The United Nations University

GEOTHERMAL TRAINING PROGRAMME
Orkustofnun, Grensásvegur 9,
IS-108 Reykjavík, Iceland

Reports 2004
Number 3

# METHODS TO EVALUATE FLOW AND SCALING IN GEOTHERMAL SYSTEMS WITH REFERENCE TO THE CASE: ALUTO LANGANO POWER PLANT, ETHIOPIA

**Mulugeta Asaye**
Ethiopian Electric Power Corporation
P.O. Box 1233
Addis Ababa
ETHIOPIA
*asayemulu@hotmail.com*

**ABSTRACT**

The Aluto Langano geothermal power plant in Ethiopia was constructed in 1998 and is the first and only one in the country. There have been problems with the wells and plant equipment that have resulted in the shutdown of the installation. The main problem relates to insufficient steam pressure compared to the original design parameters. To tackle such problems and to maintain stable production, the first step should be thorough re-evaluation of the well output, temperature and pressure profiles in the wells and scaling conditions. It is beyond the scope of this paper to do so. The paper will, however, focus on measurements and calculations that can be applied to such an evaluation. As the training took place in Iceland, data from local wells was used, but with reference to the case of the Aluto Langano power plant. Moreover, this paper tries to identify different approaches to solve the existing and other related problems. The Ethiopian Electric Power Corporation is making an effort to return the plant to its specified output, and operate the field on a sustainable basis; and also to assess the potential for increased power generation from the field.

## 1. INTRODUCTION

### 1.1 The power plant and the condition of the wells

Aluto Langano was the first Ethiopian geothermal field that was studied in detail and promoted for deep exploration drilling. The site is located about 200 km southeast of Addis Ababa (capital city). There, 8 deep wells (LA-1 – LA-8) were drilled between 1981 and 1986. Table 1 presents an overview of the well data. Wells LA-1 and LA-2 were drilled at the southern and western edges of Aluto volcanic complex, respectively. The exploration shifted to the top of the volcano and the remaining 6 wells were sited on the top of Aluto, since the first two wells were found to have low temperature and permeability. Wells LA-3 and LA-6 were drilled by the most active fault system, and they were found to have a maximum temperature of 315°C and 335°C, respectively. In addition, high enthalpy was registered in these wells, about 1650 kJ /kg. Wells LA-4 and LA-5 were drilled to the east, and LA-7 and LA-8 to the west of the Wonji Fault Belt (WFB) zone. Wells LA-4 and LA-8 were productive, but not LA-5 and LA-7, and with lower temperature and enthalpy compared to LA-3 and LA-6 (Teklemariam et al., 1996).

TABLE 1: Overview of well data at Aluto Langano
(Ketema and Solomon, 1983; Teklemariam et al., 1996)

| | **LA-1** | **LA-2** | **LA-3** | **LA-4** | **LA-5** | **LA-6** | **LA-7** | **LA-8** |
|---|---|---|---|---|---|---|---|---|
| Total depth (m) | 1317 | 1602 | 2144 | 2062 | 1867 | 2202.8 | 2448.5 | 2500 |
| Status of well | Non productive | Non productive | Productive | Productive | Non productive | Productive | Productive | Productive |
| Permeable zone (m) | - | - | 2000-2121 | 1445-1800 | - | 2000-2200 | 2100-2300 | 2300-2500 |
| Tmax. (°C) | - | - | 315 | 230 | - | >320 | 228 | 268 |
| **Chemical composition of separated water (separation pressure 5 bar-a values in ppm)** | | | | | | | | |
| $SiO_2$ | - | - | 573 | 300 | - | 749 | - | 479 |
| $HCO_3$ | - | - | 1015 | 1574 | - | 1305 | - | 1922 |
| TDS | - | - | 3072 | 4625 | - | 4260 | - | 4850 |
| pH | - | - | 7.4 | 9.0 | - | 8.7 | - | 9.2 |
| **Gas content and composition** | | | | | | | | |
| Gas. total mass (% by weight) | - | - | 2.3 | 2.1 | - | 2.6 | 0.7 | 1.5 |
| $H_2S$ content (% by weight) assuming $CO_2$+$H_2S$=100% | - | - | 0.9-1.5 | 0.05 | - | 1 | 0.1 | 0.15-0.5 |

The Aluto Langano power plant in Ethiopia is the first geothermal power plant using integrated steam and binary power technology in Africa. The 8.5 MW ORMAT Integrated Geothermal Power Plant is comprised of one 3.9 MW ORMAT Geothermal Combined Cycle Unit (GCCU) operating on high-pressure geothermal steam, and one 4.6 MW ORMAT Energy Converter (OEC) operating on both geothermal brine and low-pressure steam. The power plant was synchronized to the national power grid in May 1998, and is owned and operated by Ethiopian Electric Power Corporation (EEPCo).

The GCCU is composed of a conventional steam turbine and a binary turbine, each driving at opposing ends of a single generator. High-pressure steam from wells LA-3 and LA-6 enters the steam turbine and after driving the turbine, the exhaust steam is delivered to a heat exchanger, which boils a binary fluid (isopentane) to drive the binary turbine. The design high-pressure steam inlet pressure was 12 bar-g and the exhaust pressure 1.3 bar-g.

The OEC unit is driven by a binary fluid, which is heated and vaporized, in two heat exchangers. The vaporizer receives medium pressure steam from wells LA-4 and LA-8 (and brine from all four wells). During the 5 years of operation, the power plant has exhibited many problems that are partly caused by the generating equipment and partly related to the production wells.

### 1.2 Problems of the wells and generating equipment

According to a report prepared by the Ethiopian Electric Power Corporation, the problems at Aluto Langano can generally be grouped into three categories (EEPCo. 2003, Aluto Langano geothermal power plant project profile).

1. Problems related to the production wells:
   - Decline of well pressure;
   - Fluctuations in the output of the wells;
   - Scaling problems;
   - Parallel operation of wells LA-3 and LA-6;
   - Excess geothermal fluid drainage to the ponds;

- Wellhead valve troubles;
- Deposition problem at well LA-8;
- Deposition and corrosion problems in the pipelines.

2. Problems of the plant:
    - The cooling tower fan drive;
    - Pentane leakage in heat exchangers;
    - Level of automation of the power plant;
    - Size of the site and wellhead rock mufflers.

3. Other problems:
    - 15 KV transmission lines;
    - Lack of monitoring system;
    - Operation and maintenance staff.

It is important to "trouble-shoot" and identify the causes of these problems and to find possible solutions. To attempt to solve the above stated problems, different measures have been taken. This report will concentrate on what can be done to identify the causes and point out different approaches. Sharing experience and solutions with other countries is important. Thus, parts of data, some figures, and experiences in this report have been adopted from measurements the author has witnessed and from books and reports on different geothermal areas of Iceland.

## 2. SCALING PROBLEMS IN GEOTHERMAL WELLS AND EQUIPMENT

### 2.1 Scale prediction

Deposition and scaling are common in the geothermal industry, both in wells and surface facilities. Silica and calcite are two well-known forms of deposits that are difficult to remove. This section pays most attention to these two types of deposits, as they are most common. Deposition and related phenomena constitute a major constraint on efficient development of geothermal energy worldwide. But several methods have been applied to overcome or manage the problems they cause.

Precipitation of dissolved solids from geothermal fluids is a virtually ubiquitous phenomenon which occurs in geothermal fluids having a wide range of chemistries, and at temperatures ranging from less than 100 to 350°C. The precipitation of solids from natural fluids is a highly complex physical and chemical process that is difficult to control. When dissolved solids become solid deposits in geothermal fields and equipment, they affect the exploitation of the geothermal resources as they restrict the flow. This solid deposition affects the reservoir, liners, production casing, and surface equipment. According to inspection reports in Aluto Langano geothermal field, scaling has been observed in the wells, brine transmission lines, and in other surface equipment. The main types of scales encountered during utilization of Icelandic high-temperature fields are summarized in Table 2.

#### 2.1.1 Silica scaling

Quartz and amorphous silica are of interest in deposition studies. In liquid-dominated high-temperature geothermal reservoirs, the amount of silica dissolved in the geothermal water depends on the solubility of quartz. However, amorphous silica is the form which precipitates from geothermal fluids upon concentration and cooling. Silica deposition and scaling will occur in geothermal wells and surface facilities when the concentration of silica exceeds the solubility of amorphous silica (Gudmundsson, 1983). Silica precipitation from geothermal fluids can occur over periods of minutes or hours after super-saturation occurs. Silica scales have been found throughout the fluid handling equipment of several geothermal facilities.

TABLE 2: Main types of scales encountered in Icelandic geothermal installations (Kristmannsdóttir, 1989)

| **Types of scales** | **High-temperature fluids** | **Low-temperature fluids** | **Location of scale** | |
|---|---|---|---|---|
| | | | **Inside well** | **In surface construction** |
| Calcium carbonate (Calcite aragonite) | x | x | x | x |
| Silica (quartz-cristobalite) | x | | x | x |
| Magnesium-silicate | | x | | x |
| Iron-silicate | x | | x | |
| Iron-magnesium-silicate | x | | x | |
| Zinc-silicate | | x | | x |
| Aluminium-silicate | x | | | x |
| $FeS_2$ (Pyrite marcasite) | x | | x | x |
| FeS (Pyrrhotite) | x | x | x | x |
| $Fe_3O_4$ (magnetite) | x | | x | x |
| $F_eCl_3$ | x | x | | x |
| Other metal sulphides | x | | x | x |
| Calcium sulphate (anhydrate) | x | | x | |

Siliceous scale is typically inert to most chemicals and, once deposited, is also somewhat 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 scale deposition on surface equipment have included restricting steam separation - that is to say to operate the system at temperatures so high that amorphous silica super-saturation is not reached.

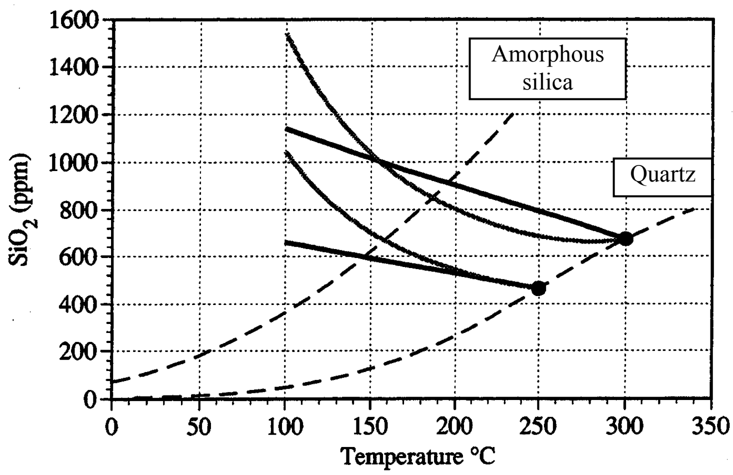


FIGURE 1: Silica in water at saturated water vapour pressures when fluids of 250 and 300°C are flashed (Arnórsson, 1995)

When initially discharged, the silica content of water from wet-steam wells is governed by equilibrium with quartz in the producing aquifers, at least if temperatures in the reservoir exceed 180°C. The aqueous silica concentrations in the boiled water can be predicted quite accurately at any particular pressure from the quartz equilibrium concentration at the aquifer temperature. This is shown in Figure 1 for aquifer waters at 250 and 300°C. Steam formation due to boiling, and therefore also the increase in aqueous silica concentration, is caused by flashing when the pressure is lowered. The resulting temperature and pressure changes due to such flashing are shown as solid straight lines. These changes can be calculated as the average fluid enthalpy is constant (adiabatic flashing). The fraction to steam can be calculated by the equation:

$$x = (h_1 - h_{2l})/(h_{2g} - h_{2l}) \tag{1}$$

where $x$ = Quality (steam fraction);
$h_1$ = Average enthalpy of well (kJ/kg);
$h_{2l}$ = Liquid enthalpy at separator temperature (kJ/kg);
$h_{2g}$ = Steam enthalpy at separator temperature (kJ/kg).

Partial separation of the flowing water and steam in producing aquifers may influence the flowing enthalpy or mixing of fluid in the well from two or more producing horizons. Usually, the steam moves preferentially to the well leading to “excess” steam in the discharge. Such is the case for Aluto Langano where the temperatures are 228 and 320°C, and the corresponding water enthalpies are 980 and 1462 kJ/kg, but the actual enthalpy is 1650 kJ/kg. Steam has maximum enthalpy at 236°C. The two dotted curves in Figure 1 represent solubility of amorphous silica and quartz (Arnórsson, 1995).

### 2.1.2 Coping with silica deposition from geothermal waters

Many treatment methods have been applied to reduce silica scaling in production wells and equipment. In order to avoid amorphous silica scaling in wells, it is common practice, whenever possible, to operate the wells at wellhead pressures higher than those corresponding to amorphous silica saturation.

During disposal of wastewater from geothermal wells by reinjection, one must take into account experience gained from the study of the processes influencing silica deposition from such waters in production wells and at the surface. Based on this experience, it appears that waste water from geothermal production wells may either be injected directly by pumping the water from steam separators to the injection wells, so called “hot injection”; or by pumping from conditioning ponds after it has cooled down and the silica has polymerized. The method deemed most favourable for each operation will be a function of:

- The reservoir temperature;
- The water salinity or the overall water composition;
- Acceptable disposal methods from geological and environmental point of view.

By the first method, “hot injection”, contact with the atmosphere is avoided. It has been claimed that this disposal method will not be associated with troublesome silica deposition in the injection well and in the receiving aquifers, as long as the water does not reach saturation with respect to amorphous silica. It is, however, considered that silica may deposit from wastewater to form moganite and quartz, if the water is injected into hot formations (Arnórsson, 1995). It is concluded that the solution to the silica deposition problem in injection wells, and their receiving aquifers, should focus on two options:

1. To find out if injection of amorphous silica undersaturated water is an acceptable solution; and
2. To find out if effective quenching of the precipitation reaction can be achieved by cooling the wastewater at the surface and then injecting it cold.

When considering injection of cooled wastewater into either cold or hot ground water, the possible effects of mixing the two compounds of silica, Mg-silicate or Al-silicate deposition should be specifically looked at.

For water disposed of on the surface, the methods of fluid disposal include:

- Direct infiltration;
- Polymerization of the silica in special conditioning ponds followed by conveyance of the treated water to infiltration ponds;

- Evaporation in large disposal ponds;
- Storage in effluent ponds where the silica polymerizes and the polymers subsequently settle by gravity before allowing the water to infiltrate;
- Chemical treatment of the water involving removal of silica from solution.

### 2.1.3 Calcite (calcium carbonate) scaling

One of the most common production problems in geothermal fields is calcite (calcium carbonate) scale deposition. Calcite blockage formed in well bores decreases significantly the output of the production wells. Calcite scaling is experienced in many geothermal fields around the world. Calcium is an abundant mineral in rocks which have been altered by geothermal water, in particular where the water boils extensively in up-flow zones. Scales of calcite, and some times of aragonite, have been observed to form in some geothermal wells but not in others (Ellis and Mahon, 1977). The rate of scale formation varies enormously from place to place (Arnórsson, 1989). In some cases, it can be dealt with, either by periodic mechanical cleaning of the wells, or by the use of chemical scale inhibitors.

Experience has shown that calcite scaling in producing geothermal wells is generally only encountered as a problem if the first level of boiling is inside the well, as most often is the case. Yet, theoretical considerations indicate that calcite super-saturation always results when extensive boiling of geothermal water is induced in discharging wells, irrespective of whether this boiling starts in the well or in the aquifer (Figure 2). The principal cause of this apparent discrepancy is considered to be the big difference in the volume of the well bore compared to the anticipated volume of connected pores in the aquifer, even at a small distance from the well (Arnórsson, 1989). Calcite does furthermore not form significant deposits unless a certain degree of super-saturation is reached (Bai Liping, 1991).

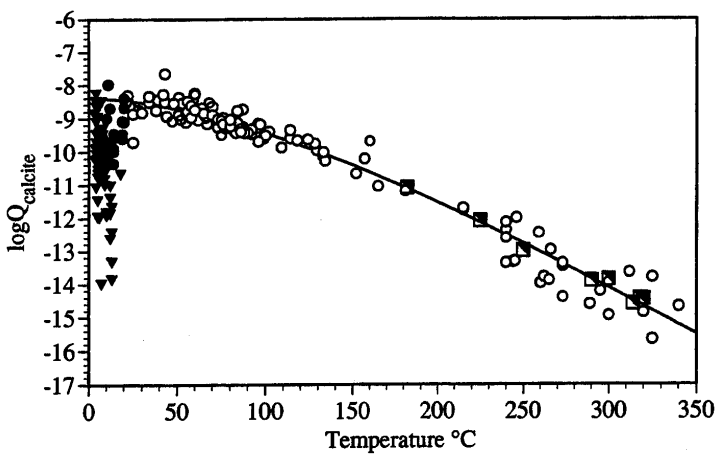


FIGURE 2: The state of calcite saturation in natural waters from Iceland; the curve represents saturation $Q = a_{Ca}{}^{+2} a_{Co3}{}^{-2}$; triangle denotes surface water; dots non-thermal groundwater; and circle thermal groundwaters. The half-filled squares represent drillhole waters (Arnórsson, 1995)

The calcium content of geothermal waters varies by several orders of magnitude, being highest for saline waters of relatively low temperature (>1000 ppm) and lowest for dilute waters of high temperature (<1 ppm). The total carbonate content of geothermal reservoir water with temperature greater than about 200°C, runs in the hundreds to tens of thousands of ppm. Thus, availability of carbon does not limit the extent of calcite deposition. Limited precipitation of calcite from boiling waters high in calcium will not reduce significantly the degree of calcite super-saturation. This, on the other hand, is not the case for dilute geothermal waters low in calcium. Production from geothermal wells will cause lowering of pressure in the reservoir. Declining reservoir pressure will cause expansion of the zone of extensive boiling around individual wells and in the production reservoir as a whole. This will in turn cause the zone of the first boiling to migrate with time away from the producing wells, thus expanding the zone of calcite precipitation and spreading it over a large part of the producing aquifer rather than concentrating it at one point. Thus, calcite scaling may present itself as an operational problem during the early stages of exploitation of a particular geothermal reservoir, if the first level of boiling is inside the wells. However, the problem is likely to vanish, when the first zone of boiling migrates into the formation in conjunction with reservoir decline. Decline in reservoir pressure will enhance natural recharge. The chemical composition of the recharging water, when entering production wells, depends on its initial composition and its reaction with the rock. It is conceivable that rapidly recharging cold and fresh groundwater may not attain calcite saturation before entering producing wells. If this happens, the recharge will diminish or eliminate any calcite scaling problems (Arnórsson, 1995).

### 2.1.4 Methods to cope with calcite scaling

Different methods have been applied to cope with calcite scaling in production and injection wells. Methods involve periodic cleaning, either mechanical or chemical, or the use of inhibitors (Tassew, 2001). The most successful mechanical cleaning method involves drilling out the scale with a small truck-mounted rig while the well is producing. By this method, the scale is brought to the surface, thus not cumulating at the well bottom. The well can be connected immediately after the cleaning operation is completed, which takes one to two days. This method of coping with calcite scales is feasible if the deposition is not very fast and cleaning is required no more than about twice a year. If scale formation is faster, the use of scale inhibitors is a more useful method. By this method, the inhibitor must be injected continuously into the well through tubing to a depth that is below the level of first boiling. Mechanical cleaning or the use of inhibitors are the most commonly applied remedies.

Chemical treatment of the geothermal water, either by an acid or $CO_2$, to make it calcite undersaturated has been tested. It has, however, several disadvantages. Due to the relatively high pH-buffer capacity of geothermal waters, a large amount of acid may be required, making this treatment expensive and, therefore, not attractive economically. Further, acidification may render the water corrosive. The $CO_2$ partial pressure of main geothermal fluids is very high (tens of bars) (Corsi, 1986). Thus, large quantities of $CO_2$ may have to be added to make the reservoir water significantly calcite undersaturated, especially after it has flashed.

## 2.2 Detecting and measuring scales in production wells

In order to determine the location and thickness of scales in geothermal wells, different mechanical methods are used. These include:

- Wire baskets of different diameters, lowered on a logging wire until it stops;
- Calliper logging tool, electrical logging tool with four fingers.

With different diameters of wire baskets the location and the thickness of scaling in the well can be determined by how deep the basket can be lowered into the well. These spot measurements can be done in the well under pressure (Figure 3). Continuous scale thickness measurements can only be done with a calliper tool. The disadvantage of the calliper tool is

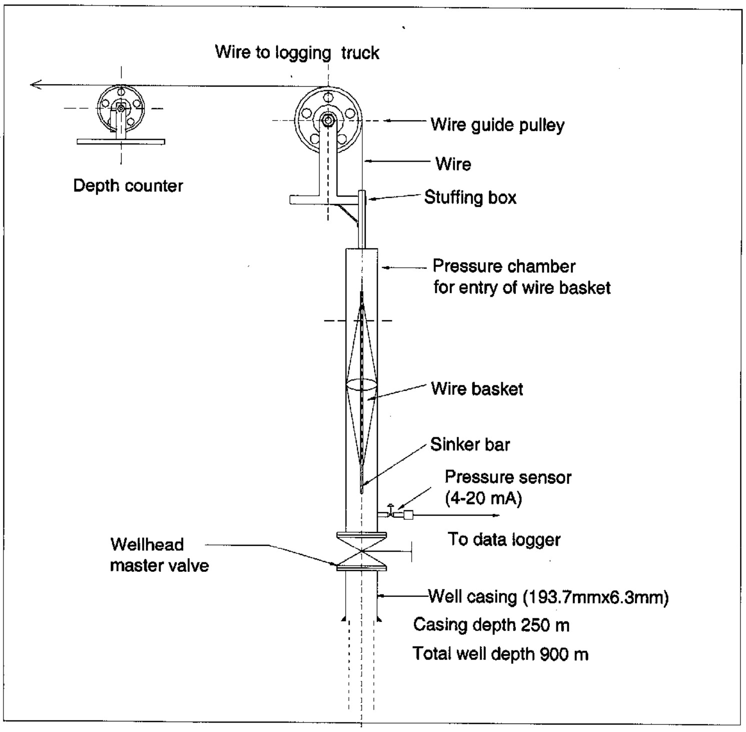


FIGURE 3: Sketch of a wire basket for scaling measurement in a production well

the temperature limitation of the electronics. Usually the well needs to be killed and cooled down for a calliper survey.

Scaling measurements were observed being made in well HE-07 located at Hveragerdi S-Iceland. The well is 900 m deep and has an open hole diameter of 6-1/4″. The well produces a large amount of $CO_2$ gas and together with a nearby well supplies Iceland's requirements for $CO_2$. During the scaling measurements, some scale deposition was observed in the well, but more in the narrow surface pipeline. Figure 4 shows the wellhead pressure data.

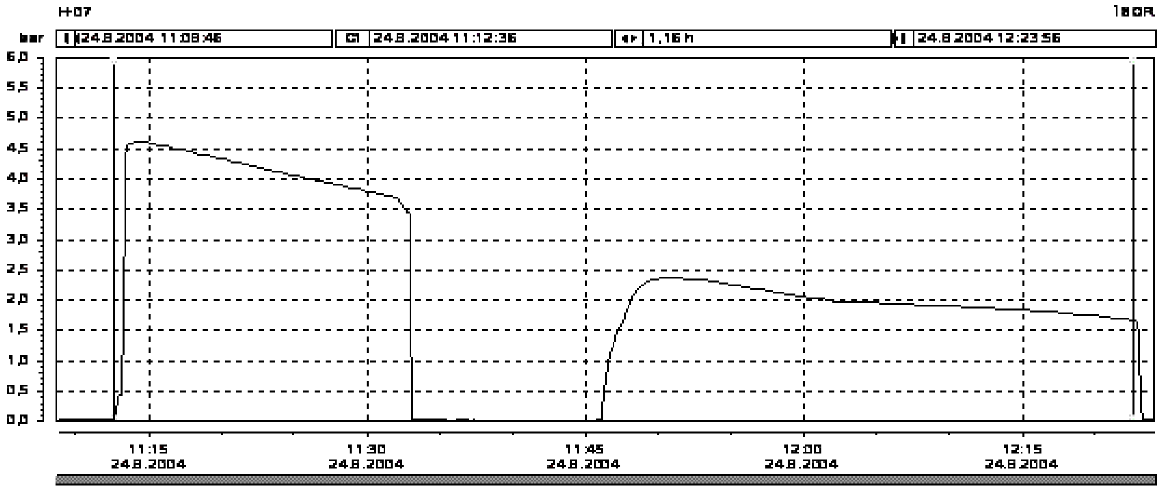

FIGURE 4: Wellhead pressure data taken when scaling measurement was done at well no. HE-07, Hveragerði, S-Iceland; the data was taken for 76 minutes. The decline in pressure is due to a slight leak on the stuffing box

Some data on well HE-07:

| | |
|---|---|
| Total depth | 900 m |
| Diameter of casing | 193.7 mm |
| Depth of casing | 250 m |
| Casing thickness | 6.3 mm |
| Diameter of well below casing | 6¼″ |
| The main feed zone | 688 m |

The first basket with a diameter of 170 mm stopped only 0.5 m below the well head master valve. Then the basket was changed to a diameter of 140 mm and was lowered to 600 m without any resistance. From these measurements, it was concluded that the thickness of the deposit is about 6.5 mm just below the master valve, and that nowhere in the well is the scale thickness greater than 13 mm. This well was thus at that time nowhere near to being clogged by scaling.

## 3. STEAM SYSTEM

### 3.1 Mass flow and pressure calculations

Two-phase flow occurs in geothermal wellbores, so it is important to have the capability of modelling vertical two-phase flow. This section is intended to show how to measure and calculate the mass flow and enthalpy from the data collected from the well discharge pipe and separator. After discharge starts from wells, the flow test will take place. The type and size of equipment needed for a flow test depends on the expected maximum flow rate and discharge enthalpy. Two basic types of flow test may be done. One involves an "output" (deliverability) or test in which flow characteristics are measured at varying wellhead pressures over short time intervals (hours, days). Alternatively, a "run-down," or production test may be performed. In this case, flow is held constant and changes in flow or pressure, respectively, with time are measured, over months or years in the well itself and preferably also in observation wells.

The two-phase flow rate of steam and water is calculated with the Empirical formula (James, 1962):

$$Q = KAP_c^{0.96} / H^{1.102} \tag{2}$$

where $Q$ = Total mass flow (kg/s);
$K$ = 1839000;
$A$ = Cross-sectional area of the pipe ($m^2$);
$P_c$ = Critical lip pressure (bar-a);
$H$ = Average fluid enthalpy (kJ/kg).

The water flow rate in a V-weir box:

$$Q_w = 1.365 q_w^{2.5} \tag{3}$$

where $Q_w$ = Water flow (l/s)
$q_w$ = Water height in V-notch weir (m)

Steam flow in chimney from separator; measured by annubar, with the following formula for a particular chimney diameter and probe:

$$Q_s = 2.731\sqrt{dP} \tag{4}$$

where $Q_s$ = Steam flow (kg/s)
$dP$ = Pressure difference in annubar probe (m bar)

We can calculate the mass flow and the enthalpy of the well from the data collected from pressure and flow measurements. There are two ways to calculate the mass flow and enthalpy with this data as is shown in Table 3:

A. Individual mass flow measurements of the water (V-weir box) and steam (annubar) are made after the separator. The enthalpies of the individual phases are found in steam tables. The separation is at atmospheric pressure. The calculation of average enthalpy is straight forward as the flow and enthalpies of both phases have been determined. The total mass flow is the sum of the steam and water measurements.

B. By using the critical lip measurement method and water flow, the enthalpy can be determined by iteration so that the calculated water flow from the R. James equation, and the actual waterflow measurements become equal. That is done by the Solver feature of Excel and Steam-Tab add-in, where Steam-Tab is a special software add-in to Excel that contains the steam tables.

TABLE 3: Mass flow and enthalpy determination by two calculation procedures A and B

| | | | | **A: Water and steam measurements** | | | | **B: R-James calculation** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **WHP, $P_o$ (bar)** | **Critical lip press. $P_c$ (bar)** | **Water flow V-notch Weir box (m)** | **Steam $dP$ annubar (m bar)** | **Water flow (kg/s)** | **Steam flow (kg/s)** | **Sum W+S (kg/s)** | **Enthalpy W+S (kJ/kg)** | **Total flow R. James (kg/s)** | **Mass flow Water (kg/s)** | **Mass flow Steam (kg/s)** | **Steam fraction $x$** | **Enthalpy R.J calc. (kJ/kg)** |
| 32 | 1.6 | 0.17 | 20 | 16.4 | 12.2 | 28.6 | 1377.3 | 28.4 | 16.4 | 12 | 0.42 | 1369.9 |

* Diameter of the critical lip pipe = 0.16 m

### 3.2 Control of steam system

Different flow controlling devices are used when transmitting high-pressure steam over long distances by pipeline to power plants. Valves on the well head, orifices, use of control valves and use of different safety valves are very important to maintain normal operation of power plants.

The master valve on the wellheads can be modified to be opened and closed by a hydraulic system with the help of a portable diesel-driven hydraulic pump.

FIGURE 5: Well head, separator and different controlling devices

In order to control the flow from the wellhead, either fixed orifices can be used or different valves such as the needle control valve, called "Ella-loki", after its Icelandic inventor. Many wells are controlled by fixed orifices. In the early years, using different control valves was difficult due to the very high-pressure drop and scaling problems that caused erosion and the valve to stick. In Iceland, they either use the "Ella-loki", that can adjust the flow to the requirements of the power plant, or fixed orifice plates. This system has been proven and widely used in Iceland. Different controlling devices are shown in the photo in Figure 5. To choose an appropriate orifice plate diameter for controlling the well flow, a semi-empirical formula can be used. In this case, the flow in the orifice has to be critical (sonic), and the flow is thus controlled only by the wellhead pressure and orifice diameter. The following equation is applicable to water-dominated reservoirs at 240°C, details are shown in Table 4.

$$Q = e^c P_o^x d^2 / 4 \tag{5}$$

where $Q$ = Total mass flow (kg/s);
$e$ = 2.718;
$x$ = 1.08284;
$c$ = 2.718;
$d$ = Orifice diameter (m);
$P_o$ = Wellhead pressure before orifice (bar-g).

TABLE 4: Chocked orifice flow (sharp edged orifices) from wells at 240°C

| **WHP (bar)** | **Diameter 0.05 m Q (kg/s)** | **Diameter 0.1 m Q (kg/s)** | **Diameter 0.15 m Q (kg/s)** | **Diameter 0.2 m Q (kg/s)** |
|---|---|---|---|---|
| 10 | 6.2 | 25.0 | 56.2 | 99.9 |
| 12 | 7.6 | 30.4 | 68.4 | 121.7 |
| 14 | 9.0 | 35.9 | 80.9 | 143.8 |
| 16 | 10.4 | 41.5 | 93.5 | 166.1 |

To control the case of sudden surplus of steam in the system, for example due to turbine tripping, it is necessary to have a pressure control valve and a vent to a chimney or a rock muffler. Should that fail, there are safety valves or rupture discs. To prevent silica scaling in the high-pressure separators and brine pipes, one must keep the pressure above amorphous silica saturation. Brine level in the separator must be controlled, and in order to release any excess, a butterfly control valve can be used.

### 3.3 Pressure and temperature profiles in flowing wells

The pressure and temperature profiles measured in discharging geothermal wells reflect the flow of fluid, single-phase and two-phase, up the vertical pipe that is the wellbore (Figure 6). This section mainly deals with two-phase flow in a vertical pipe (well).

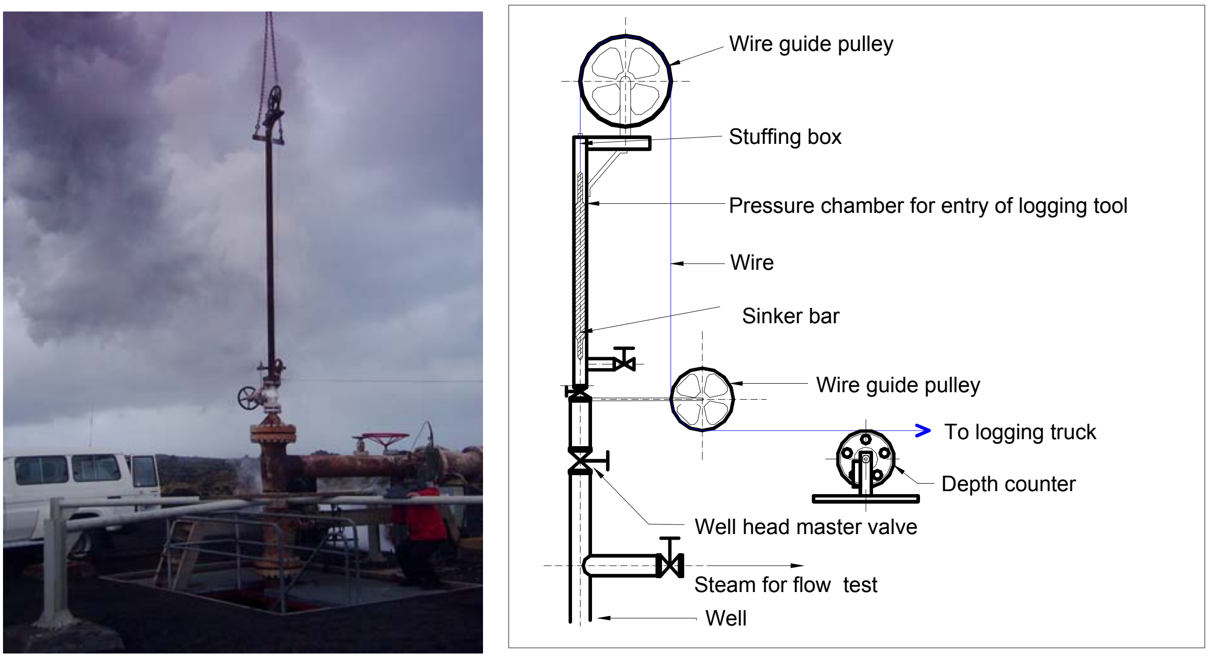


FIGURE 6: Wellhead for logging tools for temperature and pressure while the well is flowing.

Steam and water flowing up a vertical pipe distribute differently depending on the steam/water ratio and the flow rate. It is simple to imagine that the two fluids are vigorously mixed. Beginning with liquid water, the first flashing results in a comparatively small amount of steam that flows as bubbles through a continuous column of water. With increasing steam fraction, the next regime is slug, where alternatively steam-rich and water-rich fluid flows up the well. The next regime is churn or transition, which is intermediate between slug and final mist or annular mist flow. This last regime consists of water distributed as fine droplets through a continuous steam phase and of a continuous water phase clinging to the walls of the pipe.

In each regime, the fluid is distributed non-uniformly across the pipe or along a short section of it. Also, the steam and water flow at different speeds, so that there is slip between the two phases. As a result, the steam fraction of the mass flux is not equal to the steam fraction of the fluid present at any instant in a section of the pipe. As the fluid flows up the pipe, pressure falls and additional steam flashes. This increases the volume flow and, consequently, the velocity of both phases. Exit velocity to atmosphere may be sonic. The pressure drop in the pipe also increases. In order to calculate the pressure and temperature value in two-phase flow, the following equations are important:

$$dP/dz = -g\rho(T,P) - f(v,\rho,v,\nu,d) \tag{6}$$

$$T = T(Ph) \tag{7}$$

where $P$ = Pressure (bar);
$T$ = Temperature (°C);
$\rho$ = Density (kg/m3);
$v$ = Velocity (m/s) ;
$\nu$ = Viscosity;
$d$ = Pipe diameter (m);
$z$ = Height from well bottom (m);
$g$ = Acceleration of gravity = 9.81 m/s$^2$.

Assume that the fluid in the model is pure water, with no dissolved minerals or gases. The only correction made is for the density of the brine. For brines in Iceland, it can be corrected by the following equation, as a function of the chloride concentration.

$$\rho_{br} = \rho_w + 1.19 Cl_{ppm} 10^{-3} \tag{8}$$

where $\rho_{br}$ = Density of brine (kg/m$^3$);
$\rho_w$ = Density of pure water at the respective temperature (kg/m$^3$);
$Cl_{ppm}$ = Chloride concentration (kg/m$^3$).

These equations are integrated in a stepwise fashion at an interval of 10 m using an Excel spreadsheet and the steam table add-in SteamTab (Table 5). At every step of calculation, the average density and temperature is computed from the pressure and the enthalpy at that point. The process is assumed to be adiabatic (at constant enthalpy).

TABLE 5: Two-phase dP in wells, density effect only

| **Depth (m)** | **Enthalpy (kJ/kg)** | **Temp. (°C)** | **Pressure (sat) (bar)** | **X-quality** | **Vol. (steam) (m$^3$/kg)** | **Vol. (water) (m$^3$/kg)** | **Vol. (mix) (m$^3$/kg)** | **Density (kg/m$^3$)** | **Velocity (m/s)** |
|---|---|---|---|---|---|---|---|---|---|
| 2500 | | 290.81 | 170.6 | | | | | 752.731 | 0.842 |
| 1650 | | 290.81 | 105.8 | | | | | 752.731 | 0.842 |
| 1450 | | 290.81 | 90.6 | | | | | 752.731 | 0.842 |
| 1250 | | 290.81 | 75.3 | | | | | 752.731 | 0.842 |
| 1250 | 1295 | 290.81 | 75.3 | 0.001 | 0.02522 | 0.001369 | 0.00139 | 721.918 | 0.878 |
| 1237.5 | 1295.3 | 289.94 | 74.4 | 0.004 | 0.02558 | 0.001366 | 0.00146 | 686.169 | 0.923 |
| 1225 | 1295.2 | 289.10 | 73.5 | 0.007 | 0.02594 | 0.001363 | 0.00153 | 654.363 | 0.968 |
| 1212.5 | 1295 | 288.29 | 72.6 | 0.010 | 0.02629 | 0.001360 | 0.00160 | 625.824 | 1.012 |
| 1200 | 1294.9 | 287.51 | 71.8 | 0.012 | 0.02663 | 0.001358 | 0.00167 | 600.030 | 1.056 |

The initial condition for the calculation is the temperature and pressure at well bottom. These are not known, however, so some assumptions must be made as to the reservoir and inflow pressure drop. As the frictional pressure drop is not calculated in this case, neither for the single-phase nor two-phase mixture, a constant pressure drop is applied on top of the gravity term which is the dominant pressure drop. The assumed pressure drop due to friction in single-phase is assumed around 3 bar/km and in the two-phase conditions around 5 bar/km. For a 2.5 km deep well, the frictional pressure drop adds up to 9.5 bars out of the total pressure drop of more than 140 bars, or less than 6.5%. By including a guess of the frictional pressure loss, the model error becomes small (Figure 7). Simple calculations like this are useful because they will reveal any abnormality in the well behaviour, and can be used as a reference to actual dynamic pressure measurements to identify what may be wrong.

### 3.4 Instrumentation and datalogger

To follow different operational conditions during normal operation, and when some difficulties or trouble happen, a datalogger can be used (Figure 8). Such dataloggers can be used for measuring flow, rpm, temperature, pressure, etc. Recording can be made directly to the host computer (on-line recording) or temporarily to the internal memory in the logger. Recording can be made off-line, as in this case there is no need for the host computer to be connected to the datalogger.

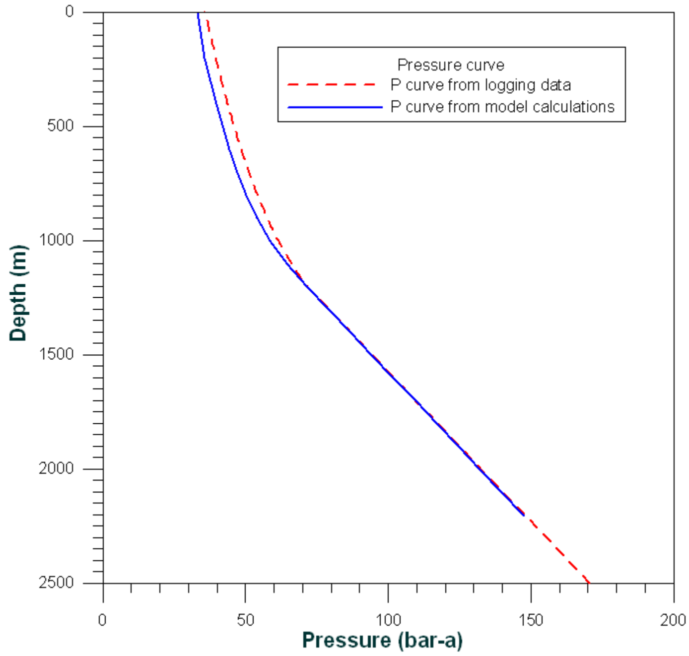


FIGURE 7: Pressure profile vs. depth in a 290°C flowing well

To know what is going on exactly at every moment and place (see Figure 9), we can use this type of loggers in addition to major instruments of the plant. The dataloggers can measure several points at a time through different channels; each channel is individually programmable (Figure 8). Moreover, the recorded data can be followed remotely with a mobile telephone modem and publishing on the internet.

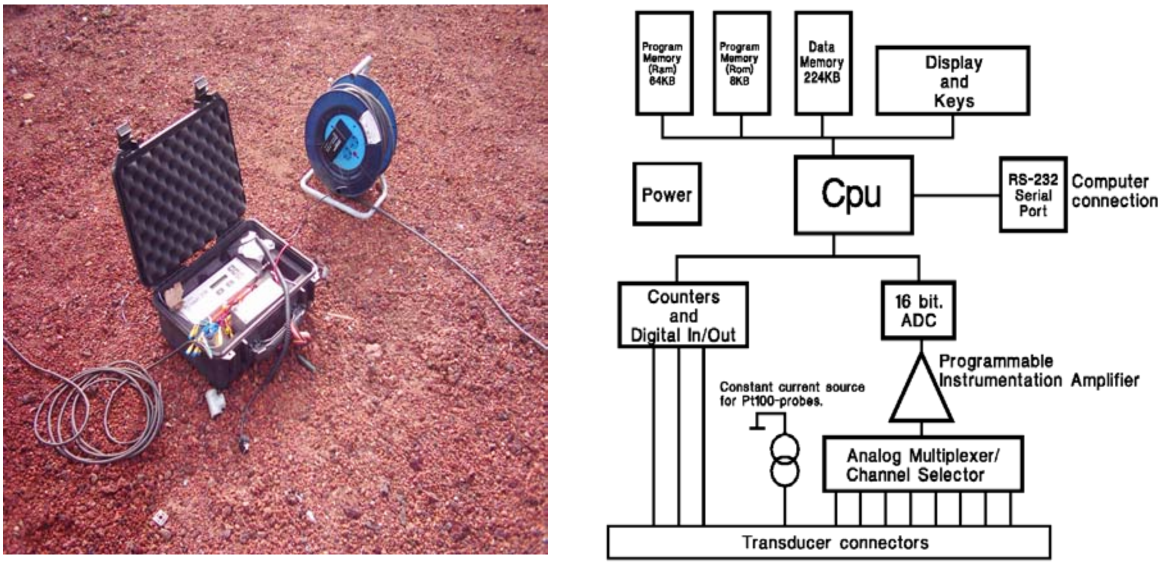


FIGURE 8: Photo and functional block diagram of the INTAB 2100-logger

## 4. FLOW TEST AND INITIATING WELLS TO DISCHARGE

### 4.1 Initiating discharge and flow measurements

The measurements of mass flow and total enthalpy of two-phase flow discharges have traditionally been done either by using total flow separators measuring water and steam flow independently (by orifice plates or annubar); or by using the empirical lip-pressure method of Russell James (1970). The James method requires a total flow to atmosphere and knowledge about the enthalpy. If both total mass flow and enthalpy are to be determined, the lip pipe has to discharge to a silencer and weir box.

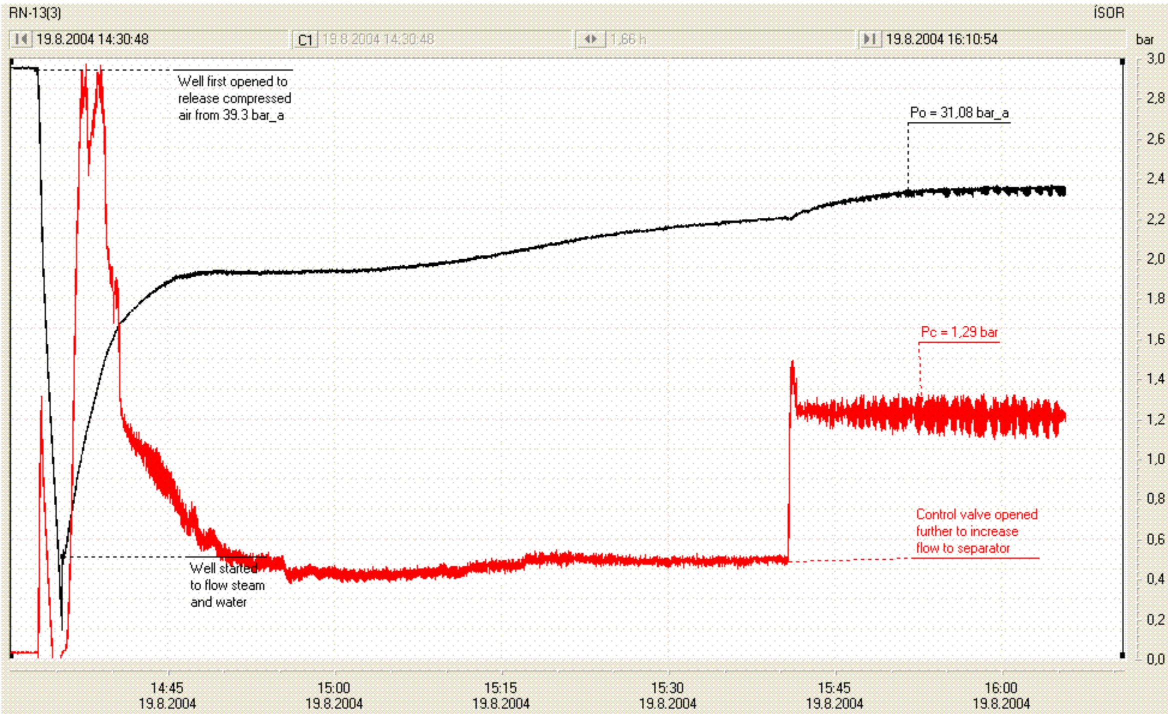


FIGURE 9: Data taken for two hours after initiating of well no. RN-13, Reykjanes, Iceland

These methods are widely used during exploration drilling, when new wells are tested over the full wellhead pressure (WHP) range.

Before any flow measurements can be taken, there must obviously be a discharge. For many wells, this is no problem. When the wellhead is under pressure, simply opening the valve initiates flow. But in some wells, and prevalently in many fields, it may be more difficult to start the flow. An open well may stand with the water level some distance below the wellhead, or the well may have built up a gas pressure at the wellhead so that when the control valve is opened, the gas is released but the boiling fluid from deeper in the well does not reach the wellhead. A well that does not spontaneously discharge, will contain a column of cold water for some depth. To create a discharge, requires boiling fluids in the well, and the problem of initiating a discharge is the problem of making the water boil. The cool water must therefore be removed and replaced by hot water, or heated, so that boiling can commence and fluid will be displaced from the well.

For most wells, there are different alternatives to initiate flow:

- Pressurising with compressed air;
- Air lift;
- Injection of steam/water;
- Nitrogen injection;
- Swabbing.

Pressurising with compressed air for flow initiation was observed at well RN-13 on Reykjanes, SW-Iceland (Figure 9). This method is used where the water surface can be depressed to a level such that the BPD curve from the depressed water level intersects the stable down-hole temperature profile. Compressed air is injected at the wellhead to depress the water level in the well. Pressure is maintained for several days (~ five days) in order to allow hole temperature to recover. Suddenly opening the wellhead control valves permits discharge of the compressed air, followed (if the procedure is successful) by boiling geothermal fluid (Figure 10). The minimum requirement of this method is that the water level can be depressed sufficiently to assure that a segment of the water

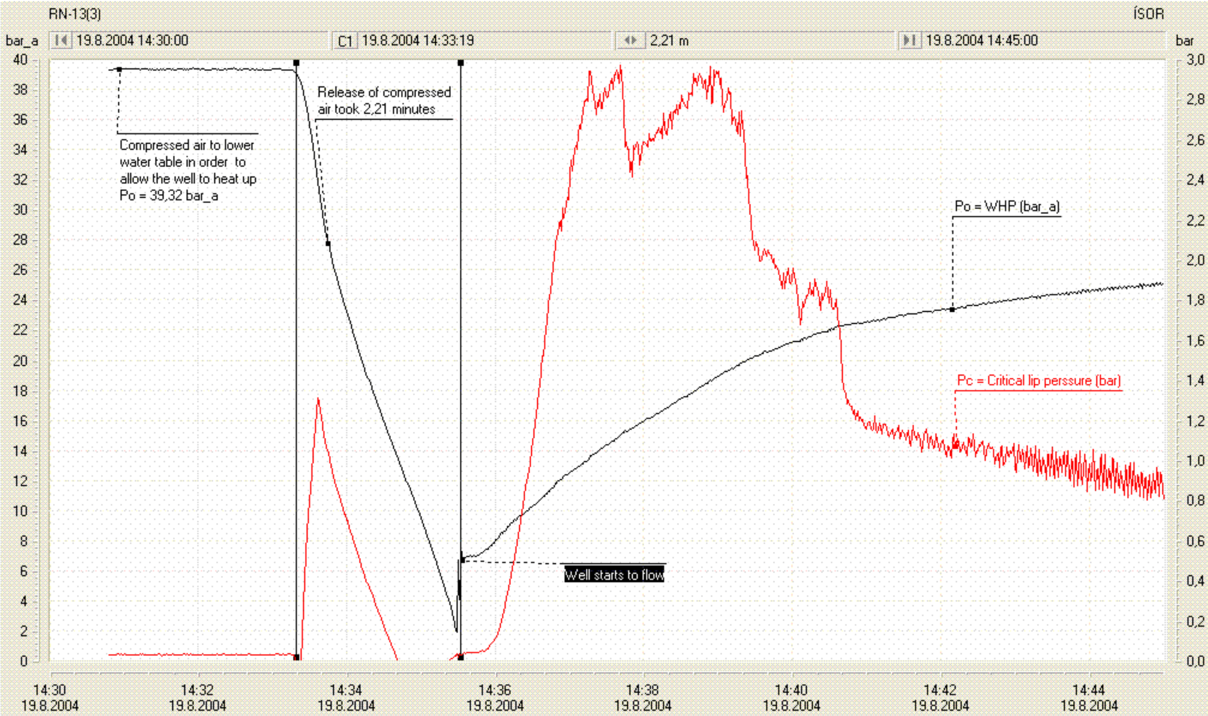


FIGURE 10: Pressure data taken during initiating of well no. RN-13 at Reykjanes by releasing the compressed air in 2.2 minutes, from the same data sequence as Figure 9

column will boil when the pressure is released. In fact, the fluid in the well does not remain static when air pressure is released. The fluid column will begin moving up the well, there will be a certain amount of draw down, and hot fluid will flow into the well at the feed points. The actual level of boiling will be controlled by feed temperature and the amount of drawdown.

It may not be possible to pressurize the well sufficiently to obtain the desired water level. Available pressure is limited by compressor capacity, and even with high-pressure compressors, the water level cannot be depressed past the first feed point below the casing shoe because this feed point will simply accept all of the injected air once it is reached. This method of initiating a discharge has a disadvantage in common with all means of suddenly initiating a discharge. It results in high stress in the cemented casing due to rapid changes in temperature. This method works satisfactorily for starting water levels down to 300-400 m, but for deeper water levels, the boiling fluid surging up the wellbore may be so cooled by the casing that all steam condenses and the discharge does not reach the surface (Grant et al. 1982). During flow testing, the continuous total mass flow rate can be monitored using a lip pipe or a complete measuring separator as described in Section 3.1.

### 4.2 Brine and steam sample collection from producing wells

For complete chemical analysis, it is necessary to take separate brine and steam samples from a separator. The sample is taken from the production well under pressure. The collection of representative samples from high-temperature drillholes is a complex procedure (Figure 11). It is done either by using a separator on the wellhead, separating the whole discharge, or by a portable separator as shown in Figure 8.

Tests have shown that the optimum location of the portable separator is on the discharge pipe about 1.5 m from the T-joint at the wellhead, where the water and steam phases are well mixed and still in thermodynamic equilibrium. The separator is connected with the steam line and kept open for 10-15 minutes to rinse it out and warm it up. Then, the separator is closed and the pressure on the separator pressure gauge recorded. In order to obtain a representative sample, the pressure on the separator gauge should be comparable to a pressure reading on the steam line itself (the wellhead pressure). After opening the separator, care is taken that the pressure in it does not significantly fall (preferably not more than 0.1 bars), because a pressure drop will cause additional boiling in the separator and upset the separation of the two-phases. It is necessary to keep the pressure constant while sampling.

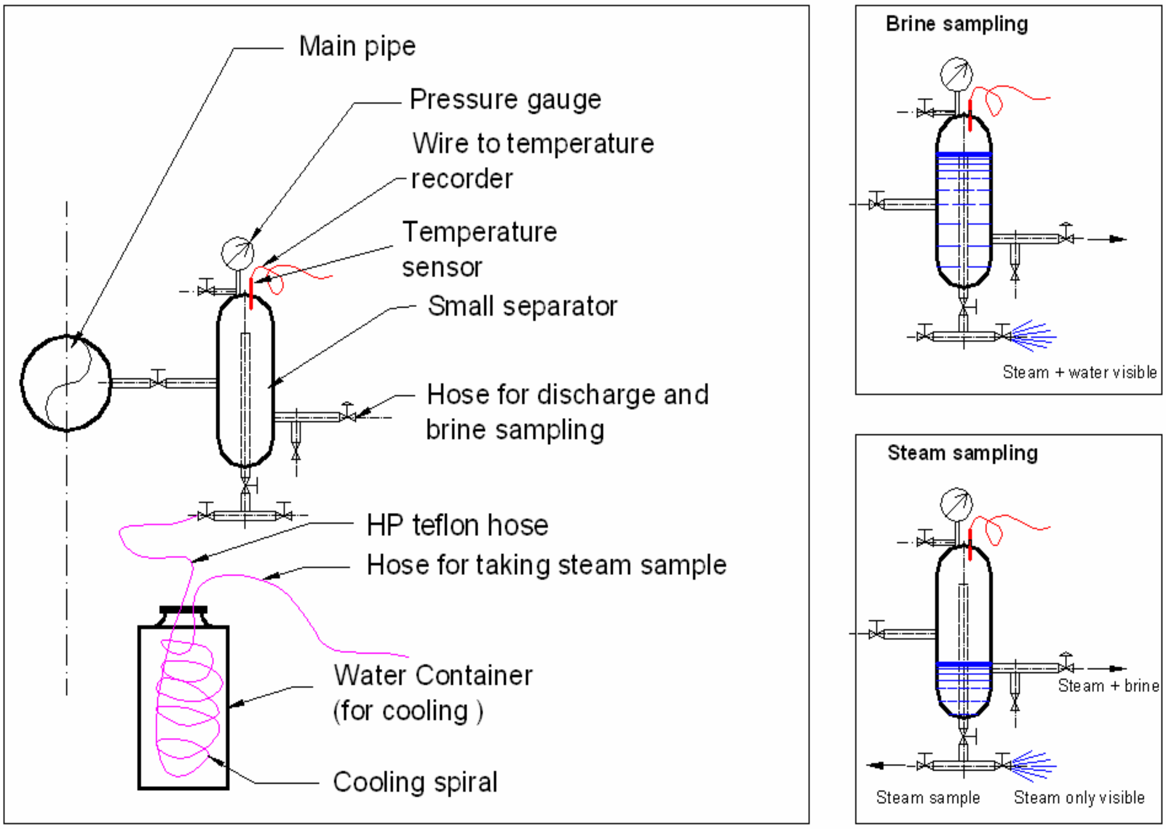


FIGURE 11: A portable separator to collect steam and brine samples

The cooling coil is connected with one of the two steam outlet valves on the separator to sample the steam phase. The valve is kept closed. The other steam outlet is opened, and the water and steam taps closed. The brine tap is then partly opened and the gas tap slightly opened so that a mixture of steam and water will discharge through the water tap and dry steam through the steam tap. The dry steam is barely visible close to the steam outlet and is conical in shape. Then the steam outlet, connected with the cooling coil, is opened but the other one closed. It must be kept open for a while to rinse the cooling coil. During sampling, the steam will condense in the cooling coil, but not the gases such as $CO_2$, $H_2S$ and $H_2$. Two phases i.e. condensate and gas are then collected. Gas and condensate are collected into two gas sampling flasks, and the condensate into a 100 ml polyethylene bottle as well. All containers are first thoroughly cleaned with the cooled steam. During the sampling procedure, the fluid temperature and separator pressure should be kept as constant as possible and recorded. The brine phase is sampled differently, with the cooling spiral connected to the valve shown as "hose for discharge" (Figure 11). The separator is adjusted so that brine will overflow to the steam side. This ensures that the separator is full of water and only brine will go to the sampling coil. The cooled brine sample is put in bottles and prepared, either filtered or unfiltered or acidified, as determined by the sampling procedure. The samples are then ready to be analysed in a laboratory.

## 5. ORMAT PLANT

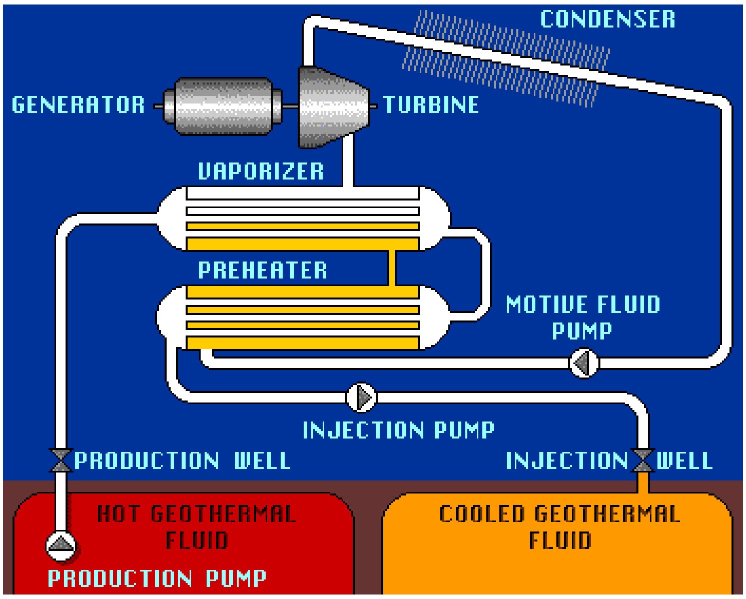

FIGURE 12: ORMAT energy converter (OEC)
(ORMAT, 2002)

The Aluto Langano power plant was constructed by the ORMAT Company. Figures 12 shows a scheme for a typical Ormat geothermal energy converter (OEC) and Figure 13 a scheme for Ormat geothermal combined cycle unit (GCCU). However, for the Aluto Langano power plant a considerably modified approach was used. There have been many problems associated with the Aluto Langano poser plant. According to the report produced by EEPCo March 2003, the transfer of the plant was made without prior acceptance tests and commissioning due to the lack of steam and pressure from the production wells. The commissioning, even though not complete, was subsequently done over a long period. During the first two years of operation, the problems which are listed in the introduction of this report were encountered. In order to deal with these problems, much maintenance work has been done. The power company (EEPCo) has now taken measures to rehabilitate the power plant. The problems, like the cooling tower belt corrosion, pentane leakage, and the size of the site and wellhead rock mufflers, need mechanical corrective actions. For example, to avoid corrosion of the cooling tower belt requires modification to change the belt system to a mechanical power assisted mechanism such as a planetary gear box. The Aluto Langano geothermal power plant is a fully computer-controlled plant. There is no option for operating the plant manually in case there are problems in the computer system.

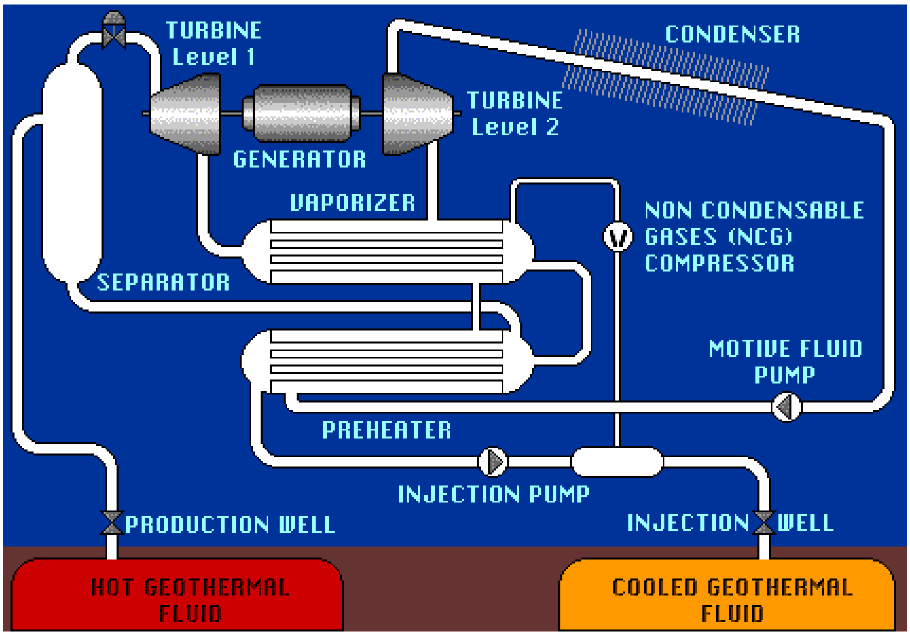

FIGURE 13: ORMAT geothermal combined cycle unit (GCCU)
(ORMAT, 2002)

It is important to have a supervisory system to analyze the cause of tripping and abnormal operation. A more detailed study is needed to make such a system. From recorded events, the power plant tripped and was isolated from the grid in most cases due to the computer system caused by some mechanical and electrical failure in the power plant. Geothermal wells may produce non-condensable gases such as $H_2S$. This gas is aggressive and may damage the computer installation and other electrical equipment, particularly electronic printed boards, plugs associated with control, instrumentation and protection. These failures caused frequent production interruptions. Consequently, the smooth flow from wells was disturbed. To avoid the $H_2S$ problem, it is necessary to protect the control room, all electronic cabinets and installations from corrosive ambient air. This is best done by a clean air supply that is air cleaned by using filter material to remove $H_2S$ and ventilation. The filter and ventilation system protects the process control from corrosive gases by (1) removing corrosive contaminates from outside intake air ($H_2S$), and pressurizing the room to prevent infiltration of corrosive contaminants; and (2) keeping the air within the space clean by recirculation and filtering. It also pressurizes the space in the cabinets to prevent infiltration of contaminated air. Coupons, dragger tubes or portable $H_2S$ monitors are used to monitor the air quality and verify the performance of the ventilation system.

Regarding the problem of parallel operation of wells, the EEPCo report showed that wells LA-3 & LA-6, the high-enthalpy wells at Aluto geothermal field, are equipped with wellhead separators. Steam transmission lines from each well join near well LA-3 with a “T” connection. After mixing of the steam from both wells, it flows through a common pipe to the power station. During production of the wells for power generation, it has been experienced that uninterrupted parallel production from wells LA-3 & LA-6 is limited to about three days. The well with the higher pressure eventually stops steam flow from the lower pressure one. This instability has resulted in reduced power generation. Different solutions were proposed in the report. To evaluate such problems, and to work with wells of different production capacity, it is necessary to know the well output curves and make models as in Section 6 of this report.

## 6. WELLHEAD PRESSURE VS. GENERATION OUTPUT

Well output curves, mass flow vs. wellhead pressure data (Figure 14), are taken from 6 production wells in Ölfusdalur geothermal area (Table 6), S-Iceland. For further calculation, HV-2, HV-3 and HV-8 were selected as the high-pressure wells and HV-4, HV-5 and HV-7 as the low-pressure wells.

For further modelling calculations, the equation for fitting a polynomial to each graph was found with the help of the Grapher program (Table 7). From these equations, the flow rate at different wellhead pressures for each well can be calculated. Thus, the power output from each well as a function of wellhead pressure can be calculated.

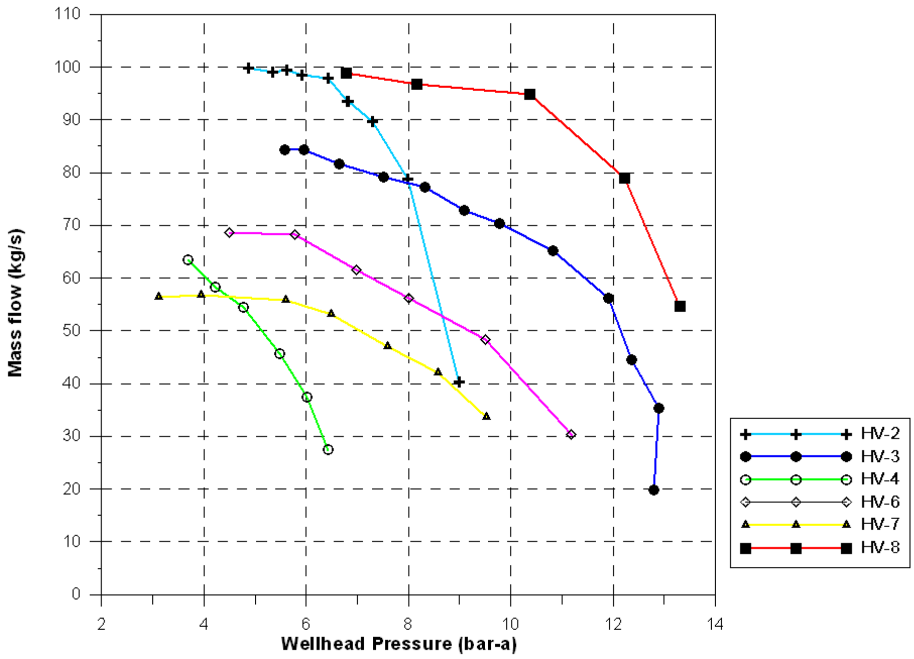


FIGURE 14: The flow characteristics of the Ölfusdalur wells

TABLE 6: Wellhead pressure and mass flow data for Ölfusdalur wells, S- Iceland

| HV-2 | | HV-3 | | HV-4 | | HV-6 | | HV-7 | | HV-8 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| P (bar) | Q (kg/s) | P (bar) | Q (kg/s) | P (bar) | Q (kg/s) | P (bar) | Q (kg/s) | P (bar) | Q (kg/s) | P (bar) | Q (kg/s) |
| 4.6 | 105.0 | 5.4 | 83.5 | 2.5 | 64.2 | 4.5 | 68.7 | 3.1 | 56.4 | 6.8 | 99.0 |
| 4.9 | 99.8 | 5.6 | 84.4 | 3.3 | 62.2 | 5.8 | 68.3 | 3.9 | 56.9 | 8.2 | 96.8 |
| 5.3 | 99.1 | 6.0 | 84.3 | 3.7 | 63.4 | 7.0 | 61.7 | 5.6 | 55.9 | 10.4 | 94.8 |
| 5.6 | 99.5 | 6.6 | 81.6 | 4.2 | 58.2 | 8.0 | 56.2 | 6.5 | 53.2 | 12.2 | 79.0 |
| 5.9 | 98.5 | 7.5 | 79.1 | 4.8 | 54.5 | 9.5 | 48.4 | 7.6 | 47.0 | 13.3 | 54.7 |
| 6.4 | 97.8 | 8.3 | 77.2 | 5.5 | 45.7 | 11.2 | 30.3 | 8.6 | 42.0 | | |
| 6.8 | 93.4 | 9.1 | 72.8 | 6.0 | 37.5 | | | 9.5 | 33.7 | | |
| 6.8 | 93.5 | 9.8 | 70.3 | 6.4 | 27.6 | | | | | | |
| 7.3 | 89.7 | 10.8 | 65.2 | | | | | | | | |
| 8.0 | 78.9 | 11.9 | 56.3 | | | | | | | | |

TABLE 7: Polynomial equations for output curves of the Ölfusdalur wells derived from their graphs

| Well condition | Well | Equation |
|---|---|---|
| High-pressure | HV-2 | $Y = -80.62133541 + 63.1393813\ X - 5.490638378\ X^2$ |
| High-pressure | HV-3 | $Y = 25.3121667 + 17.40555848\ X - 1.306988419\ X^2$ |
| Low-pressure | HV-4 | $Y = 37.19360819 + 18.01332154\ X - 3.018002383\ X^2$ |
| Low-pressure | HV-6 | $Y = 56.99309815 + 6.061420427\ X - 0.7517996193\ X^2$ |
| Low-pressure | HV-7 | $Y = 42.3887332 + 7.050780748\ X - 0.8357031629\ X^2$ |
| High-pressure | HV-8 | $Y = -27.08744962 + 30.50725394\ X - 1.813072236\ X^2$ |

The equation for the power output of a steam turbine is:

$$P_{ST} = m\eta(h_1 - h_2) \tag{9}$$

where $P_{ST}$ = Power output from steam turbine (kW);
$m$ = Mass flow (kg/s);
$\eta$ = Steam turbine efficiency (isentropic);
$h_1$ = Enthalpy at inlet (kJ/kg);
$h_2$ = Enthalpy after turbine (for isentropic expansion) (kJ/kg).

The equation for the power output from an ORC turbine is:

$$P_{ORC} = m\eta(h_3 - h_{COND}) \tag{10}$$

where $P_{ORC}$ = Power output from the ORC turbine (kW);
$m$ = mass flow (kg/s);
$\eta$ = ORC turbine thermal efficiency;
$h_1$ = Enthalpy at ORC turbine inlet (kJ/kg);
$h_2$ = Enthalpy of condensate (kJ/kg).

The results of the calculations are listed in Tables 8-11. To run this simulation, Excel was used with the Steam-Tab add-in. The idea of this simulation is to determine optimal production conditions for wells with different output characteristics. The variable data are wellhead pressure and separator pressures.

TABLE 8: Steam output, high-pressure wells

| Case | WHP Po (bar) | Mass flow HV-2 (kg/s) | Mass flow HV-3 (kg/s) | Mass flow HV-8 (kg/s) | Total mass flow (kg/s) C+D+E | Average enthalpy (kJ/kg) | High-pressure steam | | | | Low-pressure, 2nd flash | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Pressure at HP separator (bar) | Quality x | m steam (kg/s) | m water (kg/s) | Pressure at LP separator (bar) | Enthal. water (kJ/kg) | Quality x | Low-pressure m steam (kg/s) | Low-pressure m water (kg/s) |
| 1 | 5.0 | 97.8 | 79.7 | 80.1 | 257.6 | 895.0 | 4.0 | 0.136 | 35.1 | 222.5 | 2.50 | 604.7 | 0.032 | 1.1 | 215.5 |
| 2 | 6.0 | 100.6 | 82.7 | 90.7 | 273.9 | 896.5 | 5.0 | 0.122 | 33.3 | 240.6 | 2.50 | 640.1 | 0.048 | 1.6 | 229.1 |
| 3 | 7.0 | 92.3 | 83.1 | 97.6 | 273.0 | 899.2 | 6.0 | 0.110 | 30.0 | 243.1 | 2.50 | 670.4 | 0.062 | 1.9 | 228 |
| 4 | 8.0 | 73.1 | 80.9 | 100.9 | 254.9 | 903.5 | 7.0 | 0.100 | 25.5 | 229.5 | 2.50 | 697.0 | 0.074 | 1.9 | 212.4 |
| 5 | 9.0 | 42.9 | 76.1 | 100.6 | 219.6 | 910.9 | 8.0 | 0.093 | 20.4 | 199.2 | 2.50 | 720.9 | 0.085 | 1.7 | 182.3 |
| 6 | 10.0 | 0.0 | 68.7 | 96.7 | 165.3 | 926.3 | 9.0 | 0.091 | 15.0 | 150.4 | 2.50 | 742.6 | 0.095 | 1.4 | 136.1 |
| 7 | 11.0 | 0.0 | 58.6 | 89.1 | 147.7 | 927.1 | 10.0 | 0.082 | 12.1 | 135.7 | 2.50 | 762.5 | 0.104 | 1.3 | 121.5 |

TABLE 9: Turbine output, high-pressure wells

| Case | WHP (bar) | Turbine inlet p1 (bar) | Steam total mass flow (kg/s) | Steam in | | Steam out | | | Quality | Power |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | h1 (kJ/kg) | s (kJ/kg°C) | p2 (bar) | h2 (kJ/kg) | s (kJ/kg°C) | x | (kW) |
| 1 | 5 | 4 | 35.1 | 2738.1 | 6.9 | 1.2 | 2531.1 | 6.90 | 0.932 | 5443 |
| 2 | 6 | 5 | 33.3 | 2748.1 | 6.82 | 1.2 | 2502.8 | 6.82 | 0.920 | 6132 |
| 3 | 7 | 6 | 30.0 | 2756.1 | 6.76 | 1.2 | 2479.6 | 6.76 | 0.909 | 6213 |
| 4 | 8 | 7 | 25.5 | 2762.8 | 6.71 | 1.2 | 2459.8 | 6.71 | 0.901 | 5789 |
| 5 | 9 | 8 | 20.4 | 2768.3 | 6.66 | 1.2 | 2442.7 | 6.66 | 0.893 | 4977 |
| 6 | 9 | 9 | 15.0 | 2773.0 | 6.62 | 1.2 | 2427.4 | 6.62 | 0.886 | 3879 |
| 7 | 10 | 10 | 12.1 | 2777.1 | 6.59 | 1.2 | 2413.7 | 6.59 | 0.880 | 3290 |

TABLE 10: Steam output, low-pressure wells

| Case | WHP Po (bar) | Mass flow (kg/s) HV-4 | Mass flow (kg/s) HV-6 | Mass flow (kg/s) HV-7 | Total mass flow (kg/s) C+D+E | Average enthalpy (kJ/kg) | Low–pressure steam | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Pressure at LP separator (bar) | Quality x | Mass flow steam (kg/s) | Mass flow water (kg/s) |
| 1 | 5 | 51.8 | 68.5 | 56.8 | 177.1 | 869.3 | 1.2 | 0.192 | 33.9 | 143.1 |
| 2 | 6 | 36.6 | 66.3 | 54.6 | 157.5 | 894.6 | 1.2 | 0.203 | 32 | 125.6 |
| 3 | 7 | 15.4 | 62.6 | 50.8 | 128.8 | 560.9 | 1.2 | 0.054 | 7 | 121.8 |

TABLE 11: ORC turbine output, low-pressure wells

| Case | WHP (bar) | Turbine inlet p1 (bar) | Total steam mass flow (kg/s) | Steam in | | Condensate out | | Power (kW) | Total Power HP+LP (kW) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | h1 (kJ/kg) | S (kJ/kg°C) | T (°C) | h2 (kJ/kg) | | |
| 1 | 5 | 1.2 | 66.62 | 2683.05 | 7.3 | 95 | 398.09 | 16744 | 22187 |
| 2 | 6 | 1.2 | 62.61 | 2683.05 | 7.3 | 95 | 398.09 | 15736 | 21868 |
| 3 | 7 | 1.2 | 34.21 | 2683.05 | 7.3 | 95 | 398.09 | 8599 | 14813 |

From the results, it can be seen that from the high-pressure wells 5 MWe can be produced. The steam from low-pressure wells and the steam from the second flash high-pressure brine can produce an additional 17.8 MWe. By using the steam turbine and the ORC (Figure 15), the optimum total power of 23 MWe can be achieved (Figure 16). In this calculation, the power generation from wells with different production capacities, and how the selection of wellhead pressure affects the output for such wells is shown. It is not a good idea to operate them at too high a wellhead pressure.

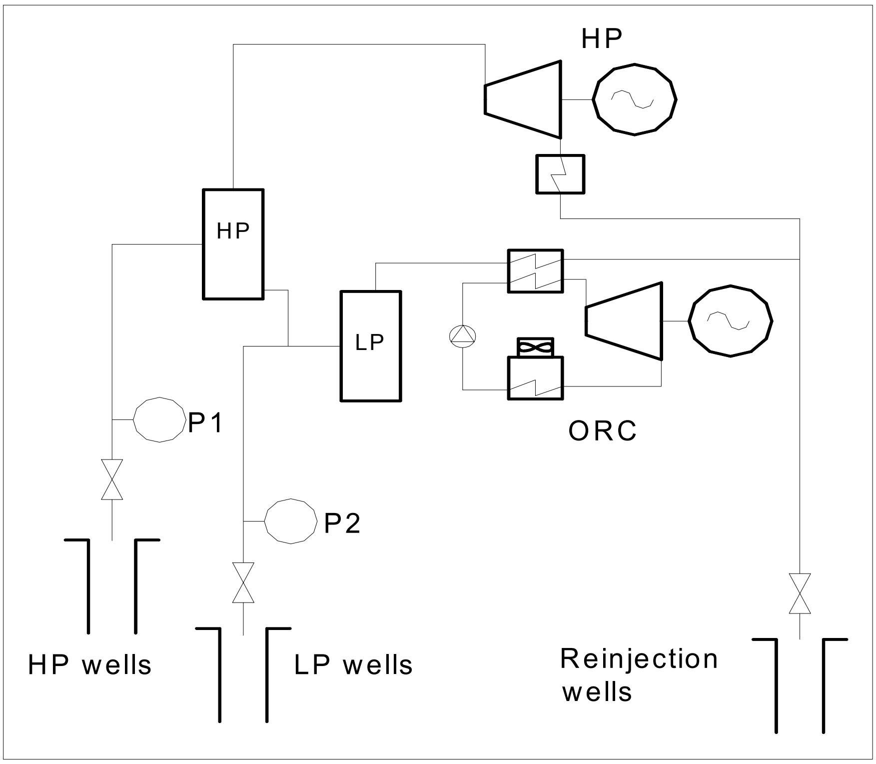


FIGURE 15: Diagram of power generation in high-pressure and ORC turbines from low-pressure and high-pressure wells on the basis of model calculations

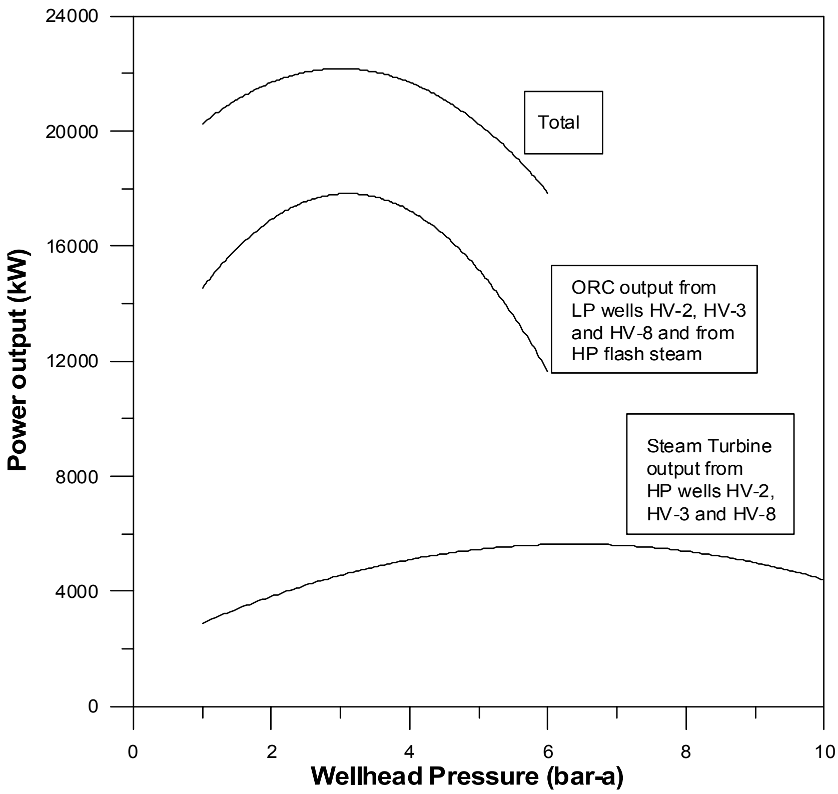


FIGURE 16: Optimum power output and well head pressure

## 7. CONCLUSIONS

The main purpose of this report was to become acquainted with some methods that might aid in identifying the problems of the Aluto Langano geothermal power plant. The problems of the pilot power plant as mentioned in this report are several, and require good understanding of the wells and system behaviour. Concentrating only on a few of the problems is, however, not enough to resolve the problems. This report identified what can be done to analyse such problems. The following are the main conclusions:

1. Deposition is a common occurrence in high-temperature geothermal systems. It is, therefore, important to realize deposition potential at various sensitive points in the system. Many different methods have been used to overcome the deposition problems. They depend up on the type of deposition encountered, the geological situation, and the economic environment. Determining the location and the thickness of the scales gives clear information for further cleaning measures.

2. Two-phase flow occurs in geothermal wellbores, so it is important to have the capability of modelling vertical two-phase flow for a production well. Quantitative information obtained from flow measurements of that discharge and its effects is important for future planning of both reservoir development and the surface plant.

3. To calculate the mass flow and the enthalpy of the wells, one has to install flow pipes and separators and collected data from pressure and flow measurements. Application of different controlling mechanisms is further more necessary for normal production.

4. The measurements of the mass flow and the total enthalpy of two-phase flow from the discharging wells should be done either by using total flow separators or by measuring water and steam flow independently. All downhole measurements, surface measurements, and other data provide supporting information that helps us understand the processes in both wells and reservoir.

5. Chemical and isotopic analyses are expensive and tedious, and all is wasted if the sampling is incorrect. Accurate sampling is a requirement and the operation of the required field equipment is described in the report.

6. During normal operation of the geothermal power plant, some problems and difficulties may occur to disturb the normal operation. It is very important to identify the problems and identify the possible solutions. Excluding non-condensable gases from the control room, $H_2S$ attack on copper in all electronic cabinets and installations of the plant can be reduced. The best way to minimize damage is by using $H_2S$ filters and maintaining over-pressure rooms where there is sensitive equipment.

7. To determine the plant size and the generation capacity, it is necessary to calculate the power output for different wells. By using such models, optimum wellhead pressure can be calculated and chosen for further design. The choice of wellhead pressure also has to consider the problem of silica deposition as too low pressure may lead to scaling.

**ACKNOWLEDGEMENTS**

I want to express my gratitude to the United Nation University, the government of Iceland and the Ethiopian Electric Power Corporation for supporting and permitting me to attend the Geothermal Training Programme. Thanks to those who coordinate the Programme, Dr. Ingvar B. Fridleifsson, director of the UNU Geothermal Programme, Mr. Lúdvík S. Georgsson, deputy director, Mrs. Gudrún Bjarnadóttir, administrative assistant, and all teaching staff of ISOR and Orkustofnun for their comprehensive presentations, willingness and exemplary dedication to the Fellows.

My special thanks go to Mr. Sverrir Thórhallsson, my supervisor, for sharing his great knowledge and experience, for his patient guidance and support during project preparation, which made it possible to complete this report. I would also to thank Prof. Páll Valdimarsson and the Faculty of Engineering at the University of Iceland for sharing their great knowledge and the valuable discussions regarding the report subjects. To all the UNU Fellows, especially the engineering (utilization) group, no words can express my gratitude.

I'm very grateful to my wife, Selamawit and our daughters Bethelehem and Mekdelawit, and all our families. You endured my long absence. It would have been impossible for me to go through this training without your support, prayers and encouragement. Thanks to you.

**REFERENCES**

Arnórsson, S., 1989: Deposition of calcium carbonate minerals from geothermal waters-theoretical considerations. *Geothermics, 18,* 33-39

Arnórsson, S., 1995: Scaling problems and treatment of separated water before injection. In: Rivera, J. (editor), *Injection technology*. World Geothermal Congress 1995, IGA pre-congress course, Pisa, Italy, May, 65-111.

Bai Liping, 1991: *Chemical modelling programs for predicting calcite scaling, applied to low temperature geothermal waters in Iceland*. UNU G.T.P., Iceland, report 3, 45 pp.

Corsi, R., 1986: Scaling and corrosion in geothermal equipment: problems and preventive measures. *Geothermics, 15*, 839-856.

EEPCo., 2003: *Aluto Langano geothermal plant, project profile.* Ethiopian Electric Power Corporation, unpublished report, 15 pp.

Ellis, A.J., and Mahon, W.A.J., 1977: *Chemistry and geothermal systems*. Academic Press, New York, 392 pp.

Grant, M.A., Donaldson, I.G., and Bixley, P.F., 1982: *Geothermal reservoir engineering*. Academic Press Ltd., New York, 369 pp.

Gudmundsson, J.S., 1983: Silica deposition from geothermal brine at Svartsengi, Iceland. *Proc. Symp. Solving Corrosion-Scaling Problems in Geothermal Systems. San Francisco, California,* 72-87.

Ketema, T., and Solomon, K., 1983: *Challenges and initiatives to be taken to develop geothermal resources in Ethiopia*. Geological Survey of Ethiopia, report.

Kristmannsdóttir, H., 1989: Types of scaling occurring by geothermal utilization in Iceland. *Geothermics, 18*, 183-190.

James, R., 1962: Steam-water critical flow through pipes. *Inst. Mech. Engrs. Proc., 176*, 741-745

James, R., 1970: Factors controlling borehole performance. *Geothermics, Sp. issue, 2-2,* 1502-1515.

Ormat 2002: *Ormat binary plant.* Ormat, Internet website,
http://www.ormat.com/index_technology.htm.

Tassew, M., 2001: Effect of solid deposition on geothermal utilization and methods of control. Report 13 in: *Geothermal training in Iceland 2001*. UNU G.T.P., Iceland, 291-310.

Teklemariam, M., Battaglia, S., Gianelli, G., and Ruggieri, G., 1996: Hydrothermal alteration in the Aluto-Langano geothermal field, Ethiopia. *Geothermics, 25-6,* 679-702.