Proceedings World Geothermal Congress 2026
Calgary, Canada, June 8 – 11, 2026

Scaling Mitigation by Brine Dilution of Two-Phase Fluids For Wells OW-52 & OW-52A, Olkaria East Production Field.

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Keywords: Silica, Scaling, Excess Enthalpy", brine, dilution, mitigation, OW-52 & OW-52A, Silica Saturation Index (SSI), Boiling effects, Mass flows, pH

Wells OW-52 and OW-52A were among 12 production wells nominated to provide steam for the development of Olkaria I Unit 6 power plant. Wells OW-52 and OW-52A are almost single-phase steam wells and exhibited "excess enthalpy". These wells were combined with wells from well pad 731 are conveyed to a common separator (Cluster A). The enthalpies of these wells are ~ 2680 kJ/kg. The evaluation of amorphous silica scaling potential in wells OW-52 and OW-52A was done to provide a basis for the design of mitigation of potential silica scaling. These wells have "excess enthalpy" and exhibit high concentrations of silica in the small amounts of brine fraction at the weir box. This is probably contributed by boiling effects. As a result of boiling and concentration of silica of ~1208 mg/kg and 1522 mg/kg respectively (corrected to 10 bar a), in the residual brine, wells OW-52 and OW-52A were at high risk of scaling. Wells from well pads 52 and 731 were combined to the same central separator (Cluster A). To provide a basis for design for mitigation of silica scaling by dilution a simple model was used to estimate how much brine from the separator was required to dilute the silica in the two (2) phase fluids in wells OW- 52 and OW- 52A to or below the saturation at the line pressure. The model was also based on some assumptions eg operating and separation pressures, measured silica values, brine pH, line pressures, complete mixing brine with OW-52 and OW-52A brine (Two phase fluids). The main goal for the above assumptions was to keep silica saturation index <1. To estimate the silica saturation the silica equilibrium equation by Fournier and Rowe, 1977). The evaluation assumed silica can scale when the brine is > saturation or when the Silica saturation Index (SSI) >1. SSI for wells OW-52 and OW-52 A are >>1 at the wellhead which suggest scale could form before brine dilution mitigates the SSI to ≤ 1. The dilution brine was combined with the high silica 2-phase fluid from OW-52 and 52A as close to the Wellhead as possible where thorough mixing occurs. The temperature of the dilution water was assumed to remain constant~180 ° C. The mass flows for the diluting brine were calculated based on heat and mass balance. An additional margin of dilution was provided to address natural variations in production and non-equilibrium conditions. On commissioning of Olkaria I Unit 6 in march 2022 the effects of dilution of the two (2-phase) fluids for wells OW-52 OW-52A were evident. The enthalpy of wells OW-52 and OW-52A decreased from ~2680 kJ/kg (discharge test data) to ~2329 kJ/Kg and ~2466 kJ/Kg (commissioning data) respectively. This decreases the risk of the silica to precipitate in the 2-phase fluids and partly mitigate silica scale formation in the 2-phase fluids.

1 INTRODUCTION

Wells OW-52 and 52 A are among twelve (12) production that were nominated for Olkaria I Unit 6 Power Plant development. The turbine inlet pressure for the wells was established from well deliverability curves. The separation pressures for the nominated wells for Olkaria I Unit 6 was set between 9 and 11 bara. The high separation pressures were to consider the safe separation of the fluids to mitigate against the risk of silica scaling. Safe separation of the fluids would ensure that formation of amorphous silica scale would be avoided in the hot re-injection wells. Wells for Olkaria I Unit 6 are located within the Greater Olkaria Volcanic Complex (GOVC) which is in the central sector of the Kenya Rift Valley to the south of Lake Naivasha and 120 km from Nairobi, the capital city of Kenya. Figure I shows the conceptual layout of wells on well pad 52 and 731 which provide fluids to Cluster A separators for Olkaria I Unit 6.



Figure1: Conceptual layout of wells on pad 52 and 731 showing cluster A separator

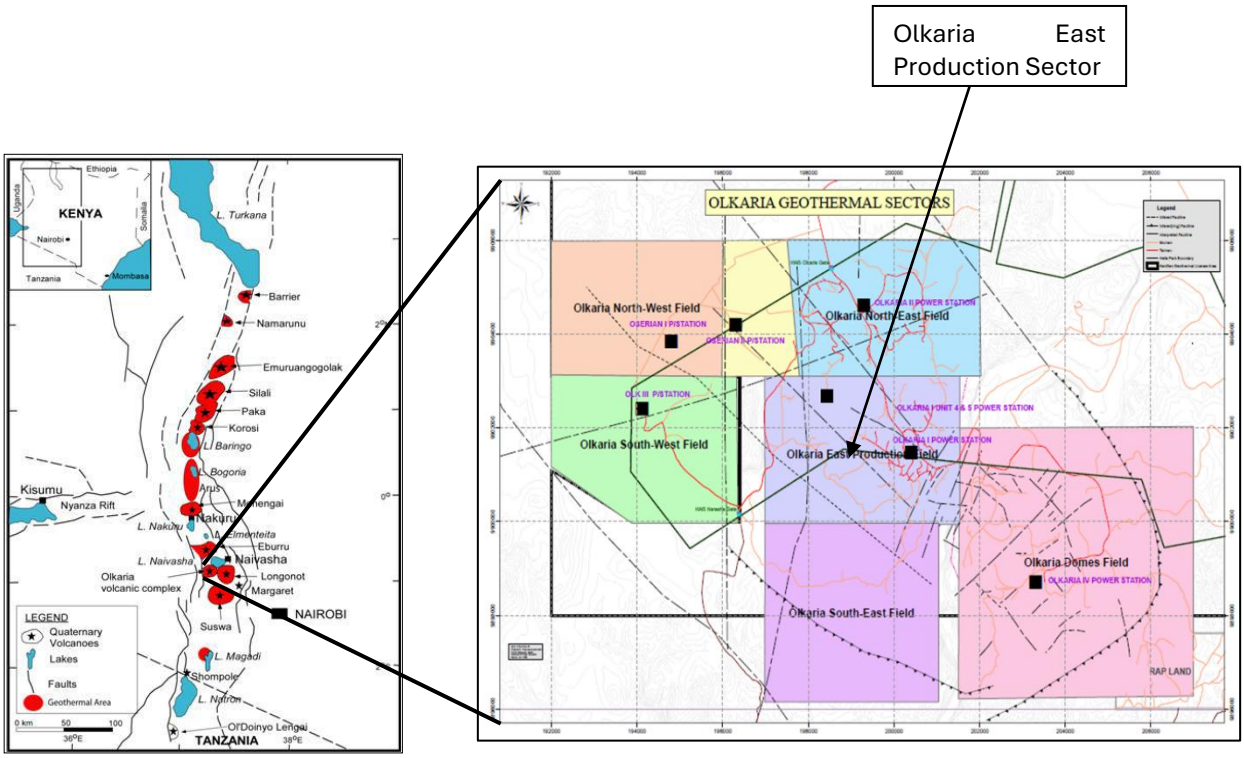


Figure 2; The Greater Olkaria Geothermal Area and sectors in Olkaria for development

The Greater Olkaria Geothermal Area (GOGA) in Fig 2 is divided into seven sectors, namely Olkaria East, Olkaria Northeast, Olkaria Central, Olkaria Northwest, Olkaria Southwest, Olkaria Southeast and Olkaria Domes for purposes of development with several power plants with an installed capacity of ~950 MWe. The first power plant (Olkaria I) was developed in Olkaria within the Olkaria East Production Field producing power since 198. This is currently under redevelopment (~63 MWe) with a planned commissioning date of June 2026. An additional 150 MWe was commissioned in December 2014, i.e Olkaria I Additional Unit 4&5 while in April 2022 Unit 6 was commissioned. Cumulatively the Olkaria East sector supports ~236 MWe when Olkaria I is excluded. The Olkaria Northeast Production field has the Olkaria II power plant, whose first two units of 70 MWe were commissioned in 2003 while the third was commissioned in 2010. It has an installed capacity of 105 MWe. This power plant is earmarked for redevelopment when the PPA term expires. In the Olkaria Domes Production Field this supports two large power plants, Olkaria IV ~150 MWe commissioned in October 2014 and Olkaria V ~172.5

MWe commissioned in July 2019. Besides the large conventional power plants there are several modular wellhead power plants spread across Olkaria with an installed capacity of ~83 MWe. In the Olkaria West Production field an Independent Power Producer (IPP) Orpower 4 Inc. generates ~ 150 MWe. We have other smaller power plants, a back pressure and binary plants (~3.8 MWe combined) owned by Oserian Development Company (ODC). The installed electricity generating capacity of geothermal power around Olkaria is close to ~905 MWe. This excludes Olkaria I 45 MWe is currently under redevelopment.

2 SILICA SCALING POTENTIAL OF WELLS OW-52 AND OW-52A

Evaluation of silica scaling potential for wells OW-52 and OW-52A was done to provide a basis for design of mitigation for potential amorphous silica scaling in Olkaria production wells OW-52 and OW-52A. These two high enthalpy wells appear to have high silica concentrations in the low volume of brine phase at the surface, probably which is concentrated because of boiling. At such high enthalpies as those of wells OW-52 and OW-52A most of the brine is evaporated and the solutes are concentrated in the brine as the vapor pressure reduces. Anorsson (2000) describes the process of excessive evaporation through a reduction of vapor of pressure. A model using chloride concentrations is applied

Chloride concentration as a function of vapour pressure at the selected enthalpies is shown in Figure 3.

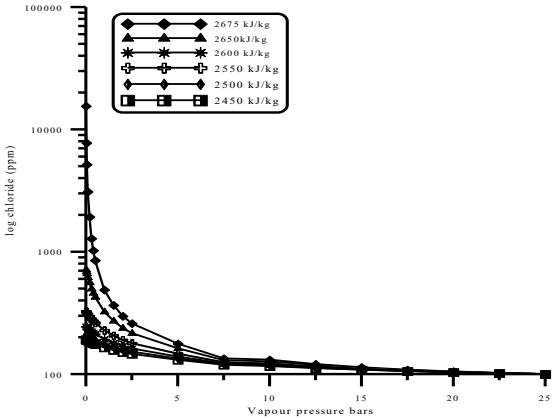


Figure 3: Modelled chloride concentration as a function of vapour pressure at selected enthalpies (Opondo and Arnorsson, 2007).

At high enthalpies close to those of dry steam i.e. 2675 kJ/kg, and low vapour pressures close to atmospheric pressure, the chloride concentration increases exponentially. By lowering the enthalpy of the well by 25 kJ/kg to 2650 kJ/kg the chloride concentrations at the low vapour pressures drops drastically. The results demonstrate that at discharge enthalpy close to that of dry steam and at low vapour pressures close to atmospheric pressure, most of the liquid is evaporated and the solutes become highly concentrated in the residual water.

Amorphous silica scaling occurs when silica concentrations reach or exceed the saturation concentration at moderate pH. Silica saturation refers to the concentration of SiO_2 at a given temperature (controlled by temperature functions) above which amorphous silica precipitates or scales, or below which silica remains in solution. The silica saturation concentration is based on experimentally derived temperature-dependent equilibrium constants for silica solubility:

$$SiO_2+H_2O=H_4SiO_4 \quad (1)$$

$$H_4SiO_4= H^+ + H_3SiO_4^- \quad (2)$$

The silica (SiO_2) saturation index (SSI) is equal to the concentration of silica (H_4SiO_4 in solution), the equilibrium concentration of amorphous silica. When this ratio exceeds a value of 1 silica scale can occur. The silica saturation index is defined by

$$Log\ (\frac{Q}{K})$$

Where Q= is reaction quotient at a given temperature

K= is the equilibrium constant at a given temperature

The SSI is dependent on both pH and temperature. Probably because of boiling and concentration of silica in the small brine fraction, the high enthalpy wells OW-52 and OW-52A were at risk of silica scaling due to high silica concentrations. The potential for silica scale to form exists if the silica SSI >1. Often silica scaling does not occur until SSI>1.2 or 1.3 due to slow nucleation and reaction kinetics. To provide a basis for design for silica scale mitigation by dilution with brine from the "Cluster A" separator for the 731 and 52 pads, a simple model (of heat and mass balance) was used to estimate how much brine from the separator was required to dilute the silica in brine in wells OW-52 and OW-52A to at or below silica saturation at the line temperature.

3 SILICA SOLUBILITY AND THE EFFECT OF PH ON WELLS OW-52 AND OW-52A

The solubility of silica is both dependent on temperature and pH (Fournier and Potter, 1982; Fournier and Rowe 1977,). Silica is more soluble at higher temperatures and higher pH (more basic conditions). When solid amorphous silica dissolves in water, it forms silicic acid H_4SiO_4:

$$SiO_2 + H_2O(l) = H_4SiO_{4\,(aq)} \quad (1)$$

H_4SiO_4 is 'dissolved' silica. This is a chemical equilibrium, and the amount dissolved is temperature dependent. At temperatures < 250° C, then the equilibrium solubility is given by

$$LogC = \left(-\frac{731}{T}\right) + 4.52 \quad (4)$$

for equilibrium and solubility with amorphous silica and

$$LogC = \left(-\frac{1309}{T}\right) + 5.19 \quad (5)$$

for equilibrium with quartz (Fournier and Potter 1982, Fournier and Rowe, 1977)

C= Concentration of Silica (mg/kg)

T= is the absolute temperature in (K)

These temperature functions are valid for 0° C and 250° C. An equation valid for higher temperatures for quartz solubility is derived by (Fournier, 1986). It considers much higher temperatures to a maximum of 340° C

Based on these equations' amorphous silica and quartz solubility and the chemical composition, of wells OW-52 & OW-52 A and wells on pad 731 (OW-731, OW-731B and OW-731C) and Table 1, a few selected silica saturation curves were derived. These are shown in Figure 4. The pH for the wells indicated is moderate to basic pH (9-10).

Table 1: Chemical composition of wells on well pads 52 and 731

Well	Date	Type	WHP Barg	GSP (barg)	Enth	pH	B	SO_4	Cl	CO_2	F	H_2S	SiO_2	Ca	Li	Na	K	Mg	CO_2	H_2S	CH_4	H_2	N_2
							ppm												mmoles/100moles steam				
OW-731	02-Jul-12	WS	4.8	4.8	1636	9.96	3.549	125	694.5	503.8	274.3	3.5	832	0.366	3.14	797.1	230.4	0.163	198.7	0.74	0.5	10	20.3
OW-731B	02-Jul-14	WS	11	10.5	1291	10.2	1.25	141	667.4	544.5	173.64	12.9	657	0.151	1.03	704.2	92.6	0.013	257.8	0.26	0.7	0.4	22.8
OW-731C	28-Jul-14	WS	7	4.8	1273	10.1	1.06	126	612.58	391.6	139.79	5.78	669	0.047	1.43	764.8	121.05	0.033	306.2	1.13	0	0	31.3
OW-52A	21-Jul-15	WS	11	11	2673	10.3	1.95	152	1035.8	821.9	69.97	17	1580		3.07	1818.9	479.37		165.1	5.38	0	14	5.42
OW-52	14-Jul-15	WS	9	8	2672	9.7	1.12	0.85	3347	190.2	177.35	16.3	1270		3.62	1293.8	432.37		108.9	5.93	0	14	8.4

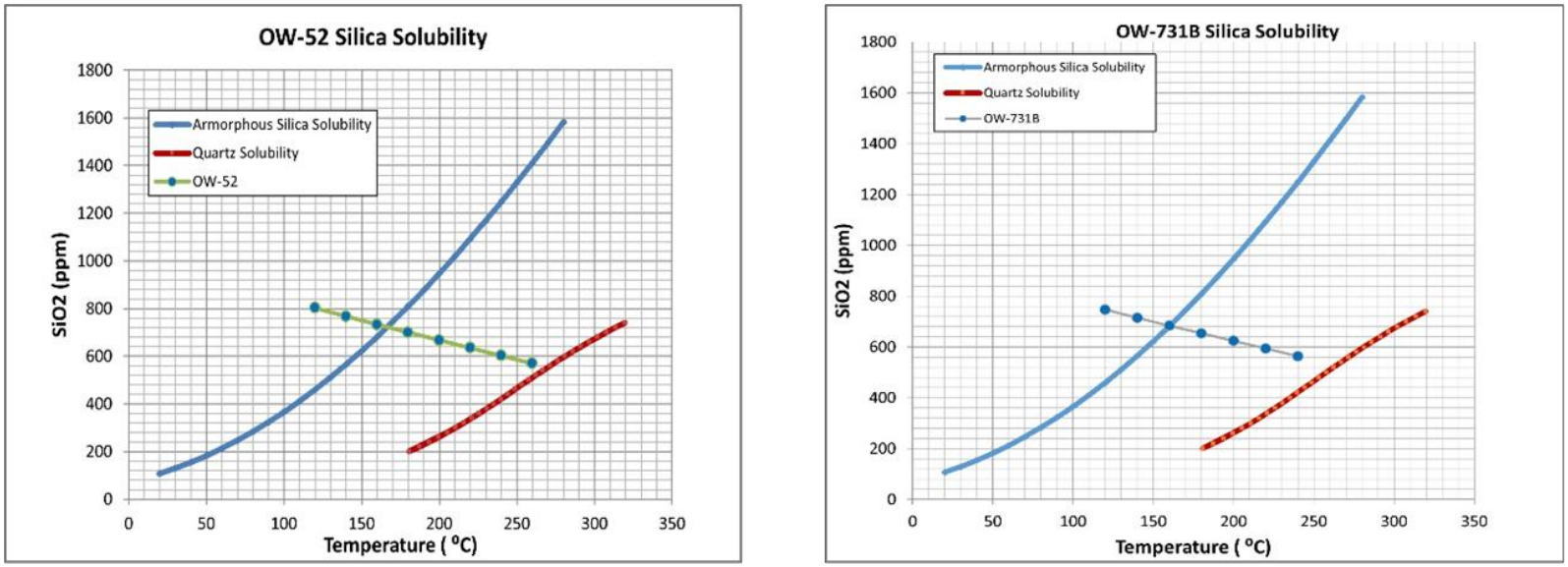


Figure 4; Silica Saturation curves derived by single step adiabatic boiling for wells OW-52 and OW731 fluids. The silica saturation is shown where the amorphous silica curve is intersected by the boiling curve.

Silicic acid is a weak acid and remains solely as H_4SiO_4 at lower pH values. As the pH is increased, it dissociates according to the equilibrium

$$H_4SiO_4 = H^+ + H_3SiO_4^- \quad (2)$$

Since it is charged, the $H_3SiO_4^-$ anion (the silicate anion) is very soluble unlike the silicic acid (H_4SiO_4) which is not charged. The dissociation starts at about pH =8.5 and increases with increasing pH. Consequently, the total solubility of the amorphous silica ($H_4SiO_4 + H_3SiO_4^-$) as a function of pH at different temperatures is derived from equation (4) and shown in Figure 3.

$$S = C * [1 + \{10^{pH} * K1/\gamma(H3SiO4-)\}] \quad (3)$$

Where C= Solubility in mg/kg from equation (4)

K1=Temperature dependent dissociation constant

$\gamma(H_3SiO_4^-)$ = Activity coefficient of $H_3SiO_4^-$ at the temperature of interest (Henley, R.W., 1983)

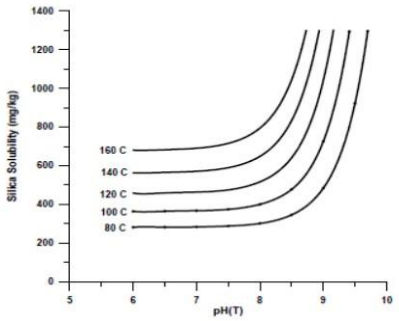


Figure 5. Calculated amorphous silica solubility with a change in pH (T) (Henley R.W, 1983)

The solubility of amorphous silica as given in equation (1) is for the H_4SiO_4 species alone and is temperature dependent. This solubility is a function of pH. It does not take account of the extra solubility due to the formation of the $H_3SiO_4^-$ anion (second dissociation constant) at higher pH values. This contributes to lower SSI. Wells with higher pH in the brine show higher concentrations whereas those where the pH(T) is much lower, and the SSI is higher and reduced solubility of silica (GEOKEM CONSULTING ,2015)

Mixing fluids from well pad 52 at separation with the wells from pad 731, the chemical composition of these wells is likely to change. Due to boiling and loss of CO_2 in the steam, bicarbonates that form cause pH to increase. Before the separator the well fluids probably have lower pH. The amount of CO_2 loss affects the pH of the fluid and most CO_2 loss occurs with a small pressure (temperature) drop. The silica saturation concentrations are evaluated at line pressures temperatures and pH of 7-8. The silica saturation concentrations at evaluated line pressures and pHt=7 is shown in Table 2. The silica saturation concentration will increase at higher pH (requiring less dilution) and therefore pHt=7 provides the most conservative (highest) dilution rates. To estimate the silica saturation, amorphous silica equilibrium equation (Fournier and Rowe, 1977) has been applied.

Table 2. The temperature of where silica saturation (SSI=1) is estimated during production and pH of 7 and 8 the subject temperature (pHt) using amorphous silica equilibrium of Fournier and Rowe (1977)

Location	Minimum Line pressure (barg)	Silica Saturation Concentrations mg/kg	
		pHt=7	pHt=8
		Fournier & Rowe (1977)	Fournier & Rowe (1977)
Post Flash	9-10	818-845	974-1003
Pre-Flash	9-11	818-858	974-1018

Concentrations of silica estimated to be representative of the production conditions are presented in Table 3. Based on these values the brine is estimated to be below silica saturation for wells on Pad 731, the total combined Pad 731 and Pad 52 brine at pre-separator line pressure and post separator line pressure. Amorphous silica is not anticipated to scale (precipitate) at these locations under the conditions evaluated. The brine of 52 and 52A is above silica saturation (Silica concentrations at sampling pressure) at neutral to moderately basic conditions and amorphous silica scale is possible. Table 3 below refers to sampling conditions

Table 3. Sampling conditions, SiO_2 concentrations after 10 bara flash, and the calculated weighted average silica of dilution brine("combined") before it is recycled into the system.

Well	Sample Date	Measured Data			Brine data corrected to 10 bara	Production Conditions			
		WHP (During Sampling) Bar a	Sampling Pressure Bar a	pH	SiO_2 mg/kg	Brine Flow2 TPH	Steam Flow TPH	Total Flow TPH	Enthalpy kJ/kg
OW-52	14-Jul -2015	10.0	9.0	9.7	1208	6	110	116	2680
OW-52 A	21-Jul-2015	12.0	12.0	10.2	1522	3	53	56	2680
OW-731	02-Feb-2012	-	8.8	9.9	785	20		77	2260
OW-731B	01-Jul-2014	11.5	11.0	10.2	678	83	27	110	1250
OW-731C	29-May-2014	11.0	8.0	9.8	641	91	29	120	1250
OW-731D	14-May-2014	9.0	8.0	9.6	401	1	14	15	2650
Weighted Average Silica			Pad 52	1313	Brine Flow	9			
			Pad 731	670		195			
			Combined	698		204			

4 SILICA MITIGATION BY DILUTION OF OW-52 AND OW-52A

Evaluation of silica assumed it can scale when the SSI> 1 or when the brine silica > saturation. The dilution rates were calculated at saturation and may be considered "minimum" dilution rates. At saturation or even slightly above, silica typically does not scale due to slow kinetics.

The SSI for wells 52 and 52 A fluids are >>1 at the wellhead providing the possibility that scale could form before brine dilution mitigates the SSI to ≤1. While the slow kinetics of silica deposition may prevent this issue, the dilution water was combined with the high silica from 52 and 52A as close to the wellhead as possible where thorough mixing was expected to occur.

The minimum amount of separator discharge at 698 mg/kg silica ("combined" weighted average silica) required to dilute discharge from wells 52 and 52A to the concentration at which silica is saturated for the given operating temperatures and mass flows at a pH of 7 are reported in table 3. In evaluating the temperature of the diluting stream, it is assumed the temperature remains constant (180° C,10 bara) between the separator and pad 52: Lower temperatures (< 170 ° C) in the dilution brine would increase dilution requirements and introduce the possibility of scale in the diluting line. Figure 5 shows the design PID and some photos of the brine dilution on wells OW-52 an/52A.

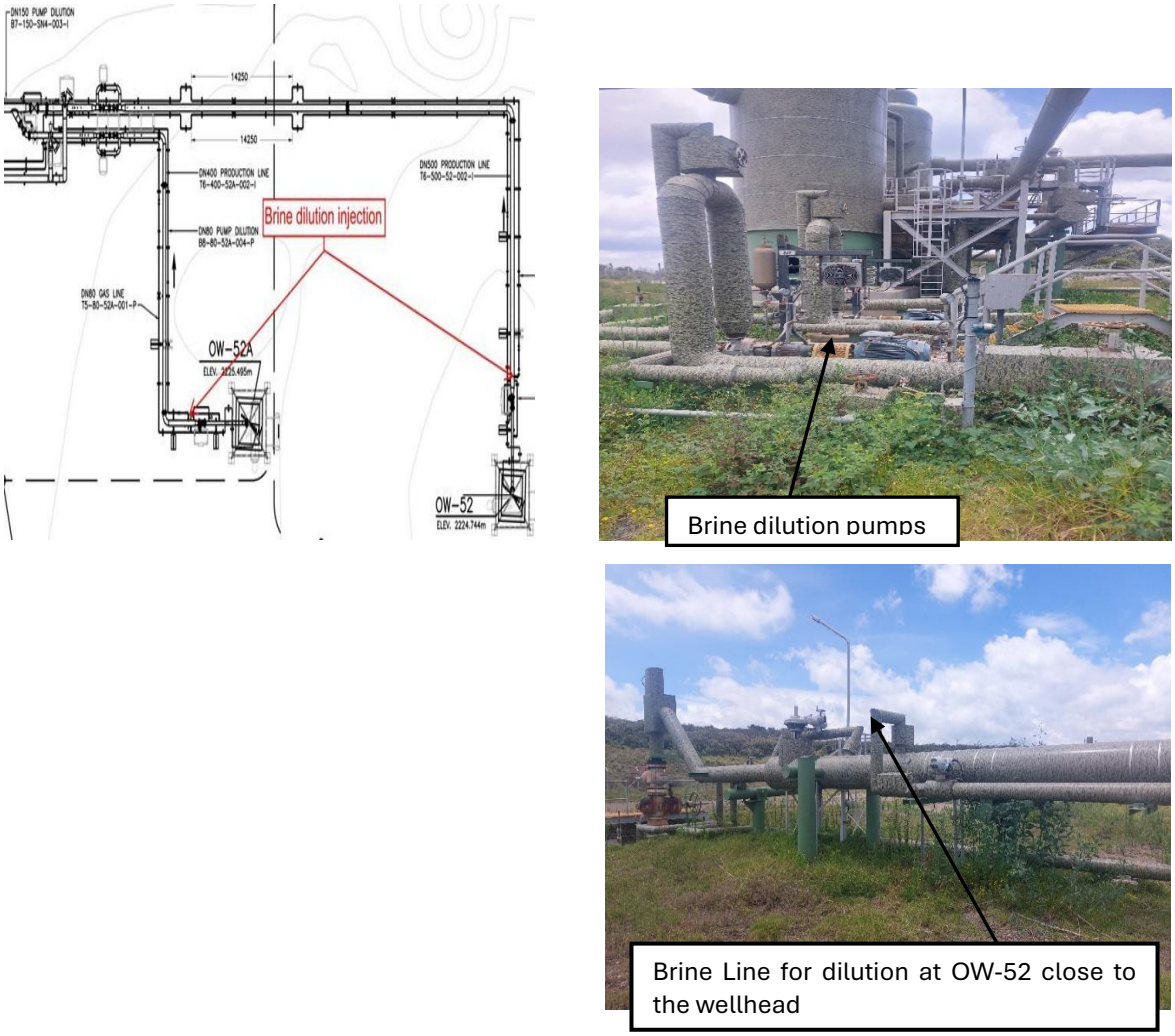


Figure 5: Brine dilution PID, pumps and dilution line on the two (2) -phase flow of wells OW-52 & OW-52A

Based on temperature and mass flows given in the cases for the wells and the process flow diagram, well OW-52 brine estimated to be diluted by 12-17 TPH separator brine and OW-52 A brine to be diluted by 11-15 TPH separator brine to maintain SSI ≤ 1 at pH7. The process flow diagram for wells on well pad 52 and well pad 731 is shown in Figure 6 below

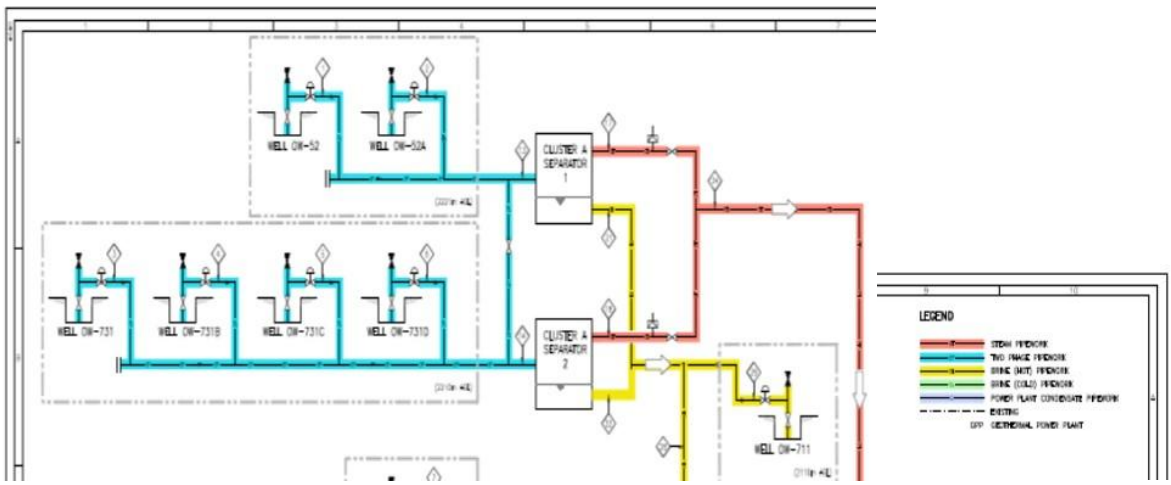


Figure 6: Process flow diagram for wells on pad 52 and 731 showing cluster A separators

Although using pH 7 which requires the maximum dilution as a basis for design is conservative, these dilution rates (table 3) are identified as minimum because they are calculated to reduce silica concentration to saturation, a concentration at which amorphous silica is not likely to precipitate under equilibrium conditions.

Another approach to estimate the dilution rates which can be applied is to reduce the enthalpies of wells OW-52 and OW-52 A from ~2680 kJ/kg to ~ 2385 kJ/kg to 2283 kJ/kg respectively. This approach considers mass and enthalpy balance which reduces the excessive evaporation within the 2- Phase line.

5 RESULTS OF DILUTION OF WELLS OW-52 AND OW-52A AT OLKARIA I UNIT 6 PLANT COMMISSIONING

Olkaria I Unit 6 power plant was commissioned in July 2022 with the commissioning activities spread from January 2022. The steam field i.e. the wells to supply steam to the power plant were commissioned between February and Aprill 2022. Brine dilution pumps had been installed at the drains of cluster A separators and were commissioned alongside the commissioning of wells on pad 52 and 731. The fluids from wells OW-52 and OW-52A were diluted by pumping the brine from the cluster A separators into the two (2) phase line. This was to test the effectiveness of the brine dilution process. Some results of the chemical composition, enthalpies and mass flows obtained during the commissioning period are presented in table 4a &b below.

Table 4a: Chemical composition of brine dilution of the two (2) phase of wells OW-52 and OW-52A

Well No	Sample date	Description	WHP (bar g)	GSP (bar g)	Cond (µΩ/cm)	TDS (ppm)	pH/T°C @20	B	SO_4	Cl	CO_2	F	H_2S	SiO_2	Ca	Li	Na	K	Mg
								ppm											
OW-52A	24-Feb-22	Drain 1 brine	11	10	8570	4285	10.37	0.26		3130.5	338.8	17.55	55.42	1693.6	0.059	2.2	3565.5	1145	0
OW-52A	22-Mar-22	Before dilution	10.3	10	11720	5860	10.04	0.56	394.1	3981	770	491.61	48.28	1703.6		2.5	3038.6	369.5	0
OW-52A	22-Mar-22	After dilution	9.3	9.3	11340	5670	10.02	0.74	408.4	4000.4	814	500.21	52.7	1814.5		2.42	3153.1	826.3	0.2
OW-52	24-Feb-22	Drain 1 brine	11.6	10	4900	2450	8.7	0.83	174.8	2214.3	173.8	5.03	10.2	1003.7	0	1.99	2060.4	1062	0.01
OW-52	21-Mar-22	After dilution	11.4	9.3	1818	909	9.94	0.1	192.5	1169.5	379.5	84.89	96.9	1035.6		2.01	990.1	224.9	0.25
OW-52	21-Mar-22	Before dilution	11.4	11	4090	2045	8.4	0.15	152.7	1610.9	297	213.96	5.78	944.6		1.7	1171	304.4	0.06

Table 4b: Enthalpy and mass flows of wells on Pad 52 and pad 731 during discharge tests and on commissioning of Olkaria I Unit 6 (March 2022)

	Discharge test data			Commissioning flow data		
Well	**Enthalpy**	**Brine(t/hr)**	**Steam(t/hr)**	**Enthalpy**	**Brine(t/hr)**	**Steam(t/hr)**
OW-52	2674	6	112	2329	34.9	120.7
OW-52A	2674	3	54	2466	12.3	65.7
OW-731	2260	20	58	2186	22.1	52.2
OW-731B	1250	83	27	1248	87.1	27.8
OW-731C	1250	91	29	1258	97	32
OW-731D	2650	1	14	2700	0	23.9

The effects of dilution by brine in the two (2) phase fluids of wells OW-52 and OW-52A were evident during commissioning in March 2022. There was an observed increase in mass flows, both brine and steam in the 2- phase fluids, probably contributed by the brine dilution. The enthalpy of wells OW-52 and OW-52A decreased from ~2680

kJ/kg (discharge test data) to 2329 kJ/Kg and 2466 kJ/Kg (commissioning data) respectively. The reduction in enthalpy in turn increases the wetness of the 2- phase fluids and this decreases the risk of silica to precipitate in the 2-phase fluids. This could partly mitigate silica scale formation in the 2-phase fluids.

6 DISCUSSIONS AND CONCLUSIONS

In the application of brine dilution to silica scale mitigation at Olkaria I Additional Unit 6 numerous operational, design and chemical variables were considered which could affect its application. Relative brine flows and concentration of silica in individual wells and combined fluids are dependent on the actual operating Wellhead pressure, enthalpies, mass flows and flash pressures. Changes in well discharge over time including mass flows, steam fraction (enthalpy), temperature, pH and fluid chemistry would affect the chemistry of the separator discharge, and the amount of dilution required. In this exercise it was assumed that the chemistry of the well discharge is representative of the operating conditions. During the commissioning of the wells on pad 52 and 731, and the brine dilution system, the enthalpies of wells OW-52 and OW-52A decreased while the mass flows increased. The increase in mass flows was probably contributed by the diluting brine.

High enthalpy geothermal wells which produce some brines are likely to change with increasing discharge. Such wells produce from a two-phase part of the reservoir which, as reservoir pressure declines with production can either tend to 100 % steam (wells OW-52, OW-52A and OW-731D) or in other cases increased brine production as liquid flows towards lower pressure. Reservoir response during production could increase the variations in factors (temperature, steam fraction (enthalpy), mass flows, pH and fluid- chemistry). Reservoir monitoring of well discharge characteristics and chemistry are critical for successful implementation of the silica mitigation system.

The potential for silica scale would occur when SSI>1 or when brine silica > saturation. The dilution rates are proposed to keep silica at saturation or below. At saturation or even slightly above, silica typically does not scale due to slow kinetics. In this exercise the potential for silica scale (SSI>1) mitigation of silica scale in wells on pad 52 by diluting with (~15-17 tph) and OW-52A (~14-15). If brine pH is higher (~9-10) under operating conditions, then dilution rates could be reduced or may not be necessary. Enough variance was provided in the pumps to address any changes during production.

Acknowledgements

This work was done as part of the steam field design considerations for Olkaria I Unit 6 to mitigate silica scale in the 2-phase of wells on pad 52. I would like to acknowledge the teams from Projects Execution, KenGen for considering this as a design improvement after serious scaling problems experienced in the surface equipment of well OW-34 which was used as a reference. And to H. Young, the contractor for detailed design of the dilution system and implementing this solution.

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