EFFECT OF SOLID DEPOSITION ON GEOTHERMAL UTILIZATION AND METHODS OF CONTROL

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ABSTRACT

Solid deposition presents a significant constraint in the design and operation of geothermal fields and power plant equipment. To improve the efficiency of geothermal utilization and to have reliable plant operation, solid deposition must be controlled or avoided. The objective of geothermal exploitation is to maintain a continuous supply of geothermal fluid to the power plant. Scaling problems can adversely affect that, but fortunately countermeasures are available, as will be described in this report.

The intent is to show what effect solid deposition has on production wells and power plant operations and to indicate the possible location of solid depositions. Describing commonly applied methods of control is one of the objectives. Two case histories illustrating the effects of solid deposition are included, from Svartsengi geothermal power plant in Iceland and from Aluto-Langano geothermal power plant in Ethiopia, where there are actual influences of solid deposition on well flow and turbine output.

1. INTRODUCTION

Utilization of geothermal energy involves the production of steam or two-phase mixtures of steam and water from geologically heated reservoirs. Steam from production wells is used to drive turbines that power electric generators. Wells producing hot water are used either for direct utilization or used to heat low flash point fluids in a closed loop (binary) that, in turn, drives the turbines. All geothermal fluids contain dissolved minerals that put constraints on the design and operation of geothermal fields.

These minerals are deposited at different points during the operation, adversely influencing the operation of the power plant. Calcite, silica, sulphides and sulphur are common solid depositions encountered in geothermal fields. Identifying the location of solid depositions and selecting proper methods of control are crucial in order to have a successful power plant. Thus, the discussion is mainly concentrated on the effects of solid depositions in geothermal utilization and to describe methods found to be effective in controlling deposition. Cost estimates are made for three control methods to combat calcite scaling in geothermal wells.

2. THEORETICAL BACKGROUND ON SOLID DEPOSITIONS

It is generally accepted, based on isotopic evidence, that geothermal water is largely meteoric in origin. As the meteoric water seeps into the ground it reacts with the hot host rock at depth, altering the characteristics of the geothermal water. The rock minerals are dissolved into the geothermal water as a result of water-rock interactions leading to equilibrium. Once the geothermal water is heated up it starts to ascend, rich in dissolved minerals, from the hotter deep zone to the surface. On the way up the geothermal fluid starts to cool while passing through rocks and fractures by conductive heat transfer and may initiate boiling near the surface due to loss of hydrostatic head.

When dissolved solids become solid deposits in geothermal fields and equipment, they affect the exploitation of the geothermal resources. Solid deposition is a major problem in exploiting geothermal resources. As silica, calcite and sulphides are common mineral depositions in geothermal systems, i.e. in reservoirs, liners, production casing and surface equipment, it is necessary to know their mechanisms of formation.

2.1 Calcite (Calcium carbonate)

Calcite is a crystalline form of calcium carbonate ($CaCO_3$) and is an abundant secondary mineral in geothermal fields worldwide. The deposition of calcium carbonate from a geothermal fluid is a major problem in a number of geothermal fields, mainly due to plugging of geothermal wells.

The most common polymorphs of calcium carbonate minerals are calcite, aragonite and vaterite. Vaterite is the first mineral to form in a supersaturated calcium carbonate solution (Dalas and Koutsoukos, 1989), but is apparently unstable, recrystallizing to form the more stable calcite. Hence, the most frequently occurring calcium carbonate deposition minerals are calcite and aragonite with the former dominating (Arnórsson 1989). As calcite is a common carbonate deposition that adversely affects the exploitation of geothermal systems, combating measures are concentrated on it.

Upon boiling, dissolved gases present in the liquid phase are strongly partitioned into the vapour phase. At the initial flashing stages, the concentration of carbonate ions in the water increases rapidly. Therefore, if by boiling a small amount of steam is lost, a large amount of CO_2 escapes from the liquid phase to the steam phase, causing an increase in pH and carbonate ion concentrations, so calcite is rapidly precipitated at the beginning of flashing. This condition favours the deposition of calcium carbonate in a well and will, in time, obstruct the geothermal fluid flow.

Several different methods have been applied to control the formation of carbonate deposition in geothermal fields. In low-enthalpy systems it can sometimes be controlled by limiting the extent of degassing and resultant pH changes that bring about super-saturation of carbonate minerals (Kristmannsdóttir, 1989; Hurtado et al., 1989). But in high-enthalpy systems, where boiling cannot be avoided, a direct removal of solid deposits by reaming with a drilling rig from the zone of deposition is found effective if the deposition has not plugged the aquifers or the slotted liner portion of the well. Tests and experience show that chemical inhibitors can be applied to prevent the development of calcite scales in the wellbore, which can eliminate or minimize any reaming activities.

One possibility is to vary the depth of the flashing zone by adjusting the wellhead pressure to reduce the frequency of cleaning the well, and to insure that the deposition is not occurring down in the open hole or slotted liner. Once it becomes known at what depth calcite plugs develop, future wells should have a production casing deep enough to insure that the plugs form inside the production casing and not in the slotted liner where it cannot be completely removed.

From the solubility curve, it is possible to conclude that calcite becomes more soluble as temperature decreases; this is sometimes called reverse solubility (Figure 1). This means that at constant concentrations of carbon dioxide and other constituents in water, calcite cannot be deposited from solution simply by cooling. This also explains why calcite forms a plug of say 100-200 m length in wells after which the wells and pipes are free of calcite; it is due to cooling of the water by further flashing.

The change in water chemistry, due to CO_2 degassing, which occurs when steam boils from high-temperature water, can be summarized by the following equations; water that was originally close to calcite saturation rapidly becomes supersaturated following boiling, due to loss of carbon dioxide, and rising pH:
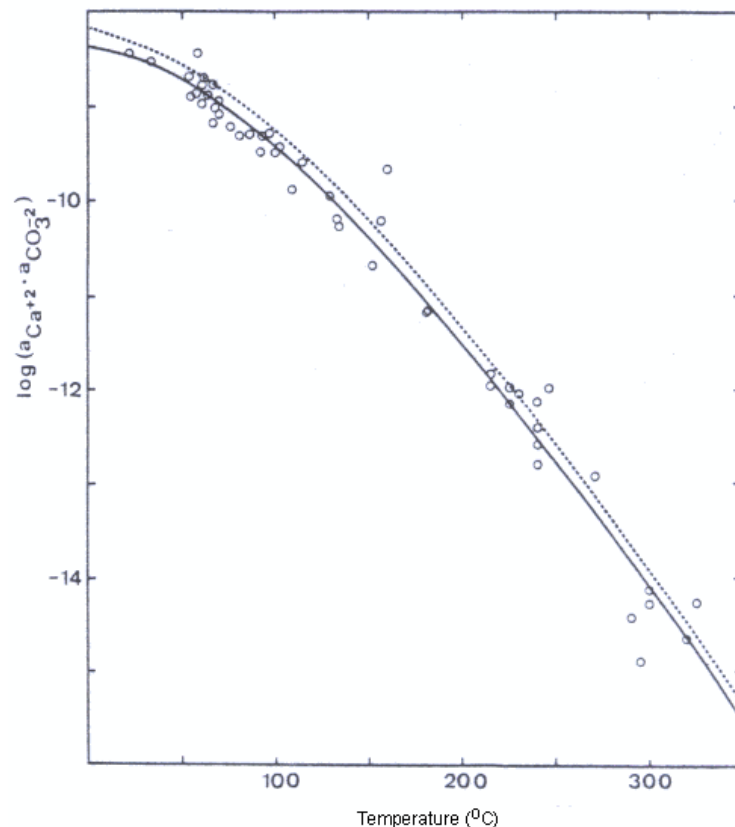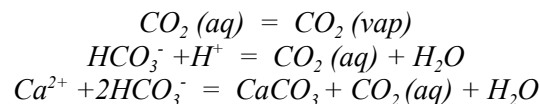

FIGURE 1: Data showing the solubility product for calcite and aragonite in selected Icelandic geothermal wells (points), and theoretical solubility curves for calcite (solid) and aragonite (broken) (Arnórsson, 1989)

$$CO_2 \ (aq) \ = \ CO_2 \ (vap)$$
$$HCO_3^- + H^+ \ = \ CO_2 \ (aq) + H_2O$$
$$Ca^{2+} + 2HCO_3^- \ = \ CaCO_3 + CO_2 \ (aq) + H_2O$$

2.2 Silica deposition

In hydrothermal areas silica deposition occurs at different depths in various forms. These include quartz, chalcedony, cristobalite, and amorphous silica. Of these, quartz is the most stable form of silica, and has the lowest solubility. Deep geothermal water is usually in equilibrium with quartz at the prevailing reservoir temperature (silica geothermometer). Deposition of quartz in wellbores and surface equipment is not a common problem due to the slow rate of formation. Amorphous silica is, however, associated with changes in temperature of the geothermal water. This is when steaming extraction and fluid cooling takes place. Deposition of amorphous silica from supersaturated water is, thus, the most troublesome scale when precipitated in surface equipment such as pipelines, separators, turbine nozzles, heat exchangers and re-injection wells. This problem is more troublesome in high-enthalpy geothermal fields as steam separation is taking place there and because of higher initial silica concentrations. In most fields, the steam separator is operated below the amorphous silica line (under- saturated) so as to avoid silica scaling in the pipelines and separator. Operation above the amorphous silica line will cause scaling but at very different rates, depending on the water composition, retention time and other factors. (Thórhallsson, pers. communication).
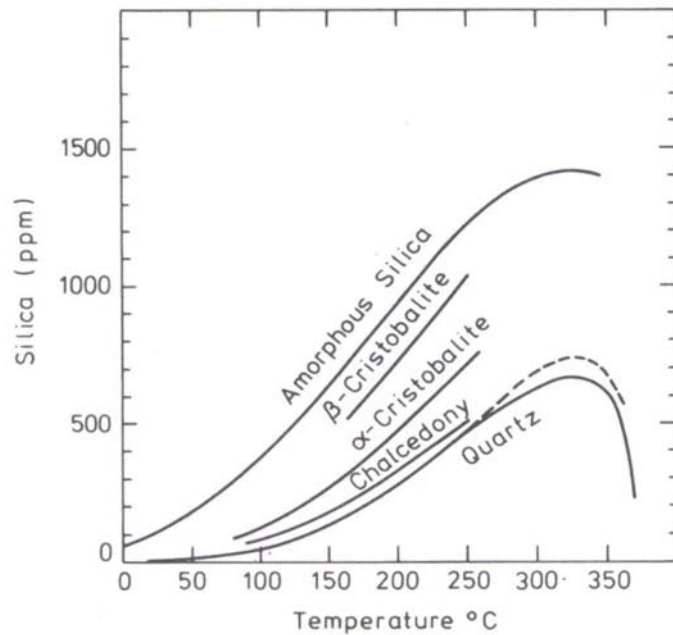
FIGURE 2:   Solubility of various forms of silica in water
at saturated water vapour pressures
(Fournier and Truesdell, 1973)

According to Mercado et al. (1989) and Hurtado et al. (1989), silica scale deposition from geothermal fluids can occur over periods of minutes or hours after super-saturation occurs. This is why silica deposition has been found throughout the fluid-handling equipment of several geothermal facilities. Therefore, unlike calcite that appears to precipitate soon after it reaches super-saturation during flashing, silica deposition can be kinetically controlled and delayed by minutes or hours after it reaches saturation.

Silica scale deposition is typically inert to most chemicals and, once deposited, is also rather resistant to mechanical removal. Hence, most treatment methods focus on prevention of silica deposition or on controlling polymer formation. Efforts to prevent silica deposition on surface equipment include restricting steam separation to temperatures at which silica super-saturation, with respect to amorphous silica, is minimized (Gallup, 1989, Gudmundsson and Einarsson, 1989).

The solubility of various silica phases in water at the vapour pressure of the solution is shown by (Fournier and Truesdell, 1973), as seen in Figure 2 and in the following equations:

Amorphous silica $t(°C) = 731/(4.52 - \log SiO_2) - 273.15$

Beta - cristobalite $t(°C) = 781/(4.51 - \log SiO_2) - 273.15$

Alpha - cristobalite $t(°C) = 1000/(4.78 - \log SiO_2) - 273.15$

Chalcedony $t(°C) = 1032/(4.69 - \log SiO_2) - 273.15$

Quartz (at 100°C) $t(°C) = 1522/(5.75 - \log SiO_2) - 273.15$

Amorphous silica precipitates at low temperatures much faster than other silica forms. Hence, amorphous silica is the dominant deposition in surface equipment as well as where wastewater disposal is discharged.

2.3 Sulphide

Sulphide scaling deposition is a problem source in the geothermal industry and also in the petroleum industry. In geothermal systems, sulphide scaling can occur in every type of geothermal fluid, whether with low, intermediate, or high enthalpy. The mechanism responsible for the formation of sulphide deposition is different in low- and high-enthalpy geothermal fluids.

Criaud and Foulliac (1989) noted that low-enthalpy fields containing high concentrations of dissolved solids could cause mild corrosion of steel production casings, which liberates iron. Therefore, the migrated iron, due to corrosion, reacts rapidly with sulphide- rich geothermal fluids that produce a higher

deposition rate of metal sulphide scale. In a high-enthalpy geothermal system, sulphide mineral deposition is due to sulphide forming metals such as iron and some other base metals (Fe, Zn, Pb, etc). When sulphide forms on nickel and chromium as secondary products, there is a probability of troublesome scale occurring, causing localized corrosion or sulphide stress corrosion cracking. Sulphide depositions in high-enthalpy resources can be severe in water with high TDS content since it combines with silica scaling. In high-enthalpy systems, metal sulphides and oxides are frequently deposited directly from the geothermal fluids upon a change of phase or pH.

The rate of metal sulphides / oxide deposition in most of high-enthalpy systems is controlled by the degree of pH change accompanying the fluid flashing process and by the (usual low) concentration of metal ions (Karabelas et al., 1989). Therefore small concentrations of metal ions in geothermal fluids limit the rate of deposition of metal sulphides in high-enthalpy fields but, under some severe conditions with high salinity, such as at Salton Sea field, or where large quantities of acidic magmatic gases are injected into the reservoir fluids (e.g. the Krafla field), metal ion concentrations can be high resulting in high rates of sulphide scaling (Kristmannsdóttir, 1989).

2.4 Sulphur

Sulphur forms a solid deposition in surface equipment in a similar way as formed around fumaroles. Sulphur deposits from geothermal fluids rich in H_2S gases, and causes operational troubles in power units, especially in condensers and cooling towers. Sulphur exchanges between sulphate and hydrogen sulphide depending on its concentration, temperature and pH. The reaction is rapid under acidic conditions, but is very slow in alkaline environments (Robinson, 1973). Elemental sulphur (S) is deposited in direct contact condensers, where gases come into contact with oxygen (Kristmannsdóttir et al., 2000). Sulphur can also plug the water distribution nozzles on top of cooling towers.

2.5 Methods of detection of solid deposition

The decline of well output or a drop in wellhead pressure is a sign to run down-hole logs to identify the cause. Different methods have been adopted to detect the location and thickness of solid deposition in a wellbore.

Calliper logging tools and Go-devil tools are commonly used to determine the location and thickness of deposition. Calliper logging tools are equipped with an electric motor to open the arms once the tool has been lowered into the hole. The arms centralize the tool in the well, and the position of the spring-loaded arms is sensed through variable resistance. This technique requires quenching the well with cold water because of the temperature limitations of electrical cables and tools. Go-devil is the second technique used to survey high-temperature wells. It is unaffected by temperature. Also, wire baskets of different diameters are used to log deposits in wells. In Figure 3 below, a sketch of the tools is shown.

The type and chemical composition of scales can be analysed by:

- Microscopy;
- X- ray diffraction (XRD);
- X-ray fluorescence (XRF);
- Scanning electron microscopy (SEM);
- Microprobe;
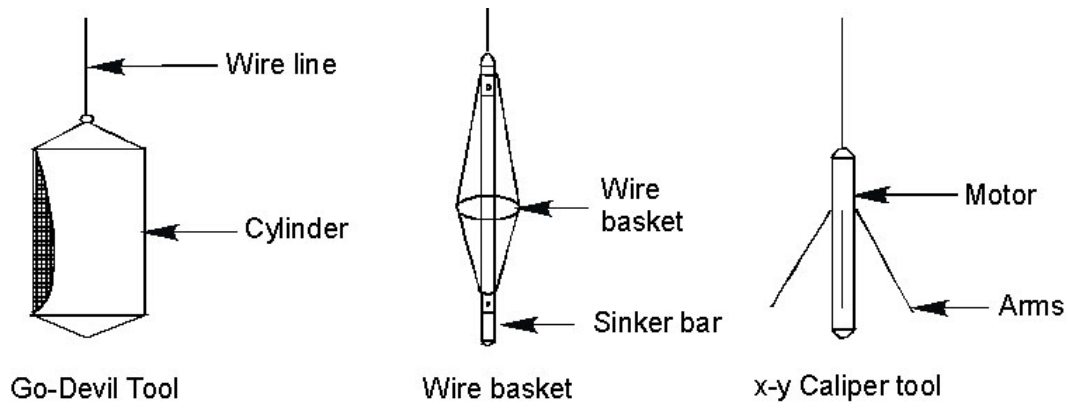- Wet chemical- analysis.

FIGURE 3:   Sketch of logging tools for detecting scaling in wells

3. INFLUENCE OF SOLID DEPOSITION ON POWER PLANT OPERATIONS

Geothermal energy is used both for electric generation and direct utilization. In both cases the energy source is the geothermal reservoir that feeds the wellbore with a variety of dissolved fluid compositions. Liquid-dominated geothermal reservoirs are hydrothermal reservoirs that contain circulating liquids which transport the thermal energy of the hot host rock with dissolved minerals near to the surface by natural fluid circulation. The fluid produced from such reservoirs may form scales. A sketch showing possible locations of solid deposition is shown in Figure 4.
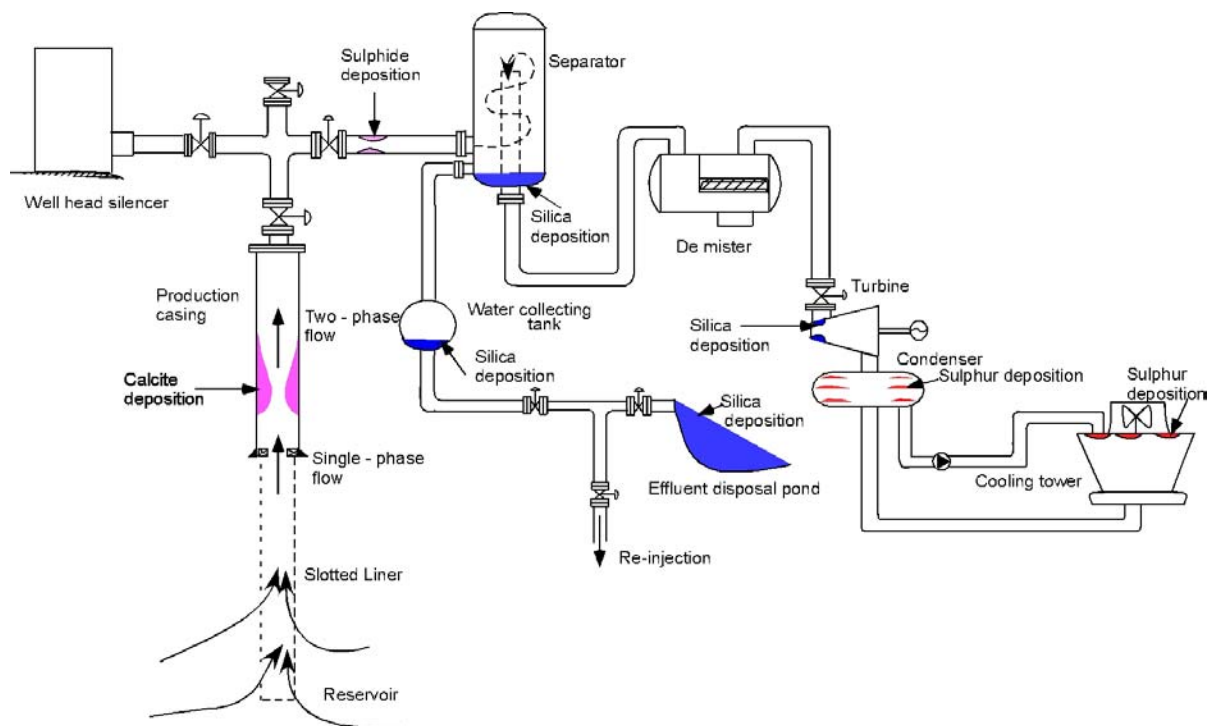

FIGURE 4:   Flow diagram showing common locations of solid deposition

3.1 Deposition of solids in a wellbore and decline of well output

The production rate of a geothermal well depends on the size and number of fractures intercepted by the well, on the hole and casing size, on the depth of the well, and on the reservoir temperature and pressure. Normally wells have a very stable output. Bearing this in mind, when a drastic decline in well output is observed during production of the wells, it must be explained. The main objective of the steam field operator is to maintain a continuous supply of steam or hot water to the power plant.

Possible causes for well output decline are

- When the reservoir pressure decreases due to the effect of exploitation;
- When solid deposition plugs the flow line inside or outside the wellbore;
- Increased colder water recharge that causes a decline of temperature and enthalpy in the fluid;
- A combination of some of the above;
- Casing damage.

One effect of pressure drawdown is increased recharge of water into the reservoir. If colder water invades the system, the reservoir temperature or enthalpy of the fluid can drop, causing a decline of well output (Axelsson and Gunnlaugsson, 2000).

Obstruction from solid deposition in the flow area in a well is another likely cause of well decline. A geothermal fluid is harnessed inside the reservoir and comes from depth with solutes. The geothermal fluid is let into the power units through geothermal wells and pipelines. Depending on the temperature and pressure of the fluid, it can initiate boiling in the reservoirs or liners and wellbore, causing precipitation of solids. For instance, with calcite precipitation the formation mechanism is due to gases being liberated from the liquid phase and degassed into the steam phase. This causes super-saturation and calcite starts to precipitate inside the wellbore which, in time, results in fluid obstruction. This deposition causes a reduction of the flow area and, thus, a decline in well output, i.e. wellhead pressure drop. So control of solid deposition is very crucial in order to maintain stable well output.

Separators are pressure vessels where a two-phase fluid from the production well is separated, i.e. steam from water. Water is separated from the steam by a centrifugal action and falls to the bottom due to its density. Steam is let into the power generation unit, whereas the brine flows to the water-collecting tank. In the separator, silica is deposited at the bottom where water is in contact with the body.

3.2 Case histories from two geothermal fields

3.2.1 Aluto-Langano geothermal field

Aluto-Langano is an active high temperature geothermal field inside the main Ethiopian rift. In this field, a total of eight wells (with a depth of 1320-2500 m below ground level) have been drilled, of which four are potentially productive and one is a re-injection well. The field presents two temperature ranges. Wells in the up-flow zone have a temperature ranging from 300-350°C, and wells in the zone of lateral outflows have temperatures ranging from 150 to 270°C. The geothermal wells produce two-phase flow with a mass flow rate of 10.4-25.6 kg/s (Endeshaw, 1988; Gianelli and Teklemariam, 1993).

Power plant description: Aluto-Langano geothermal power plant was constructed by Ormat under a turnkey contract of Genzl (EPC) and has been operational since May 1998. It is the first geothermal power plant in Ethiopia, and also the first combined steam and binary turbine unit in Africa. The power plant is designed to generate a net power output of 7.28 MWe (8.52 MW$_e$ gross) with two units. These are: (i) A geothermal combined cycle unit (GCCU), a steam turbine integrated with a binary turbine that generates 3.9 MWe; (ii) An Ormat energy converter (OEC) with an output of 4.6 MWe (Ormat, 2001).

There are four production wells from which steam and brine are supplied to the power plant. The wells are LA-3, LA-4, LA-6 and LA-8 and one re-injection well, LA-7. Wells LA-3 and LA-6 are high-enthalpy wells supplying steam to the first unit (GCCU) and brine from a flash tank to heat the binary fluid in a pre-heater. The second unit, the Ormat energy converter, uses a binary fluid (isopentane) as a working fluid that exchanges energy with the geothermal fluid. Wells LA-4 and LA-8 are low-pressure wells supplying steam to the evaporator for vaporizing the binary fluid and brines to the flash tank. Each well has its own steam separator near the wellhead.

Decline of well output: Recently, the well output of the high-enthalpy wells LA-3 and LA-6 has declined (Table 1). The possible explanations are

- Decline of reservoir capacity (pressure);
- Plugging due to solid deposition in the wells;
- Casing damage.

TABLE 1: Wellhead pressure drop of Aluto-Langano wells after one year' production

Description	LA-3	LA-4	LA-6	LA-8
Initial pressure (bar)	12.5	6.4	13.5	8.4
Pressure at present (bar)	5.0	3.2	6.2	3.0

There are some indications of solid deposition observed in wellhead equipment and other ground facilities. Scale samples have been taken from the surface equipment of LA-6 and LA-3 and on the ground where wastewater is discharged on the surface. Specifically, at the bottom of the wellhead separator for LA-6, a scale deposit was found. Additionally, the brine line valves are hard to open and close, which could be due to scaling. From the chemical analysis of the geothermal fluid, the scale potential can be assessed by WATCH program (Arnórsson et al., 1983; Bjarnason, 1994). The results show a great possibility of calcite scaling. This and others problems are presently causing operational difficulties at the power plant.

Therefore, it is possible to conclude that

- A possible case for decline in well output at Aluto-Langano is due to solid deposition, possibly calcite. Running baskets of different diameters into the well is required to confirm this.
- The other case is pressure drawdown and decline in enthalpy/temperature. Monitoring of the reservoir (down-hole pressure and temperature logs) is required to confirm this.

3.2.2 Svartsengi geothermal field

The power plant at Svartsengi was erected in several stages to provide heat and electricity to communities on the Reykjanes peninsula. The first power plant operation started in 1976 and the second power plant went on-line in late 1980. The design approaches were different due to the combined requirements of heat and electricity. The later designs were made to maximize electrical output.

Scale deposition has been experienced in the wells and turbines. This problem has been successfully managed and is not causing operational difficulties at the power plant. Examples of the effect of calcite scaling in the wells can be seen in the steam production rate vs. time curve for wells 8 and 11 (Figures 5 and 6). As shown in the curves, well operation is interrupted for cleaning time at a few years interval. This does not affect the power plant, as there are ample steam supplies.

Table 2 shows dates of cleaning (reaming) of the wells, production and amount of precipitation removed. The calculations in Table 2 assume that 2000 kg of calcium carbonate precipitation being removed each time the well is cleaned. The graphs in Figure 5 demonstrate how solid deposition influences well output. It also shows that after cleaning with a drill rig, the well output fully recovers.
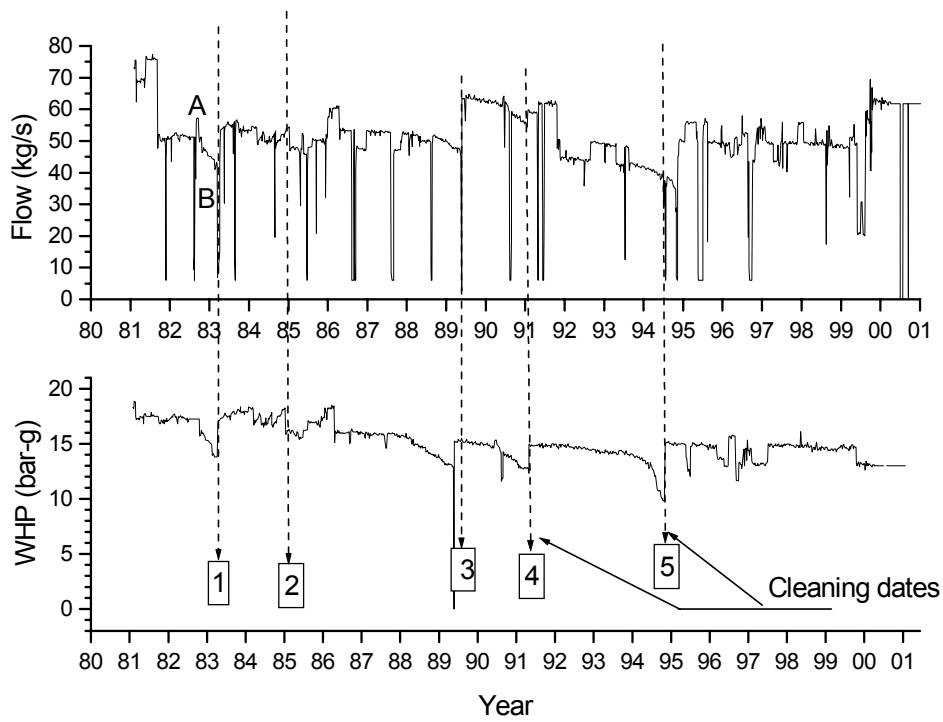
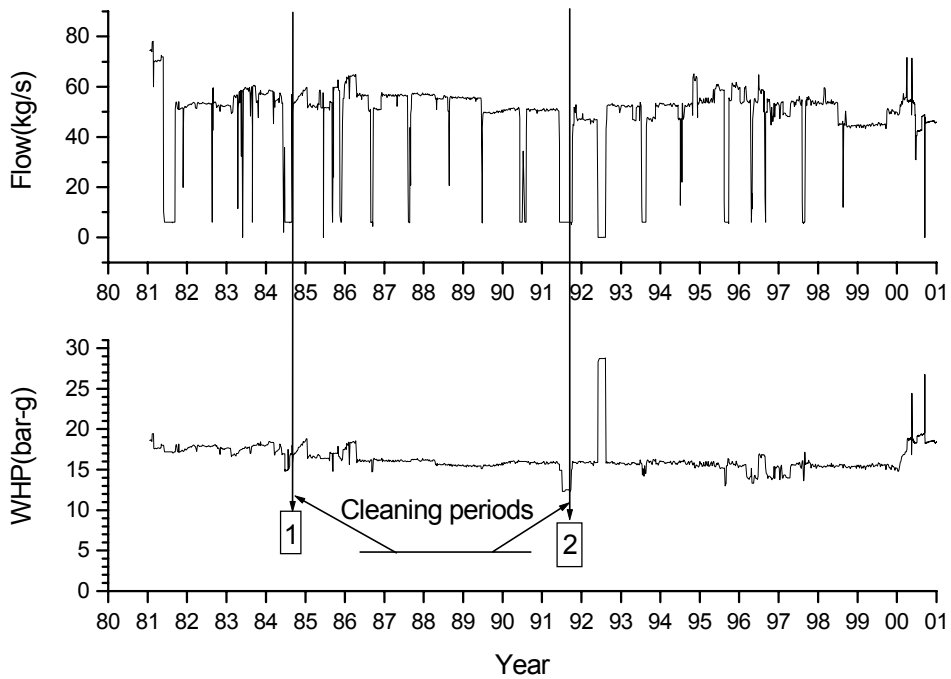FIGURE 5: Flow and wellhead pressure for well 8 in Svartsengi

FIGURE 6: Flow and wellhead pressure for well 11 in Svartsengi

TABLE 2:   Production and cleaning of well 8 in Svartsengi
with the amount of deposition from the water

Date of cleaning	Days of production	Well production (tons)	Amount of precipitation (mg/kg)	Rate of deposition (mg/s)
7.3.1983	750	3,618,429	0.55	30.8
2.1.1985	660	2,833,177	0.71	35.1
3.4.1989	1551	6,451,823	0.31	14.9
2.1.1991	634	3,172,741	0.63	36.5
6.6.1994	1249	5,040,870	0.39	18.5
28.6.1999	1847	7,281,428	0.27	12.5

Well 11 was cleaned only twice during 20 years of service, probably due to its high enthalpy (Figure 6). Comparing the two production wells, well 8 is cleaned more often than well 11. This shows that the rate of solid deposition depends highly on the type of fluid chemistry and well enthalpy.

3.3   Deposition of solids on turbines and power plant equipment

Along a long pipeline, the geothermal fluid is transported to a power plant where the final energy conversion takes place. Utilization of a geothermal resource involves extracting mass and heat from the fluid to drive a turbine which, in turn, drives a generator. It is through nozzles that fluid enthalpy is converted to kinetic energy that drives the turbine. The mechanical energy developed by the turbine can be converted into electricity by direct coupling to an electric generator.

Turbine output is measured by the amount of enthalpy change of the fluid. In liquid-dominated high-temperature geothermal fields scale deposition is a problem for steam turbines. A deposition of silica scaling takes place mainly in turbine inlet nozzles and not on the rotating turbine blades. Only a little deposition can be found on the first stage of turbine blades. This results in a loss of power output due to restrictions of the steam flow.

Power output of the turbine is a direct function of mass flow rate and change in enthalpy. The power output is expressed by

$$P = m (h_i - h_o) \, \eta_t \, \eta_g$$

where P = Power generated (kW);
       m = Mass flow rate (kg/s);
       h_i = Enthalpy at turbine inlet pressure (kJ/kg);
       h_o = Enthalpy at turbine outlet pressure (kJ/kg);
       η_t and η_g = Turbine and generator efficiencies.

Silica scaling narrows the throat of turbine nozzles and consequently decreases the amount of steam flow into the turbine. Thus, the power output, which is highly dependent on the steam mass flow, declines as a restricted mass flow rate passes through the turbine blades. To exploit geothermal fluid with maximum efficiency, the quality and purity of the steam must be maintained.

Condensers can suffer from sulphur deposition on the water distribution plates. This results in a loss of vacuum and power. So, for a condensing turbine, a clean condenser is crucial for optimum power output. As condensers are part of the power making equipment, they have to be clean all the time for efficient cooling. Similarly, sulphur deposits can plug the water distribution nozzles on top of a cooling tower, adversely affecting water distribution over the tower fills and, hence, the cooling tower performance.

Silica scale is substantially deposited in waste fluid pipes. Build-up of silica deposits in drains and the pipe carrying waste geothermal water from different lines has been a particular problem.

4. METHODS OF CONTROLLING SOLID DEPOSITION

Naturally pure geothermal fluids are not available. They contain impurities that can be deposited in a reservoir, in wellbore and surface equipment. Hence, controlling the deposits is crucial to maintain a continuous supply of steam or hot water from the reservoir to the power plant. As the depositions are not uniform, identifying the type and location of depositions is essential prior to applying the controlling methods. Possible locations of deposition could be:

- •   In the production zone or reservoir;
- •   In the production casing or slotted liner;
- •   In surface pipes and equipment;
- •   In turbines and heat exchangers;
- •   In re-injection system.

4.1 Mechanical methods

Mechanical methods have been effective in removing geothermal scales and are among the preferred methods in removing depositions that have plugged the production casing. The most widely used and accepted method for hard solid deposit removal has been the use of a workover-drilling rig utilizing a conventional drill bit and scraper. This method does not, however, fully address the impediment of solid deposition in the well screen or inside the reservoir - a drill bit and a scraper simply do not remove what is out of reach. Another problem encountered by using this method is the probability of damaging the slotted liner during the cleaning operation (Molina, 1995).

Two methods have been adopted in the removal of solid deposits with a drill rig. The first is removing the deposits with the well quenched or "killed" with a continuous coldwater injection into the well. This cools down the well, putting great thermal stresses on the casing, and heating up takes a few days or weeks to recover production after removal of clean out. So this method has its drawbacks. The second and more efficient method is removing the scale from wells during discharge. This method is performed with geothermal fluid continuously flowing from the well. Figure 7 illustrates how this can be done, and what equipment is needed.
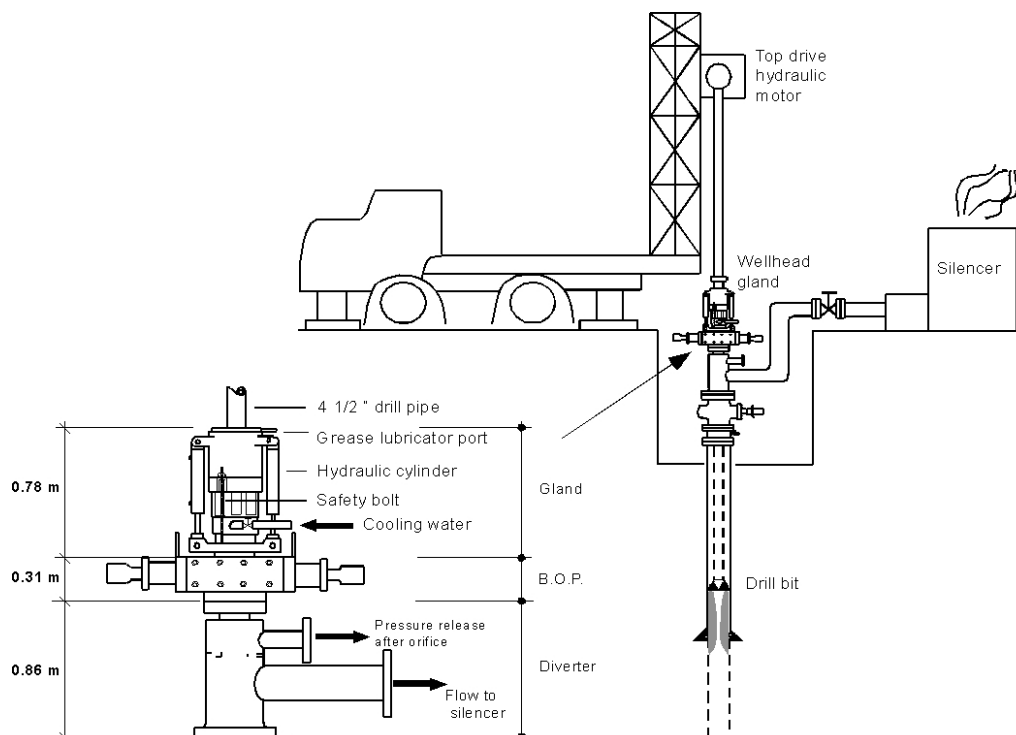

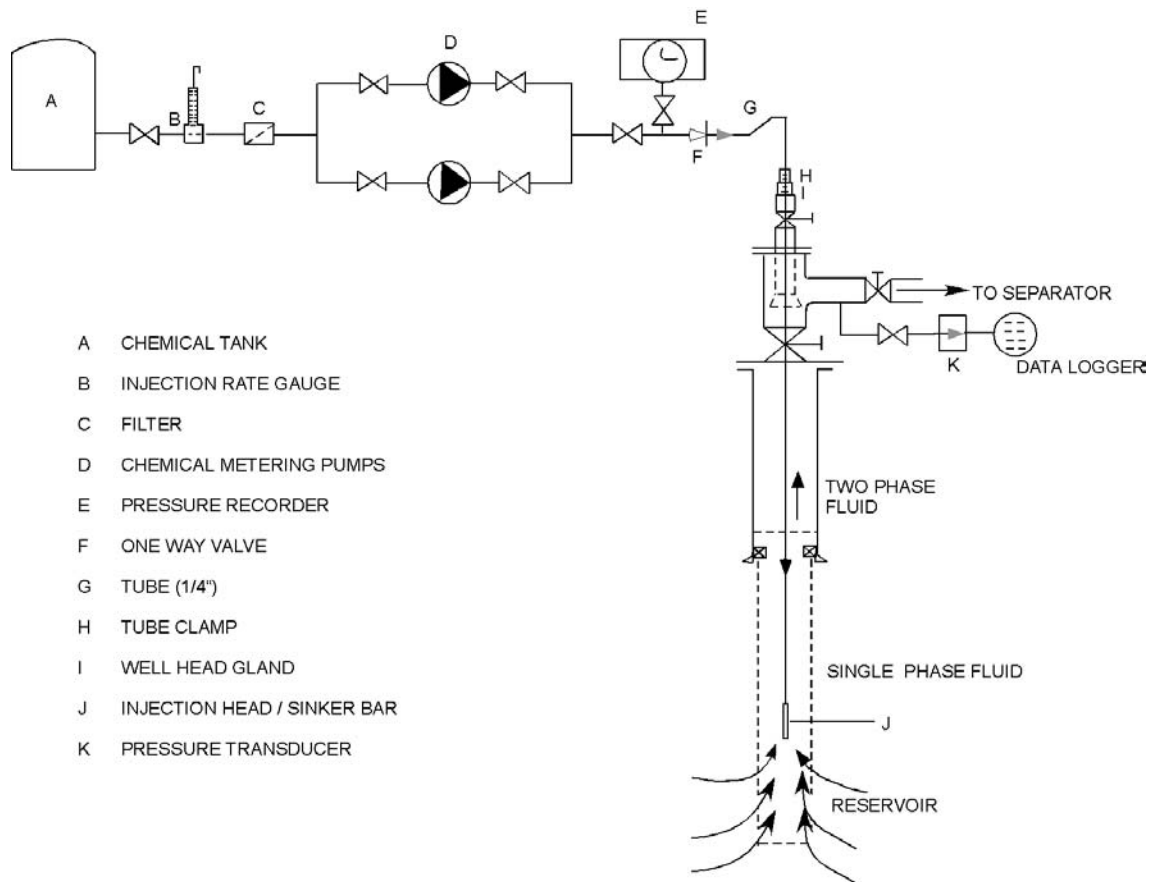FIGURE 7:   Mechanical cleaning with a drill rig during discharge of the well

FIGURE 8: Sketch of chemical inhibition system for a geothermal well

4.2 Chemical scale inhibitors

By injecting a chemical scale inhibitor down hole, some forms of scale deposits can be greatly reduced or eliminated. Scale inhibition is a promising system both technically and economically, as compared to mechanical controlling methods, for example for calcite. Of course, choosing a suitable inhibitor and the system for injecting it into the well is crucial in application (Pieri et al., 1989, Hauksson et al., 1999). The inhibitors reduce, delay or prevent any deposition. This method requires running a coiled tube into the well at a point below the scaling plug and dosing the chemical continuously into the well (Figure 8).

The inhibitors react against solid deposition in one of the following ways:

- By preventing the deposited crystals from adhering to a surface;
- Absorption onto the surface of incipient crystals, thereby distorting the crystal structure so that the crystal is prevented from growing.

4.3 Turbine washing and steam scrubbing

Turbines are susceptible to scaling as any water carry-over from the separators dries out when the steam expands in the inlet nozzles. Scaling narrows the throats of turbine nozzles, consequently decreasing the amount of steam mass flowing into the turbine. This directly influences turbine output, i.e. electric power generation drops.

The deposition can be removed by turbine washing while the machine is in operation (Figure 9). By
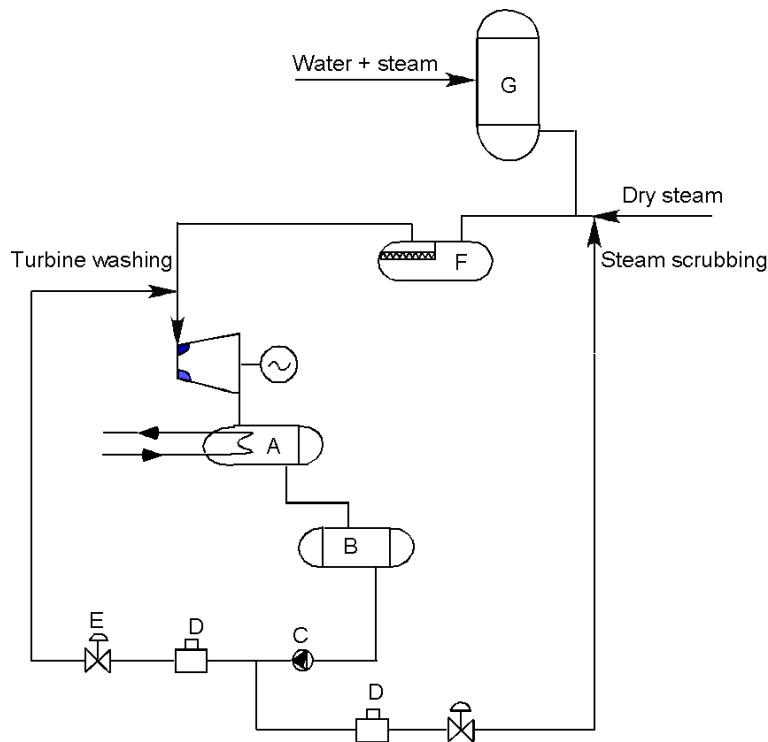
A Turbine condenser - preheater for dist. heating
B Condensate receiver
C Pump for washing water (condensate)
D Flow meter
E Control valve
F Demister
G Steam separator

FIGURE 9:   Turbine washing system

injecting clean water from the condensate into the incoming steam line, a mist is formed that will erode any solid deposition from the turbine nozzles and turbine blades.   The mass of water injected is about 5% of the incoming mass of steam entering the turbine. It is crucial to have clean water free of oxygen and with limited amounts of total dissolved solids (TDS), since poor quality water can cause serious problems rather than providing a solution. To improve steam purity, steam scrubbing is sometimes applied by injecting clean water into the incoming steam line before the final separator (demister). This is effective for steam-dominated reservoirs (dry steam).

Both methods have been employed at the Svartsengi power plant and the effect of cleaning a 1MWe unit by turbine washing is shown in Figure 10. Once a month or every two months, the turbine was cleaned and a 15-20 % recovery obtained.

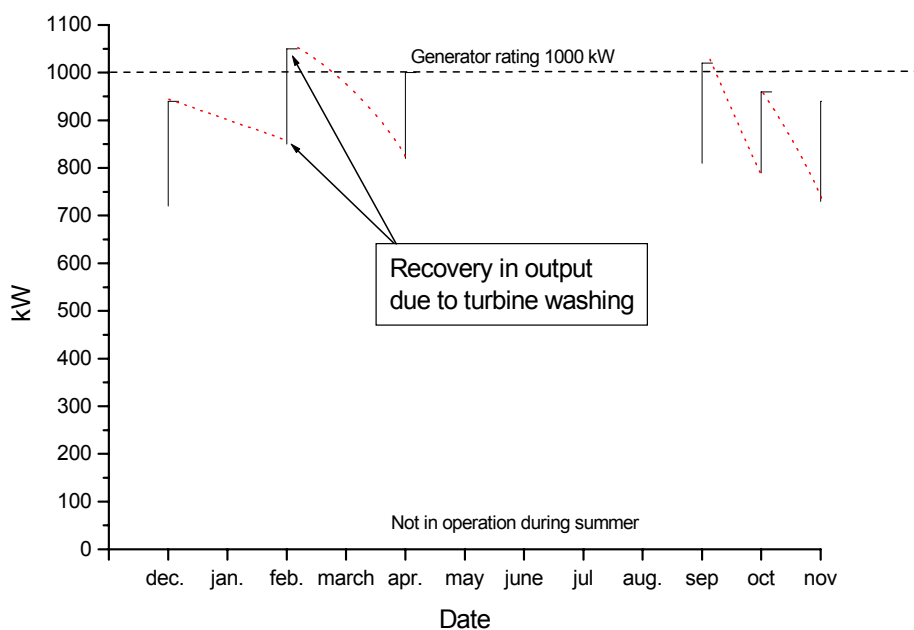Using high-pressure water (water

FIGURE 10:   Decline of turbine output with time and recovery after turbine washing

jetting), any kind of scale deposit can be removed, if accessible. The photograph in Figure11 shows scale deposits in the inlet nozzles of a 6 MW turbine at the Svartsengi geothermal power station. This type of solid deposition is removed by using high-pressure washing. It is simply high-pressure water rushing onto the deposited surface. During high-pressure washing, a big truck with pumping equipment generates high-pressure water with a handheld jetting-gun directed at the deposition. This type of maintenance takes place during annual or semi-annual turbine overhauls.
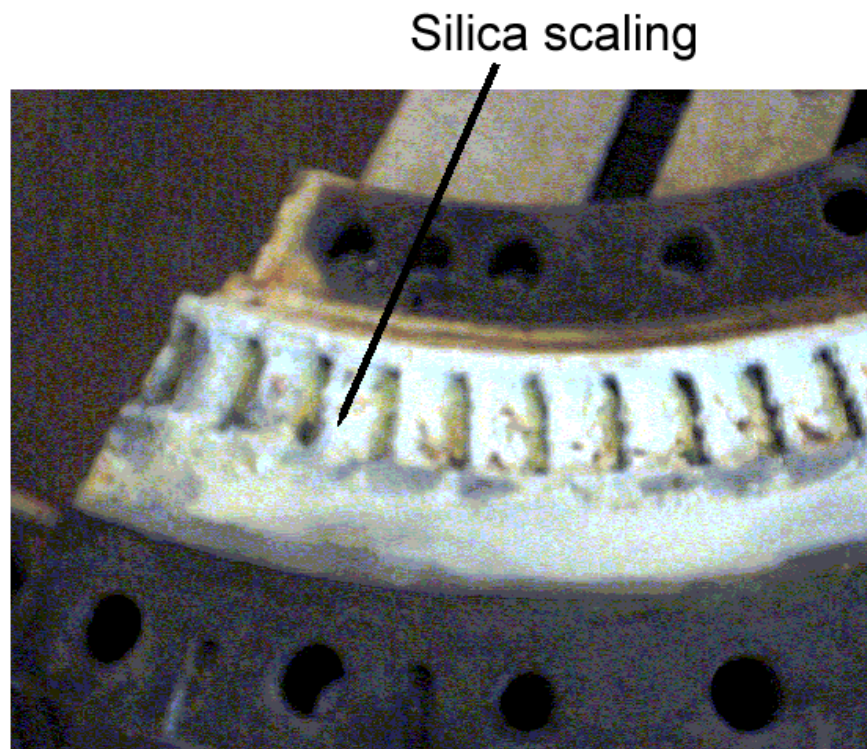

FIGURE 11:   Photo of turbine at the Svartsengi geothermal power plant before cleaning

4.4 Silica suppression

Gas or condensate mixing can reduce silica scaling by lowering the pH value in the solution and by dilution. Hirowatari and Yamauchi (1990) suggest the following on silica suppression:

- Mixing 50tons/hr of water with 17.5tons/hr condensate at 60°C lowers the molecular deposition rate to 0.01mm/yr;
- All super-saturation in 175°C water would be removed by mixing with the fluid with an equal amount of 60°C condensate.

From this experimental discussion, it is possible to conclude that silica scaling can be controlled by dilution. To bring silica concentration below amorphous silica saturation, simply inject condensate into the brine disposal line. This is neither expensive nor difficult to prepare. Another method for controlling silica concentration is by keeping the temperature above the amorphous silica saturation temperature.

4.5 Acid cleaning

Solid deposition removal can also be achieved by dissolving it chemically. The principle is using hydrochloric acid (HCl) with a corrosion inhibitor to dissolve deposition, such as calcite that exists as scale (see Figure 12). The success of the treatment can be seen by an increase in wellhead pressure and production rate. Acid treatment usually costs much less than a rig clean-out. This treatment for calcite may be summarised in the equation below:
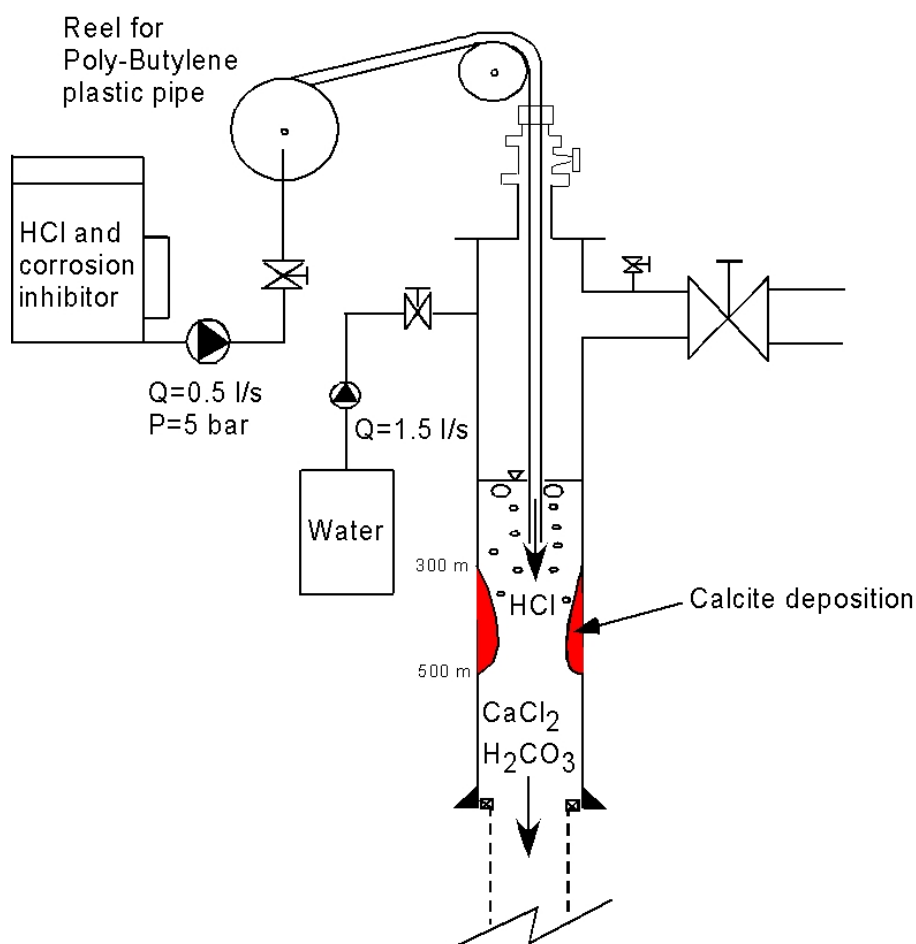
$$2HCl + CaCO_3 \rightarrow CaCl_2 + H_2CO_3$$
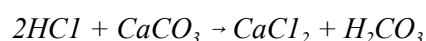
FIGURE 12:   Sketch of an acid cleaning system

5. PRICE ESTIMATION OF CONTROLLING SCALES IN WELLS

Price estimation between methods for controlling solid deposition is essential for making clear decisions.

5.1 Chemical scale inhibition

The cost of chemical injection equipment to remove scale is shown in Table 3 and Table 4 gives the price estimates for some scale inhibitors.

TABLE 3:   Cost of chemical injection equipment

Items	Price (USD)
Pipes (100 m)	1500
Metering pump	900
Valves	100
Gauges	600
Seal on WH	140
Total	**3240**

TABLE 4:   Price estimation for some scale inhibitors

Type of inhibitor	Dosage	pH	Density	Price (USD/kg)
Polyacrylate	2-10	4.1	1110	5
Polycarboxylic acid 40-50%	0.5-10	1	1173	5
Polymaleic acid 30-60% and maleic acid 1-5%	1-5	<2	1170	5
Aminotri (metylene phosphoric acid) 38-42%	2-10	10-11	1390-1450	1.5

Scale inhibition for calcite requires 260 kg of polyacrylate per month for one well, having a mass flow of 50 kg/s and a inhibitor concentration of 2 ppm. So, per year about 3200 kg of chemicals are needed costing 16,000 USD.

5.2 Acid cleaning

The cost of 33% HCl acid is 0.64 USD/kg, and the required dosage is assumed to be 0.5 l/s. If the total amount needed for injection is 7 tons, it costs about 4,500 USD to clean one well. The injection equipment, including pumps, costs about 4,600 USD.

5.3 Mechanical removal with a drilling rig

Table 5 shows the time schedule for cleaning of a well with a drill rig while discharging and price estimation of well cleaning in Ethiopia with a mechanical method is found in Table 6 (information from Dr. E.T. Elíasson).

TABLE 5:   Time schedule for the mechanical cleaning of one well

	Time schedule				
	1st week	2nd week	3rd week	4th week	5th week
Transportation					
BOP transportation to Ethiopia	■				
Supervisor travel to Ethiopia	■				
Operator travel to Ethiopia		■			
Transport to shipping port				■	
BOP transportation to Iceland					■
Well no. 1					
Formal training of staff		■			
Well/rig preparations		▨			
Transport to site no.1		■			
BOP rig-up			■		
Well cleaning			■		
BOP rig- down				■	
Clean-up etc.				■	
Operator travel to Iceland				■	
On the job training		▨	▨		
Supervisor return to Iceland				■	

BOP - blow out preventer

TABLE 6: Cost estimate for de-scaling a well with wellhead equipment allowing cleaning while discharging with rental of equipment and services (not including withholding taxes/customs duties etc, and equipment insurance fees during transport)

Basic premises for estimate	Unit	Number	Comment
Shipping by air Iceland/Ethiopia/Iceland	day	4	Estimated 2 days each way
Land transportation from port/jobsite/port	day	6	Estimated 3 days each way
Rig-up/rig-down of tools - fixed rate per job	job	1	Estimated 1 well
BOP equipment operation/well	hour	50	Icelandic average/well
Down-time/well	day	1	Estimate
Redress once per batch of jobs-max. 3 wells	batch	1	Batch of 1 well cleaned
Travel Iceland/Ethiopia/Iceland	day	2	Estimated 1 day each way
Supervisor on site	day	17	17 days
Operator on site	day	13	13 days
Operator travel time/return trip	day	2	One trip per each well

Component	Unit	Rental rate (USD/unit)	Chargeable units	Estimated cost (USD)
1. Stand-by during transportation of equipment and waiting time				
Stand-by during shipping Iceland/Ethiopia	day	550	2	1,100
Transport from port to first jobsite	day	550	3	1,650
Transport between jobsites	day	550		0
Transport to port from last jobsite	day	550	3	1,650
Stand-by during shipping to port of exit	day	550	2	1,100
Stand-by during shipping Ethiopia/Iceland	day	550	2	1,100
			Total	**6,600**
2. Rental of de-scaling BOP				
Rig-up of tools	well	1,320	2	2,640
Equipment in operation	hour	110	100	11,000
Down-time/stand-by	hour	550	2	1,100
Repair/redress after use	batch	6,820	1	6,820
			Total	**21,560**
3. Supervisor/operator charges				
Engineer/supervisor in Ethiopia	day	900	17	15,300
Operator in Ethiopia	day	750	13	9,750
			Total	**25,050**
4. Travel, accommodation, sustenance				
Travel costs Iceland-Ethiopia-Iceland / trip		1,300	2	2,600
Per diem travelling	day	308	4	1,232
Accommodation/sustenance	day	308	30	9,240
Other expenses (visa/vaccinations) / person		308	2	616
			Total	**13,688**
		Grand total for one well in USD		**66,898**

Comparing the costs between the different cleaning methods, i.e. chemical cleaning, acid cleaning and mechanical cleaning, the following conclusions are reached:

- About 3,200 kg of chemicals are consumed for one year for the inhibition of solid depositions, which costs 16,000 USD.
- Mechanical cleaning, which can be assumed to be done according to a 2-year cleaning schedule, costs about 67,000 USD for one well.
- Acid cleaning costs about 4,500 USD.

Therefore it can be concluded that chemical inhibition or acid cleaning is more economical against calcite deposition than drilling out the deposits, and it can also be more effective.

6. CONCLUSIONS

1. Solid deposition (scaling) in geothermal systems constrains the design and operation of geothermal power plants.

2. Well output declines as a result of solid deposition that may precipitate, in the reservoir, liners and wellbores or production casing.

3. Calcite, silica, sulphide and sulphur are common solid depositions encountered in geothermal systems. They have different forms depending on the composition of the water (fluid), and, thus, need different approaches for control. For instance, the magnitude of calcite super-saturation is strongly affected by CO_2 loss, as the calcite saturation index increases with flashing of water.

4. The application of control methods depends on the type of scale and the location of the deposits. Scaling is being successfully treated in most geothermal plants.

5. Solid deposition can also occur at different points in surface equipment including turbines and turbine condensers. Scale deposition in turbine nozzles causes loss of power output because of restricted flow. In the same way, scale depositions in a condenser result in a loss of vacuum and power.

6. A chemical inhibition system is a promising method to combat calcite scaling, both technically and economically, when compared to mechanical methods.

7. Case histories for two geothermal power plants and the effects of solid deposition are presented in this study, the Svartsengi geothermal power plant in Iceland and the Aluto-Langano geothermal power plant in Ethiopia. For Aluto-Langano, it is probable that solid depositions have caused the decline in well output. This needs to be confirmed by well logging.

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