4: Interior part of separator № 2 of first stage (Moskalev, 2005a)

One solution to the silica scale problem involves the mixing of water from well 5E with the discharge of well 26 (Moskalev, 2005a). Such mixing will prevent the excessive evaporation of the small water fraction in the discharge of well 26 and maintain the mixed water undersaturated with respect to amorphous silica at the temperature in the steam separator.

3. RESULTS

3.1 Chemical data from production wells connected to the Mutnovsky GeoPP-1

Joint Stock Company (JSC) “Geotherm” is responsible for carrying out the chemical analysis of fluids from the wells of the Mutnovsky power plant for monitoring studies. The work includes the sampling of separated water and condensed steam from production wells every three months and sampling of gases from the same wells every month (Moskalev, 2005b).

The water discharged from the production wells is of the chloride-sulphate-sodium and sulphate-chloride-sodium types with low gas content (<0.1% by volume of the steam). The most common gas components are CO_2, H_2S and N_2. Hydrogen and Ar are present in lower concentrations and O_2 in some samples (Moskalev, 2005b).

Waters discharged from wells are mildly alkaline with a high content of dissolved silica. The dominant anion in the water is Cl and the most abundant cation Na. Potassium, Li, Ca and NH_4 are present in significant concentrations (Moskalev, 2005b).

As already stated, there are ten production wells in operation at present: 26, 4E, O37, O13, 24, O16, 5E, Gk-1, O29w and A-2. Samples of water and steam collected from the production wells of the Mutnovsky power plant by “Geotherm” JSC were analysed in the chemical laboratory of the Geological State Company “Kamchatgeology” - for liquid water and condensate and gases by the chemical laboratory of the Institute of Volcanology of Far Eastern Branch of Russian Academy of Sciences (Moskalev, 2005b).

Chemical data from the production wells of Mutnovsky GeoPP-1 are given in Table 2 (Maximov et al., 2005). The numbers represent averages for samples collected in 2003 and 2004. During this period, water and steam compositions from each well generally remained quite constant justifying taking averages. Wells Gk-1 and O13 were put into operation at the end of 2004 so the results of chemical analysis of their discharged fluids are not yet available. These wells were, therefore, not considered for the present study.

TABLE 2: Chemical data from production wells of Mutnovsky power plant (Maximov et al., 2005 and data from *Geotherm JSC*)

Well		**4E**	**A-2**	**O29w**	**5E**	**O16**	**O37**	**24**	**26**	**Ms**
Sampling pressure (bar-g)		5.1	5.1	5.0	5.1	5.1	5.0	5.1		5.1
Discharge enthalpy (kJ/kg)		1120	1248	1227	1038	2768	1189	913	2763	1692
Water samples (mg/l)	**pH at 20°C**	8.30	8.24	7.40	7.73	5.24	7.52	5.93		7.73
	Dissolved solids	1442.7	1380.7	1450.0	1516.9	225.4	1338.1	952.4		1516.9
	Cl	210.8	249.7	243.2	209.3	15.4	233.3	126.1		209.3
	SO_4	219.6	94.8	149.2	272.1	84.2	120.8	113.2		272.1
	CO_2^a	30.5	29.6	37.5	37.6	38.7	37.5	38.3		37.6
	F	2.44	2.15	1.91	3.37	0.20	1.79	1.28		3.37
	Na	232.9	196.1	212.8	263.5	48.4	216.5	134.8		263.5
	K	40.4	38.6	37.7	39.8	4.93	35.5	16.5		39.8
	Li	1.45	1.54	1.49	1.50	0.04	1.40	0.77		1.50
	Ca	2.70	0.86	2.79	1.73	1.28	0.75	1.35		1.73
	Mg	2.52	0.12	3.13	1.66	0.15	0.09	0.12		1.66
	Fe^{2+}	0.05	0.09	0.08	1.13	0.08	0.06	0.08		1.13
	NH_4	0.91	2.05	0.96	1.47	8.17	1.49	1.81		1.47
	SiO_2	603	666	657	625	13	571	477		625
	As	2.6	5.7	3.5	2.1	0.3	3.3	1.6		2.1
	B	15.36	20.01	18.62	12.24	2.49	16.87	8.83		12.24
	H_3BO_3	78		96	81					81
	Fe(OH)	0.1	0.1		0.1			0.1		0.1
Steam samples (mmol/kg)	**He**	0	0	0	0	0	0	0	0	0
	H_2	0.2	0.2	0.5	0.1	0.1	0.9	0.0	1.3	0.9
	O_2	0.67	0.43	7.72	3.19	0.26	1.66	0.46	0.95	1.70
	Ar	0.04	0.01	0.18	0.09	0.01	0.08	0.03	0.06	0.07
	N_2	2.43	0.59	15.19	7.29	0.93	4.05	1.29	3.06	4.47
	CO	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.001	0.001
	CH_4	0.11	0.04	0.05	0.02	0.01	0.78	0.05	0.30	0.20
	C_2H_6	0.001	0.000	0.001	0.000	0.000	0.004	0.000	0.002	0.001
	CO_2	48.33	32.20	33.29	23.59	44.81	53.21	17.96	47.85	39.76
	H_2S	2.81	5.03	4.19	3.08	5.07	4.95	2.50	6.18	5.15

[a]Total carbonate carbon.

The mixed discharge of wells 26 and 5E has been calculated from the reported flow rates and steam and liquid water from these wells and analysed using:

$$M_{Ms} = M_{5E}\frac{R_{5E}}{R_{5E}+R_{26}} + M_{26}\frac{R_{26}}{R_{5E}+R_{26}}$$

where M_{Ms} = Chemical composition of the steam of the mixed discharge;
M_{5E} and M_{26} = Chemical compositions of the steam from wells 5E and 26, respectively;
R_{5E} and R_{26} = Rate parameters for the steam phase of wells 5E and 26, respectively.

The composition of the liquid water from the mixed discharge was taken to be that of well 5E as well 26 discharges dry steam only for all practical purposes.

3.2 Methodology and obtained results

The WATCH chemical speciation program (Arnórsson et al., 1982), version 2.1A (Bjarnason, 1994) was used to calculate aquifer water compositions from the analytical data on water and steam samples collected at the wellheads. To make these data compatible for the WATCH input file, the primary data were modified. The concentrations of gases in steam were initially presented in percentages of mass initially (Maximov et al., 2005), but were converted into mmol/kg of steam.

Except for wells 016 and 26, the enthalpies of the fluid from the production wells were based on the quartz equilibrium temperature assuming liquid water only to be present in producing aquifers. Wells 016 and 26 discharge dry steam only. Their enthalpy is therefore that of dry steam. The quartz geothermometer equation used is that of Fournier and Potter (1982). Degassing of the boiling water was taken to be at maximum, that is equilibrium distribution was attained for the gases between the liquid water and steam phases. Speciation distribution was calculated after various amounts of adiabatic boiling to study the effect of this boiling upon calcite and amorphous silica saturation. The saturation indices (SI) for calcite and amorphous silica for each temperature, respectively, were estimated by WATCH. The diagrams of SI for calcite and amorphous silica of water boiled from the initial aquifer temperature to 100°C are shown for individual wells in Figures 5 and 6, respectively.

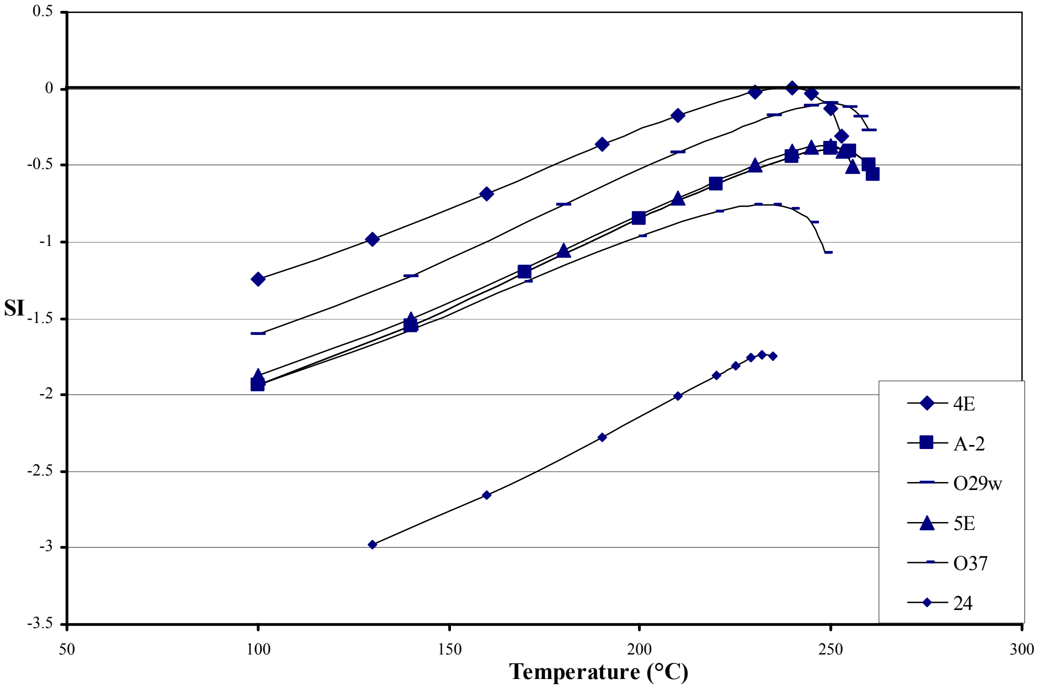

FIGURE 5: Relationship between calcite saturation and the temperature of variably boiled aquifer water

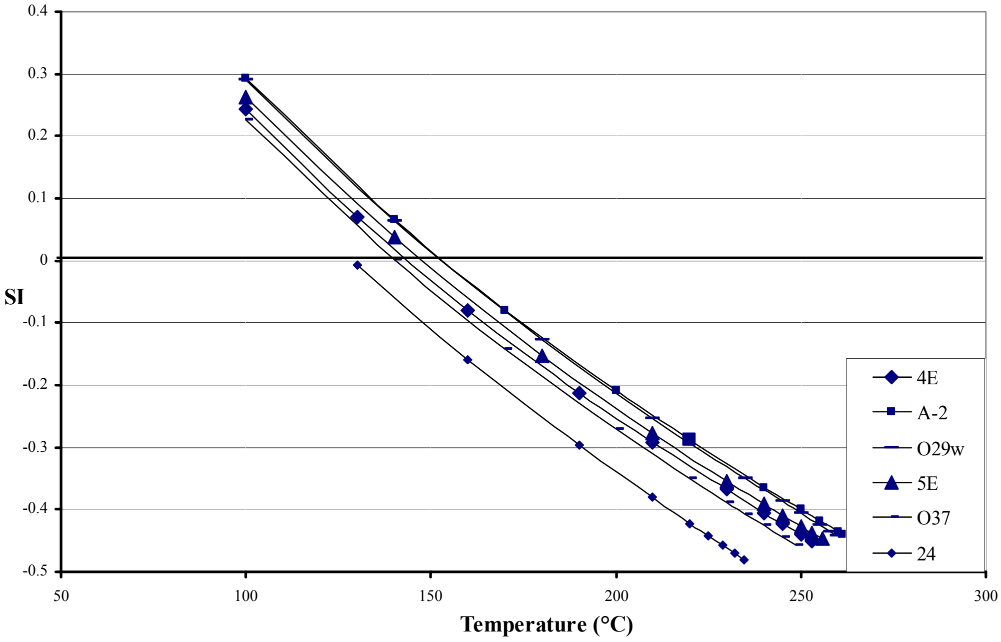

FIGURE 6: Relationship between amorphous silica saturation and the temperature of variably boiled aquifer water

As already noted, the solution to the amorphous silica scaling problem inside the equipment of Mutnovsky GeoPP-1 is considered to involve mixing of the discharges of wells 5E and 26 (Moskalev, 2005a). Fluids from these two wells were mixed theoretically in this contribution (Table 2).

The enthalpy of this "mixed" fluid was based on the discharge enthalpies of the individual wells. With the aid of the WATCH program, the state of saturation with respect to amorphous silica and calcite was calculated for variable extent of adiabatic boiling. Equilibrium degassing was assumed. The results are shown in Figures 7 and 8. The results depicted in these figures indicate the amorphous silica scaling from well 26 will be stopped by mixing its discharge with that of well 5E. It will not

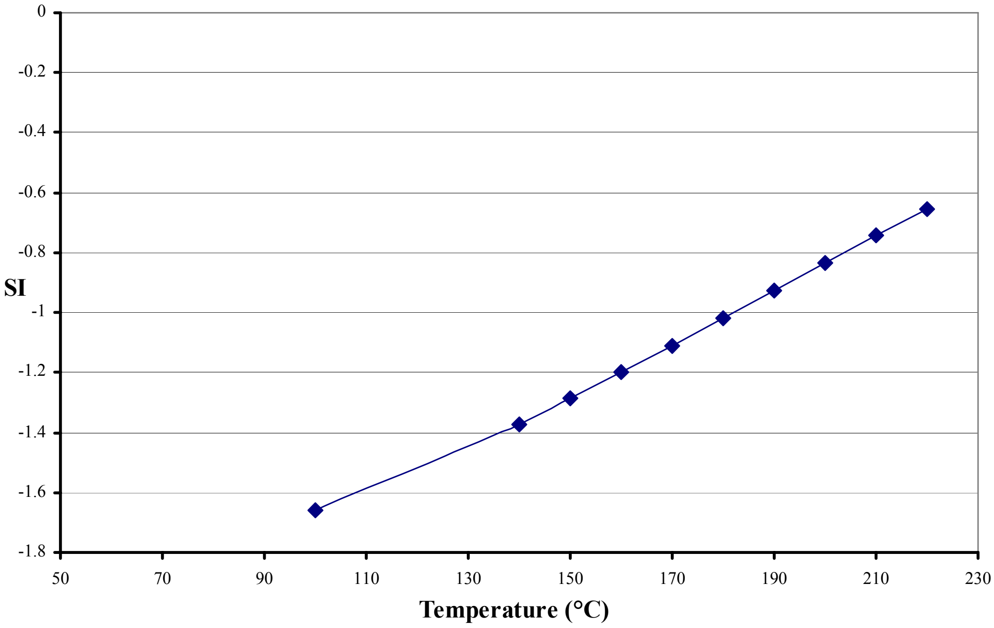

FIGURE 7: Relationship between SI of calcite and temperature for the mixed fluid from wells 26 and 5E

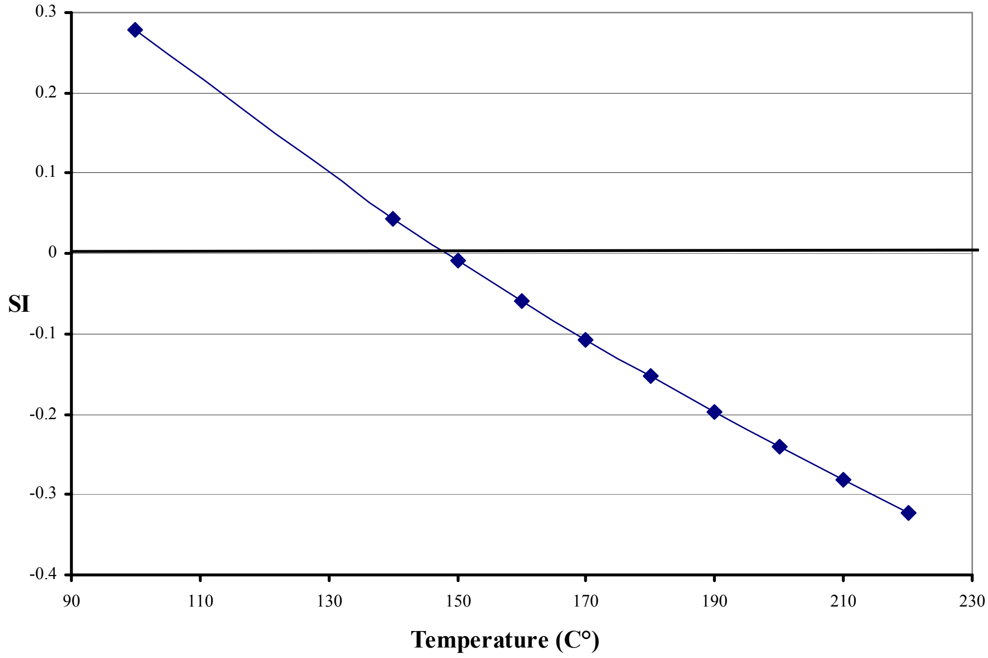

FIGURE 8: Relationship between SI of amorphous silica and temperature for the mixed fluid from wells 26 and 5E

occur at temperatures above about 150°C. Also, calcite scaling is not expected.

It is not certain whether degassing of the boiling water is sufficient to reach equilibrium distribution between the liquid water and steam phase. Based on this, the WATCH program was used to calculate amorphous silica and calcite for one well (A-2), assuming that the degassing was only 20% of maximum. The results of these calculations are presented in Figure 9. They indicate that calcite oversaturation is not produced when degassing of the boiled water is limited to this extent.

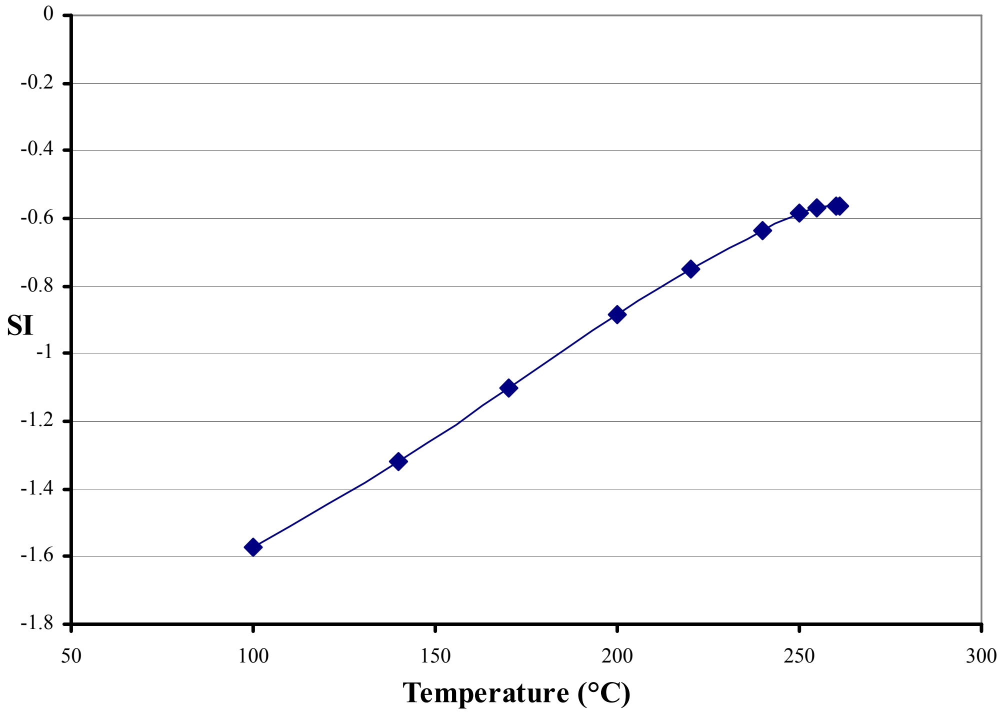

FIGURE 9: Relationship between calcite saturation in well A-2 and the temperature of variably boiled aquifer water assuming that the degassing was only 20% of maximum

4. DISCUSSION AND CONCLUSIONS

As geothermal energy is a relatively favourable energy resource environmentally, its utilization is to be emphasized in the future. One of the most attractive utilizations of geothermal resources is power generation. There are, however, various problems associated with this. They mainly include reservoir pressure decline, recharge of cooler water leading to declining temperatures of producing aquifers, and scaling. The precipitation of solids from natural fluids is a highly complex physical and chemical process that may be difficult to control. When dissolved solids in geothermal fluids form deposits in geothermal wells and installations, they affect the exploitation of the geothermal resource. This solid deposition may occur in the reservoir, liners, production casing, and surface equipment. Silica and calcite are the two most common scale forming phases. They are costly and technically difficult to remove, especially the amorphous silica. In geothermal systems, the formation of silica minerals occurs at different depths in various forms. The known silica minerals include quartz, chalcedony, cristobalite, and amorphous silica. Deposition of amorphous silica from oversaturated water is troublesome when it forms in wells and surface equipment such as pipelines, separators, turbine nozzles, heat exchangers and injection wells.

The Mutnovsky geothermal power plant, Kamchatka, Far East Russia was commissioned in 2002. The deposition of solids inside the equipment of Mutnovsky GeoPP-1 was observed after three months of operation. At Mutnovsky the main scaling problem is due to deposition of amorphous silica, which possesses high mechanical strength and is therefore difficult to remove. Observable deposition only occurs within separator 2 of the first stage and in the pipeline of well 26. No scale formation could be seen in separator 1 of the first stage. The observed silica scale in separator 2 has been explained by deposition from water from well 26. The discharge enthalpy of this well is very close to that of dry steam. Apparently, pressure drop leads to complete evaporation of this water. One possible solution to the silica scale problem involves the mixing of water from well 5E with the discharge of well 26 (Moskalev, 2005a). Such mixing will prevent the excessive evaporation of the small water fraction in the discharge of well 26 and maintain the mixed water under-saturated with respect to amorphous silica at the temperature in the steam separator.

The main aim of this project was to calculate and assess the scaling potential of calcite and amorphous silica from production wells in the Mutnovsky geothermal field and to predict the behaviour of amorphous silica after mixing the discharges from wells 26 and 5E. All calculations were conducted by the WATCH chemical speciation program. The following results were obtained:

- The geothermal fluids of wells 4E, A-2, O29w, 5E, O16, O37, 24 from Mutnovsky Geothermal field are not expected to deposit calcite in appreciable quantities nor amorphous silica when water temperatures are in excess of about 150°C.
- The scaling potential of the mixed discharge of wells 5E and 26 is very similar to that of other liquid-enthalpy wells in the area. Amorphous silica scaling may be avoided from the discharge of well 26 by mixing its discharge with that of well 5E.

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