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REHABILITATION OF GEOTHERMAL WELLS WITH SCALING PROBLEMS

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ABSTRACT

This report presents an overview on the problems caused by solid deposition in production wells and describes methods to minimize the problem they cause. The main scale types found in geothermal systems are described along with case histories. Several methods to rehabilitate wells with scaling problems have been adopted in various countries in order to recover the well output. The location of the scaling zones and the mechanical conditions of wells are most influential in selecting the appropriate alternative for rehabilitation.

Two case histories are included in this report, where the author witnessed cleaning operations. They are from the Ahuachapán geothermal field in El Salvador and the Krafla geothermal field in Iceland. The main activities carried out in wells of these geothermal fields are presented in order to compare the methodology used. Also, deposition cases from other geothermal fields in the world are presented. The author considers that the study of the methods used to clean the wells mechanically with a drill rig, will be very useful for similar future operations in the geothermal fields of El Salvador.

1. INTRODUCTION

Geothermal resources play an important role in the energy development of a number of countries around the world. The economic exploitation of this resource may be seriously affected when the rate of production in a geothermal field decreases due to solid deposition inside the casings of wells or in reservoirs. Solid deposition is one of the major problems found in exploiting geothermal wells in liquid dominated geothermal fields. Calcite and silica are the most common scaling minerals present in geothermal systems, and they have been found in production casings and slotted liners in production wells. The problems caused by these scales are associated with changes in the production of the wells due to the flow restrictions and subsequent reduction in well output. But this scaling problem has been minimized by the following simple but effective solutions that have been adopted.

Calcite scaling is associated with the onset of boiling inside the well, as calcite supersaturation occurs after boiling. A wellbore simulator such as HOLA (Björnsson et al., 1993) can be used to study where boiling or degassing takes place and at what depth. On the other hand, silica deposition is associated with reinjection of waste water in the disposal of effluent water of high-temperature fields. This problem has been overcome by operating the system at temperatures above the amorphous silica limit.

One method to affect the depth of the deposition zone consists of controlling the position of the downhole boiling zone in the geothermal well. This does not prevent scale formation, but it is possible to spread the deposition zone to a place where its cleaning is successful. Also, injection of chemical inhibitors inside of a capilar tube set to a depth below boiling point has been successful in minimizing the solid deposition (inhibition of calcite).

The main objective of this report is to present an overview of scale formation in the casing of production wells; how these depositions affect its production and how the problems are being solved.

2. SCALE FORMATION IN GEOTHERMAL WELLS

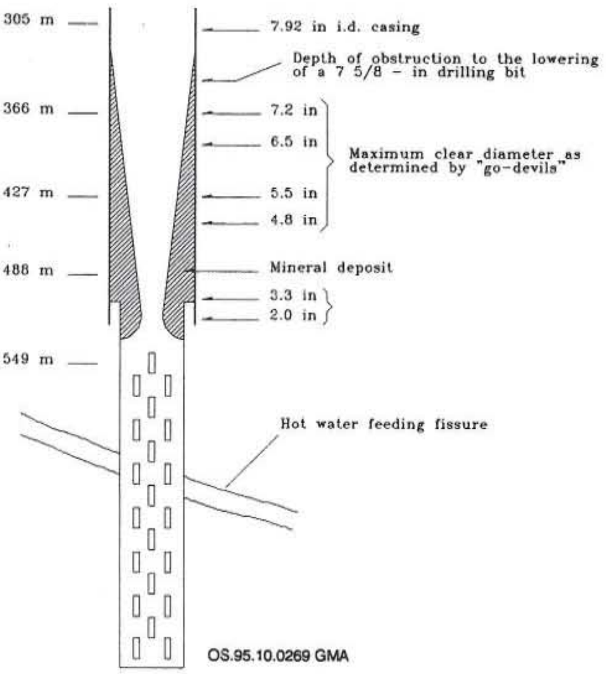


FIGURE 1: Typical calcite deposit build-up in a geothermal well (not to scale) (redrawn after Armstead, 1983)

Deposition of scales is a major problem in the exploitation of geothermal reservoirs. Deposition, or scaling, occurs not only in the casings and surface equipment but also, in some cases, inside the reservoirs. This can result in a marked decline in fluid yields, and consequently can limit the output of geothermal installations.

Scale deposition commonly occurs just above the slotted liner hanger in the lower part of the production casing, where flashing of the uprising hot water causes the concentration of some components to rise and pH to change, and consequent precipitation, of the insolubles, as is shown in Figure 1. Usually, and fortunately, this is a relatively slow process that can be remedied, at intervals of a year or two, by reaming out the deposit so as to restore the full internal diameter to the well (Armstead, 1983).

Different types of scales are found in geothermal fields. The most common are calcite ($CaCO_3$), silica (SiO_2) and sulphide. These present different behaviour with respect to the precipitation form and conditions at which they form (concentration, temperature, pressure and pH).

2.1 Detection of scaling in wells

Decline in production of wells can be detected as a decrease in the wellhead pressure. If scaling is suspected in the well it is necessary to run surveys to calibrate the casing to determine its location and thickness. Deposition is also sometimes discovered during logging operations, or by direct observation by means of a caliper survey. For sophisticated work, several types of measuring tools exist. The ordinary type is a three arms caliper (Figure 2D), but tools with one up to 60 arms are available. The arms are in all cases motorized, i.e. an electrical motor is present inside the caliper tool to open the arms. The logging cable makes it possible to read the diameter of the well continuously. The arms will centralize the tool in the well, and the position of the arms is sensed through a variable resistance. A caliper log measures continuously from the bottom to the top of the well. Because of the electrical cable and the downhole electronics, high-temperature wells can only be caliper-logged with this technique after having been cooled down by quenching with cold water. The maximum temperature to run surveys with these tools is 150°C. Go-devils are also used frequently in high-temperature wells as they are unaffected by the temperature. They are in fact sinker bars or wire baskets of different diameters, and therefore show the maximum depth of each diameter in the well. They are mainly used for distinguishing between well deposits and casing damages (Stefánsson and Steingrímsson, 1980), and to schedule reaming operations.

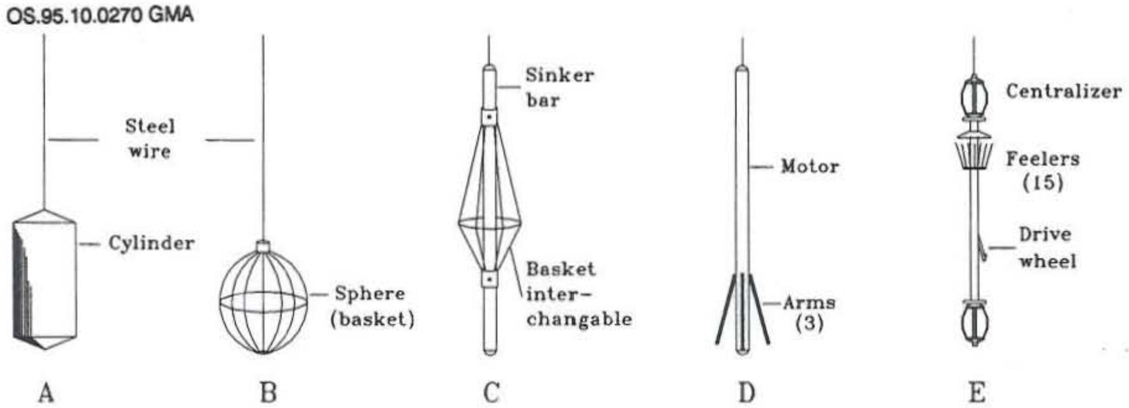


FIGURE 2: Go-devils (A, B and C) and caliper logging tools (D and E) used to detect scaling in wells

Figures 2A and 2B show go-devils used in El Salvador for calibrating of casing. Figure 2C shows a go-devil used in Iceland and 2D the electrical caliper logging tool. Figure 2E shows the Kinley Microscopic Caliper used for sophisticated work. This circumferential survey makes possible to find and measure deformed tubing, rings of corrosion and erosion, isolated pits, lines of pits, and scale. The caliper is lowered into the well on a solid wire line through a lubricator. When the desired depth is reached, the caliper is pulled up, which releases the drive wheel. The turning of the drive wheel releases the centralizer runners and the feelers. Each feeler is attached to its own stylus, making a separate and continuous record of its movement on the chart within the tool. The caliper should be pulled slowly up through the well at about 18 m/min.

2.2 Calcite (Calcium carbonate)

Calcite is a common secondary mineral in geothermal fields worldwide. It is the most common form of carbonate bearing minerals in deposits in geothermal wells. The formation of calcium carbonate ($CaCO_3$) scale in production wells is perhaps the most common scaling problem in geothermal wells. This is associated with flashing and the resulting change in pH due to degassing. In studies carried out on geothermal scaling, scale thickness ranged from 0.7 to approximately 3 cm and resulted in costly fluid restrictions of 10 to 45% (Vetter, 1987). The approximate mass of calcite deposited in the casing of production wells can be estimated using caliper logs.

The rate of deposition of calcite from some wells can be highly variable, depending on the saturation index (S.I.) and fluid composition. Some fluids contain sufficient calcium to completely obstruct well flow in a matter of a few weeks (Vaca et al., 1989). The solubility of $CaCO_3$ in pure water decreases with increasing temperature, unlike most other minerals (retrograde solubility). Almost all geothermal water is at equilibrium with respect to calcite in the reservoir. The amount of CO_2 present is proportional to the partial pressure of the gas in contact with the solution, according to Henry's Law (Corsi, 1986). The scaling occurs when the boiling of reservoir fluid and the evolution of CO_2 cause a rise in pH and an increased concentration of calcium and carbonate ions in the liquid phase, resulting in the supersaturation and precipitation of $CaCO_3$ (Michels, 1981; Arnórsson, 1989). Changes in conditions such as sudden widening of the well at the casing-liner joint, or even small changes in geometry, such as the lower end of the casing in a well without liner, may cause a more rapid deposition. However, these conditions may be created once the deposit has started to form (Ármannsson, 1989).

In high-enthalpy systems where boiling cannot be avoided, direct removal of scale formed in the flash zone by reaming the wells has been found to be effective. Reaming may be ineffective if scale deposition has plugged the production aquifers or the slotted liner portion of the well (Benoit, 1989; Hurtado et al., 1989; Líndal, 1989; Thórhallsson, 1988; Vaca et al., 1989). The most significant improvement in the reaming method involves the use of a well head that allows the drill crew to ream wells during steam production. This method is described in Chapter 4.

Calcium carbonate scale can be left in the formation of high-enthalpy, high-drawdown wells as a result of fluid flashing before it reaches the wellbore. Scale in the formation is then indicated by a production decline in two-phase or steam-entry wells. In some geothermal reservoirs, especially if they have been producing for several years, the front of first boiling can be in the reservoir hundreds of metres away from individual wells. Continuing pressure decline in exploited geothermal reservoirs will cause progressive expansion of the front of first boiling. In this way the zones of most intensive calcite deposition will be continually shifting, decreasing the possibility that this deposition will reduce permeability around individual wells. It is considered likely that in most instances such deposition will have a negligible effect on permeability over the lifetime of individual wells (20-50 years) (Arnórsson, 1989). Calcite scaling is also found in a number of low-temperature wells (Bai Liping, 1991).

2.3 Silica

Amorphous silica heads the list of scaling problems associated with the reinjection of waste water. Deposition of silica in and around the wellbore causes reduction in formation permeability and subsequently the injectivity of the well (Hauksson and Gudmundsson, 1986). Also, some form of silica deposition has been encountered in virtually all high-enthalpy, liquid-dominated, geothermal fields. As the geothermal fluid is extracted and steam is separated, considerable supersaturation with respect to amorphous silica can develop in the waste water. This problem is usually overcome by limiting the amount of flashing and the temperature to values above the amorphous silica saturation curve. In practice, this means that the fluid temperature can be lowered at maximum some 100°C below the reservoir temperature without scaling (Thorhallsson, 1988). The deposition of amorphous silica that may then occur appears to be governed by several factors. These include the degree of supersaturation, temperature, pH, presence of dissolved salts and foreign ions, availability of nucleating species, and fluid flow regime. Deposition is known to occur by direct deposition on solid surfaces (heterogeneous nucleation) or by polymerization followed by colloidal deposition (homogeneous nucleation) (Malate and O'Sullivan, 1993).

There are many factors which affect the rate of silica precipitation, and experimental data obtained in field tests are required to understand the mechanisms of these processes. Silica precipitation from geothermal fluids can occur over periods of minutes or hours after supersaturation occurs, which is why silica scale has been found throughout the fluid handling equipment of several geothermal facilities.

Siliceous scales are formed by reactions between silanol radicals and the rate of reaction is controlled by various factors such as pH, temperature and salt concentration (De Pasquale et al, 1995). They are typically inert to most chemicals and, once deposited, very resistant to mechanical removal. Hence, most treatment methods focus on prevention of silica deposition or on controlling the morphology of the silica deposited. Efforts to prevent deposition of scale on surface equipment have included restricting steam separation to temperatures at which silica supersaturation is minimized (Hibara et al., 1989; Hurtado et al., 1989; Karabelas et al., 1989) and acidification of the brine phase to inhibit silica deposition (Gallup, 1989; Gudmundsson and Einarsson, 1989; Líndal, 1989). Studies have been made since 1978 to stabilize silica in hyper saline geothermal brine by means of organic compounds such as polymers and surfactants, not only in a processing plant, but also when the brine comes in contact with the geologic formation of the injection wells (Harrar et al., 1978).

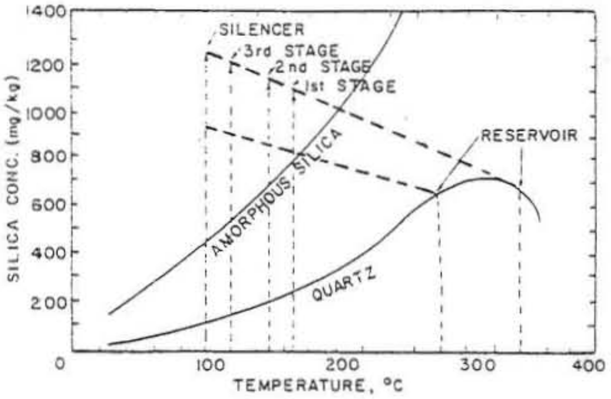


FIGURE 3: Trajectories for the brine silica concentration as a function of steam separation temperature, Cerro Prieto, México (Hurtado and Mercado, 1990)

Figure 3 shows the changes in silica concentration during the flashing of the brine from reservoir to atmospheric conditions for the range of silica composition of the Cerro Prieto brine (Hurtado and Mercado, 1990).

2.4 Sulphide

Sulphide scaling has often been identified as a source of problems in the production of large flows of water from drill holes, especially in the oil and geothermal industry. This scaling occurs both in low- and high-temperature environments. In high-enthalpy geothermal systems, sulphide minerals are precipitated because the concentration of metallic cations (Fe, Zn, Pb, etc) in the fluids are high owing to the presence of chloride complexes and according to solubility rules. The sulphide concentration controls the amount of scale formed, that is to say the quantity of deposit is limited by the stock of sulphide in the solution (Criaud and Fouillac, 1989). In some geothermal fields, these scales may be intermixed with amorphous silica or with metal (commonly iron) silicates.

It is reported that the mechanisms responsible for the formation of metal sulphide in low-enthalpy geothermal systems are fundamentally different from those occurring in high-enthalpy systems and require different approaches to solve. The process responsible for sulphide deposition from low-enthalpy geothermal fluids appears to be the mobilization of iron due to corrosion of well-casing alloys. In high-enthalpy systems, the source of scale-forming dissolved ions is typically the reservoir fluid, and the scale minerals formed are different from those found in low-enthalpy systems. Similarly, the chemical mechanism for the formation of metal sulphide is also different, the phenomenon appears to be related to a decrease in pH associated with fluid flashing and degassing of the reservoir fluid (Thomas and Gudmundsson, 1989).

3. ALTERNATIVES IN DEALING WITH SCALING PROBLEMS IN WELLS

When a geothermal field is exploited, one of the main objectives is to maintain a continuous yield of steam or hot water from the wells to the power plant. If some drastic decreasing in the natural flow conditions are observed during production of the wells, it is necessary to find all conditions that restrict the flow of geothermal fluids to the surface. The main causes of decreasing production are:

a) Deposition in the production casing or slotted liner;
b) Deposition in the production zone or reservoir;
c) Well casing damage;
d) Admission of lower temperature water, or reservoir pressure decline;
e) A combination of some of these problems.

In order to select a suitable alternative for the rehabilitation of the well, several important aspects must first be evaluated and considered:

a) Mechanical condition of the well and its design;
b) Geological conditions;
c) Wellhead pressure, enthalpy and production conditions;
d) Results of temperature and pressure logging;
e) Level of success expected after the operations.

After this analysis has been made, one of several alternatives can be selected representing proven methods for restoring the production, as discussed here below.

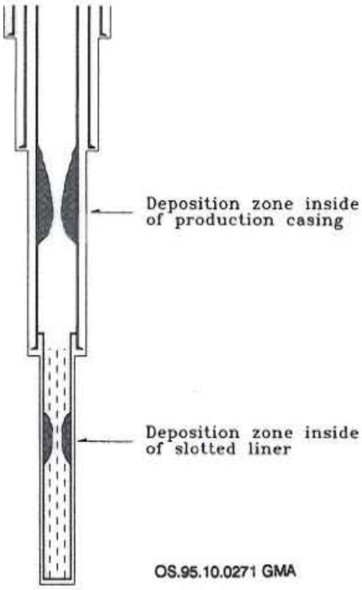


FIGURE 4: Two possible zones of solid deposition formed in geothermal wells

3.1 Cleaning of the wells

This method basically consists of mechanically reaming the scales using a drill rig. It can be successful if the deposits are formed inside the production casing (Figure 4). Reaming of the well in this section will recover the original well output fully. However, if the deposits are formed in the slotted liner and the slots, the deposits cannot be cleaned completely by reaming (Figure 4). In this case, it is necessary to evaluate carefully the next step. An exhaustive study on the mechanical condition of the well must be made. But it is important to keep in mind that cleaning operations of the wells must be an economically acceptable method. The mechanism for carrying out these operations is discussed in Chapter 4.

3.2 Chemical inhibition

The inhibition of scale deposit by using chemical products has gained importance both technically and economically, and seems to be one of the most promising systems. The choice of a suitable inhibitor and the system for injecting it into the well (Piere et al., 1989) is critical in this case. Scale inhibitors are added to normally scaling water in order to reduce, delay or prevent scale formation.

Basically, this method consists of running a coiled tube into the well and setting it at the desired depth. In most cases this depth will be below or at the flashing zone. Figure 5 shows two injection systems used for calcite inhibition, one in Kawerau, New Zealand (Robson and Stevens, 1989) and the other in Latera, Italy (modified from Piere et al., 1989). As can be seen from the Figure 5, the arrangements for inhibition are very similar. In some cases it is necessary to previously remove the scale mechanically using a drill rig.

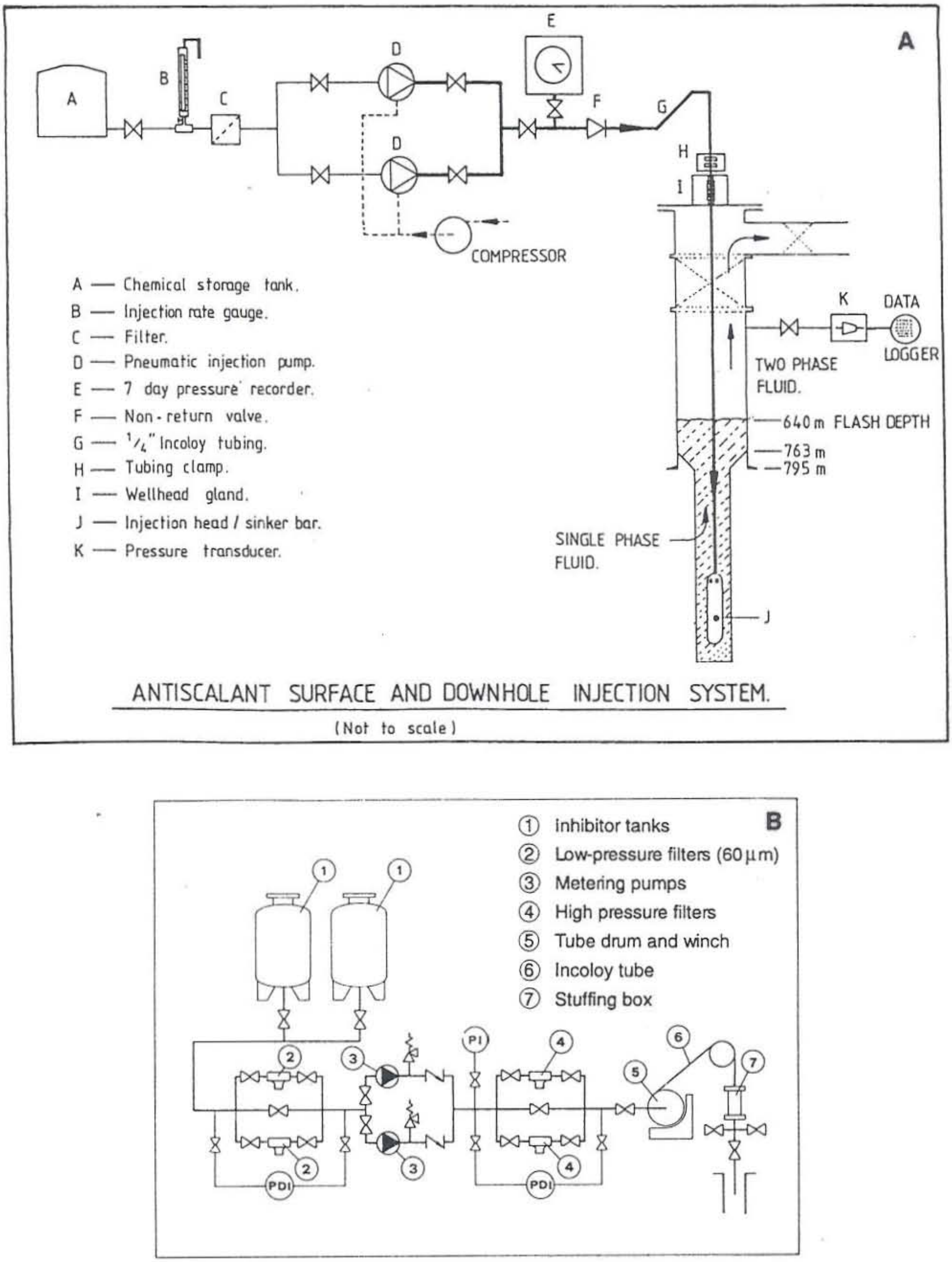


FIGURE 5: Injection systems for calcite inhibition, a) from Kawerau, New Zealand (Robson and Stevens, 1989), b) from Latera, Italy (Modified after Piere et al., 1989)

The mechanisms of scale inhibition are as follows:

a) Preventing precipitated scale crystals from adhering to surfaces;
b) Absorption onto the surface of incipient crystals and thereby distorting the crystal structure so that the crystal is prevented from growing.

Most modern scale inhibitors function by the mechanism called "Threshold Inhibition". For calcite scaling, poly maleic acid (PMA), organic phosphate esters, organic phosphonates and organic polymers are the most common types of inhibitors in use today (Parlaktuna and Okandan, 1989; Corsi, 1986). However, the main problem found with downhole injection of the scale inhibitors is corrosion of the injection pipe, caused by the inhibitor itself at high temperature. This problem can be solved by using an injection pipe made of a suitable corrosion-resistant alloy (Piere et al., 1989). At this time, a specific inhibitor for silica is not known for use in geothermal wells, but efforts to control silica scaling have been made (Harrar et al., 1978).

3.3 Side tracking (deviation of the well)

When the mechanical conditions of the well casing is poor or when the deposition zone is located in the liner zone side tracking may be the only option. Sometimes it is decided to pull up the liner in order to replace it for a new one, but these operations may be very difficult. In this case the side tracking of the well seems to be the most favourable alternative if the well is a good producer. In countries like México this technique has been the most rewarding one for the rehabilitation of the wells and results have been satisfactory since 1988 (Gutiérrez and Mendoza, 1994).

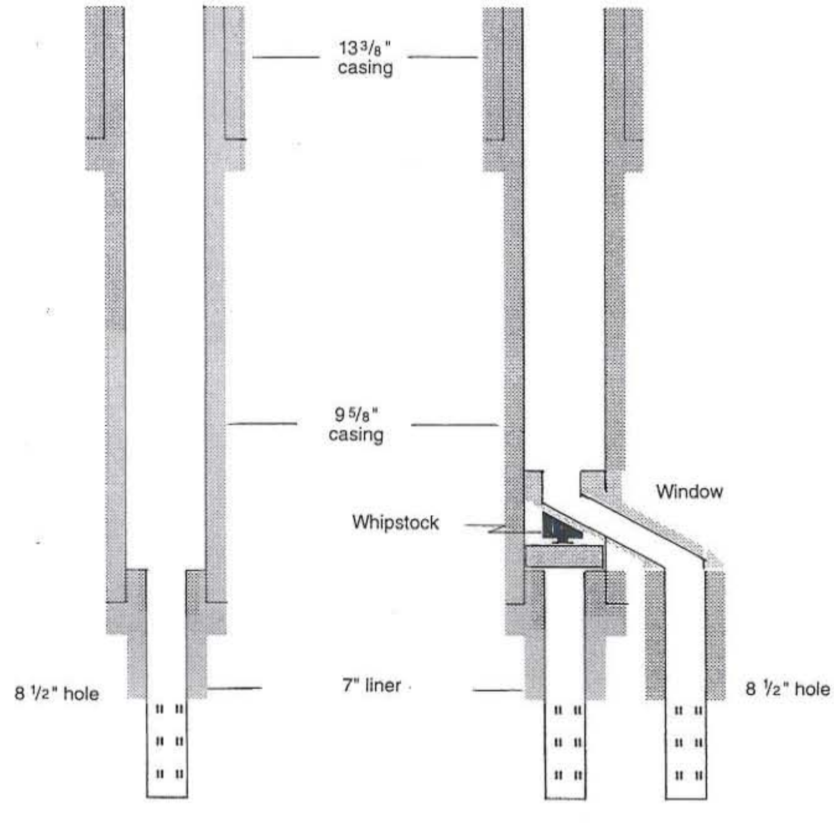


FIGURE 6: Typical profile of a side tracking operation adopted in Cerro Prieto, México (modified from Castillo, 1995)

The side tracking operation basically consists of opening a window in the production casing. This can be done by setting a special tool named "Whipstock", in the place where the deviation will start. A downhole motor which directs the drill bit to drill at an angle is used initially. The new hole will bypass the problematic zone and may be drilled down to the zone of interest. The lithology must be very stable for allowing the lateral drilling with the same diameter of bit to the end. Figure 6 shows a typical profile of a side track operation carried out in wells in México (Castillo, 1995). Also, a plug can be set in the same casing in order to isolate and avoid damage to the production zone. It is essential that an experienced directional driller is in charge of the operations with the proper tools and logging equipment available.

3.4 Deepening the well

If the steam production is decreasing due to a drastic process of scaling near to the exploitation zone deepening of the well may have to be considered. A correlation with the lithology of bordering wells must be done in order to determine if lower layers present adequate conditions for exploitation. Deepening of the well can be carried out, drilling the hole with a drill-bit smaller in diameter than the liner, until the favourable zone is reached. A new slotted liner smaller in diameter must be hung from the existing one in order to reinforce the crumbly zone. Figure 7 shows how wells are deepened in Cerro Prieto geothermal field, México, since 1988 (Castillo, 1995).

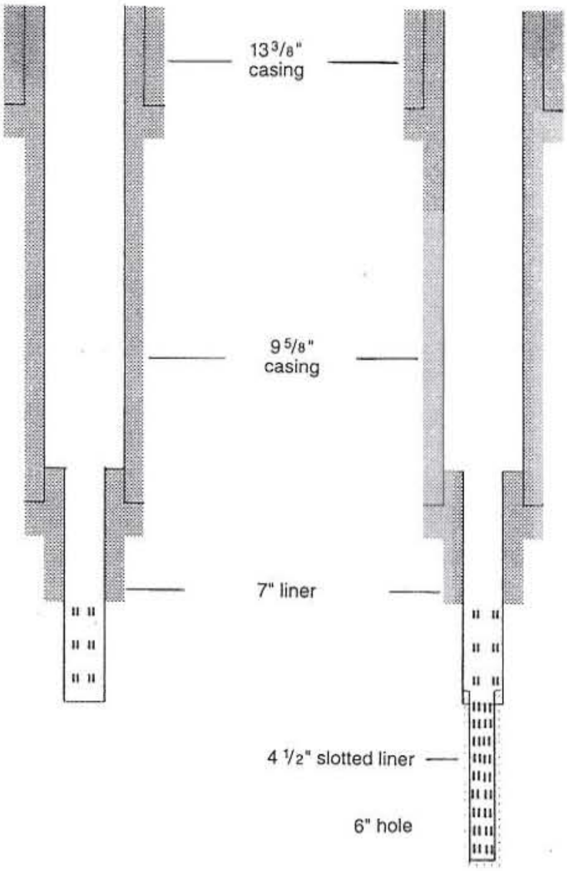


FIGURE 7: Typical profile on deepening of wells adopted in Cerro Prieto, México (modified from Castillo, 1995)

3.5 Mode of operating wells

Scale may occur in the surrounding reservoir (in the production strata) sealing it completely or diminishing its permeability with no means of cleaning it. To prevent this, orifice restrictions are installed on wellheads, which maintain higher pressure in the well and diminish scale formation (Mercado et al., 1989). One alternative to control the depth of deposition zones involves controlling the downhole boiling zone in a geothermal well. This does not prevent scaling, but it is possible to spread the deposition zone to a place where its cleaning may be successful, e.g. into the production casing. One method to obtain more total energy between each cleaning operation is running the wells at different wellhead pressure to spread out the deposition zone.

3.6 New well design

When the deposition zone is located in the liner or its surrounding, a new well design should be considered. If the deposition interval is known it is possible to drill a new well in such a way that the deposition zone will be inside the production casing. In Iceland the diameter of the production casing has, for example, been increased from the typical 9 5/8" to 13 3/8", and similar changes were made in the Miravalles geothermal field, Costa Rica. Such a case is presented in Chapter 5.

4. METHODS TO CLEAN OUT SCALES IN WELLS BY DRILLING

Cleaning operations using a drill rig are recommended when the deposition zone is in the production casing. Two methods of mechanically cleaning out the scales with a drill rig have been adopted:

a) Reaming the deposits with the well quenched by injection of cold water during all operations;
b) Reaming during well discharge.

This has its limitation as there are many cases of the liner being damaged by these operations.

4.1 Reaming the deposition with the well quenched

When the reaming is carried out with this method, it is necessary to quench or "kill" the well. This means that continuously, cold water must be pumped into the well to keep it under control. This method requires about 10 days to carry out all the operations, and it can lead to casing damage due to the injection of cold water and resulting thermal strain. Therefore, cooling of the well must be moderated. The temperature or flow rate of water must be increased or decreased gradually in order to minimize thermal strain in the pipes. Once the well has been controlled the cleaning operation can start, maintaining the injection of cold water to the end. One problem found by using this method is that the deposits fall to the bottom of the well and make it shallower, or the cuttings are introduced into the formation. Sometimes this problem is overcome when the well is discharged again. Case histories are presented in Chapter 5.

4.2 Reaming the deposition during well discharge

This method has been developed in Iceland over a period of 25 years. The reaming of the scale is done without cooling or quenching (killing) the well. The cleaning operation is performed with the well flowing. The main benefits of the method (as compared to the conventional method of cooling the wells), are that the cuttings are swept out of the well, the thermal strain on the casing due to the quenching operation is eliminated, and the well can be back in production after 2 or 3 days (Thorhallsson, 1988). A special gland was developed in Iceland to seal against the drill pipes. This is shown in Figure 8. The gland can only be used with straight outside-flush drill pipes because of the sealing requirement. Also, a blowout preventer (BOP) is included in this arrangement. The fluid from

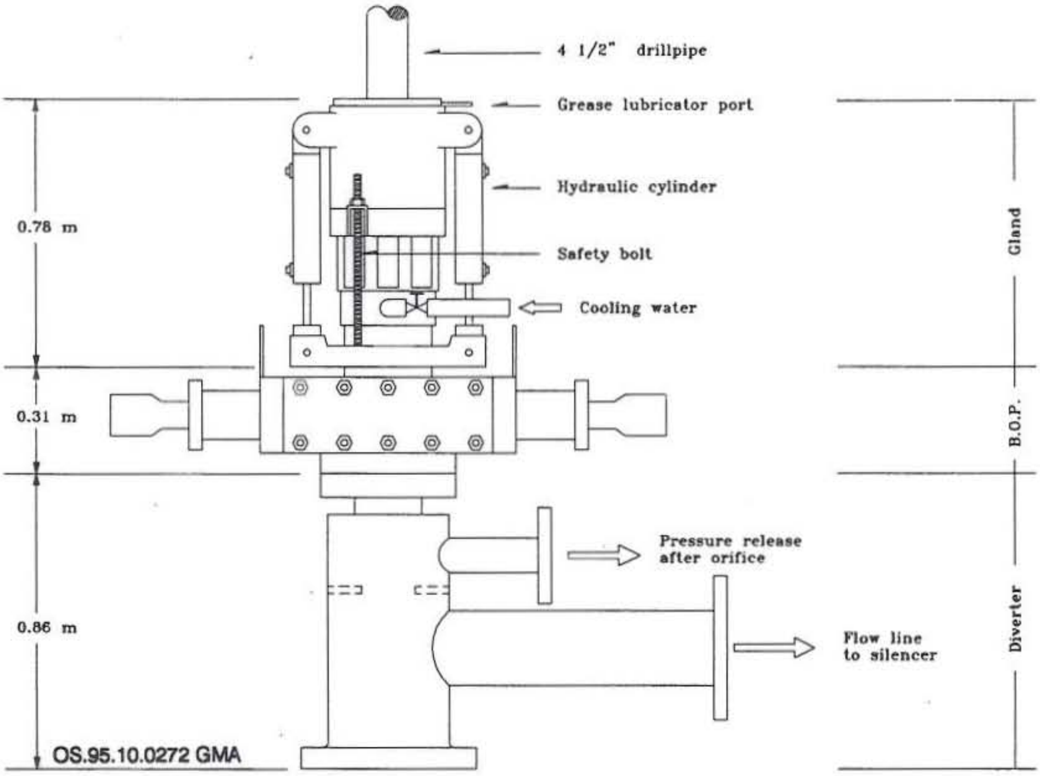


FIGURE 8: Special wellhead system used for reaming calcite in geothermal wells in Iceland during discharge

the well flows through the flow line by a diverter placed above the master valve. The diverter is connected to the silencer. The sequence for this cleaning operation is shown in Figure 9, and consists of the following steps:

a) The well is in normal production (Figure 9A), but has to be cleaned;
b) First, the master valve is closed and the wellhead removed (Figure 9B);

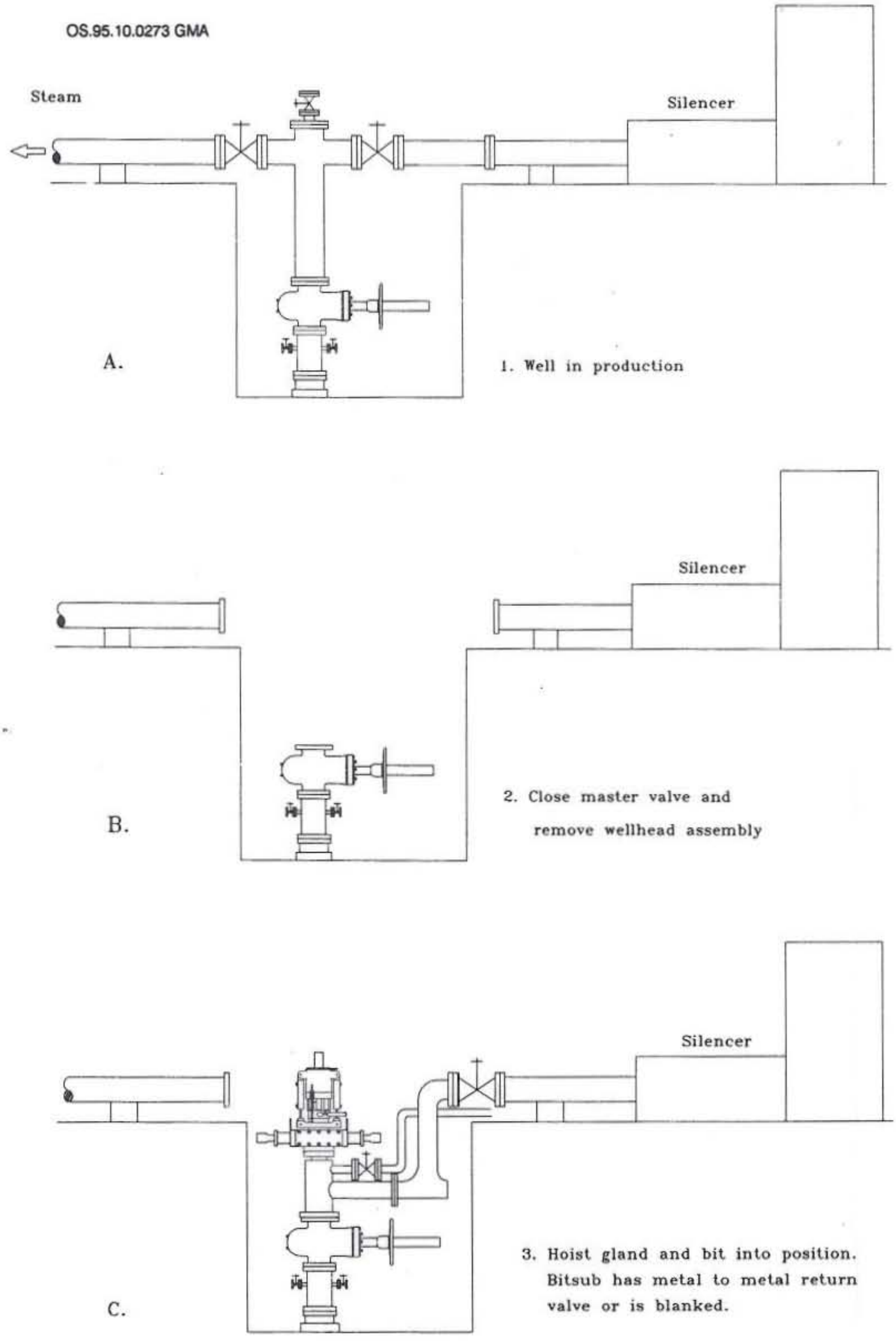
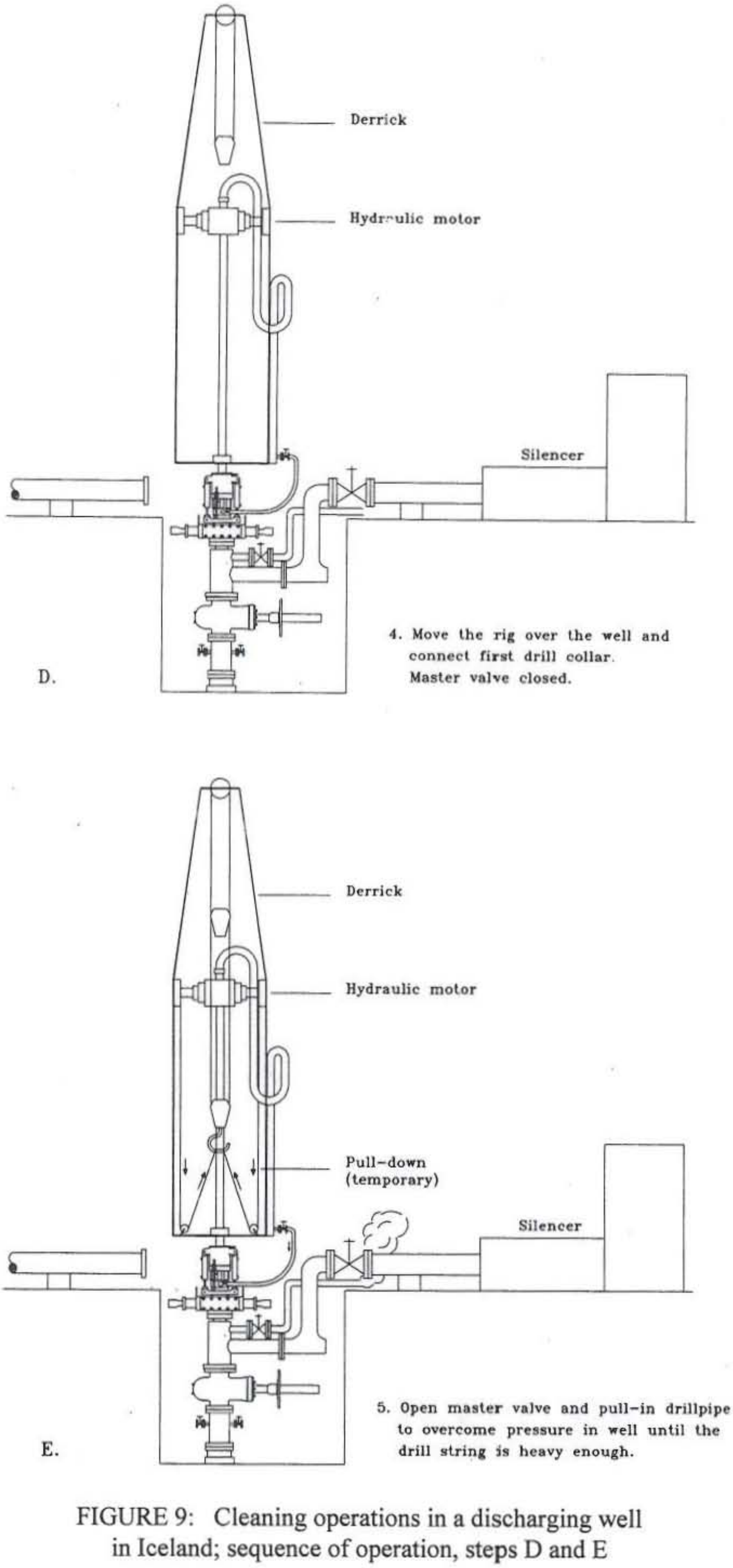


FIGURE 9: Cleaning operations in a discharging well in Iceland, sequence of operation, A, B and C



4. Move the rig over the well and connect first drill collar. Master valve closed.

5. Open master valve and pull-in drillpipe to overcome pressure in well until the drill string is heavy enough.

FIGURE 9: Cleaning operations in a discharging well in Iceland; sequence of operation, steps D and E

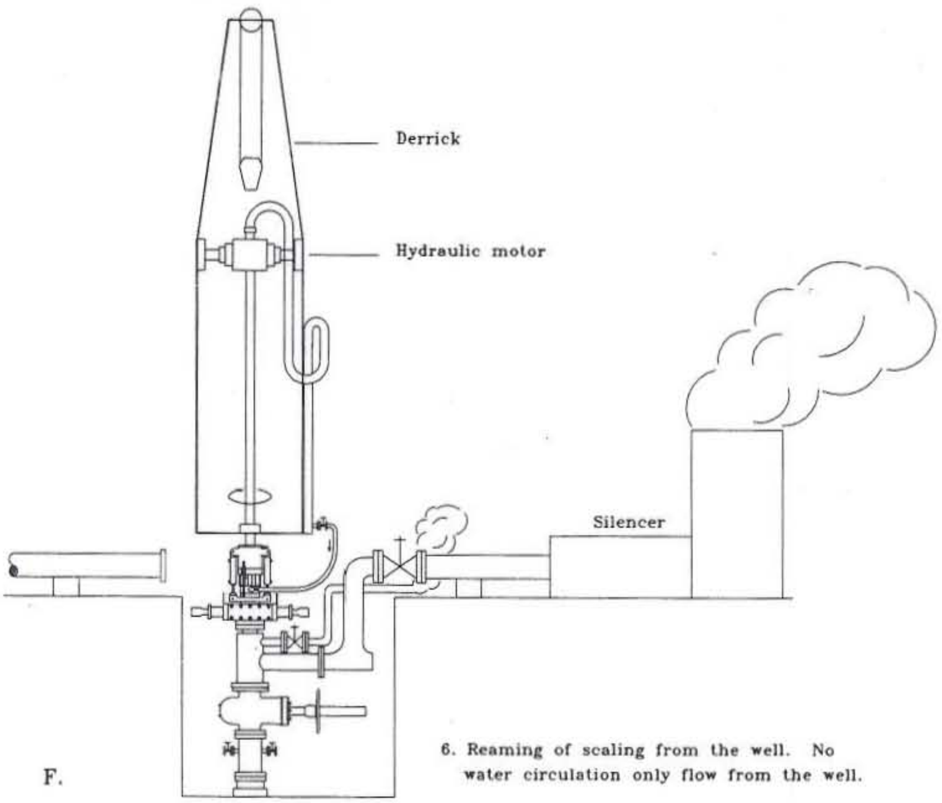
c) Then the special gland with the BOP is installed. Due to the restriction in the internal diameter of the gland (4 ¾") and BOP (7 ⅝") the 12 ¼" bit is placed inside the diverter with a short drill collar extending through the gland. The flow line and a valve to limit the flow is then connected to the silencer (Figure 9C);

d) The rig is brought in and installed over the well. The water line is connected to the gland for cooling. The first drill collar is connected to the short drill collar. The master valve is closed during this step (Figure 9D);

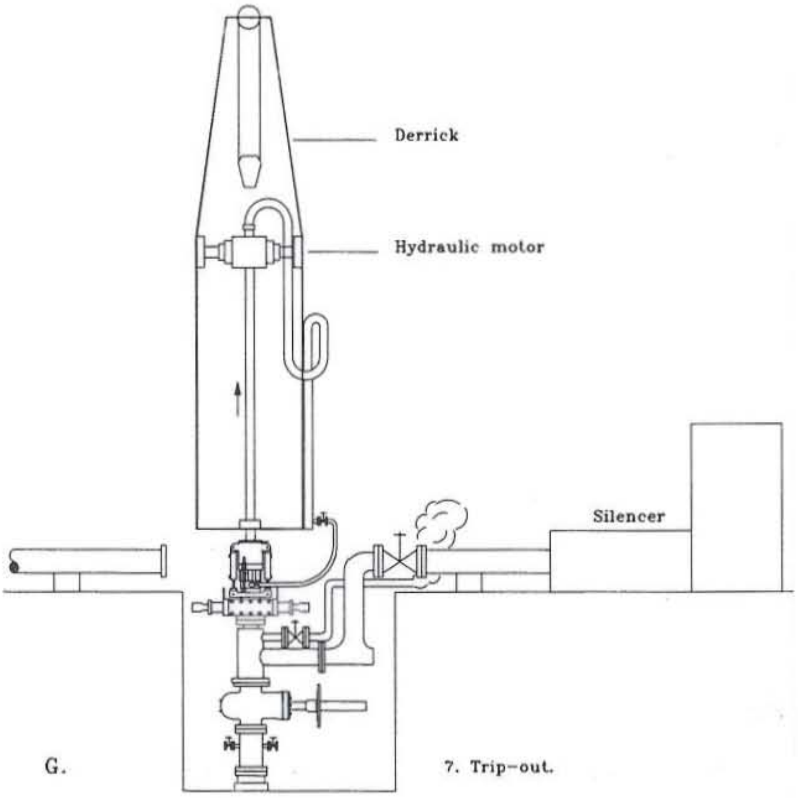
e) Because the rig used for this operation is not a new model with top drive, it was necessary to improvise a special temporary arrangement. It consists of a hydraulic motor and two pulleys fixed to the base of the rig. The pulleys are required to pull-in the drill string to overcome the pressure from the well until the drill string is heavy enough. In this step the master valve is open, but the valve on the flow line is kept closed (Figure 9E);

f) The reaming of the scale from the well starts. No pumping of water into the well takes place, only to the cooling chamber of the gland. The flow from the well is observed in the silencer and adjusted to give high enough velocity for bringing out the cuttings (Figure 9F).

g) Once the scaling has been cleaned out, the drill string is tripped-out with the flow line valve closed (Figure 9G). The cleaning operation is finished and the master valve shut.



6. Reaming of scaling from the well. No water circulation only flow from the well.



7. Trip-out.

FIGURE 9: Cleaning operation in a discharging well in Iceland; sequence of operations, steps F and G

The pull-down required at different depths and for different values of wellhead pressure

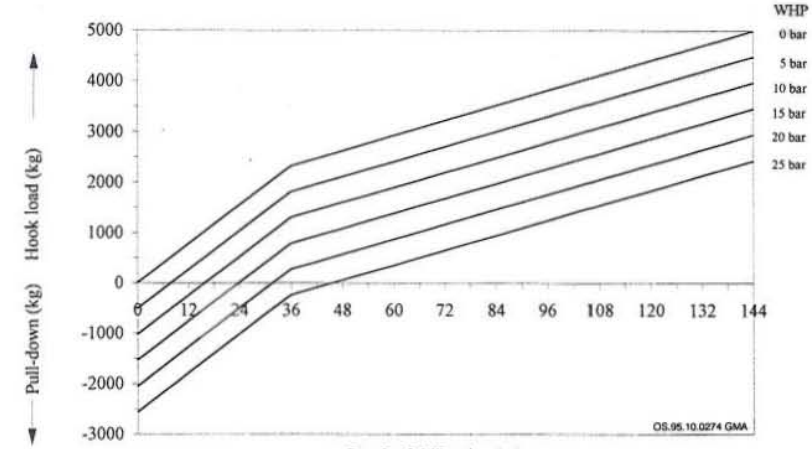


FIGURE 10: Pull-down required to overcome pressure from the wells

(WHP) is plotted in Figure 10. If the wellhead pressure is for example 15 bars, it is necessary initially to apply 1539 kg pull-down to the drill string in order to overcome the pressure from the well. Furthermore, at 24 m depth the equilibrium state is reached and at that moment the drill string is heavy enough to overcome the pressure from the well. The special arrangement used for pull-down (Figure 9E), can be taken off. The first part of each curve shown in Figure 10 represents the weight of 36 m of drill collars (4 ½" OD, 2" ID) and the second part is the weight of straight drill pipe (4 ½" OD, 16.60 lb/ft).

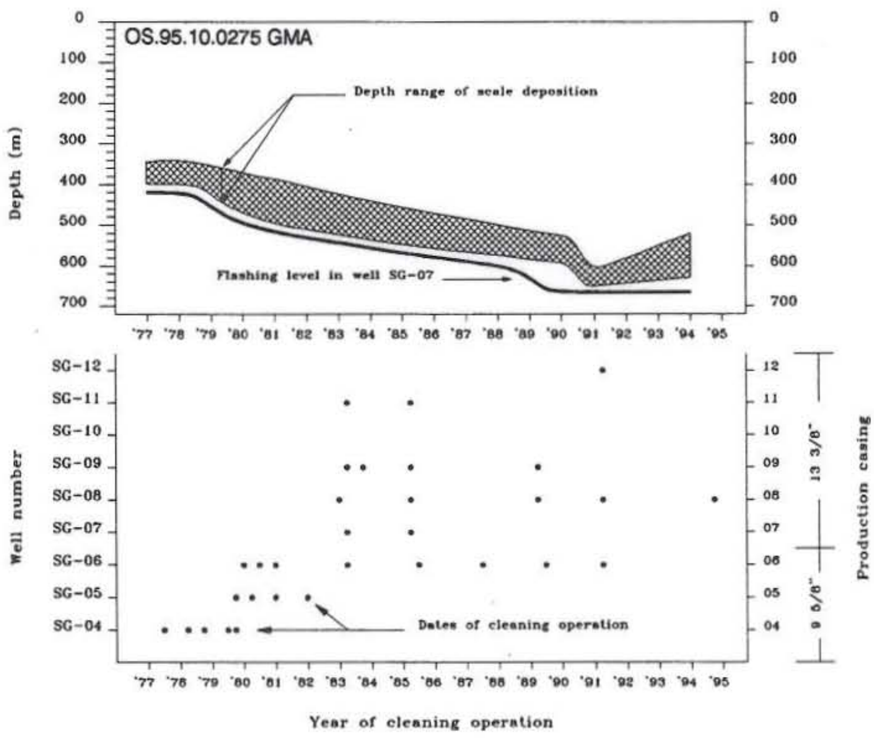


FIGURE 11: Dates of cleaning operations and depth range of scale deposition found in the wells of the Svartsengi geothermal field, Iceland

The method shown was developed for cleaning operations in the wells of the Svartsengi geothermal field in Iceland. The results obtained by this method have been very favourable as the wells have been cleaned 31 times, recovering the original output every time. The black points in the lower part of Figure 11 represent the date of cleaning operations in the wells of the Svartsengi geothermal field. As is shown, the wells SG-04 to SG-06 have 9 ⅝" OD production casing. The wells SG-07 to SG-12 have 13 ⅜" OD production casing. It is clear that the number of cleaning operations is less frequent in the wells with the larger diameter of production casing. The design of casing programme was changed in 1980 in order to get more production and reduce the frequency of cleaning operations. The depth range of deposition found in this field is shown in the upper part of Figure 11 as determined from driller logs along with a graph showing the flashing level in well SG-07. These curves reflect the lowering of pressure in the reservoir during this period.

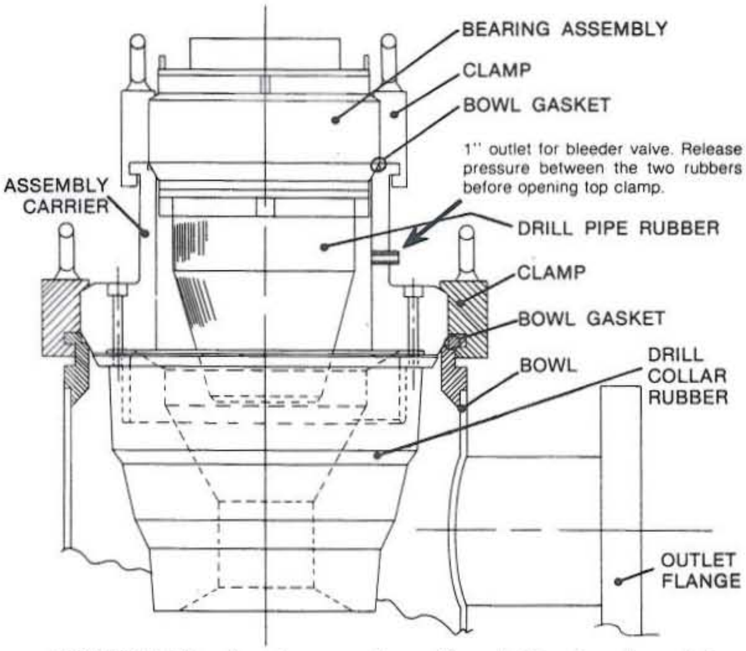


FIGURE 12: A cutaway view of a rotating head model for geothermal wells (Williams Tool Co., Inc.)

Other equipment proposed for cleaning the wells during discharge is a special rotating head instead of the gland used in Iceland. A new concept of Double Rubber Rotating Head for geothermal drilling has been developed. The main purpose of the head is to provide a means for sealing on the entire drill string of conventional design while stripping the hole in or out. When drilling with mud or water, the flowline outlet provided on the head is used. Also, for the cleaning operations the well flows through this flowline during discharge. Figure 12 presents a cutaway view of geothermal rotating head model. This special design allows the bearing assembly to be replaced without tripping out of the well, and taking only a few minutes instead of hours. The head is, according to information provided by the manufacturer, designed to operate to 500 psi (34.5 bar) nominal and 2000 psi (138 bar) static. Some features of this model are:

a) Sealing on the entire drill string of conventional design with tool joints while stripping in or out of the well;
b) Bearing assemblies designed to pass through a 17 ½" rotary table;
c) Assembly carriers designed to pass through a 27 ½" rotary table;
d) Special rubber compounds provide long life at high temperature;
e) Stationary drill collar rubber that is bolted to the assembly carrier providing easy removal without making a trip.

5. CASE HISTORIES OF GEOTHERMAL WELL REHABILITATION

The objective of this chapter is to present and to compare the methods and techniques utilized for the rehabilitation of wells with scaling problems in different countries. A detailed description on the cleaning operations in wells of the Ahuachapán (C.E.L., 1994) and Krafla geothermal fields is presented. In both of these fields, the author witnessed the cleaning operations. For comparison, similar operations carried out in Cerro Prieto, México, and in Miravalles, Costa Rica, geothermal fields are described, based on reports.

5.1 Ahuachapán geothermal field, El Salvador

The Ahuachapán geothermal field is the main geothermal field in El Salvador used for the generation of electricity and located in the west part of El Salvador. The installed capacity in the Ahuachapán geothermal power station is 95 MW$_e$ with three units (30, 30 and 35 MW$_e$) which were put on line between 1976 and 1981. A total of 32 wells have been drilled in this field between 1968 and 1981, 15 of which are producers. Figure 13 shows the geothermal field, the location of wells and the power station (Montalvo, 1994).

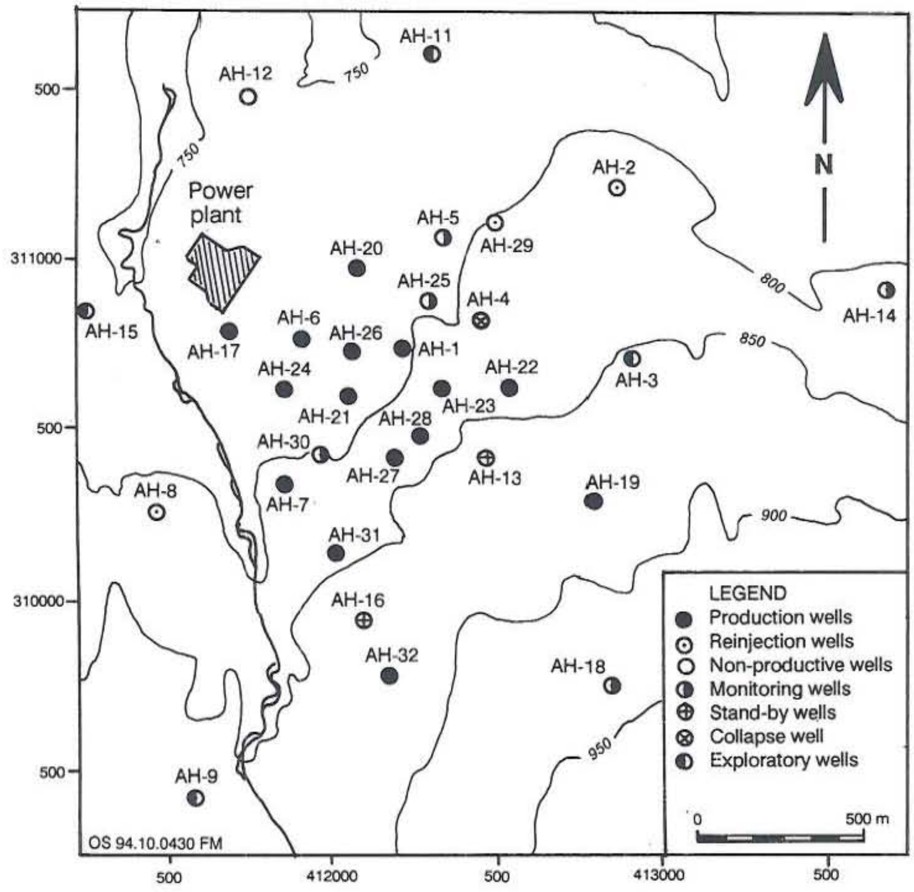


FIGURE 13: Location of the Ahuachapán geothermal field and wells, El Salvador (Montalvo, 1994)

Between 1992-1993 a decrease in the steam production was detected in wells AH-17 and AH-32 (1,200 and 1,500 m deep, respectively). Calibration with spheres (baskets) of different diameters was carried out inside the production casings and slotted liners in both wells. Chemical analysis of solids sampled in surface equipment was also made.

The calibration surveys showed reduced well diameters due to scaling at 20 m depth inside the 9 ⅝" OD production casing in well AH-17 (Figure 14) and in well AH-32 at 850 m depth inside the 7 ⅝" OD slotted liner (Figure 15). Based on these results it was concluded that deposition problems were present in both wells and probably caused the decrease in the wellhead pressure. According to the chemical analysis it was determined that silica scaling was present in well AH-17 and calcite scaling in well AH-32. Figures 14 and 15 show the casing profiles and the estimated deposition zones in these wells. It was thus decided to carry out cleaning of these wells. The intention was to:

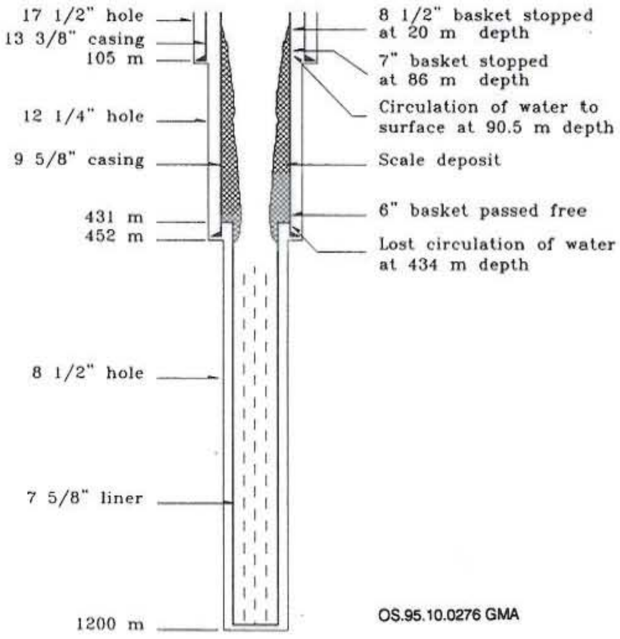


FIGURE 14: Casing profile and estimated deposition zone in well AH-17, Ahuachapán, El Salvador

a) Increase the availability of steam to the Ahuachapán geothermal power station;
b) Decentralize the exploitation zone of the field;
c.) Maintain acceptable pressure levels in the reservoir;
d) Make reserve wells available for the

maintenance of wells in the field

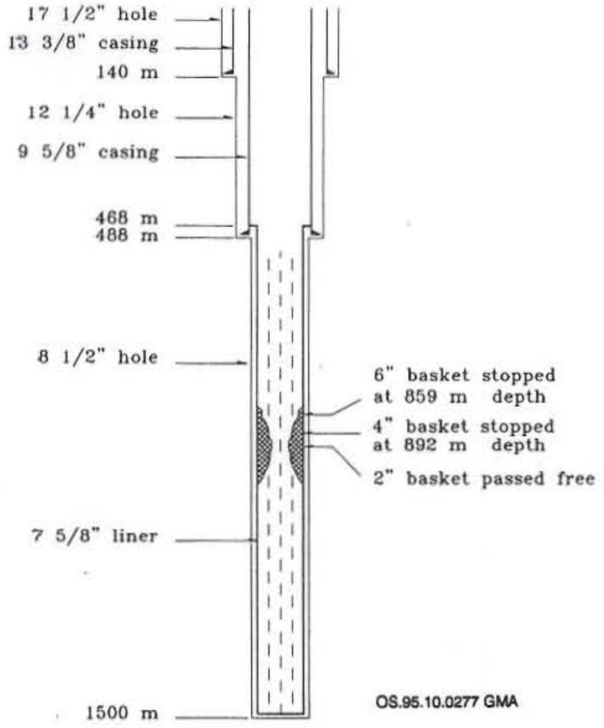


FIGURE 15: Casing profile and estimated depostion zone in well AH-32, Ahuachapán, El Salvador

AH-17: Well data and cleaning operations

Latitude: 310,761.95;
Longitude: 411,697.32;
Elevation: 773 m a.s.l.;
Depth: 1200 m;
Drilling date: 29 June-30 August, 1976.

Casing programme:
Surface casing: 13 ⅜" OD,
cemented at 0-104.5 m depth, 17 ½"ø bit;
Production casing: 9 ⅝" OD,
cemented at 0-450 m depth, 12 ¼" ø bit;
Slotted liner: 7 ⅝" OD,
hung from production casing
at 431-1200 m depth, 8 ½" ø bit.

Repair date: 22 April-01 May, 1994.

Drilling equipment: IDECO Rig;
Height: 36 m (117 feet);
Static capacity: 162,386 kg;
Hoist IDECO H-1000, 950 HP;

Sub-structure: IDECO, 5 m height;
Nominal capacity: 158,757 kg;
Stowed capacity: 90,718 kg.

Pumps: Two IDECO T-800, Triplex;
Flow rate: 26.3-42.5 l/s.

The drill rig was moved in and operations started to kill the well which was at 19 bar (275 psi) wellhead pressure at the time. Cold water was injected into the well by the kill line of the expansion spool with gradual increase in the rate from 5 to 11 l/s until the well was controlled obtaining a wellhead pressure of 0 psi. The BOP arrangement was installed and tested.

Drill string with 8 ½" ø insert bit was run into the 9 ⅝" OD production casing detecting resistance to its descent at 20 m depth. Rotation and weight on bit of 1-2 tonnes was applied and drilling to 90 m in water loss circulation. At this point circulation of water was obtained bringing silica cuttings to the surface. Weight on bit was increased to 4 tons going down to 432 m. It was not possible to drill further because the liner hanger was intersected.

A new drill string with 6 ¾" ø milled tooth bit was run into the well drilling the plug of silica formed inside the liner hanger until 434 m depth. From 434 m the string was lowered without rotation in water loss circulation to 1188 m. It was not possible to lower the bit below 1188 m due to resistance. The reaming of the well was thus completed.

To ensure the cleaning of the 9 ⅝" OD production casing a string with 8 ¾" ø insert bit and 8.96" diameter Casing Scraper was also lowered into the hole, descending and reaming down to 432 m in loss of circulation of water. During all these operations cold water was injected into the well by the kill line. Later, a Mechanical Survey of Calibration (Kinley) was carried out in the 9 ⅝" OD production casing. It was made with the Kinley Microscopic Caliper to the internal surface of the 9 ⅝", 36 l/ft casing at 0-431 m. The casing was in good condition with respect to corrosive damage and scale cleaning.

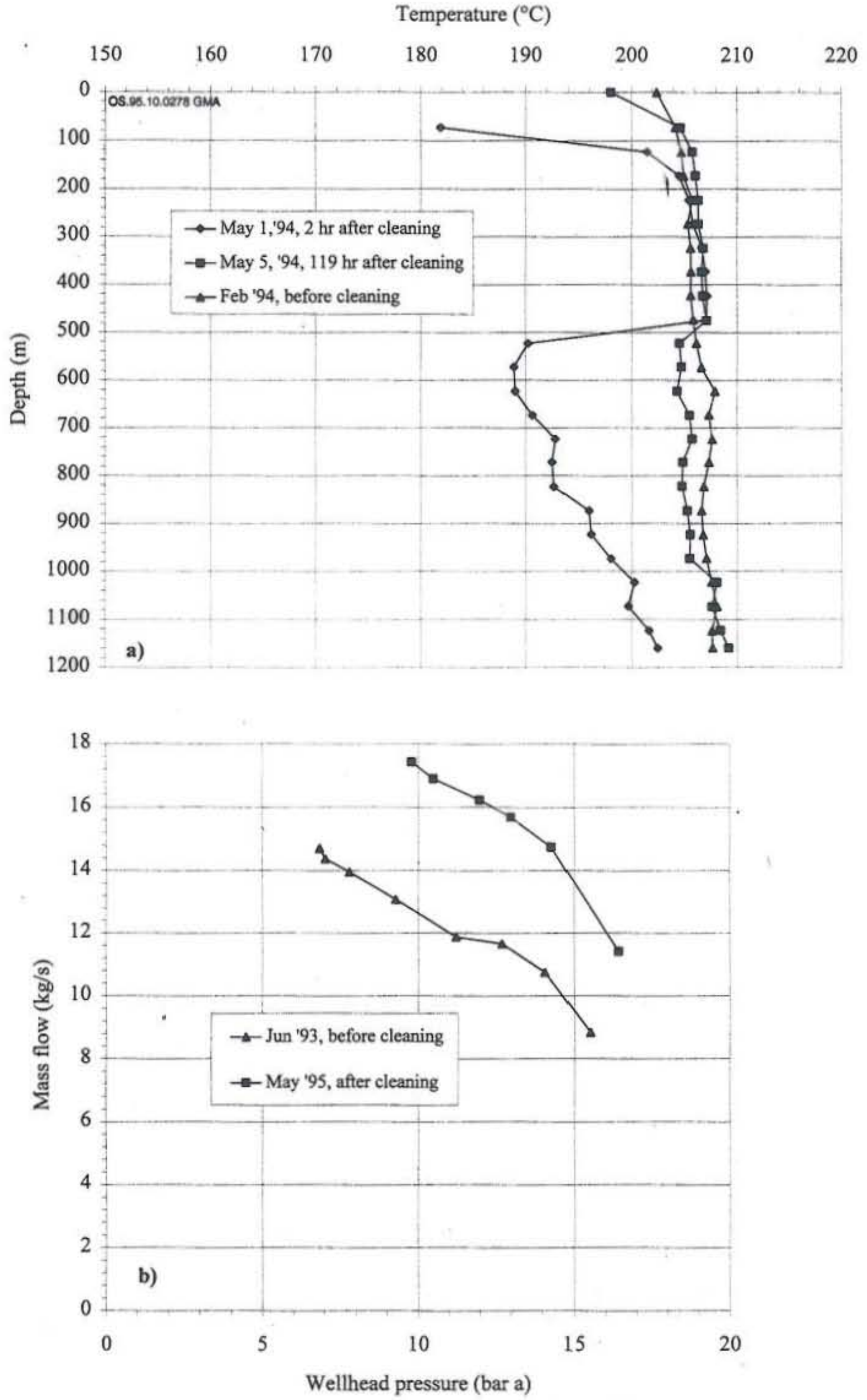


FIGURE 16: The dry steam well AH-17 in Ahuachapán, a) thermal recovery surveys and b) production tests made before and after cleaning

A new wellhead arrangement consisting of Master Valve and Foster Expansion Spool type RDD (with 3 lateral valves, one of which is 60° for future chemical inhibition) was installed. Later, thermal recovery surveys and production tests were made. The result of these surveys and a comparison with former surveys are presented in Figure 16. It is clear that the well conditions reached after cleaning are satisfactory.

After cleaning, the thermal recovery was very rapid and the total mass flow, which is steam only, had increased with respect to the former test made in 1993. AH-17 now produces approximately 8-9 ME_e (April, 1995).

AH-32: Well data and cleaning operations.

Latitude: 412,210;
Longitude: 309,721;
Elevation: 882 m a.s.l.;
Initial depth: 1500 m;
Drill.date: 13 October-25 December, 1981.

Casing programme:

Surface casing:	13 ⅜" OD, cemented at 0-137 m depth, 17 ½" ø bit;
Production casing:	9 ⅝" OD, cemented at 0-487 m depth, 12 ¼" ø bit;
Slotted liner:	7 ⅝" OD, hung from production casing 468-1499 m depth, 8 ½" ø bit.

Repairing date: 14 May-15 October 1994; Repairing depth: 1150 m;
The same drilling equipment was used as for cleaning well AH-17.

Figure 17A shows the profile of the well before cleaning operations. Initially the well was drained through the lateral valve of the expansion spool to 0 psi. The behaviour of this well is different from that of well AH-17 since it needs induction to flow Water was injected into the well by the kill line with gradual increase in rate from 5 to 11 l/s. Later, the BOP arrangement was installed and tested.

A 6 ¼" ø milled tooth bit was lowered to 852 m depth without rotation where resistance was detected. Rotation of 40 RPM and weight on bit of 1 tonne was applied and calcite scale was removed in total loss of circulation of water until 888 m depth. At 888 to 889.5 m depth jumps were observed in the string. There was no advance made below 889.5 m. The bit was taken out showing some broken teeth. In the opinion of GeothermEx's Consultant the slotted liner had collapsed or was damaged at this depth. Due to this result, it was decided to pull out the slotted liner and replace it with a new one.

A new string consisting of: 5 ¾" ø casing spear, 6" ø safety joint, 6 ½" ø bumper jar, 6 ½" ø drill collar and 4 ½" ø drill pipe was deployed. Descent was free and without rotation. The casing spear was placed inside 7 ⅝" OD liner (2 m below the liner hanger) to 470 m depth and was operated (turning counter-clockwise). Gradually tension was applied until the liner hanger was detached (theoretically), and the slotted liner was lifted. The total weight was not in accordance with what was expected. Only 173 m of liner were pulled out on surface, representing 14 pieces of slotted liner. Remaining in the well were approximately 560 m of liner. The pieces no. 13 and 14 showed the slots plugged with calcite, which means that a deposition zone is located between 660 and 680 m depth. The last piece of the slotted liner pulled out showed that the thread was not totally engaged.

A second trial to fish the slotted liner was made with the casing spear. This time a total of 247 m of slotted liner was recovered, i.e. 20 pieces, which meant that 303 m remained in the well. It is necessary to mention that the last piece of slotted liner pulled up was totally fractured and some of the other pieces showed fissures between the slots, which indicated material failure. Furthermore, pieces 30, 31 and 32 of slotted liner located between 821 and 860 m depth showed calcite deposition of 1 cm thickness along each piece. Other attempts to fish the remaining slotted liner in the well failed. To mill the top of the

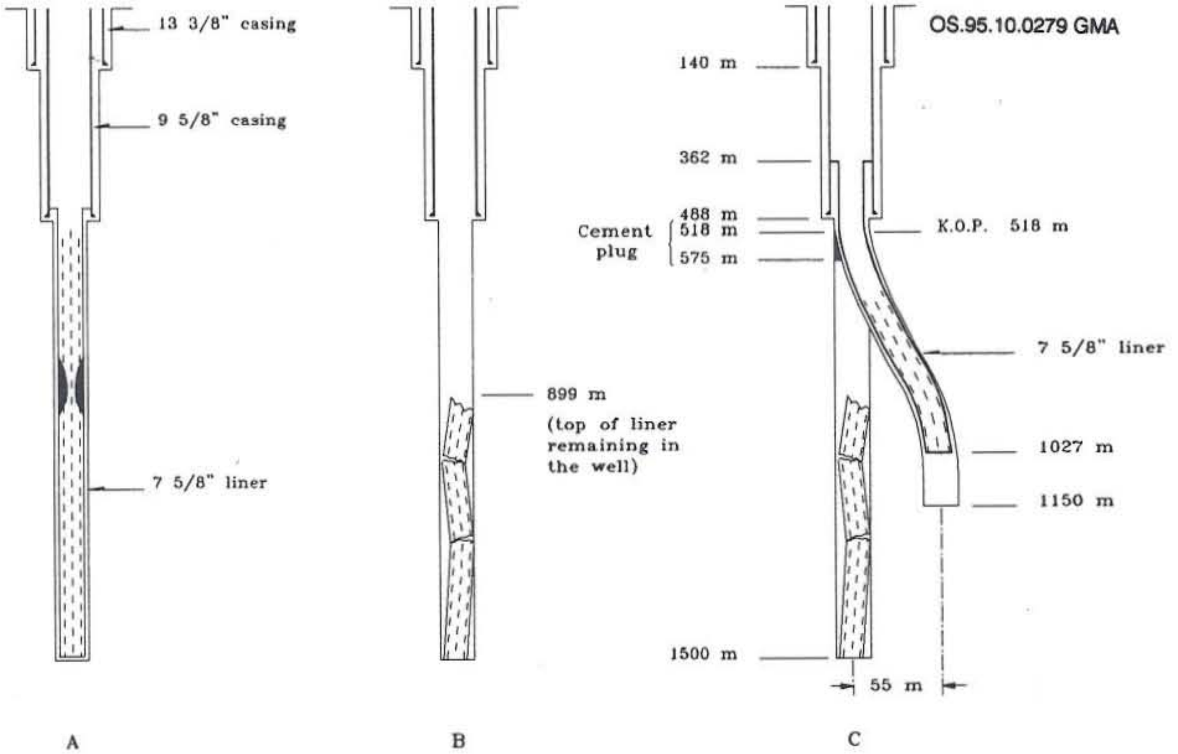


FIGURE 17: Well AH-32 in Ahuachapán, a) profile before cleaning operations; b) condition of well after cleaning and fishing operations, c) final profile after side tracking

fish, first a taper mill and then a home-produced mill were used to dress the casing for a casing spear. but without results. The fishing operations were thus adjourned.

In order to determine the conditions of the open hole and the 9 ⅝" OD production casing, a contract with Schlumberger Surenco of Guatemala was made for the following surveys:

a) Use of dual caliper, borehole geometry tool (BGT) to obtain information about the geometry of the 8 ½" ø open hole, and analyze the possibility to set an inflatable packer in a stable zone for a possible side tracking operation;
b) Multifinger Caliper survey (MFC) to verify the condition of 9 ⅝" OD production casing;
c) Cement bond log (CBL) to find out the condition of cementing behind the 9 ⅝" OD casing. To make this survey it is necessary to set a retrievable borehole packer (RBP) at the end of the production casing to fill the hole with water.

The Dual Caliper Log was made into the 8 ½" ø open hole and it indicated that the geometry of the open hole was not uniform. In some places the inside diameter was greater than 30 inches. It was determined that the best zone to set the inflatable packer was at 562-565 m depth. The MFC survey indicated that the production casing was in good condition, no corrosion, no scaling, no fissures, and the inside diameter was uniform. It was not possible to carry out the CBL survey because of problems in setting the Retrievable Borehole Packer.

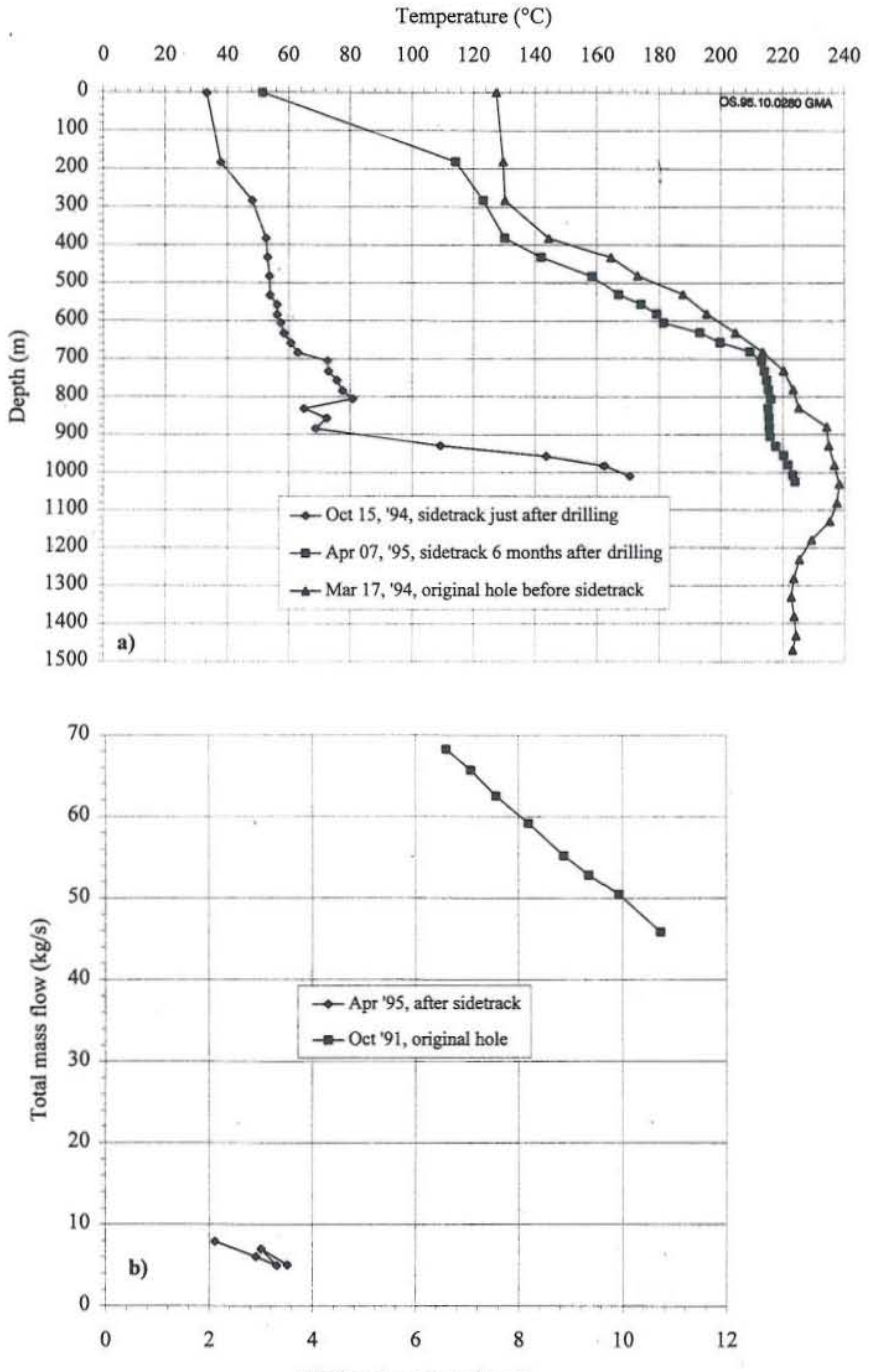


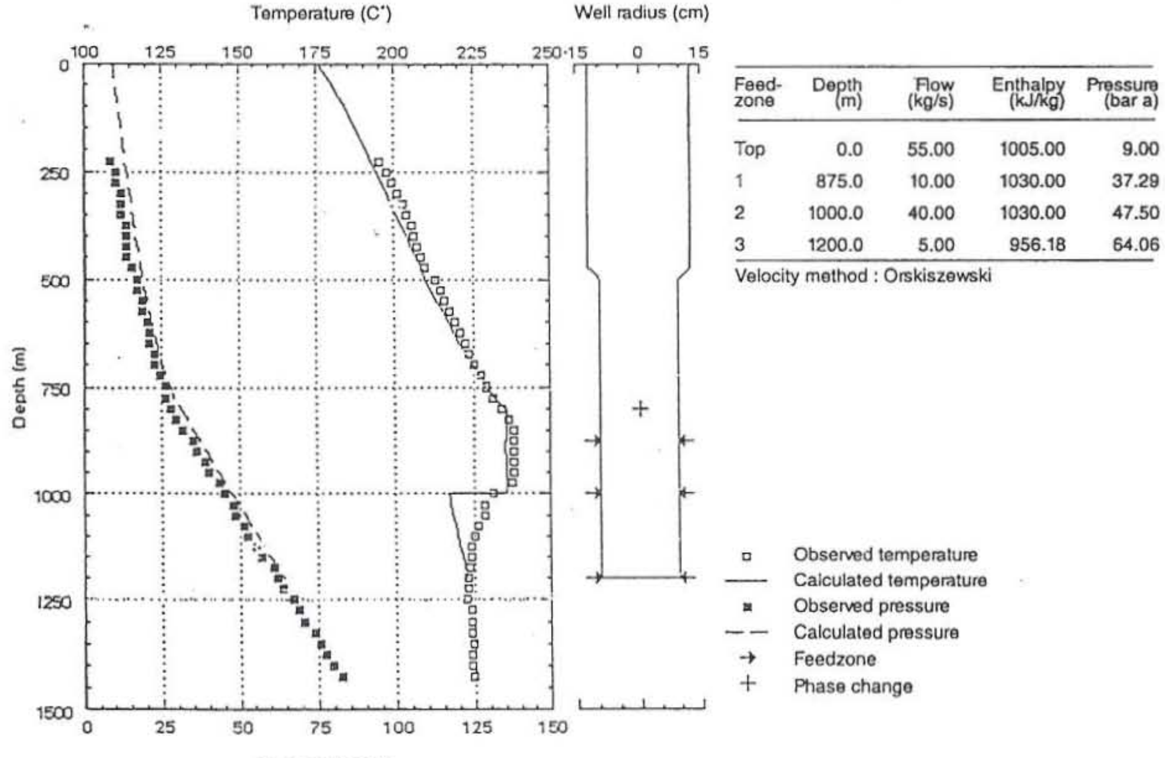
FIGURE 18: Well AH-32, Ahuachapán, a) thermal recovery surveys and b) production tests before and after side tracking

The Consultant's opinion was that because of the geometry of 8 ½" ø open hole, the fish could be inclined and leaning against the wall of the borehole as is shown in Figure 17B. Different alternatives to continue with the operation were evaluated and the recommendation was to drill a side track, putting a cement retainer packer at 563 m depth. This was not successful and, thus, it was necessary to pump a viscous slug to the same depth consisting of bentonitic mud. Cement was pumped over this plug in order to isolate the production zone (reservoir).

All these operations were carried out with success and later side tracking operations started by drilling directionally from 518 m depth (kick-off point) with 8 ½" ø diamond bit and downhole motor to 528.5 m depth. The well was drilled directionally to 677 m depth obtaining a maximum angle of 5° 45' with 8 ½" ø insert bit. Later, drop off operation was initiated at 677 m depth drilling to 1,150 m depth. The 7 ⅝" ø slotted liner was lowered and hung at 362 m inside the 9 ⅝" OD production casing. It is necessary to mention that during drilling operations an unstable zone was detected between 650 and 700 m depth. Collapses of the hole at this depth took place several times. Figure 17 shows the conditions of the well before cleaning operations, after cleaning and fishing operations, and the final profile after side tracking.

The wellhead arrangement consisting of Master Valve and a new Foster Expansion Spool type RDD (with 3 lateral valves one of which is 60° for future chemical inhibition) was installed. Later, thermal recovery surveys and production tests were made. The results of these surveys and comparison with former surveys are showed in Figure 18. As is shown in this figure, the main feed zone is located between 800 and 950 m depth. The well has been discharged to the atmosphere seven times between December 1994 and July 1995 in order to clean the well and to accelerate its thermal recovery process. At the present time, the well has not reached production conditions (July 1995).

With the utilization of the wellbore simulator HOLA (Björnsson et al., 1993) several runs were made to calculate the flashing level. Figure 19 shows the results obtained. This figure establishes that the main feedzone is located from 875-1000 m depth and the phase change (flashing point) takes place at 800 m depth. Also the flashing depth determined with this simulator corresponds to observed calcite scaling depth obtained by caliper surveys.



Feed-zone	Depth (m)	Flow (kg/s)	Enthalpy (kJ/kg)	Pressure (bar a)
Top	0.0	55.00	1005.00	9.00
1	875.0	10.00	1030.00	37.29
2	1000.0	40.00	1030.00	47.50
3	1200.0	5.00	956.18	64.06

Velocity method : Orskiszewski

FIGURE 19: Results of the HOLA simulator calculation for well AH-32, Ahuachapán

5.2. Krafla geothermal field, Iceland

The Krafla high-temperature geothermal area lies within the active volcanic zone in northern Iceland, about 10 km north of the Námafjall field. It is located within the caldera of the Krafla central volcano, which formed about 100 thousand years ago (Saemundsson, 1983). A 50 km fissure swarm associated with the central volcano intersects the caldera. Volcanic activity is extensive and there have been several eruptive periods during the last few thousand years. Nine eruptions took place in this area in the period 1975-1984, the last one in September, 1984 (Björnsson, 1985).

The exploration of the Krafla field started in 1970-73, and in 1974 two exploration wells were drilled. A decision was made to build a 60 MW_e power station concurrent with the drilling for steam. Only one of the two 30 MW_e turbines has been installed (Ármannsson, 1989), due to inadequate steam supplies.

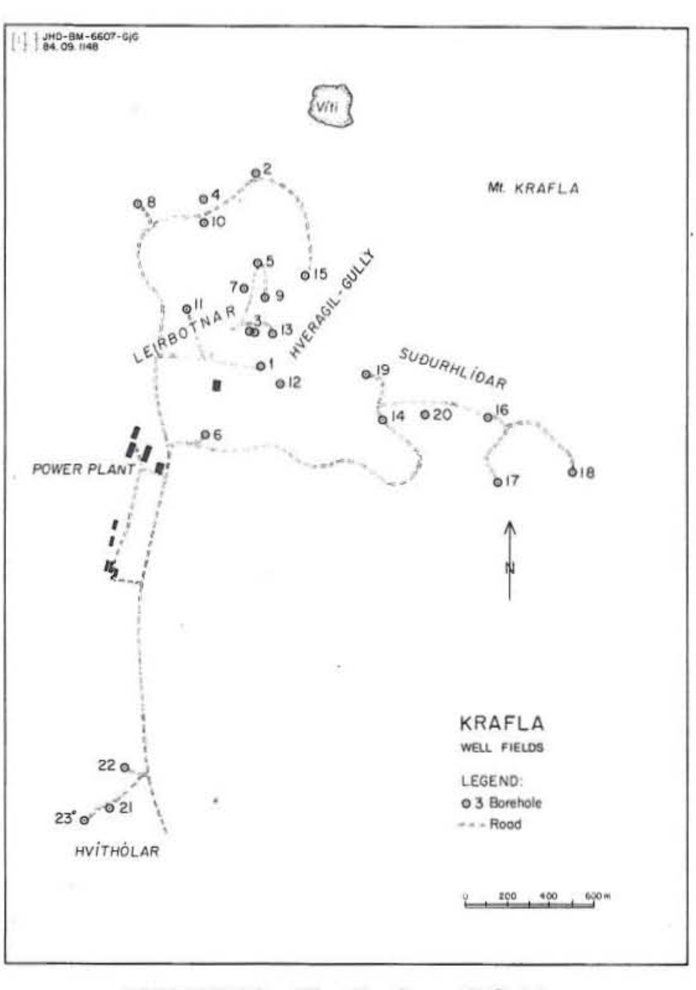


FIGURE 20: The Krafla well fields, N-Iceland (Ármannsson, 1989)

Three fields have been drilled in this area, revealing a complex geothermal system: *Leirbotnar* with a relatively cool liquid-dominated (190-220°C) upper zone and a hot two-phase (300-350°C) lower zone; *Sudurhlídar* a system that conforms to a boiling point with depth temperature-pressure curve, and *Hvíthólar* with a relatively hot two-phase upper part (260°C at 600 m depth) and a much cooler lower part (180°C at 1200 m depth gradually increasing to 240-250°C at 1800 m depth) (Ármannsson, 1989). The upper zone in the Leirbotnar field and the lower zone in the Hvíthólar field are the only liquid dominated parts of the system. Figure 20 shows the Krafla well fields.

Well KJ-9 is at Leirbotnar and intersects both the upper and lower reservoirs. It is the only well experiencing calcite deposition in Krafla. Some studies have been done with the aim of preventing or controlling calcite deposition (Ármannsson, 1989).

KJ-9: Well data and cleaning operations

Well KJ-9 taps fluid from the border of the upper and lower zones. The results of enthalpy measurements suggest that the inflow is liquid-dominated and that flashing takes place in the well. Well KJ-9 was originally drilled in 1976. It was deepened in 1977, and referred to as KJ-9a. In late 1982 it was deepened again after which it is referred to as KJ-9b. Figure 21 shows the location and trajectory of this well (Gudmundsson et al., 1983).

With the wellbore simulator HOLA (Björnsson et al., 1993) the flashing depth of the well was calculated. The calculated flashing depth and the observed depths of deposits in the well are presented in Table 1 (modified from Ármannsson, 1989).

Temperature and pressure logs made in the flowing well suggest a flashing zone now at about 300 m depth in this well. Some very deep seated scale deposits were observed after the 1979 reaming, when the enthalpy was considerably higher.

After deepening the well in 1977, the maximum deposition depth has been found at 730 m. The well required drilling out the deposits 1-2 times per year from 1977 to 1991. From that time until 1995 the well has been cleaned every 2 years. The well mass flow was an average of 16 kg/s, at 5 bar-a pressure for 180 days after which the liner was pulled out, the thickness of calcite scale measured, and a caliper log run on the casing. A sample of these deposits was analysed with the results shown in Tables 2 and 3 (modified from Ármannsson, 1989). The scale consists essentially of calcium carbonate with a trace of magnesium carbonate.

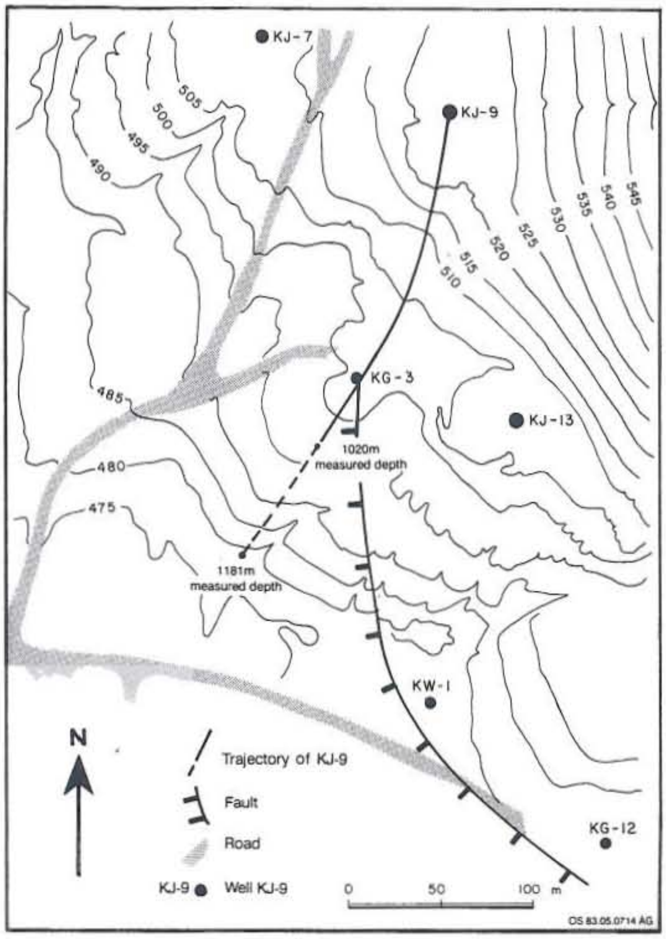


FIGURE 21: Location and trajectory of well KJ-9, Krafla, N-Iceland (mod. after Gudmundsson et al., 1983)

TABLE 1: Calculated flashing depths and observed depths of deposits in well KJ-9, Krafla, Iceland.

Well No.	Depth (m)	Casing Inner radius (m)	Casing Depth (m)	Liner Inner radius (m)	Liner Depth (m)	Calculated minimum flashing depth (m)	Observed depth of deposits (m)
KJ-9	1101	0.158	0 - 251	0.88	259 - 1101	675	250 - 290
KJ-9a	1263	0.111	0 - 1074	0.88	1062 - 1259	625	450 - 950
KJ-9b	1280	0.111	0 - 1074	0.88	1063 - 1274	625	390 - 560

TABLE 2: Chemical analysis of scale from well KJ-9, Krafla, 1977

CaO	MgO	Fe_2O_3	Al_2O_3	SiO_3
55.6%	0.6%	0.1%	0%	0%

TABLE 3: Scale from Krafla KJ-9, probable composition

$CaCO_3$	$MgCO_3$	Fe_2O_3
98.6%	1.3%	0.1%

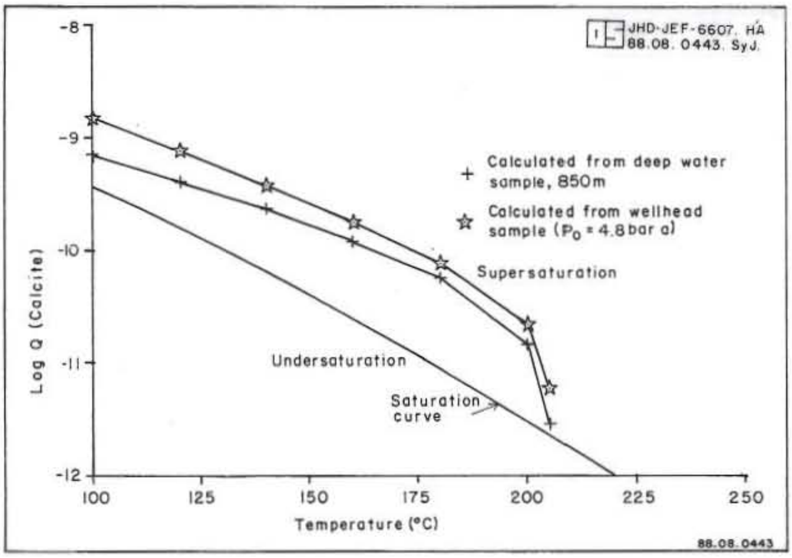


FIGURE 22: Well KJ-9, Krafla, N- Iceland, calcite supersaturation as a result of flashing,

Figure 22 shows the results of calculations of calcite supersaturation in well KJ-9. While conditions were stable, the blocking times of well KJ-9 due to scaling, were relatively constant.

Figure 23 shows the length of time of undisturbed flow after removal of deposits from KJ-9a and KJ-9b to be about 200 days (Ármannsson, 1989).

Figure 24 shows the scaling of liner and casing measured in well KJ-9 by a caliper log (Ármannsson, 1989).

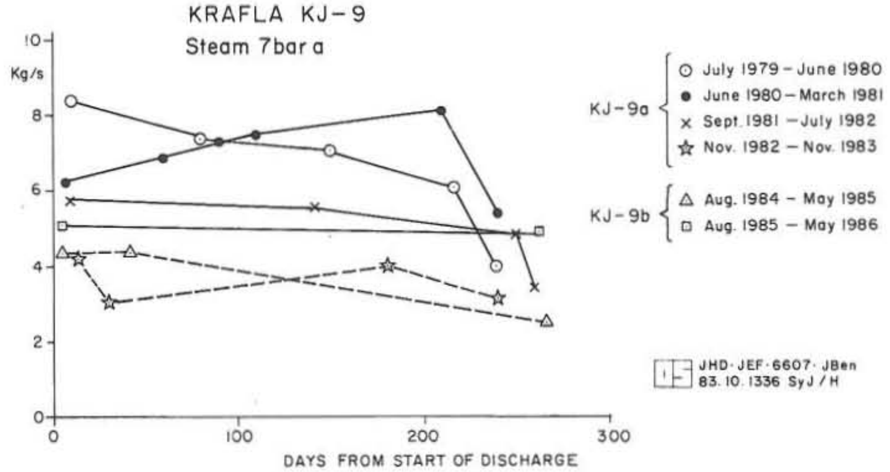


FIGURE 23: Time of undisturbed flow after removal of deposits from KJ-9a and KJ-9b (Gudmundsson et al., 1983)

Figure 25 presents the estimated scaling profile in well KJ-9. The black points in this figure are the dates of cleaning operations in the well. The shadow area is the depth range of scale deposition found from 1979 to 1995.

Figure 26 shows the dates of past cleaning operations and the depth interval where the deposits have been found as determined from driller logs. As shown the deposition zone is moving higher up the well every time. This means that the flashing level is changing too. With these parameters it is easy to conclude that the well is cooling down with time, if the well is being operated at the same wellhead pressure every time. Measurements in this well show a decrease in temperature from 300 to 240°C over this period. The main feed zone of this well is receiving fluids of lower temperature coming from some non productive shallow wells drilled near to well KJ-9.

The empirical prediction of well blockage time has proven useful for the planning of dates for work-overs. Due to this, a new cleaning operation of the deposits in this well was programmed to be carried out in the summer of 1995 as preventive maintenance. In the following paragraphs a summary of this operation is presented.

The drill rig was moved in and was installed on the well on August 23, 1995. The operation was carried out by Jardboranir hf, an Icelandic drilling company with the following drilling equipment:

Name of drill rig: Narfi; Type: Failing 3000;
Derrick height: 18 m; Rig capacity: 1200 m;
Draw-works: 54.432 kg;
Pumps: Two Gardner Denver FXD-172, Duplex
5 ½" ø piston, 15 l/s each one.

The operation started on August 24, 1995, with injection of water to the well through the kill line. The well self-quenches when shut-in. A 8 ½" ø milled tooth bit was run into the well without rotation to 305 m depth where an obstruction was detected. The kelly was connected to apply rotation of 40 RPM and weight on bit of 1-2 tonnes to remove calcite deposition, pumping water at a rate of 30 l/s through the kelly. At the beginning circulation of water was not obtained to surface, but it was from 430 m depth. The pump pressure was increasing from 335 m depth varying between 70-100 psi, and the weight on bit was also increased to 2-3 tonnes at the same depth. Rotation of 80 RPM and weight on bit of 2-3 tonnes was applied as the calcite was drilled from 430 to 450 m depth with circulation of water to surface. The string was lowered free between 450 and 476 m depth. After that, calcite was removed from 476 to 490 m depth applying weight of 1-2 tonnes and 80 RPM on the bit. The string went down free without rotation from 490 to 1060 m depth. This means that a plug of 3 m length was formed over the liner hanger by the cuttings of calcite falling down the hole during the reaming. This plug was removed with rotation from 1060 to 1063 m depth, which is the top of the liner hanger. During these operations circulation of water was observed on

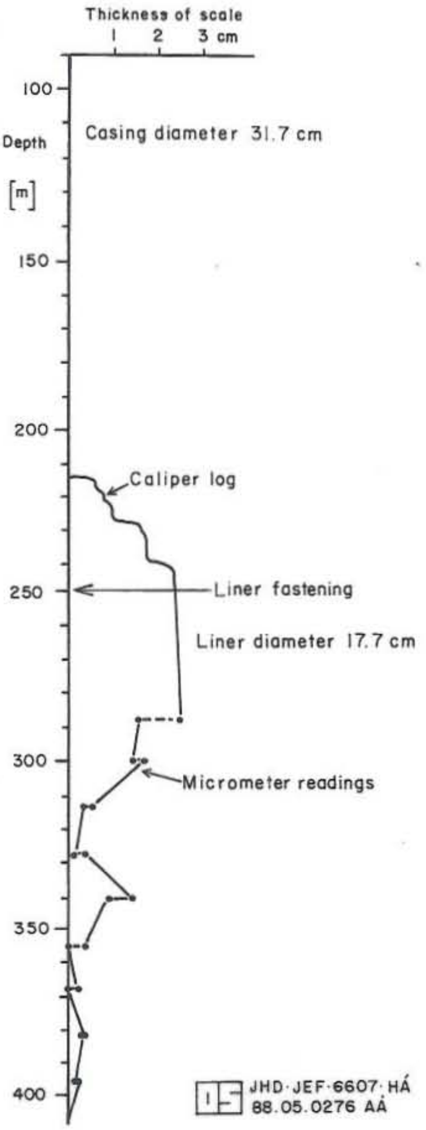


FIGURE 24: Scaling of liner and casing in well KJ-9, Krafla (Ármannsson, 1989)

A new drill string with 6 ¼" ø milled tooth bit was lowered free and without rotation into the well until 1224.5 m depth with injection of water by gravity through the kill line. Resistance was detected at this depth due to the cuttings of calcite seated on the bottom of the well. With rotation of 30-50 RPM and pumping water to 30 l/s the string was lowered to 1240.5 m depth. This was the final

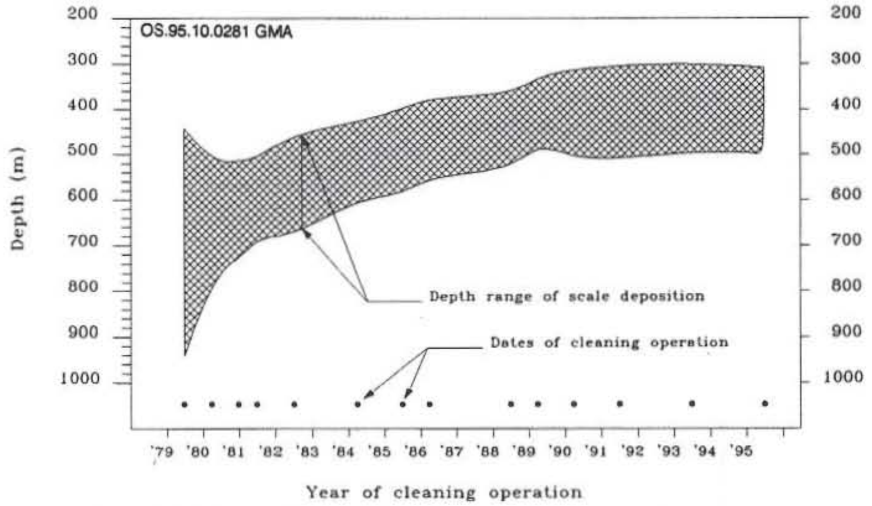


FIGURE 25: Estimated scaling profile of well KJ-9, Krafla

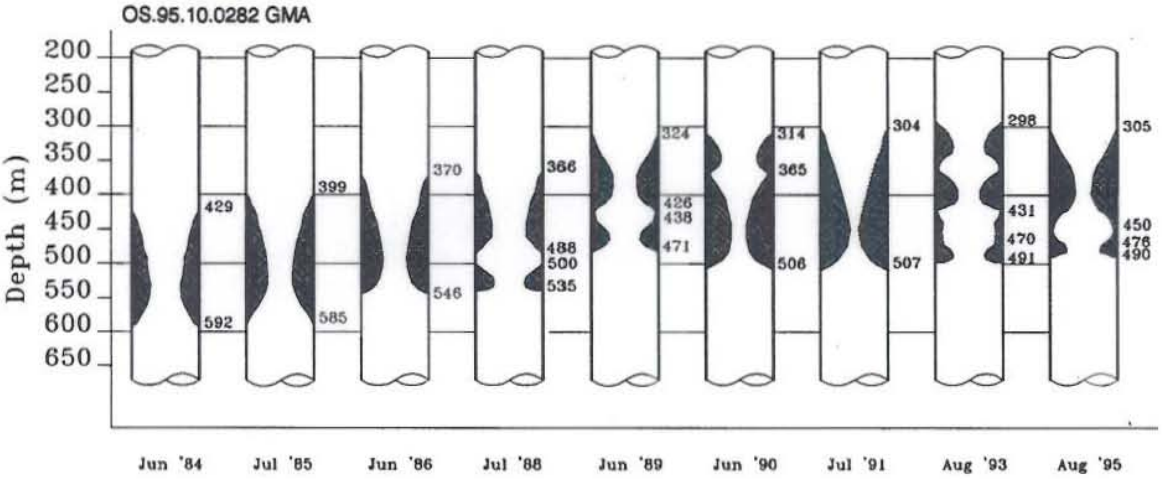
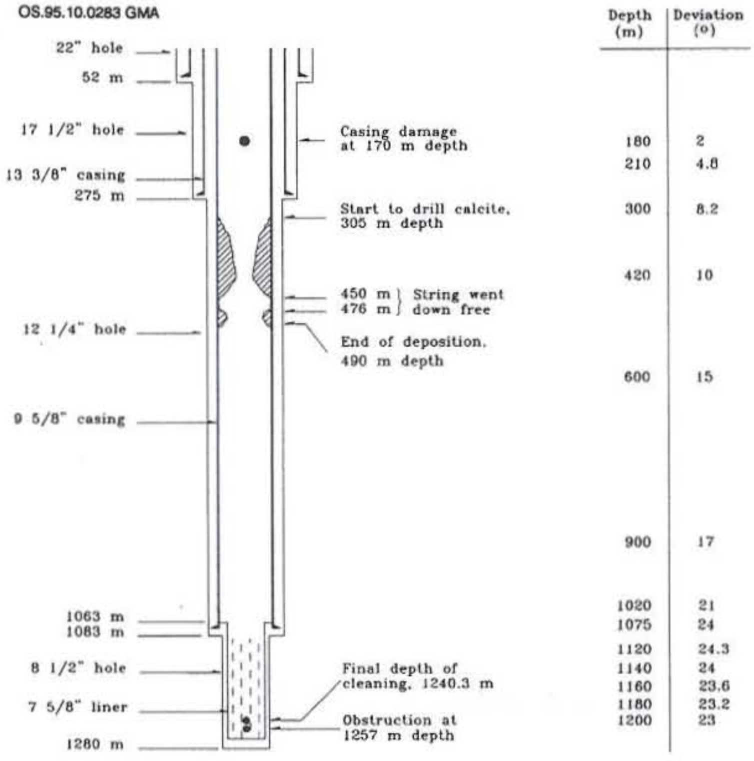


FIGURE 26: Date of cleaning operations and depth range of scaling in production casing of well KJ-9, Krafla

depth for cleaning because at 1257 m depth an obstruction has been detected in former surveys. After that, water was pumped for two hours through the kelly with returns to surface in order to sweep out the cuttings of calcite seated on the bottom of the well. The operation was finished on August 26, 1995, after 3 days. Figure 27 shows the profile and deposition zone found in this well during the cleaning operation and a brief summary of the main drilling parameters used for this operation is presented in Table 4.



Depth (m)	Deviation (°)
180	2
210	4.8
300	8.2
420	10
600	15
900	17
1020	21
1075	24
1120	24.3
1140	24
1160	23.6
1180	23.2
1200	23

FIGURE 27: Profile and deposition zone cleaned out in well KJ-9, Krafla, in August 1995 during reaming of scaling

Figure 28 shows a comparison between the general arrangement of equipment used for cleaning of wells in Iceland and El Salvador. The rig used in Iceland is smaller and can only trip out with one drill pipe at a time. The height from the ground to the rotary table is about 1 m. The rig used in El Salvador is around twice as big in height as that used in Iceland and can trip out with two drill pipes at a time. The height from the ground to the rotary table is 5 m (sub-structure height). When the operations are just for reaming of scales, the smaller rig is sufficient. But, if the operation requires to pull up the liner it is advisable to use the other one.

TABLE 4: Drilling parameters observed during cleaning operations in well KJ-9, Krafla.

ø Bit (")	**Depth** (m)	**Rate of penetration** (m/h)	**Weight on bit** (ton)	**Rotation** (RPM)	**Pump pressure** (psi)	**Conditions observed**
8 ½	0-305	-	-	-	-	Free descent
	305-335	8	1-2	40	0	Total loss of circulation
	335-380	7	2-3	40	60-90	Total loss of circulation
	380-440	7	2-3	80	75-100	Total loss of circulation
	440-450	9	2-3	80	75-100	Water on surface
	450-476	-	-	-	-	Free descent
	476-490	12	1-2	80	75-100	Water on surface
	490-1060	-	-	-	-	Free descent
	1060-1063	-	-	40	75-100	Water on surface
6 ¼	0-1224.5	-	-	-	-	Free descent
	1224.5-1240.3	8	1	30 - 50	550	Water on surface

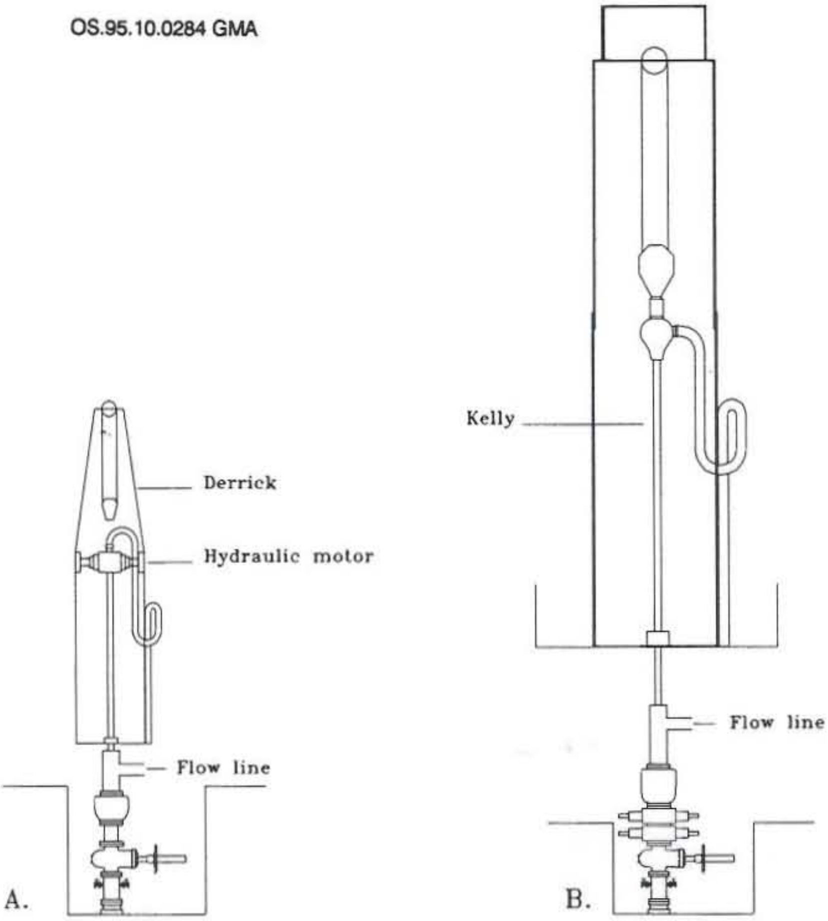


FIGURE 28: Comparison of general arrangement of equipment used for cleaning of wells in a) Iceland, and b) El Salvador

5.3 The Cerro Prieto geothermal field, México

The Cerro Prieto geothermal field, shown in Figure 29, covers an area of 40 km^2, and is contained in sands and shales of the Colorado River delta. The wells cover approximately two thirds of this area and an evaporating pond the rest (Mercado et al., 1989). Up to 1994, 223 wells have been drilled in this field to depths ranging from 700 to 3650 m. An average of 120 of these wells are integrated to the electricity generation system as production wells. The others are used as monitoring, reinjection or exploration wells. The geothermal power plant has been progressively enlarged from 75 MW$_e$ capacity in 1973 to 620 MW$_e$ in 1989 (Gutiérrez and Mendoza, 1994; Vaca,1990).

Every year an average of 12 to 16 production wells are repaired in this field, mainly due to silica deposition found in the wells or in the surrounding formation. Because of this, the rehabilitation of wells in Cerro Prieto is a continuous and necessary activity for its operation. The most common techniques for the rehabilitation of the wells have been:

a) Cleaning of deposition in the casing;
b) Deepening of a well;
c) Deviation by opening windows in the production casing of a well.

Experience has shown that the cleaning operations are the least efficient for rehabilitation in this field. Table 5 presents a summary of the statistical data obtained from repairing operations during 1988-1994 (Gutiérrez and Mendoza, 1994).

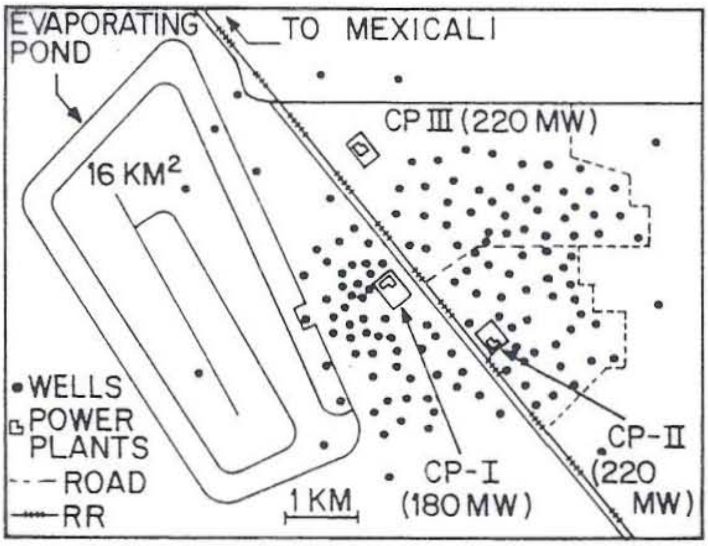


FIGURE 29: The Cerro Prieto geothermal field (Mercado et al., 1989)

TABLE 5. Statistical data on repairing activities of wells in Cerro Prieto, México, during 1988-1994 (modified from Gutiérrez and Mendoza, 1994)

Type of operation	Repaired wells	Average initial production per well (Tons/h)	Average production after repairing (Tons/h)	% of production recovered with respect to initial conditions
Cleaning	30	79	38	48
Deviation	29	69	49	70
Deepening	30	76	52	68

Well E-26: Well data and rehabilitation

Well E-26 is located in the central part of the exploitation area called Cerro Prieto III. This well was drilled between July 10 and October 13, 1986, with a final depth of 2480 m. It was connected to the power station Cerro Prieto III on March 15, 1987. During its production, approximately 52 months, the wellhead pressure decreased from 101 bar (99 kg/cm$^{2)}$ in March 1987 to 55 bar (54 kg/cm^{2}) in April 1991. Also, pieces of 7" OD pipe were found in the production hole.

The first repair was made in this well during July 27 to September 29, 1991. At this time the 9 ⅝" OD production casing was caliper logged down to 1822 m, where the liner hanger is located, and casing damages were detected at 722, 847, 889, 1096, 1100, 1718 and 1736 m depth. Due to this, a window was opened in the interval from 1662 to 1678 m in the production casing, and then drilling was continued with a 8 ½" ø bit down to 2050 m depth and with 6" ø bit from 2050 to 2236 m depth (side track). The 7" OD casing was installed in three stages; the first section between 2043 and 1512 m depth; the second one between 1511 and 593 m depth; and the third one from 591 m to the surface. These casing strings were all cemented full length. The open hole is between 2044.0 and 2236 m depth. The well was again connected to the power station on December 6, 1991.

Since December 1993, a drastic decrease in the production of steam from this well was observed. The main problems identified with the decrease in steam production were:

a) Possible silica deposition in the open hole, due to the flashing point in this zone;
b) Deposition in the production pipe and probable entry of fluids at lower temperatures.

Because of this, a second repairing operation of this well was initiated. Operations started on April 13, 1994, with the installation of the drill rig J-750 property of Compañía Perforadora Magma, S.A. de C.V. of México in the site of well E-26. On April 21, 1994, after testing the equipment, the well was quenched by injection of 38 m^3 of bentonitic mud.

A drill string with 6" ø bit was run free into the 7" OD casing to 1118 m depth. Rotation of 60 RPM and weight on bit of 1-2 tonnes was applied and drilled to 1149 m depth with circulation of mud on surface. Descent was free again to 1516 m depth. A new drill string with 5 ¾" ø rotary shoe was run into the well drilling the deposition until 2028 m depth. All these operations were carried out from April 21-26, 1994.

Between April 26-30, 1994, hydrostatic tests were made on the well. To carry out this three cement plugs were placed, the first one at 1585-1626 m depth, the second one at 1385-1426 m depth. The test to the first plug was positive, but not to the second one. Due to this, it was necessary to place a third plug at 1347-1511 m depth. Now the hydraulic test to the lower hanger using 83 bar (1200 psi) for 30 minutes was positive. The cement plug was drilled out with a 6" ø bit and possible deposition was also drilled to a depth of 2049.4 m.

On April 30 to May 2, 1994, the 6" ø open hole was cleaned out and reamed with a 6" diameter bit from 2049.4 to 2241.4 m depth. A brief seizing up of the drill string was observed at 2209.2 m depth but the problem was solved quickly.

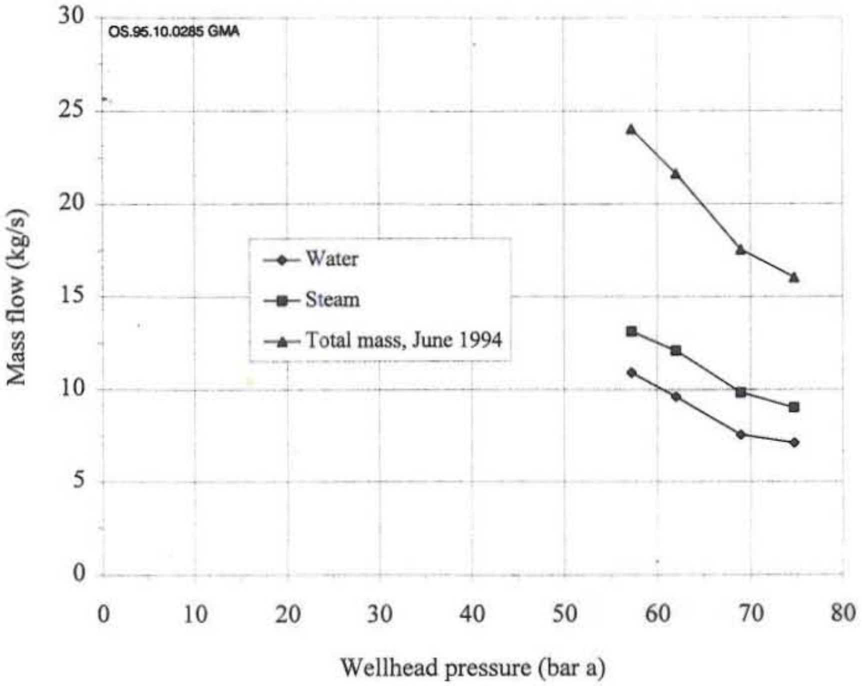


FIGURE 30: Production test in well E-26, Cerro Prieto, México, carried out after deepening operations in June 1994 (modified after Gutiérrez, 1994)

A new drill string with 6" ø bit was run into the well deepening it from 2241.4 to 2450 m in total loss of circulation. The operation finished on May 21, 1994. After these operations the 7" OD casing is free of deposition material, mechanical damage and mud. The actual production zone is located at 2048.7- 2450.0 m depth.

Figure 30 presents the production test carried out in well E-26 after the rehabilitation on June 1994. This figure has been modified but the data are taken from Gutiérrez (1994).

According to the results obtained from these operations the rehabilitation of the well was successful, and the well was again connected to the power station on June 29, 1994.

5.4 Miravalles geothermal field, Costa Rica

The Miravalles volcano is located in the north sector of Costa Rica, and the lower southwestern slopes contain scattered hot springs and fumaroles. A large caldera is located in the southwestern part of the volcano, which allowed the formation of sedimentary layers (Vaca et al, 1989). The first wells were drilled in Miravalles in 1979 (PGM-1, PGM-2 and PGM-3) discovering a liquid dominated geothermal reservoir of about 240°C. During a long-term production test, drop in the flow rate of wells PGM-1 and PGM-3 was observed and calcite depositions inside the wells were confirmed (Sanyal et al., 1985). Six additional wells were completed from 1984 to 1986 increasing the power available to 23 MW_e. Calcite deposition was found in all these wells.

Due to this observed calcite scaling, a new well design was adopted to minimize the cleaning operations in the wells. Knowing the possible location of calcium carbonate deposits or the flashing zone, the depth of the production casing is selected to minimize the damage of the well. Figure 31 shows the profiles of the first wells, the later design changes, and the new design (Vaca et al., 1989). This new design, with larger casing sizes, increase in the cross-sectional area to the flowing fluid and decrease in the loss of pressure through the casing is achieved. The expected zone of deposition will be inside the production casing. With the new design the cleaning operations are expected to be required only three times a year for each well instead of five times, even if no inhibitor is used. Another advantage is that the cleaning operation will be easier because it will take place in a cemented casing (Vaca et al., 1989).

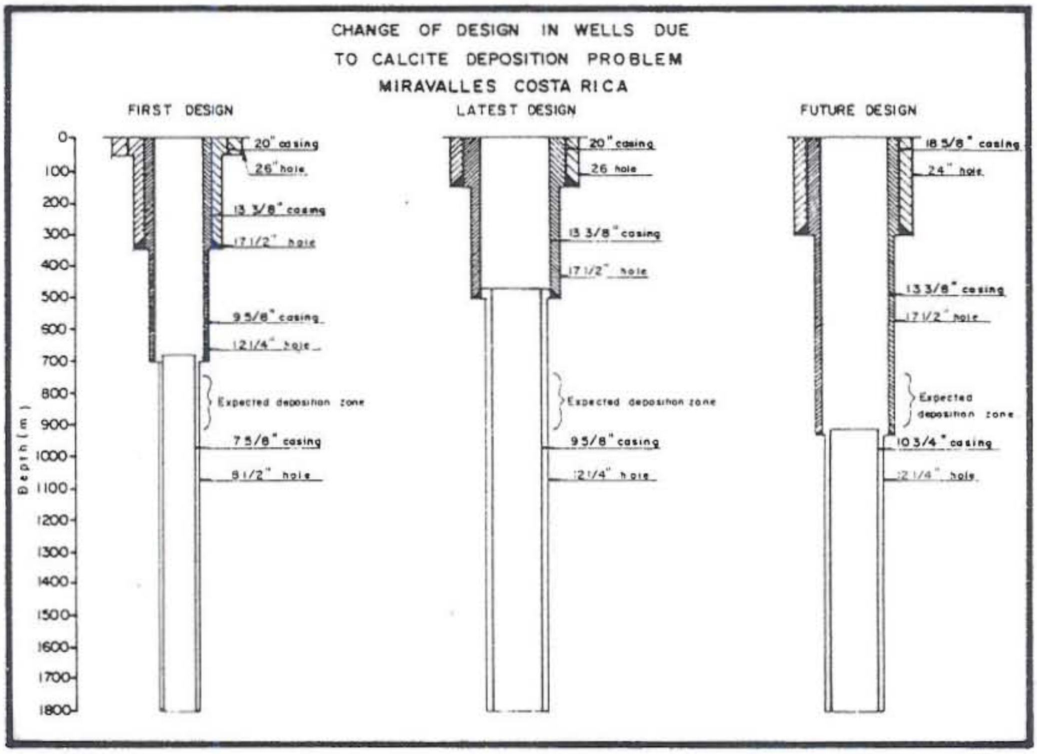


FIGURE 31: Changes in design of wells in Miravalles, Costa Rica, due to calcite deposition problem, (Vaca et al., 1989)

6. CONCLUSIONS

The objective of this report is to present methods used for fighting scale problems in geothermal wells mainly by drilling. The main conclusions of these studies are the following:

1. A common reason for a decrease in the wellhead pressure or in the rate of production of a geothermal well is solid deposition inside the well or a nearby reservoir.

2. Calcite, silica and sulphide are the most common scales found in liquid dominated geothermal systems. Each one of these presents different behaviour with respect to the precipitation form. Calcite is mainly associated with the flashing point in the wells. Silica is associated with the reinjection of silica supersaturated waste water in the well, and sulphide is associated with the flashing and the concentration of metallic cations (Fe, Zn, Pb, etc) in the fluids.

3. Several methods of rehabilitation of wells with scale problems have been presented. Also, brief summaries of case histories of cleaning operations have been included in order to compare the methods used in different geothermal fields around the world. In Iceland, El Salvador and Costa Rica the most common method is by reaming the deposition using a drill rig type workover, and the results have been acceptable. But in México the side tracking or deepening the well in order to intersect zones without deposition have been the most favourable.

4. Two methods to remove mechanically the scaling using a drill rig have been developed. These are keeping the well quenched by injection of cold water during all the operations and the other one keeping the well flowing. It seems that the best method to remove deposition in wells is under flowing conditions, because the well casing does not undergo thermal cycling and the cuttings are swept out of the well. Furthermore, the wells can be integrated almost immediately to the power station. A special arrangement consisting of a gland made in Iceland or a rotating head for geothermal drill can be used for reaming scale in wells during discharge.

5. It is necessary to know the mechanical conditions of the casing and the production history of the well to select a suitable method for its rehabilitation.

6. By varying the flash-point depth and wellhead pressure the scale can sometimes be spread out over a longer interval of the wellbore. This has the advantage of reducing the maximum thickness of the scale which, in turn, will extend the time between scale clean-outs. By knowing the relationship between flashpoint depth and wellhead pressure it is possible to design a casing programme so that the flash point stays in the larger diameter production casing.

7. It is clear that carrying out a caliper log (measuring the diameter of the well casing) can give valuable information about the condition of the well and allow clean-outs to be planned in time.

8. It is possible to obtain greater flow rate and reduce the frequency of cleaning operations by increasing the diameter of the production casing.

9. A new well design with a deeper production casing should be considered in order to avoid having the deposition zone inside the liner and, instead get the scaling at a place where a cleaning operation might be successful.

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