The struggle against silica: brutal methods and subtle ones

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ABSTRACT

The concentration of silica in a geothermal brine increases with temperature. When steam is separated from brine with initial temperature greater than about 250°C, silica-rich deposits accumulate in steam separators and brine pipes. When more steam is separated or the brine is discharged at atmospheric pressure, massive precipitation of colloidal amorphous silica commonly occurs. Aside from increasing separator pressure to avoid super-saturation in respect to amorphous silica, the most common method employed to control silica precipitation is addition of sulfuric acid to the brine to decrease pH, which greatly slows polymerization of dissolved silica and formation of silica deposits. While sulfuric acid is cheap, this method requires large capital investment to avoid corrosion. Brine acidified with sulfuric acid is poorly buffered, whereby acid feed rate must be strictly monitored and controlled, and the vessel wherein acid is added to the brine must be made of a costly, corrosion resistant alloy.

There is no such thing as a practical true silica inhibitor. Products promoted as “silica inhibitors” actually inhibit metal silicates, or act to disperse colloidal silica particles. Formation of silica-rich deposits in separators and other equipment at high temperature generally involves precipitation of minute particles of amorphous aluminosilicate composition similar to zeolites or clays. These particles serve as seeds that initiate the growth of amorphous silica particles, which form the deposits. Injecting a silicate inhibitor at the wellhead enables control of such deposits by preventing formation of the aluminosilicate seeds.

Organic acids or carbon dioxide present in the condenser vent gas of a geothermal generating unit can be used to decrease brine pH without the danger of corrosion or expensive investments to prevent corrosion. When acetic acid is used, the acidified brine is well buffered by the equilibrium of acetic acid/acetate anion, whereby over-feeding the acid causes a small decrease in pH. Brine acidified by adding carbon dioxide is buffered by the equilibrium with bicarbonate ion in the brine; alkalinity of the brine is preserved and the acidified brine is strongly buffered.

This paper presents examples of successful application of these control methods.

Keywords: Geochemistry, silica scaling, silica inhibitors, brine acidification.

Métodos brutales y sutiles de combatir a la sílice

RESUMEN

La concentración de sílice en la salmuera geotérmica aumenta con la temperatura. Cuando se separa el vapor de la salmuera a temperaturas iniciales mayores de unos 250°C, se acumulan depósitos ricos en sílice en los separadores y en las tuberías de la salmuera. Cuando se separa más vapor o cuando la salmuera se descarga a presión atmosférica, comúnmente ocurre un depósito masivo de sílice amorfa coloidal. Además de aumentar la presión de separación para evitar sobresaturación de sílice amorfa, el método más común que se utiliza para controlar el depósito de sílice es agregar ácido sulfúrico a la salmuera para reducir su pH. Esto reduce enormemente la polimerización de sílice disuelta y su consecuente depósito. Aunque el ácido sulfúrico es barato, este método requiere una alta inversión para evitar la corrosión. La salmuera acidificada con ácido sulfúrico es difícil de manejar, por lo que la adición del ácido debe monitorearse y controlarse cuidadosamente, además de que el recipiente en el que se agrega el ácido a la salmuera debe estar fabricado de una costosa aleación resistente a la corrosión.

No existe ningún inhibidor de sílice realmente práctico. Los productos que se comercializan como "inhibidores de sílice" son realmente inhibidores de silicatos metálicos, o bien actúan como dispersantes de partículas de sílice coloidal. La formación de depósitos ricos en sílice a elevada temperatura en separadores y otros equipos, implica generalmente la precipitación de diminutas partículas de aluminosilicatos amorfos de composición similar a las zeolitas o a las arcillas. Estas partículas actúan como semillas que detonan el crecimiento de partículas de sílice amorfa, que finalmente se depositan. La inyección de un inhibidor de silicatos en el cabezal del pozo permite controlar tales depósitos evitando la formación de semillas de aluminosilicatos.

Se pueden utilizar ácidos orgánicos o el bióxido de carbono en el escape de gases del condensador de una planta geotermoeléctrica en operación a fin de disminuir el pH de la salmuera, sin riesgo de corrosión y sin necesidad de hacer gastos mayores para evitarla. Cuando se emplea ácido acético, la salmuera así acidificada queda bien controlada por el equilibrio entre el ácido acético y el anión acetato, y cualquier exceso de ácido provoca una pequeña reducción del pH. La salmuera acidificada con bióxido de carbono se controla gracias al equilibrio con el ion bicarbonato que contiene la propia salmuera; se preserva así su alcalinidad, y la salmuera acidificada resulta bastante bien amortiguada.

Este trabajo presenta ejemplos de la aplicación exitosa de esos métodos de control.

Palabras clave: Geoquímica, incrustación de sílice, inhibidores de sílice, acidificación de salmueras.

Introduction

The brine in a geothermal reservoir exists in a state of chemical equilibrium with minerals in the reservoir rock. The concentration of solutes in equilibrium with the minerals is governed mostly by temperature and pH of the brine, which is in most cases controlled by the concentration of carbon dioxide dissolved in the brine. When steam is separated from the brine, temperature drops, the concentration of solutes increases, and pH increases because carbon dioxide is removed together with water vapor. These changes disturb chemical equilibrium, and the brine becomes supersaturated in respect to a variety of minerals. Which minerals actually precipitate, and at what rate, is determined by the rate of the chemical reactions involved.

Brines with initial temperature up to about 200^{o}C typically deposit calcium carbonate, starting immediately after steam starts to separate from the brine inside the well. If the separated brine is then passed through a heat exchanger, an amorphous metal silicate material consisting of silica plus the oxides of magnesium, iron and calcium commonly accumulates inside the heat exchanger tubes.

Brines with initial temperature greater than about 250^{0}C typically deposit an amorphous aluminosilicate material and amorphous silica. In the interval 200 to 250^{0}C there is a transition, with calcium carbonate becoming less important, and silica becoming more important as temperature increases.

Silica is different

Calcium carbonate is a crystalline salt. Deposits of calcium carbonate grow as layers of positively charged calcium ions (cations) and negatively charged carbonate ions (anions) that are deposited on the surface in alternation. Metal silicates are often confused with silica, but their properties and the processes which produce them have more in common with calcium carbonate than with silica. Silicate minerals are also salts; in this case, the silicate anion is a large polymer.

Silica itself –SiO_2 -- is not a salt. It is a covalently bonded material which contains no distinct cations or anions.

Formation of calcium carbonate deposits is very rapid, because the cations and anions simply diffuse to the surface and bind to it by electrostatic attraction. Metal silicates deposit more slowly, because chemical bonds must form to produce the polymeric anions. Deposition of silica is even slower, because each step of the process involves a chemical reaction that occurs only at a negatively charged site on the surface of amorphous silica.

The amount of calcium carbonate potentially deposited is limited by the concentration of calcium in the brine or by the alkalinity of the brine. If one of these parameters is high, the other one is necessarily low. Therefore, the amount potentially precipitating is small and rarely exceeds 20 parts per million parts (ppm). Likewise, the amount of metal silicate potentially deposited is limited by the amount of Mg, Fe and Al in the brine and rarely exceeds 10 ppm.

The concentration of silica in brine in equilibrium with quartz at 250^0C is about 450 ppm, and increases with temperature. Separating steam from the brine further increases the concentration of silica in the separated brine. As a result, silica concentrations as high as 800-1,000 ppm are sometimes encountered in brine after steam has been separated from it.

These factors make silica very different from calcium carbonate and metal silicates.

First, deposition of silica directly from solution is very slow and rarely significant. In most cases, silica deposits are produced by accumulation of colloidal particles of amorphous silica formed by polymerization of silica dissolved in the brine.

Second, products which inhibit deposits of calcium carbonate and metal silicates do not directly inhibit silica deposits. Scale inhibitors are negatively charged polymers like polymaleic acid or large molecules carrying many negative charges; for example, pentaphosphonates. These molecules bind to cations exposed on the surface of a growing deposit of calcium carbonate or metal silicate and block further deposition. Silica contains no cations; therefore, these products do not adhere to the surface of amorphous silica, and do not inhibit deposition of dissolved silica upon the surface.

Third, the amount of silica that can precipitate and be deposited from a hot geothermal brine is potentially very large, sometimes several hundred ppm.

These factors make silica deposits harder to control, and require different control methods.

Processes that produce silica deposits

Figure 1 (all figures presented at the text end) illustrates the processes that form silica deposits.

Silica dissolved in the brine as monosilicic acid $Si(OH)_4$ ("a" in Figure 1) can deposit directly on to a solid surface (m), but this process, called "molecular deposition", is very slow and rarely produces visible deposits (n) by itself. It is, however, the process causing colloidal particles to grow and cements deposits of colloidal particles to form solid deposits.

When saturation ratio S is larger than about 2.5, colloidal particles of amorphous silica are rapidly produced by homogeneous nucleation. Molecules of monosilicic acid link up to form dimers, trimers, etc. (b), until seeds (c) large enough to grow as particles are produced. These particles continue growing by the process of molecular deposition (d) until the concentration of silica dissolved in the brine approaches the solubility of amorphous silica, which is approximately expressed by the formula

$\text{Log } c_0(\text{ppm}) = -731/(t+273) + 4.52,$ where t is temperature in degrees Celsius.

The particles produced are very small, commonly with radius of 1 to 2 nanometers.

Silica particles have a negative surface charge that increases with pH. Calcium ions in the brine attach themselves to the negatively charged sites, neutralizing the negative charge and forming bridges between the particles. This bridging mechanism causes the colloidal particles to coagulate (f) and precipitate from the brine (g). This mechanism produces massive silica deposits in the brine ponds at Cerro Prieto where brine is discharged at atmospheric pressure.

The colloidal particles also adhere to solid surfaces (h), and molecular deposition of dissolved silica cements the particles (I) to form solid deposits (j).

The homogeneous nucleation process is well understood and can be accurately modeled, at least in low salinity brines. Figure 2 compares values of silica concentration vs time at 50^0C calculated using computer program SILNUC with experimental data (Weres et al., 1981). The SILNUC program is described and documented in an earlier report, which includes a review of silica chemistry relevant to geothermal brines (Weres et al., 1980).

The saturation ratio S (concentration of dissolved silica divided by the solubility of amorphous silica) has a large effect upon the rate of homogeneous nucleation. Figure 3 shows calculated curves at 50^0C and pH 5.71. Note that the X axis is logarithmic and spans time from 4 minutes to 100,000 minutes = 69 days.

There are no effective, commercially viable scale inhibitors capable of directly inhibit molecular deposition of silica or the homogeneous nucleation process. These processes can only be controlled by controlling the saturation ratio S or decreasing pH of the brine.

Silica deposits seeded by aluminosilicates can be inhibited

When saturation ratio S is less than about 2.5 (this threshold value varies with temperature and pH) homogeneous nucleation is very slow, and the formation of colloidal particles of amorphous silica is seeded by particles of metal silicate composition (k, l, d in Figure 1). The experimental and calculated curves for 50^0C and 0.5 g/kg (= 500 ppm) in Figure 2 diverge, because even under laboratory conditions, heterogeneous nucleation caused by impurities in the chemicals used is more rapid than homogeneous nucleation at S = 2.75 and 50^0C.

Chemical analysis of deposits formed at high temperature and modeling of geothermal brines indicate that these seeds usually have an aluminosilicate composition with the weight ratio of SiO_2 to Al_2O_3 about 6:1, similar to the zeolite mineral clinoptilolite.

The concentration of aluminum in geothermal brine rarely exceeds 1 ppm and is commonly below the limit of detection. Because 1 mg of aluminum can produce 20 mg of amorphous aluminosilicate and seed the formation of silica deposits, the concentration of aluminum in the brine is an important parameter. Increased concentrations of aluminum are correlated with the presence of calcic plagioclase in mafic reservoir rocks and low pH of brine in the reservoir.

Figure 4 illustrates the large effect of seeding by aluminosilicate at a field in Central America. Initial brine temperature is about 300^0C and steam is separated from the brine at about 5.4 bars-absolute and 155^0C. The separated brine flows from the separator to an injection well at high pressure and temperature through an insulated pipeline. The brine is undersaturated in respect to amorphous silica at the wellhead ($S < 1$) and deposits of aluminosilicate composition with weight ratio SiO_2:Al_2O_3 about 6.3 are present in brine pipe leading from the well to the separator. Separating steam from the brine increases S to about 1.4, and heavier deposits containing a greater fraction of SiO_2 accumulate in the pipeline leading the injection well. These deposits are composed of particles with an aluminosilicate core coated with amorphous silica, cemented to the metal surface by further deposition of dissolved silica.

The commercially available computer program Geochemist's Workbench, Standard Edition, was used to calculate dissolution and precipitation of minerals. The initial concentration of Al in the brine was calculated to be 0.27 ppm assuming equilibrium with anorthite ($CaAl_2Si_2O_8$). About 12.8 ppm of clinoptilolite-K with SiO_2:Al_2O_3 = 5.9 was calculated to precipitate from the separated brine. This result is consistent with the deposits observed before the separator at $S < 1$. The presence of 12.8 ppm seed particles accelerates the conversion of dissolved silica to colloidal silica particles by a factor of about one million (Fig. 4).

Unlike silica itself, precipitation of aluminosilicates from geothermal brine can be inhibited using properly selected scale inhibitors. In order to achieve maximum benefit, the inhibitor would need to be injected into every well, below the depth at which steam begins to separate from the brine. So doing would slow down polymerization of silica and formation of silica deposits by orders of magnitude up to about $S = 2$.

Because downhole treatment of these very hot wells is difficult, the inhibitor is actually injected at the wellhead, before the brine becomes supersaturated in respect to amorphous silica. Some aluminosilicate seeds are already present in the brine at this point, but the inhibitor stops them from growing, and blocks molecular deposition of dissolved silica upon them. In this way, deposits of aluminosilicates and silica can be inhibited up to about $S = 1.5$.

Brine pH controls the rate of silica deposition

The rate at which dissolved silica deposits on to colloidal particles of amorphous silica and makes them grow or cements them together is proportional to the density of negative charge on the surface of the particles. The density of negative charge increases with pH and therefore the rate of molecular deposition increases with pH as illustrated in Figure 5. Note that the Y axis in Figure 5 is logarithmic. Up to about pH 7, increasing pH by one unit increases the rate of molecular deposition by nearly a factor of ten.

In fact, pH influences every process involved in the formation of silica deposits as illustrated in Figure 6.

1. The rate of molecular deposition increases with pH until the solubility of silica starts increasing due to ionization of monosilicic acid, an effect that becomes important above pH 8.

2. The rate of homogeneous nucleation increases even more rapidly. The seed particles become more stable as pH increases, because the surface free energy of the silica/water interface decreases as negative charge accumulates with increasing pH. Similarly, increasing pH accelerates the formation of aluminosilicate particles that serve as seeds. In both cases, the seed particles grow by molecular deposition of dissolved silica upon them. As with molecular deposition, nucleation slows when the solubility of silica increases above pH 8.

3. Increasing pH increases the density of negative sites on the silica surface, favoring adhesion of the particles to surfaces mediated by calcium ions.

In combination, these effects ensure that changing brine pH by one unit changes the rate that silica deposits form by a factor greater than ten, in some cases much greater than ten. For example, compare the calculated curve for C = 0.6 g/kg and pH = 5.71 in Figure 3 with the calculated and experimental values in Figure 2 at pH 7.21. Increasing pH by 1.5 units accelerates the polymerization of dissolved silica by a factor of about 100.

Figure 7 illustrates the effect of increasing pH of a brine formulated to resemble flashed brine at Cerro Prieto (Weres and Tsao, 1981). “Molybdate active SiO_2” is silica dissolved in the brine. “Total SiO_2” also includes colloidal silica suspended in the brine. Sixty percent of the dissolved silica initially present in the brine polymerized to form colloidal silica within 4 minutes, and the colloidal silica slowly coagulated and settled out of the brine at pH 7.2. Adding NaOH to increase pH to 7.8 immediately removed all of the colloidal silica, leaving the brine crystal clear.

If sufficient calcium is present in the brine, colloidal silica can be removed from the brine by increasing pH. Conversely, colloidal silica present in the brine can be stabilized and prevented from forming deposits by decreasing pH.

Silica deposits can be controlled by adding acid to decrease pH of the brine

Because each step involved in the formation of silica deposits decreases with pH, adding acid to geothermal brine to decrease pH has been the most common method employed to control silica deposits. Most commonly, sulfuric acid is added to the brine to decrease brine pH to about 5.5. Decreasing pH to 5.5 will in most cases inhibit deposition of silica from flashed brine by a factor of 100 or more, and the increase in corrosion is manageable. Sulfuric acid is cheap, but a large capital investment is needed to use it safely.

First, the pH of geothermal brine is buffered by the equilibrium of carbon dioxide and bicarbonate ion. Sulfuric acid converts bicarbonate to carbon dioxide, leaving the brine without a buffer to stabilize pH. As a result, a small excess of sulfuric acid can cause a large drop in pH, causing serious corrosion. An accurate and highly reliable control system is needed to monitor pH of the treated brine and precisely control acid feed to prevent dangerous overdosing with acid and corrosion.

The calculated effect upon pH of adding sulfuric acid to the brine reinjected at Los Azufres is illustrated in Figure 8. This brine contains 0.72 meq/kg bicarbonate = 36 ppm Alkalinity as $CaCO_3$. Adding 37 ppm sulfuric acid decreases pH to 5.7; adding 46 ppm, a 25% excess, would decrease pH to 3.9 causing severe corrosion.

Second, when acid is injected into a pipe carrying brine, it does not instantaneously disperse and mix with the brine. The distribution of acid for several pipe diameters downstream of the injection point is characterized by packets of brine containing a high concentration of acid which quickly disperse as acid flows down the pipe. When such a packet of highly acidic brine touches the inner surface of the pipe, corrosion results. In order to prevent corrosion near to the injection point, a section of pipe made of Hastelloy or another alloy highly resistant to corrosion is installed, and the acid is injected into this section of pipe.

Additionally, acid resistant storage tanks, pumps and other equipment is needed. All of these things add up to a large capital investment, typically in excess of one million US dollars.

Carbon dioxide is a much safer alternative to sulfuric acid

Carbon dioxide is the major constituent of the vent gas extracted from the condenser of a geothermal power plant. Thus, CO_2 is available at no cost. The pH of flashed geothermal brine can be decreased by contacting the brine with condenser vent gas, causing CO_2 to be absorbed.

Figure 9 illustrates the effect of adding CO_2 to the brine at Los Azufres (Weres, 2015). Adding 150 ppm decreases pH to 5.7; adding 188 ppm, a 25% excess, further decreases pH only to 5.5 with little effect upon corrosion. Carbon dioxide is a much weaker acid than sulfuric acid, and adding CO_2 to the brine does not eliminate bicarbonate. Therefore, the brine remains buffered by CO_2 / bicarbonate, with pH shifted due to increased concentration of CO_2.

The nearly flat curve of pH vs CO_2 added greatly simplifies process control. However, as with sulfuric acid, decreasing pH will increase corrosion to some degree and a corrosion inhibitor would need to be applied.

Treatment of Los Azufres brine with CO_2 was modeled and compared with using sulfuric acid. Steam condensate is also reinjected at Los Azufres, and steam condensate can be combined with the brine in the proportion 1:3 to dilute the brine.

In the model, brine is discharged into a weir box at 0.73 bar-absolute (atmospheric pressure at Los Azufres) and 91^{o}C. The brine contains 6.05 ppm aluminosilicate seeds, and cools to 70^{o}C in 3 minutes. At this point, one of three treatments is applied:

1. Excess condensate from the cooling tower is added to the brine in the proportion 1:3.

2. Excess condensate from the cooling tower is contacted with condenser vent gas and added to the brine in the proportion 1:3, adding 150 ppm CO_2 and reducing pH to about 5.7.

3. Sulfuric acid is added to decrease pH to 5.7 without diluting the brine.

The brine then cools to 36^{o}C (40^{o}C if not diluted) and is injected at t = 10 minutes.

The same calculations were also performed with no aluminosilicate seeds present in the brine.

The results are summarized in Figures 10 and 11. Figure 10 shows the decrease in dissolved silica concentration vs time, and Figure 11 shows the rate of silica polymerization vs time; that is, the rate at which dissolved silica is being converted to colloidal silica. “Polymerization rate” is a good stand-in for the rate at which silica deposits form, because the rate of deposit formation will be highest at about the time polymerization rate is highest.

With pH unchanged, the dissolved silica in the brine polymerizes nearly as quickly as the brine cools, and the rate of polymerization peaks at about 10 minutes, exactly when the brine is reinjected. In this case, deposits form most rapidly in the wellbore and in the receiving formation near to the wellbore where they do most damage. This is the present situation that is gradually damaging the injection well. Diluting the brine has little effect, and the effect of aluminosilicate seeds is insignificant because homogeneous nucleation is rapid under these conditions.

Adding sulfuric acid without diluting the brine delays the time of maximum polymerization rate from a few minutes to over 10 hours, and decreases the peak rate by a factor of 50. Adjusting pH using condenser vent gas and diluting the brine extends the time of maximum polymerization rate to about 40 hours, and decreases the maximum rate by a factor greater than 100. In either case, the rate of deposition will peak at a much reduced value at some distance from the wellbore, effectively protecting the well. In fact, the decreased rate of polymerization understates the benefit of reducing pH, because the degree to which colloidal particles bind to surfaces will also be reduced, further reducing the rate at which deposits form.

If the brine is further treated to inhibit the formation of aluminosilicate seeds, an even greater benefit would result. In order to attain the maximum benefit, each well contributing to the brine would need to be treated by injecting the silicate inhibitor downhole, below the depth at which steam starts to separate from the brine. A smaller, but still useful benefit would be realized by applying the inhibitor at the wellhead of each well, before steam is separated from the brine.

Organic acids can also be used to inhibit silica

Carbon dioxide is available at low cost and is much safer than sulfuric acid, but can only be used to treat brine after steam has been separated from the brine. If CO_2 is added to the brine before separating steam, separating steam will remove it from the brine, negating the benefit. Besides, if condenser vent gas is used, oxygen will be added to the brine, increasing corrosion in addition to the effect of lower pH.

Adding an organic acid to the brine at any point will decrease brine pH and inhibit silica and other deposits at all locations downstream of the injection point, even if steam is subsequently separated. Acetic acid is most practical. Acetic acid is a stronger acid than CO_2 and it will eliminate bicarbonate, but it is much weaker than sulfuric acid, and the treated brine will be buffered by the couple acetic acid/acetate ion.

Figure 12 illustrates the effect of adding acetic acid to a brine with containing 0.24 meq/kg bicarbonate = 12 ppm Alkalinity as $CaCO_3$. Adding 17 ppm acetic acid decreases pH to 5.5; adding 21 ppm, a 25% excess, further decreases pH only to 5.1. Figure 13 illustrates treating the same brine with sulfuric acid. Adding 13 ppm decreases pH to 5.5; adding 16 ppm, a 25% excess, decreases pH to about 4.1, risking serious corrosion.

Summary

Controlling silica deposits from high temperature geothermal brines is challenging, because the amount of silica potentially precipitating from the brine is large, and no effective silica inhibitors are available. Fortunately, the complex processes that produce silica deposits are well understood, and silica can in fact be controlled over a wide range of conditions.

Deposits of silica and aluminosilicates in high temperature surface equipment are successfully inhibited using silicate inhibitors at several fields in Central America and Turkey.

Field trials of silica inhibition using condenser vent gas and acetic acid are under way at two locations in Mexico, and I expect that these trials will bring positive results.

It is true that decreasing pH of the brine makes it more corrosive, but corrosion inhibitors effective at pH 5.5 are available and effective at low cost. In this case, the difficult problem of inhibiting silica polymerization is replaced by an easier one, inhibiting corrosion at pH 5.5.

Acknowledgment

My colleague Mark Stapleton developed and implemented the method of inhibiting silica deposits in high temperature surface equipment and injection wells using silicate inhibitors; my contribution was to explain how it works.

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Figures in the following pages

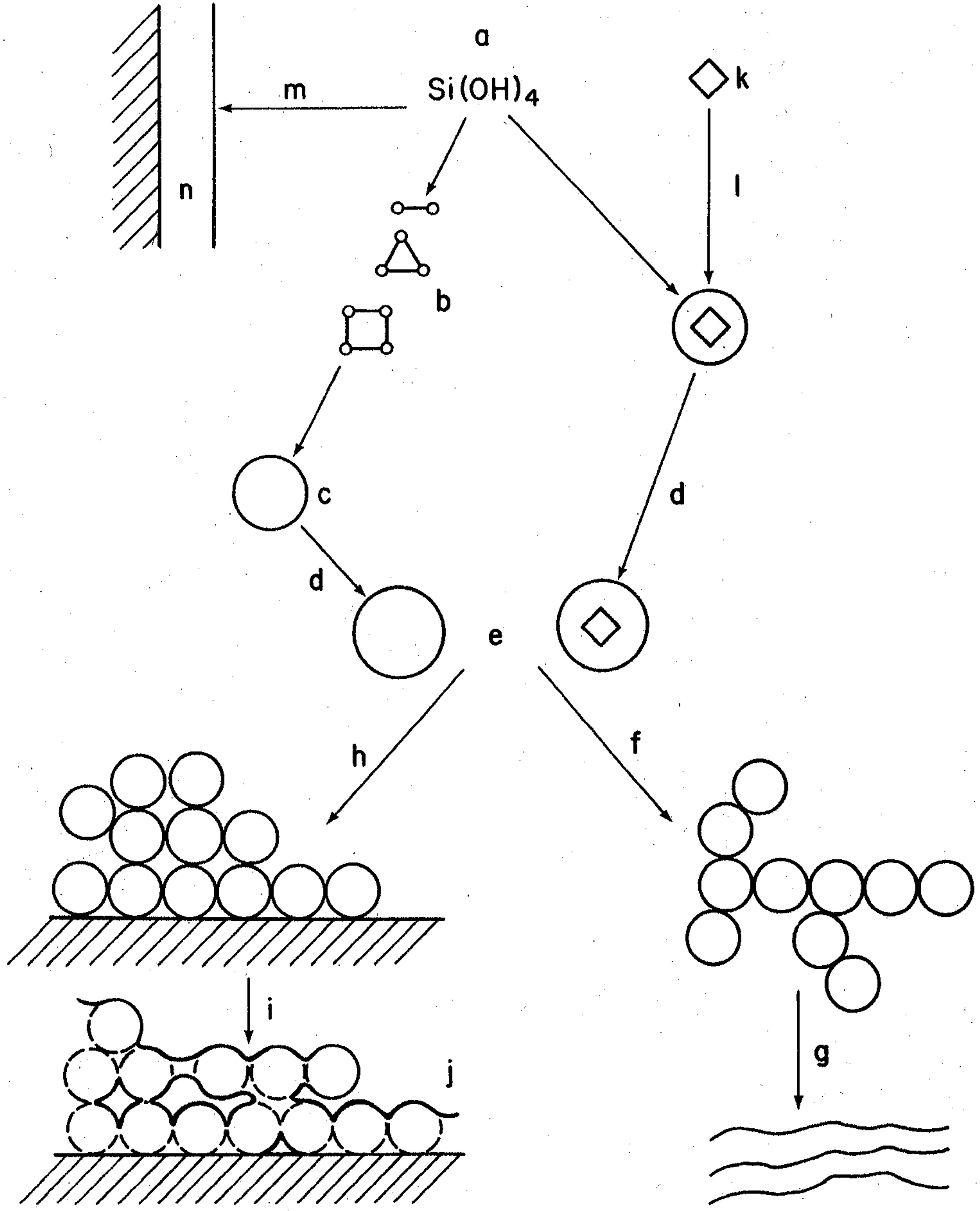

Fig. 1. Processes that form silica deposits (see text for explanations).

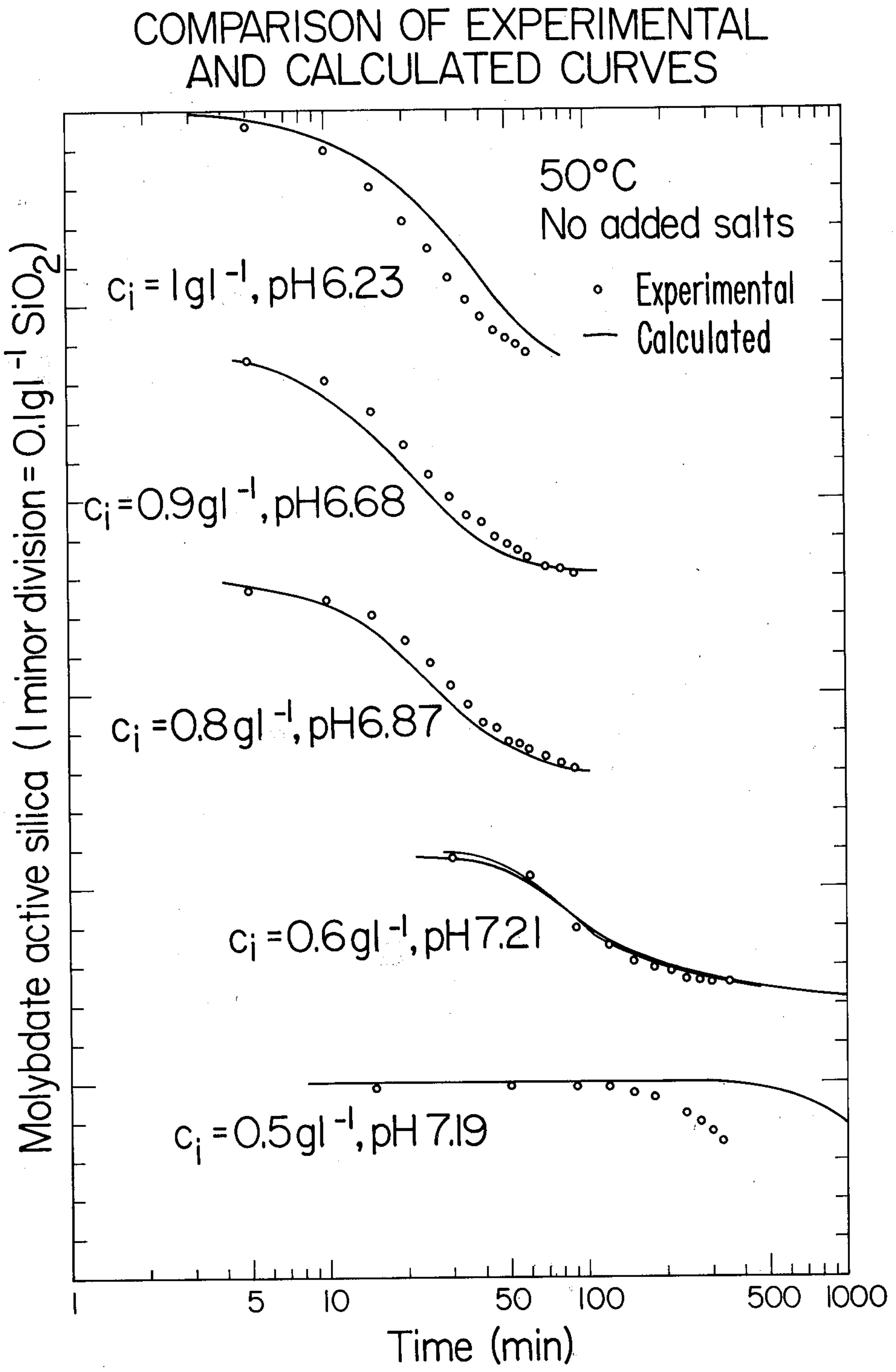

Fig. 2. Silica polymerization at 50°C. Curves calculated using program SILNUC compared with experimental data.

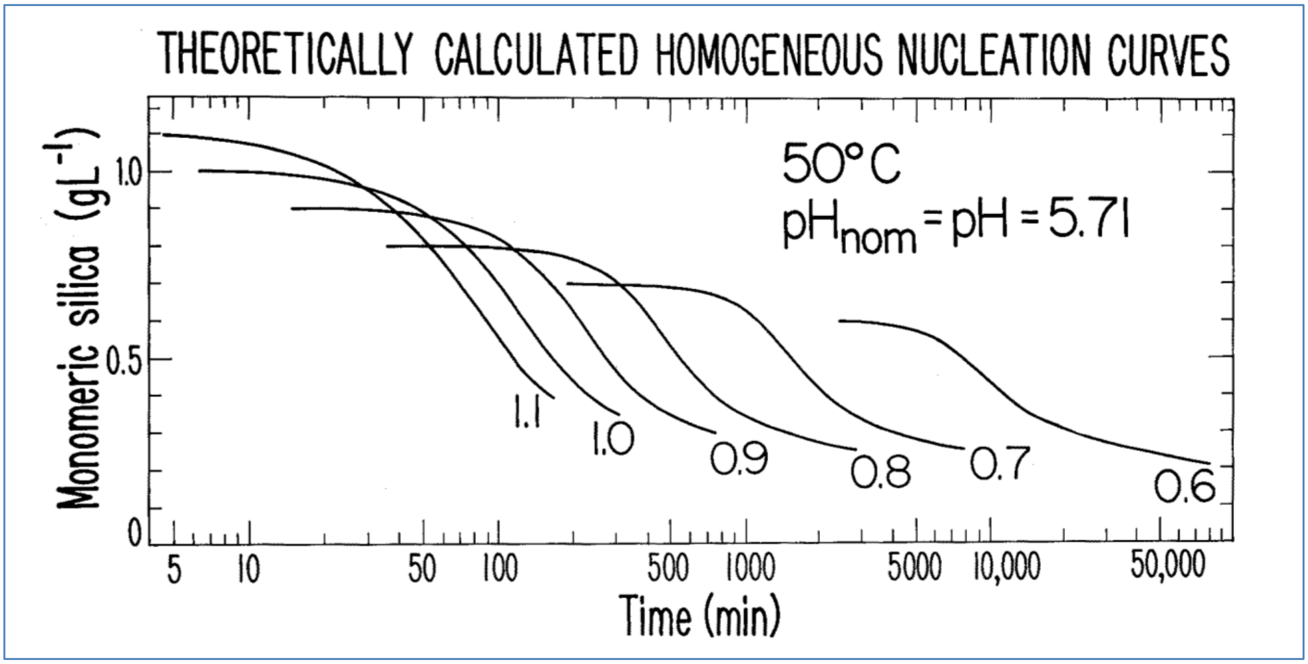

Fig. 3. Silica polymerization at 50°C. Curves for pH 5.71 calculated using program SILNUC.

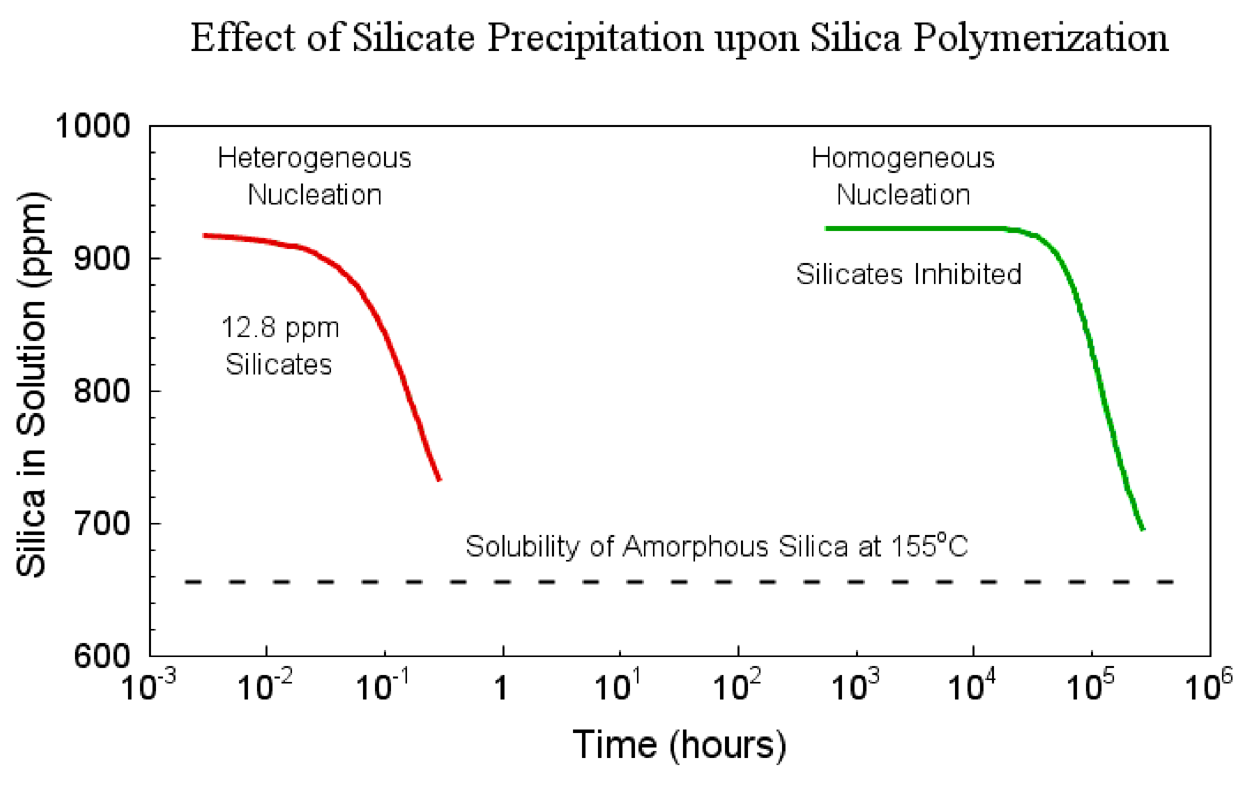

Fig. 4. Presence of aluminosilicate seeds accelerates silica polymerization at saturation ratio S = 1.4. Amount of aluminosilicate seeds calculated using program Geochemist's Workbench, curves calculated using program SILNUC.

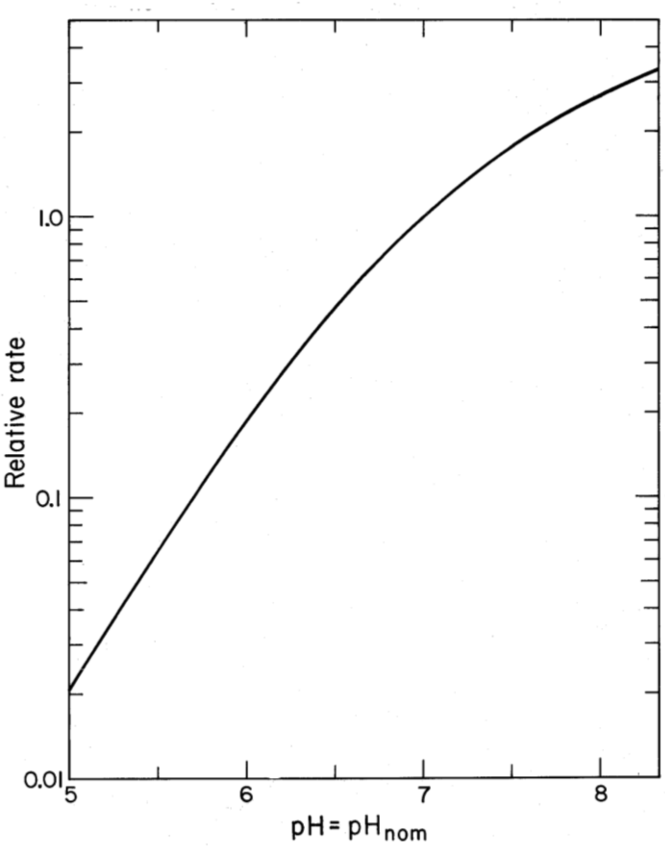

Fig. 5. Effect of pH upon the rate of molecular deposition of dissolved silica. Smoothed curve based on experimental data.

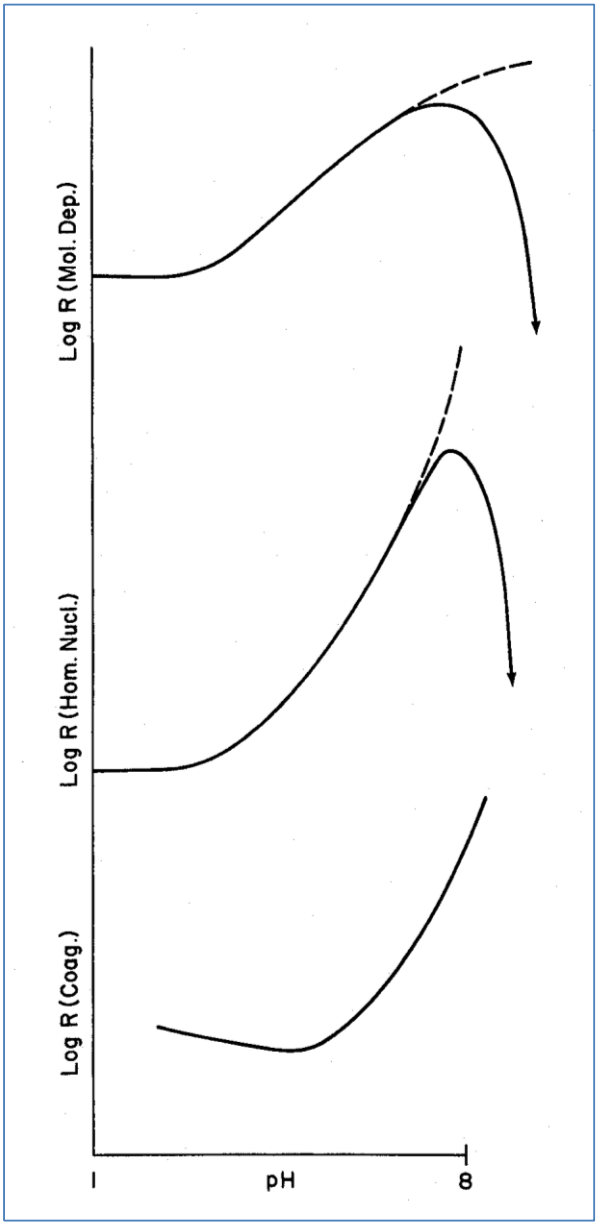

Fig. 6. Effect of pH upon the rate of molecular deposition, homogeneous nucleation and coagulation of colloidal silica, schematically illustrated.

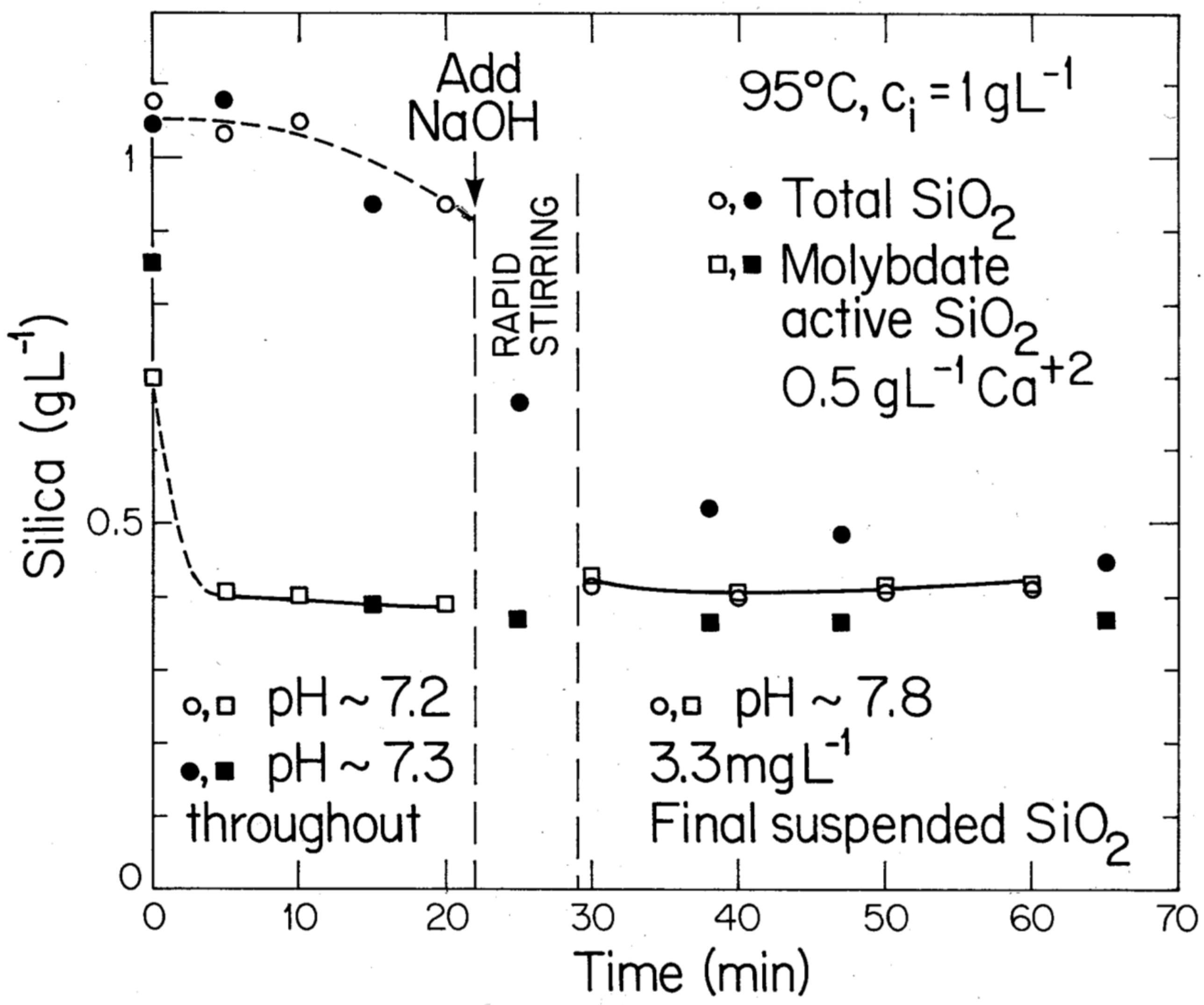

Fig. 7. Increasing pH accelerates coagulation of colloidal silica. Synthetic brine formulated to resemble flashed brine at Cerro Prieto.

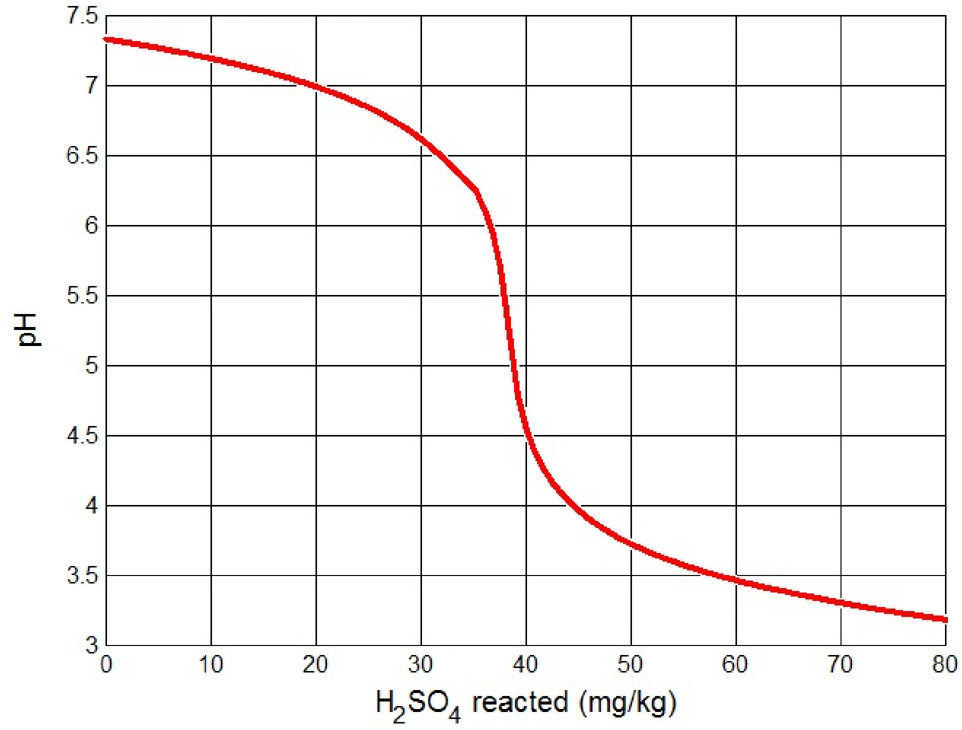

Fig. 8. Los Azufres brine titrated with sulfuric acid, calculated using program Geochemist's Workbench.

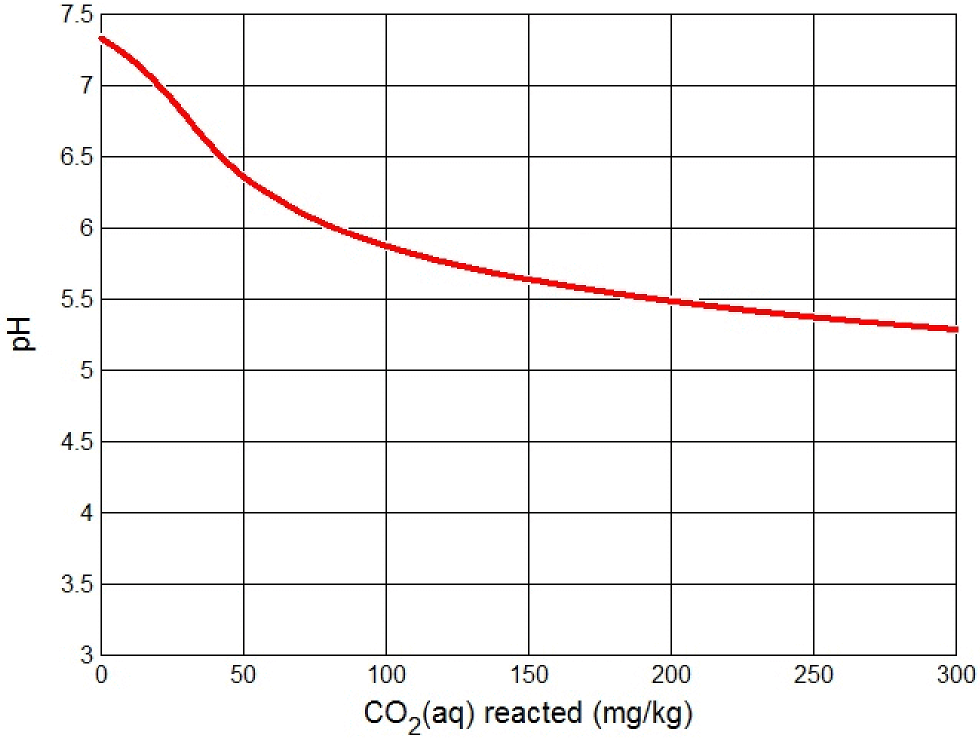

Fig. 9. Los Azufres brine titrated by adding carbon dioxide.

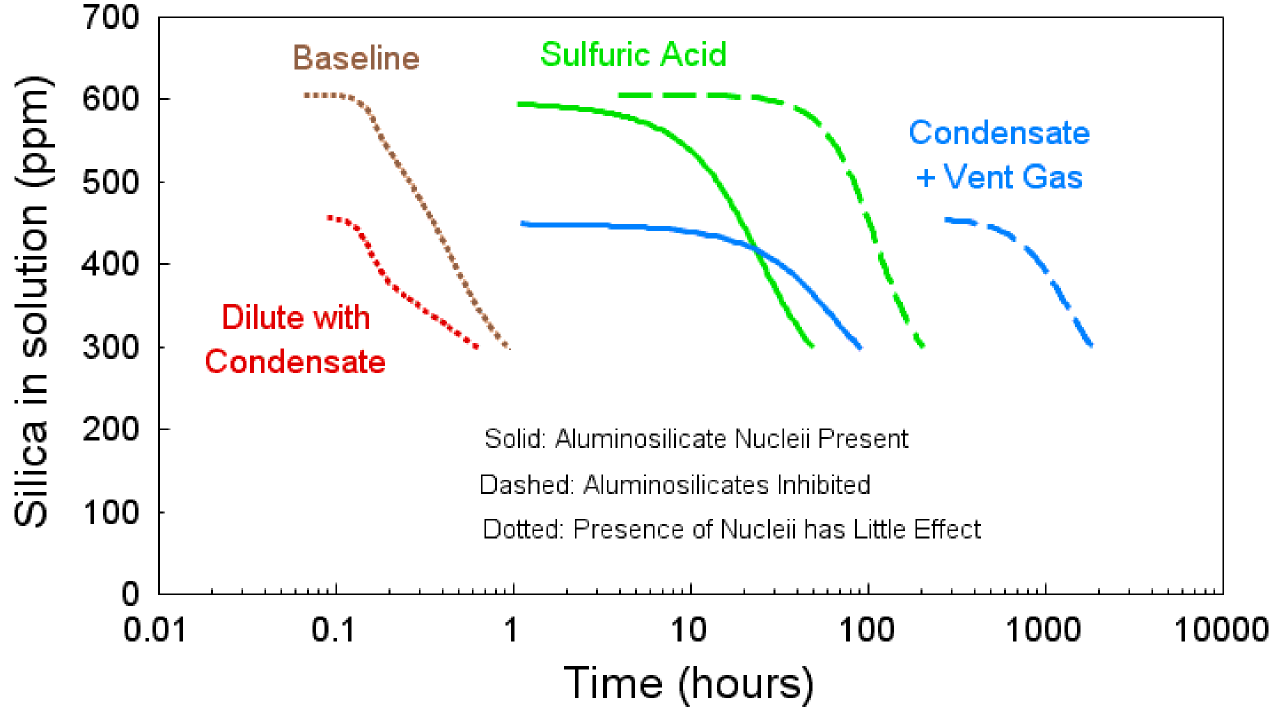

Fig. 10. Comparison of treatments for Los Azufres brine. Dissolved silica concentration vs. time calculated using program SILNUC.

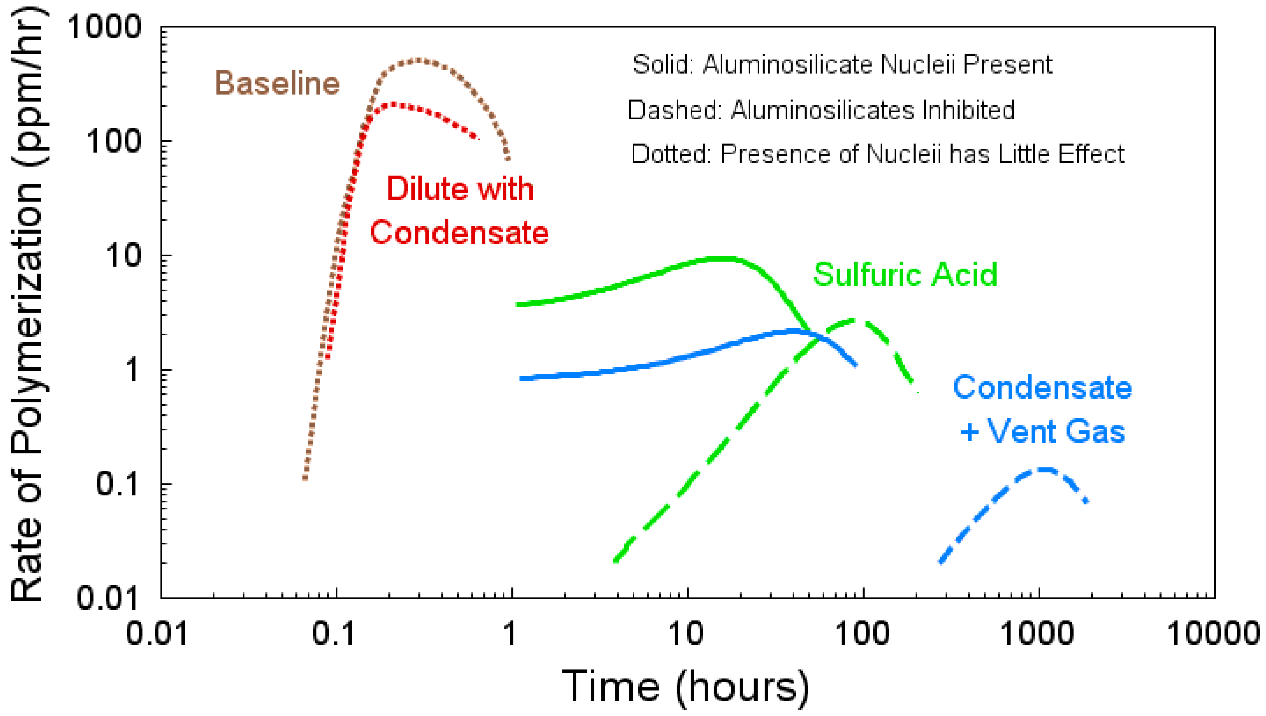

Fig. 11. Comparison of treatments for Los Azufres brine. Rate of polymerization of dissolved silica concentration (time derivatives of the curves in Fig. 10).

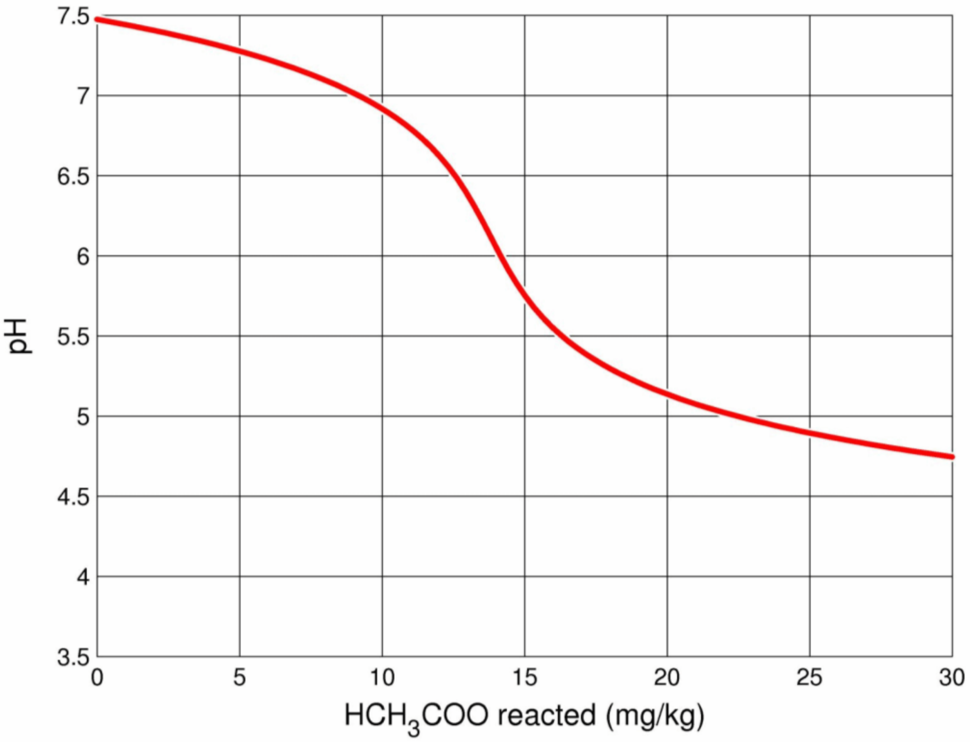

Fig. 12. Low alkalinity geothermal brine titrated using acetic acid. Calculated using program Geochemist's Workbench.

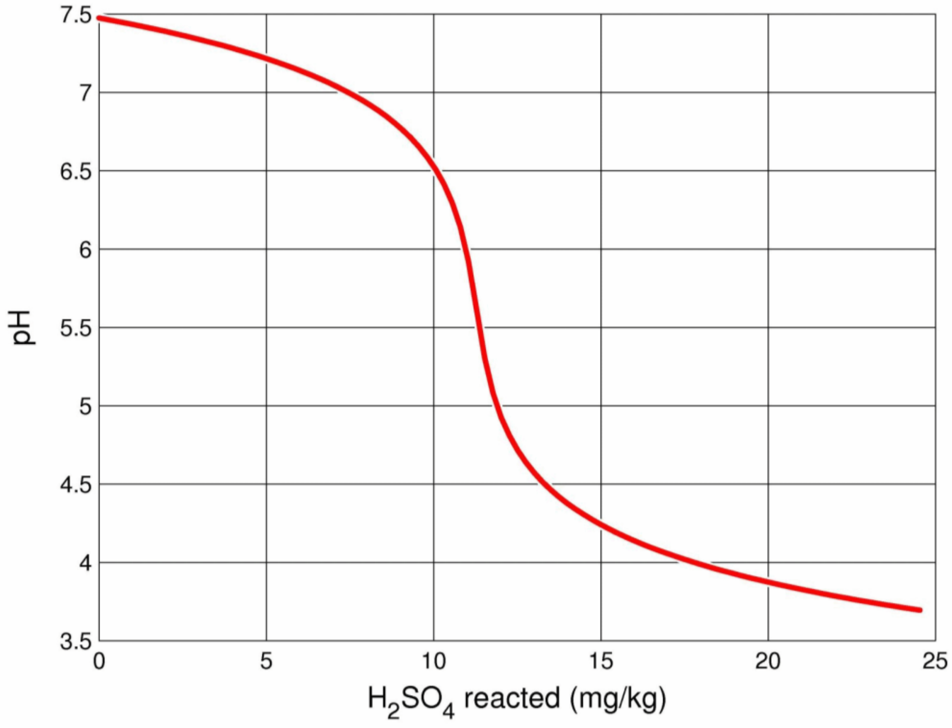

Fig. 13. Low alkalinity geothermal brine titrated using sulfuric acid.