# TWO-PHASE WELLBORE SIMULATOR AND ANALYSIS OF REINJECTION DATA FROM SVARTSENGI, ICELAND

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## ABSTRACT

A computer program is developed for the simulation of flowing geothermal wells. The necessary corrections of the salt and $CO_2$ concentrations on the thermophysical properties of the geothermal fluid are included in the program. The program is tested with the data from the Svartsengi geothermal field in Iceland and the Kizildere geothermal field in Turkey.

The response of the Svartsengi geothermal field to the injection is also investigated. A lumped model, called "the steam model" is used to analyze the effect of injection, and the actual data from the injection test at the Svartsengi field in 1984 is used for that purpose.

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## NOMENCLATURE

| | |
|---|---|
| $A$ | : Cross-sectional area to flow, ($m^2$) |
| $A_1$ | : Flow area in water zone, ($m^2$) |
| $A_2$ | : Flow area in feed zone, ($m^2$) |
| $B$ | : Pressure drop factor for skin effect and long term drawdown, (Pa/(kg/s)) |
| $c$ | : Leakage constant for steam model (kg/sec/m) |
| $C$ | : Turbulence factor, (Pa/(kg/s)$^2$) |
| $c_m$ | : Specific heat of the rock matrix, (J/kgK) |
| $D$ | : Diameter of pipe, (m) |
| $(dp)_t$ | : Total pressure drop, (Pa) |
| $(dp)_{acc}$ | : Pressure drop due to acceleration, (Pa) |
| $(dp)_{fri}$ | : Pressure drop due to friction, (Pa) |
| $(dp)_{pot}$ | : Pressure drop due to gravitational gradient, (Pa) |
| $dz$ | : Incremental pipe length, (m) |
| $E$ | : Energy of fluid, (J/s) |
| $f$ | : Friction factor |
| $G$ | : Mass flux, (kg/$m^2$ s) |
| $g$ | : Acceleration due to gravity, (m/$s^2$) |
| $H$ | : Enthalpy, (kJ/kg) |
| $h_1$ | : Drawdown between two-phase and liquid phase interface, (m) |
| $h_2$ | : Drawdown in feed zone, (m) |
| $k$ | : Permeability of the aquifer, ($m^2$) |
| $K$ | : Thermal conductivity of rock, (W/mK) |
| $m$ | : Molality of the solution, (moles/kg) |
| $n_L$ | : Concentration of carbondioxide in liquid phase, (% by weight) |
| $P$ | : Pressure, (Pa) |
| $P_S$ | : Steam saturation pressure, (Pa) |
| $P_{wf}$ | : Bottom hole flowing pressure, (Pa) |
| $P$ | : Wellhead pressure, (Pa) |
| $Q$ | : Heat loss to surroundings, (J/s/m) |
| $q$ | : Amount of water flowing out of storage in the water zone, (kg/s) |
| $r$ | : Radial distance, (m) |
| $R$ | : Universal gas constant, (kJ/kmoleK) |
| $Re$ | : Reynolds number |
| $r_w$ | : Wellbore radius, (m) |
| $S_1$ | : Storage in the liquid zone |
| $S_2$ | : Storage in the feed zone |

$T$ : Temperature, (°C)
$t$ : Time, (sec)
$V$ : Fluid velocity, (m/s)
$W$ : Mass flow rate, (kg/s)
$x$ : Steam quality, (%)
$z_a$ : Aquifer depth, (m)
$z^*$ : Flashing point in the well, (m)

Greek symbols:

$\rho$ : Fluid density, (kg/m3)
$\rho_1$ : Density of fluid in water zone, (kg/m$^3$)
$\rho_2$ : Density of fluid in feed zone, (kg/m$^3$)
$\varepsilon$ : Absolute roughness factor of the pipe, (m)
$\mu$ : Dynamic viscosity of fluid, (Pa s)
$\alpha$ : Void fraction
$\lambda$ : Slip factor
$\Phi^2$ : Two-phase multiplier
$\nu$ : Specific volume of fluid, (m3/kg)
$\kappa$ : Thermal diffusivity of the rock, (m$^2$/sec)

Subscripts

L : Liquid phase
m : Rock matrix
s : Vapour phase

# 1 INTRODUCTION

## 1.1 Purpose of the study

This report is the final part of a 6 month training at the UNU Geothermal Training Programme, at the National Energy Authority in Reykjavik, Iceland in the summer of 1985.

The author's training programme can be divided into four main sections, namely introductory lectures in various disciplines of geothermal technology, lectures on reservoir engineering for the specialized training in this subject, two weeks field excursion and seminars on the various geothermal fields of Iceland and the final project on the subjects of simulation of flowing wells and response of the Svartsengi field to injection.

The experience and knowledge gained will be helpful to solve not only problems dealt with in this report but a wide range of problems associated with evaluation and utilization of geothermal energy in Turkey.

## 1.2 Statement of the problem

Among the several factors affecting the flow performance of the wells, diameter of the well as well as the reduction in the diameter due to calcite scaling and the drawdown in the reservoir can be mentioned. It is a common practice to develop simulators to study the effects of those factors. Because of the chemical composition of the geothermal fluid, the thermodynamic properties of pure water should be corrected for salt concentration. Another factor which should be taken into account in the two-phase pressure drop calculations is the effect of non-condensable gases.

Reinjection is increasingly becoming an integral part of the design of geothermal projects. The necessity of reinjection mainly arises from three factors, disposal of chemically hazardous geothermal waste water, possibility of pressure recovery of the declining aquifer and more heat extraction from the reservoir rock.

The main problems encountered in geothermal fields in Turkey are the reduction in the yields of the wells due to both scaling and drawdown in the reservoir, and the disposal of waste water. These two problems were selected to provide the writer with a useful experience and knowledge on the methods of solution.

# 2 FLOW PERFORMANCE CALCULATIONS IN GEOTHERMAL WELLS

## 2.1 Introduction

Good production wells in high temperature fields are characterized by high flowrates which make the downhole measurement of the flowing wells impractical. This difficulty makes simulation of the flowing wells important. Therefore, it is necessary to develop and test the flow models for geothermal wells by using limited data which exists for low flowrates.

Wells in high temperature, liquid dominated geothermal reservoirs generally produce two-phase mixtures. In the case of liquid water inflow to the wellbore, the drop in pressure during upflow results in flashing of the fluid in the wellbore. Since the thermodynamic properties of a brine change with the salt concentration, it is necessary to correlate the properties of fluid with respect to salt concentration. One of the constituents in geothermal fluid is non-condensable gas, especially $CO_2$, which causes an increase in the flashing pressure. To analyze the behaviour of flowing wells, a wellbore simulator was developed which takes the effects of salt and $CO_2$ concentration into account. This simulator was used to estimate the deliverability curves for two wells in the Svartsengi geothermal field in Iceland. The effect of $CO_2$ was studied by using data from the Kizildere geothermal field in Turkey. As a final application, the changes in the output of a well as a result of calcite deposition was also studied.

In the following sections, the derivation of flow equations and corrections for salt concentration and $CO_2$ are presented.

## 2.2 Derivation of the equations for fluid flow in a vertical pipe

To describe the fluid flow in a vertical pipe, one can use the equations of conservation of mass, momentum and energy. During the following derivation of equations it is assumed that the flow is homogeneous, steady and one-dimensional.

- Equation for conservation of mass:

$$W = \rho V A \tag{1}$$

- Equation for conservation of momentum:

This equation is generally written from a pressure drop point of view. Total pressure drop is made up of three individual gradients,

$$-(dP)_t = (dP)_{fric} + (dP)_{acc} + (dP)_{pot} \tag{2}$$

Let us define each gradient separately.

i) Frictional pressure drop

This pressure drop is defined by the Darcy-Weisbach equation as;

$$(dP)_{fric} = \frac{\rho f V2}{2D} dz \tag{3}$$

The friction factor "f" is a function of the Reynolds Number, Re, and the relative roughness of pipe and is given by the modified Colebrook's equation as;

$$f = \left[\left[ -2 \log \left(\frac{\varepsilon}{3.7D}\right) + \left(\frac{7}{R_e}\right)^{0.9}\right]^2\right]^{-1} \tag{4}$$

where

$$Re = \frac{\rho V D}{\mu} \tag{5}$$

ii) Acceleration pressure drop

$$(dP)_{acc} = \rho V dV \tag{6}$$

If the mass flux is defined as $G = W/A$, and from Eq. 1, $V = G/\rho$, then the acceleration pressure drop can be expressed as;

$$(dP)_{acc} = G\ dV \tag{7}$$

iii) Potential pressure drop

This pressure drop is defined as;

$$(dP)_{pot} = \rho g dZ \tag{8}$$

By using equations 3,7 and 8 the total pressure drop can be written as;

$$-(dP)_t = \frac{\rho f V2}{2D} dZ + GdV + \rho g dZ \tag{9}$$

- Energy equation:

The total energy equation can be expressed as;

$$dE = WdH + Wd\left(\frac{V2}{2}\right) - WgdZ - QdZ \tag{10}$$

since there is no energy input for a self-flowing well, E=0, equation 10 becomes;

$$0 = dH + d\left(\frac{V2}{2}\right) + gdZ - \frac{Q}{W}dZ \tag{11}$$

The total enthalpy is a function of the enthalpies of each phase, $H_l$ and $H_s$, and the flowing steam quality, x.

$$H = xH_s + (1-x)H_l \tag{12}$$

Integration of equation 11 between any two points in the well in an upward direction gives;

$$H_2 = H_1 - 0.5(V_2^2 - V_1^2) - g(Z_2 - Z_1) + \frac{Q}{W}(Z_2 - Z_1) \quad (13)$$

By introducing equation 12, the steam quality at point 2 can be found as;

$$X_2 = \frac{H_1 - 0.5(V_2^2 - V_1^2) - g(Z_2 - Z_1) - H_{l,2} + (Q/W)(Z_2 - Z_1)}{H_{s,2} - H_{l,2}} \quad (14)$$

The heat loss to the surrounding, Q, will be discussed in a later section.

It is known that a liquid-dominated geothermal reservoir will initially produce undersaturated water at the wellbore sand-face. During the upflow of the fluid along the wellbore, the drop in pressure results in saturated water and the flow becomes a two-phase flow. In order to examine these two different sections, namely single-phase and two-phase, it is necessary to study the above equations at each section separately.

### 2.2.1 Singe-phase region

In this section, the fluid density is almost constant which corresponds to the density of the inflow temperature. This constant density results in a constant velocity, $V_1 = V_2$, then according to equation 7 $(dP)_{acc} = 0$.

Now, total pressure drop for single-phase region is reduced to;

$$-(dP) = \frac{\rho f V^2}{2D} dZ + \rho g dZ \quad (15)$$

### 2.2.2 Two-phase region

When the fluid starts flashing in the wellbore, it undergoes different two-phase flow regimes, namely bubble, slug and annular. These flow regimes have been studied by several authors (Ros, 1961; Hagedorn, 1964; Orkiszewski, 1967). In these flow regimes, the vapour and liquid phases travel separately at different velocities. Since the vapour always "slips" past the liquid in vertical flow, equation 9 has to be corrected.

In general the mixture density is presented in terms of actual void fraction defined from the volume occupied by the vapour phase,

$$\rho = \rho_s \alpha + \rho_l (1-\alpha) \tag{16}$$

where

$$\alpha = \frac{A_s}{A} \quad \text{or} \quad (1-\alpha) = \frac{A_l}{A} \tag{17}$$

On the other hand the slip factor, $\lambda$, is defined as the velocity ratio,

$$\lambda = \frac{V_s}{V_l} \tag{18}$$

Another important definition for the two-phase region is the steam quality, x.

$$x = \frac{W_s}{W} \quad \text{or} \quad (1-x) = \frac{W_l}{W} \tag{19}$$

Now, let us define individual pressure drops in the two-phase region.

i) Potential pressure drop

By substituting equation 17 into equation 8

$$(dP)_{pot} = [\alpha\rho_s + (1-\alpha)\rho_l]gdZ \tag{20}$$

ii) Acceleration pressure drop

From the equation for conservation of mass, equation 1, the velocities of each phase can be written as;

$$V = \frac{xW}{\rho_s A_s} \tag{21}$$

and

$$V = \frac{(1-x)W}{\rho_l A_l} \tag{22}$$

On the other hand, the acceleration pressure drop in two-phase region is defined as;

$$(dP)_{acc} = \frac{1}{A}\, d(W_l V_l + W_s V_s) \tag{23}$$

By substituting the definitions of velocities from equations 21 and 22

$$(dP)_{acc} = \frac{1}{A}\, d\left(\frac{WW_l(1-x)}{\rho_l A_l} + \frac{WW_s x}{\rho_s A_s}\right) \tag{24}$$

By making further substitutions for rates of mass flow and cross-sectional areas for each phase from equations 17 and 19 the final equation is obtained as;

$$(dP)_{acc} = G^2 d\left(\frac{X2}{\alpha\rho_s} + \frac{(1-x)2}{(1-\alpha)\rho_l}\right) \tag{25}$$

iii) Frictional pressure drop

If we introduce the definition of mixture density, equation 16, into equation 3 the frictional pressure drop for the two-phase region can be obtained.

$$(dP)_{ftp} = \frac{fV^2(\alpha\rho_s + (1-\alpha)\rho_l)}{2D} dZ \qquad (26)$$

But the difficulty arises here in the evaluation of the two-phase friction factor and velocity of the fluid, because of the definition of the two-phase viscosity and the difference between the velocities of phases due to slip. In order to overcome this difficulty several empirical correlations have been studied.

Martinelli-Nelson (1948) defined an empirical relation to calculate the friction pressure gradient by assuming a ratio, called two-phase multiplier.

$$(dP/dZ)_{ftp} = \Phi^2_{l\,or\,s} \cdot (dP/dZ)_{l\,or\,s} \qquad (27)$$

where $(dP/dz)_{ftp}$ is the two-phase frictional pressure gradient, $(dP/dz)_l$ and $(dP/dz)_s$ are the frictional pressure gradients for the liquid or gas respectively if they are flowing alone in the same tube.

Other correlating parameters have been defined if the total mass is flowing with the physical properties of one of the phases.

$$(dP/dZ)\ ftp = \Phi^2_{lo\,or\,so} \cdot (dP/dZ)_{lo\,or\,so} \qquad (28)$$

where $(dP/dz)_{lo}$ and $(dP/dz)_{so}$ are the pressure gradients for the total flow of fluid having the liquid or gas physical properties respectively.

In this correlation, frictional pressure drop for the single phase is obtained by assuming that all the flowing fluid is in this phase, then this single phase pressure drop is multiplied by the two-phase multiplier to obtain the frictional pressure drop in the two-phase flow.

In the literature, there are several correlations for a two-phase multiplier. In this report, the correlation given by Chisholm (1972) is used.

$$\Phi^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \qquad (29)$$

where

$$X^2 = \left(\frac{1-x}{x}\right)^2 \cdot \frac{\nu_l}{\nu_s} \qquad (30)$$

and

$$C = 1 + \frac{x\nu_s}{x\nu_s + (1-x)\nu_l} - \alpha \qquad (31)$$

As can be seen in equation 31 the void fraction, hould be known to calculate the two-phase multiplier. In order to calculate the void fraction the correlation by Armand and Teacher (1959) is used.

$$\alpha = \frac{0.833 + 0.05\log(P)}{1 + \frac{(1-x)}{x} \cdot \frac{\nu_l}{\nu_s}} \qquad P \text{ in bar} \qquad (32)$$

This concludes the equations for pressure drop in the two-phase section. The location of the flashing point can be calculated as follows.

$$-(dP)_t = (P_{wf} - P_s) = (dP)_{fri} + (dP)_{pot} \qquad (33)$$

From equation 15, by substituting $dZ = Z_a - Z^*$

$$-(dP)_t = \left(\frac{\rho f V2}{2D} + \rho g\right)(Z_a - Z^*) \qquad (34)$$

$$Z^* = Z_a - \frac{P_{wf} - P_s}{\rho g + \frac{\rho f V2}{2D}} \qquad (35)$$

But, the high flowrates and temperatures in geothermal wells, make it difficult to run downhole measurements under normal operating conditions. Therefore, in order to get the value of the bottom hole flowing pressure, $P_{wf}$, we should find a relationship between the conditions of static well and flowing well.

During the flow of fluid in the reservoir, the pressure drops from undisturbed reservoir pressure, $P_a$, to the bottom hole flowing pressure, $P_{wf}$, at the sand-face. This pressure drop in the reservoir is due to the skin effect, the longterm drawdown factor, and the turbulence pressure drop. (Kjaran, 1983) Therefore, $P_{wf}$ can be written as;

$$P_{wf} = P_a - (BW + CW^2) \tag{36}$$

where B and C are some factors.

In the high flowrate geothermal wells, initially the pressure drop due to turbulence is the dominant factor and equation 36 can be rewritten as;

$$P_{wf} = P_a - CW^2 \tag{37}$$

Since we have some measurements of $P_{wf}$ for the low flowrates, equation 39 can be solved analytically by taking the slope of $(P_\alpha - P_{wf})/W$ vs. W graph as turbulence factor C.

Another way of obtaining the C value is the use of simulators to match the deliverability measurements of the wells since the wellhead pressure is given by,

$$P_o = P_{wf} - (dP)_t = P_a - CW^2 - (dP)_t \tag{38}$$

In this procedure, $P_a$ is an input and C is the variableto match the measured wellhead pressure for a given flowrate.

## 2.3 Wellbore heat transfer

During the flow of fluid in the wellbore, some heat is transferred by conduction through the rock surrounding the wellbore. This heat transfer to the surrounding has been studied by Ramey (1962). By assuming that the conductive heat flow is normal to the axis of the well, the equation for heat conduction can be written as;

$$K \frac{1}{r} \cdot \frac{\partial}{\partial r}\left(r \cdot \frac{\partial T}{\partial r}\right) = \rho_m C_m \frac{\partial T}{\partial T} \qquad (39)$$

The boundary conditions are as follows,

$$T \rightarrow T_r \qquad (r \rightarrow \infty),$$
$$T = T_w \qquad (r = r_w)$$

where $T_r$ = undisturbed reservoir temperature, (°K)
$T$ = temperature at the well face, (°K)

The conductive heat transfer per unit length of the wellbore is given by;

$$Q = 2\pi r_w K \frac{(T_r - T_w)}{f(t)} \qquad (40)$$

where f(t) is defined as;

$$f(t) = \ln\left(\frac{2\sqrt{Kt}}{r_w}\right) - 0.29 \qquad (41)$$

In fact, the boundary condition given for undisturbed reservoir temperature occurrs at a certain distance from the wellbore instead of infinity. By introducing this new boundary condition, the solution of the problem becomes more complicated and is given by Carslaw and Jaeger (1959).

## 2.4 Thermodynamic properties of geothermal fluids

Geothermal fluids are solutions of various types of salts. These are primarily NaCl, KCl, and $CaCl_2$, but it is a common practice to use the "equivalent NaCl content" to define the salinity of a geothermal fluid. The "equivalent NaCl content" is the amount of NaCl in solution that will bring the same effect on the properties as the amount of all the salts combined.

For the modelling of the geothermal well, it is necessary to know some thermophysical properties accurately, such as the density, the enthalpy, the entropy, the viscosity and the saturation pressure at a given temperature. To make the corrections on the pure water properties, Michaelides (1981) presented some formulas which are based on "equivalent NaCl content".

One of the effective changes in the properties of pure water with salt content is the depression of saturation pressure at a given temperature,

$$\Delta P = \frac{1.8R(T + 273.15)}{\nu_s - \nu_l} \cdot \frac{m}{55.56} \qquad kP_a \qquad (42)$$

where R = (8.314/18) = 0.4619 kJ/kgK, 55.56 is the moles of water in 1 kg of the substance

$$\text{and } m = \frac{\text{Salinity of water in ppm}}{\text{Molecular weight of NaCl}}$$

The saturation pressure of pure water is given by the following simplified correlation;

$$P(T) = \exp(0.21913E\text{-}6T^3 - 0.17816E\text{-}3T^2 + 0.0653665T - 4.96087) \qquad (43)$$

In his paper Michaelides gives the gas constant as 8.314 kJ/kgK for equation 42, but if the unit analysis is done carefully, it is found that the actual gas constant is the ratio of universal gas constant (8.314 kJ/kmoleK) to the molecular weight of water (18 kg/kmole). The reader should give attention to this change in the formula.

Let us take an example to show the effect of salt on the depression of saturation pressure. If we take the common values from the Svartsengi geothermal field in Iceland,

T = 240°C and salinity = 20.000 ppm

by using equation 43, P(T) = 32.93 bar

$$m = \frac{20.000 \ mg/kg}{58.500 \ mg/mol} = 0.342 \ mol/kg$$

and $\nu_s = 0.0595 \ m^3/kg$, $\nu_l = 0.0012 \ m^3/kg$ from the steam tables for pure water.

By substituting the above values into equation 42

$$\Delta P = 45.05 \ kPa = 0.45 \ bar$$

The true saturation pressure therefore reduces to,

$$P = P(T) - \Delta P = 32.93 - 0.45 = 32.48 \ bar$$

For the correlations of density, enthalpy, viscosity, entropy and elevation of saturation temperature, the reader is referred to Michaelides (1981).

## 2.5 Effect of $CO_2$

$CO_2$ provides an important component to the total pressure of geothermal fluid. Presence of $CO_2$ causes the transition between single-phase and two-phase flow to happen deeper in the wellbore than one would expect by ignoring $CO_2$.

The pressure of the vapour phase is the sum of steam and gas partial pressures,

$$P = P_s + P_g \tag{44}$$

The partial pressure of gas can be expressed in terms of the concentration of gas in liquid phase and solubility. The solubility data for $CO_2$ was fitted to an equation by Sutton (1976).

$$\alpha(T) = \{5.4-3.5(T/100)+1.2(T/100)^2\}E-9, \ (1/Pa) \tag{45}$$

The partial pressure of $CO_2$ is given by the following formula,

$$P_g = \frac{n_l}{\alpha(T)} \tag{45}$$

In order to show the effect of $CO_2$ on the flashing pressure of the fluid, let us take an example from the Kizildere geothermal field in Turkey.

The well number KD-6 is producing 15% $CO_2$ by weight in the steam phase and the wellhead steam quality is measured as 9.47%. The inflow temperature of fluid is 201°C.

In order to get the flashing pressure, the steam saturation pressure and $CO_2$ partial pressure should be calculated separately.

By using equation 45 the steam pressure can be found.

$$P_s(T) = 15.79 \text{ bar}$$

Now,first of all we should convert the wellhead $CO_2$ measurement to downhole concentration. By assuming all the $CO_2$ was in the vapour phase at the wellhead,

$$n_1 = 0.15 \cdot 9.47 = 1.42 \text{ \% by weight}$$

By using equation 45, $\alpha(T) = 3.21E{-}9 \quad 1/Pa$

$$P_g = \frac{0.0142}{3.21E{-}9} = 4.42E6, \quad Pa = 44.2 \text{ bar}$$

Therefore, the flashing pressure of this system is;

$$P = 15.8 + 44.2 = 60 \text{ bar}$$

which is far beyond the steam saturation pressure.

After flashing, the $CO_2$ pressure in the vapour diminishes from its initial value as flashing progresses. Most of the mass of $CO_2$ is exsolved in the first few weight percent of flashing. Michels (1981) developed a relationship for the $CO_2$ pressure in a developing vapour phase.

The partial pressure of $CO_2$ is given accurately enough by the real gas equation, PV = znRT, and the final form can be expressed as a function of three factors, namely initial

$CO_2$ partial pressure, the present temperature of the system, and the weight percent of flashing that has developed.

$$P_c = P_{c(0)}\left\{1 + \frac{44\ \nu_s x}{\alpha(T)R(T+273.15)}\right\}^{-1} \qquad (47)$$

where $P_{c(0)}$ = Initial $CO_2$ partial pressure and 42 is molecular weight of $CO_2$.

## 2.6 Applications of the program

The developed computer program can find the main applications in the following subjects:

i. Prediction of flowing well pressure and temperature profiles.

ii. Development of deliverability curves for a certain well for different aquifer pressures.

iii. Determination of the effect of salt and $CO_2$ concentration on the flashing point of the fluid.

iv. Determination of the effect of calcite deposition and plugging on production.

These four items were analyzed for two wells in the Svartsengi field in Iceland and one example is given for the effect of $CO_2$ from the Kizildere field in Turkey. During the application of the computer program, the relative roughness coefficients of the slotted liner, casing and calcite deposition were taken as 1.37 E-4, 4.57 E-5 and 3.047 E-4 m respectively.

The listing of the program is presented in Appendix A.

### 2.6.1 Svartsengi Well No. 4

This well was initially drilled to 1713 m depth, and it was used as a production well until a casing damage occurred in the well in 1980. Presently it is used as an observation well.

The depth of the aquifer is found from the temperature profiles as 1024 m, initial temperature and pressure values were 240°C and 88 bars respectively.

During the application of the computer program, the deliverability curves of the well, with or without calcite deposition, and the pressure profile of the well were obtained. These results are compared with the actual measurements. The output measurements for well 4 in Svartsengi are given in Table 1. As can be seen from Fig. 1, the deliverability curves for the cases with or without calcite are in good agreement with the measured ones. This fit was obtained by using the turbulence coefficient as 0.0035 bar/(kg/s)$^2$.

TABLE 1: Svartsengi well no 4 output measurements

| WHP(bara) Without calcite | Flow(kg/s) Without calcite | WHP(bara) With calcite | Flow(kg/s) With calcite |
|---|---|---|---|
| 19.0 | 33.0 | 18.9 | 28.0 |
| 17.1 | 59.0 | 16.8 | 39.0 |
| 14.0 | 75.0 | 13.5 | 49.0 |
| 13.2 | 80.0 | 11.2 | 50.0 |
| 11.7 | 85.0 | 9.2 | 51.0 |
| | | 8.9 | 52.0 |

Data derived from Fig. 2 was used to see the effect of calcite deposition. The length of deposition was taken as 60 m between the interval 350-410 m and the best fit was obtained by using 11.5 cm as the average diameter of the calcite section. The calcite deposition causes a very high pressure drop in high flowrates and the change in deliverability curve is very abrupt at a particular flowrate. In Svartsengi 4, this flowrate is found as 51 kg/s and with a flowrate higher than this value the flow is choked.

The measured and calculated pressure profiles were also compared at Fig. 3. The calculated pressure profile at 30 kg/s flowrates gives a good fit with the measured one.

As a final application, mass flowrate vs. flashing depth from wellhead was plotted, and the caliper log of the well, Fig. 2, was compared with this plot (Fig. 4). By taking the flashing depth as 410 m from Fig. 2, the corresponding flowrate is found as 31 kg/s from Fig. 4 which was the actual average flowrate of the well before caliper log.

The computer outputs for Svartsengi 4 are given in Appendix B.

### 2.6.2 Svartsengi Well No. 11

This well was used as an example for the effect of reservoir pressure and casing size on the deliverability curves. The family curves for different reservoir pressures are shown on Fig. 5. The pressure drawdown causes a reduction in the wellhead pressure but this reduction is not of the same order of magnitude as the reduction of reservoir pressure. On the other hand, the shape ofthe deliverability curves are almost the same for all reservoir pressures, therefore it is possible to find a common formula depending on the reservoir pressure, wellhead pressure and mass flowrate by knowing only one deliverability curve for a reservoir pressure.

As a part of this study, three production tests were carried out and the data is used in the program. The lip pressure method developed by James (1970) was use to test the well. A V-notch was used to measure the low mass flowrates and the enthalpy of fluid is calculated from James's formula which relates mass flow, discharge pipe area, enthalpy of fluid, and lip pressure. For a higher mass flowrate, the well was discharged vertically, direct to the atmosphere. The enthalpy value obtained from low flowrates is used to get the flowrate from James's formula. The results of the test are given in Fig. 5. Since there is about 12 bar pressure reduction in the field from the initial reservoir pressure, due to the production, the reservoir pressure is taken as 76 bar. The best fit is obtained by using zero turbulence factor.

The effect of casing size on the output curves was also studied and the results obtained for two different wells are plotted in Fig. 6. The main effect of the casing size on the output characteristics of the wells is the decrease in the turbulence pressure drop in the wider wells. The deliverability curve for Svartsengi 11 was obtained by using zero turbulence factor and as can be seen from Fig. 6, the change in flowrate does not affect the wellhead pressure in the wider well as in the narrower well.

### 2.6.3 Kizildere Well No. 6

To see the effect of $CO_2$ on the output curves, data from Kizildere geothermal field in Turkey was used. The Kizildere field is a hot-water type geothermal field which is producing through six wells. One of the important problems in this field is CaCO scaling in wells which is related not only to the calcium but also to the $CO_2$ content of the geothermal fluid. High percentage of $CO_2$ in the geothermal fluid of Kizildere causes early flashing of the fluid because of higher $CO_2$ partial pressure. The data from Kizildere Well no 6 (KD-6) was used in the program and the flashing depth and the wellhead pressure were examined. The actual data (Tan, 1982) and computer output for this well are given in Table 2. Fig. 7 shows the configuration of casing string and flashing point.

By using zero turbulence pressure drop, the wellhead pressure was obtained as 3.14 bar and the flashing point is at 576 m which shows a good agreement with the measurements.

## TABLE 2: Data and computer output for Kizildere well No. 6

NAME OF FIELD: KIZILDERE
WELL NAME : KD-6
DATE OF CALC : 17-09-85

SINGLE-PHASE(WATER) SECTION:

Pa (BARS) = 84.000
(dp)turb (BARS) - 0.000
Pwf (BARS) = 84.000
CCO2 (ppm) = 14204.0
CNACL (ppm) : 1200.0

| DEPTH(m) | P(bar) | Vel(f) | Ffactor | D(cm) | DPWAT. | DPPOT | DPFRIC | W(kg/s) | T(C) | PFLASH |
|---|---|---|---|---|---|---|---|---|---|---|
| 800.000 | 79.594 | 3.034 | 0.018 | 21.590 | -4.406 | -4.242 | -0.164 | 96.00 | 201.0 | 59.985 |
| 700.000 | 70.782 | 3.034 | 0.018 | 21.590 | -8.812 | -8.485 | -0.328 | 96.00 | 201.0 | 59.985 |
| 665.600 | 67.750 | 3.034 | 0.018 | 21.590 | -3.031 | -2.919 | -0.113 | 96.00 | 201.0 | 59.985 |
| 665.600 | 67.752 | 2.366 | 0.014 | 24.448 | 0.002 | 0.000 | 0.000 | 96.00 | 201.0 | 59.985 |
| 600.000 | 62.096 | 2.366 | 0.014 | 24.448 | -5.656 | -5.566 | -0.090 | 96.00 | 201.0 | 59.985 |

TWO-PHASE SECTION:

Wt (Kg/s) = 96.000
Pwf (BARS) = 84.000
H (KJ/Kg) = 856.637
Pflash (BARS) = 59.985

| DEPTH | P | PC | DPC | D | X(%) | DPT | DPPOT | DPACC | DPFRIC | H(J/g) | T(C) | FF | SLIP | VOID | TY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 575.5 | 59.99 | 44.21 | 0.000 | 24.45 | 0.0 | 0.000 | 0.000 | 0.000 | 0.000 | 856.6 | 201.0 | 0.0141 | 1.00 | 0.00 | BU |
| 500.0 | 15.29 | 2.79 | -41.421 | 24.45 | 2.5 | -44.700 | -3.004 | -0.156 | -0.112 | 855.9 | 189.8 | 0.0141 | 1.56 | 0.70 | AN |
| 400.0 | 11.26 | 1.23 | -1.559 | 24.45 | 4.6 | -4.021 | -2.172 | -0.070 | -0.220 | 854.9 | 179.8 | 0.0141 | 2.21 | 0.79 | AN |
| 300.0 | 8.65 | 0.69 | -0.542 | 24.45 | 6.6 | -2.613 | -1.703 | -0.057 | -0.317 | 853.0 | 169.9 | 0.0141 | 3.17 | 0.83 | AN |
| 200.0 | 6.32 | 0.40 | -0.288 | 24.45 | 8.9 | -2.331 | -1.508 | -0.070 | -0.466 | 852.7 | 157.8 | 0.0141 | 4.89 | 0.84 | AN |
| 100.0 | 3.90 | 0.22 | -0.178 | 24.45 | 12.1 | -2.424 | -1.267 | -0.204 | -0.776 | 851.2 | 140.1 | 0.0141 | 6.19 | 0.88 | AN |
| 0.0 | 3.12 | 0.18 | -0.039 | 24.45 | 13.5 | -0.771 | -0.294 | -0.105 | -0.334 | 850.5 | 132.5 | 0.0141 | 6.71 | 0.90 | AN |

WHP (BAR)- 3.12

| | | | |
|---|---|---|---|
| Mass flow rate | : 96 kg/s | Bottom hole pressure | : 84 bar |
| Depth | : 851 m | Temperature | : 201 C |
| WHP | : 3.0 bar | $CO_2$ content of steam | : 15 % by weight |
| Salt content | : 1200 ppm | Steam quality | : 9.47 % |

Table 2. Data and computer output for Kizildere Well no 6

# 3 RESPONSE OF THE SVARTSENGI GEOTHERMAL FIELD TO INJECTION

The Svartsengi geothermal field is a high temperature liquid dominated field with a temperature range 235-240°C and the fluid produced is in composition of two-thirds sea water and one-third fresh water. The geology of the Svartsengi field has been described by Franzson (1983). Reservoir engineering studies in Svartsengi are discussed by Kjaran et al. (1979) and Gudmundsson et al. (1985a, 1985b). The fluid production in Svartsengi has resulted in a drawdown of 135 m, after a fluid production of about 41 E9 kg. The rapid drawdown in the field may affect the following items of the future performance of the field: i) cold water encroachment from surrounding aquifers, and cooling of the formation, ii) decline in the output of production wells with falling reservoir pressure, iii) migration of the flashing zone down the wells and into the formation, iv) sealing of the producing fractures by calcite deposition if the fluid flashes in the formation. Injection would be a solution to the pressure recovery of the field as well as the efficient disposal of waste brine and condensate.

To study the effects of injection in the field two injection and tracer tests were carried out in 1982 and 1984. These tests are discussed by Gudmundsson (1983) and Hauksson (1985). The purpose of this study is to investigate the pressure response of the field to injection and match one year production history of the field by using a lumped-parameter model.

## 3.1 Analysis of injection data

In the Svartsengi injection test, a brine-condensate mixture was injected for 72 days between 25th July to 4th October, 1984. The mixture was 80 percent flashed brine and 20 percent steam condensate and the injection flowrate was kept at 50 kg/s. The mixture had a pH close to 6.7 and the temperature 80°C. During the injection test, the drawdown was measured as water level in a monitoring well. The critical problem encountered during the injection was the silica scaling in the injection well. It was tried to avoid this by controlling the pH of the injected fluid and by dilution of the brine with the condensate of the power plant. During the test the condensate concentration could not be kept constant because of the unavailability of adequate amount of condensate from the power plant. As a result the concentration of the condensate decreased down to 10 percent which caused an increase in the rate of silica deposition. One of the proposed solutions to decrease the rate of silica deposition is the injection of $CO_2$ with the condensate, which produces a weak acid to lower the pH down to 5.5 (Hauksson, T. personal communication).

To see the effect of injection on the drawdown of the field, the rate of production and drawdown data are used for the time period of October 1983 to January 1985. The total rate of production and injection data are shown in Fig. 8 with time, and the net production is the difference between production and injection rates. The water level drawdown is shown in Fig. 9 with time.

The drawdown data shows a linear trend for the first seven months in which the net production rate is almost constant. But after a decrease in production, the rate of drawdown also decreases and during the time of injection the water level starts to increase. The effect of reinjection can also be seen from the late portion of the data when the production rate reaches the initial value. During this period, the change in drawdown shows the similar trend as of the early data. By using these two graphs it can be concluded that the injection can be helpful to recover pressure.

## 3.2 Model description

Fluid extraction and reservoir drawdown in the Svartsengi field developed an increased steam zone after a few years of fluid production. This is evident from Well 10 which changed from being liquid-fed to producing steam only which is the shallowest well among the six main producing wells (424 m deep). Other wells in the field are still liquid-fed. A conceptual model of the Svartsengi reservoir is shown in Fig. 10. The liquid dominated reservoir is overlain with a steam zone, which increases in size with drawdown (Hauksson, 1985).

Based on the above conceptual model Vatnaskil (1983) developed a lumped parameter model of the field. The schematic representation of the model is given in Fig. 11. The boundaries of the reservoir are impermeable and there is a slightly impermeable barrier between the feed zone and the liquid dominated zone. The drawdown in the feed zone leads to a leakage from the water zone. This leakage results in an increase in the size of the two-phase zone. The balance equations for this model can be written as;

$$W = q + A_2 S_2 \rho_2 \frac{dh_2}{dt} \tag{48}$$

$$q = A_1 S_1 \rho_1 \frac{dh_1}{dt} \tag{49}$$

$$q = c(h_2 - h_1) \tag{50}$$

where c is a constant.

If we solve these equations for $h_1$ and $h_2$ we get;

$$h_1(t) = C_3 \int_0^t m(t-\tau) e^{-\tau/k} d\tau \tag{51}$$

$$h_2(t) = C_1(t) - C_2 \int_0^t m(t-\tau) e^{-\tau/k} d\tau \tag{52}$$

where;

$$C_1 = \frac{1}{(\rho_2 A_2 S_2)^2} \tag{53}$$

$$C_2 = \frac{C}{\rho_2 A_2 S_2} \tag{54}$$

$$C_3 = \frac{C}{A_1 \rho_1 S_1 A_2 \rho_2 S_2} \tag{55}$$

$$K = \frac{1}{C} \frac{A_1 \rho_1 S_1 A_2 \rho_2 S_2}{A_1 \rho_1 S_1 + A_2 \rho_2 S_2} \tag{56}$$

and

$$M(t) = \int_{o}^{k} W(\tau) d\tau \tag{57}$$

The same set of production and drawdown data given in Figs. 8 and 9 were used to test the proposed model. The production rate of Well 10 was subtracted from the total field production, because it is producing from the two-phase region. For the best fit of drawdown, the variables in Eq. 54 are found as;

K = 125 days, C = 5.1 E-9 m/kg, C = 2.5 E-11 m/kg/day

A good fit is obtained for the long term behavior of the drawdown (Fig. 12), but the model was not able to produce the sharp changes in the drawdown. This is due to the nature of the model, which assumes the storage is given by the free surface effect at the boiling surface, which is the long term effect thus neglecting the short term elastic storage. The model also assumes that all the introduced change in the flowrate should reach to the boundaries to be effective on the drawdown. The time required to see the boundary effects in the Svartsengi field was found to be 10-30 days by Kjaran et.al. (1979). Therefore, it is not possible to simulate any changes in the flowrate for a time less than 30 days.

## 4 SUMMARY

Simulation of flowing wells can be a useful tool for geothermal well analysis. Using the flow model, it is still possible to get information for the conditions where the actual measurements failed. The following parameters can be deduced by the application of a wellbore simulator.

1. The temperature and pressure profiles of flowing wells can be obtained.

2. The change in the performance of the well after scaling development in the well can be simulated.

3. The magnitude of decline in wellhead pressure with aquifer pressure can be found

4. The wellbores with wider production casings give higher flowrates than those with smaller sized wells.

The practical use of the model presented here can be listed as follows:

a. The flash level of the geothermal fluid can be found within a good accuracy, therefore it gives a valuable data for the cleaning operations of the wells.

b. The wellhead pressure and mass flowrate history of the wells can be forecasted by using the predicted drawdown of the reservoir itself. This information is used for the planning of the operational life of a geothermal power plant, since it requires some minimum values for both mass flowrate and pressure values in the turbine.

It is found that the decline in the drawdown can be reduced by injection. Reinjection also has merits for the waste disposal problems of geofluid which causes pollution problems. To fit the immediate response of the Svartsengi field to injection, a new model should be developed which can respond to changes in the flowrate over a period of less than a month. In order to see the validity of the steam model the flowrate of injection should be kept constant for a longer time.

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JHD-HSÞ-2300-MP
85.09.1179-ÓD

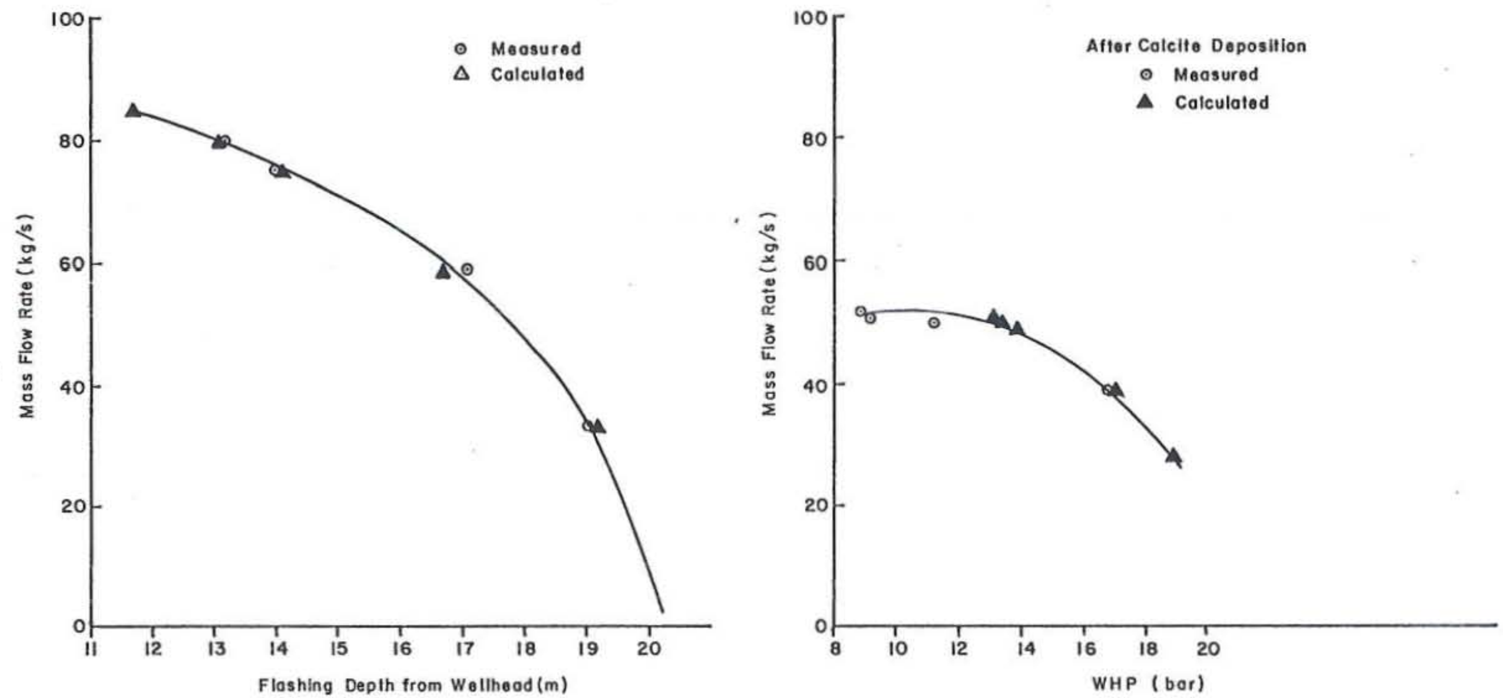


Figure I. Svartsengi Well no. 4 Output Characteristics

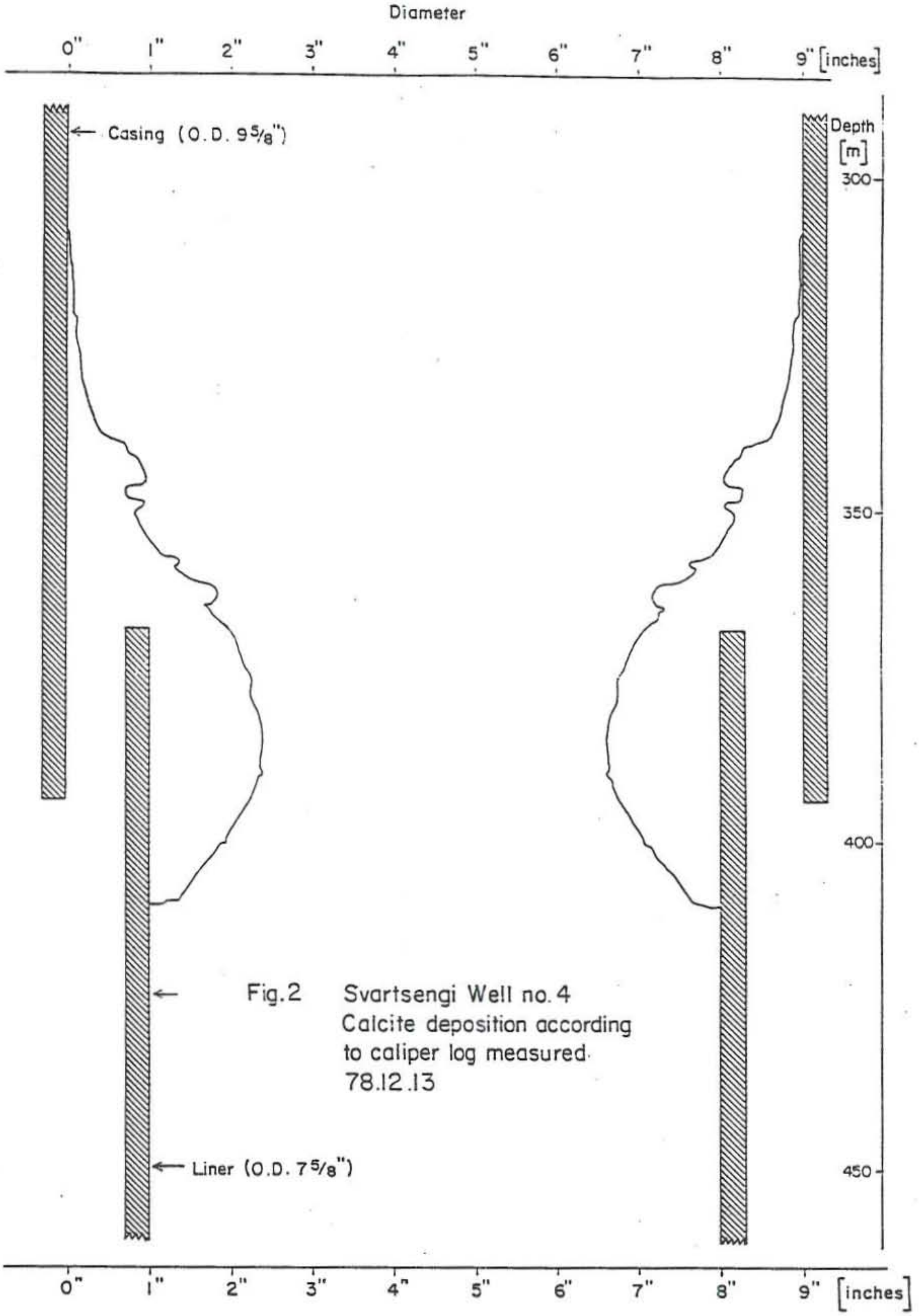


Fig. 2 Svartsengi Well no. 4
Calcite deposition according to caliper log measured 78.12.13

79.01.24. B.S/IS J-Svartsengi F-18019

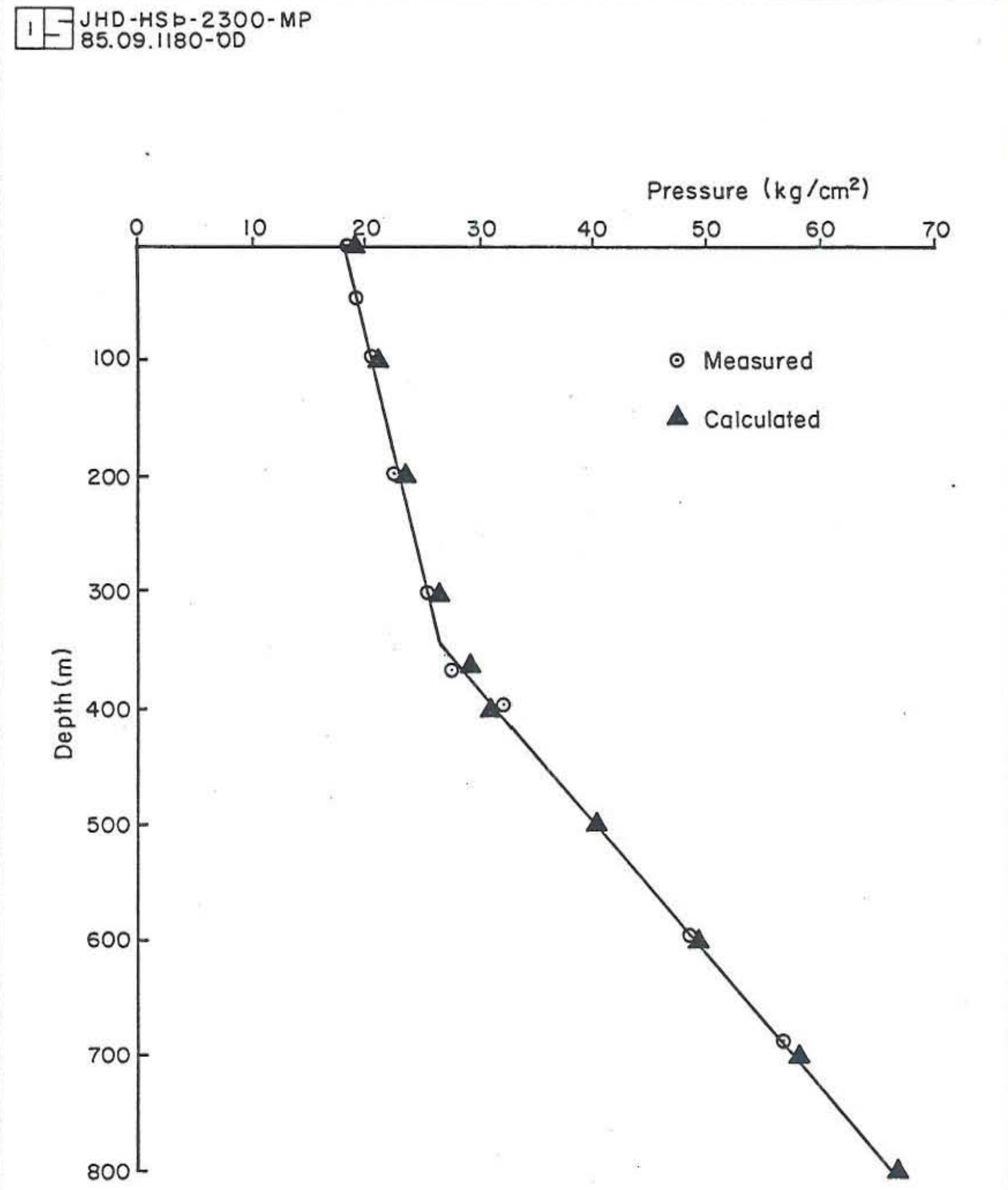


Figure 3. Pressure Profile in Svartsengi Well no. 4

JHD-HSp-2300-MP
85.09.1181-OD

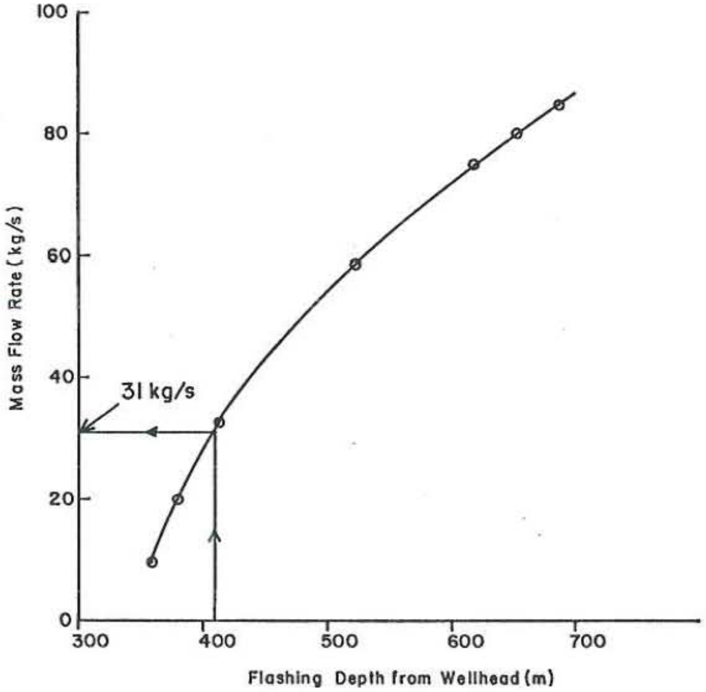


Figure 4. Change in Flashing Depth with Mass Flow Rate

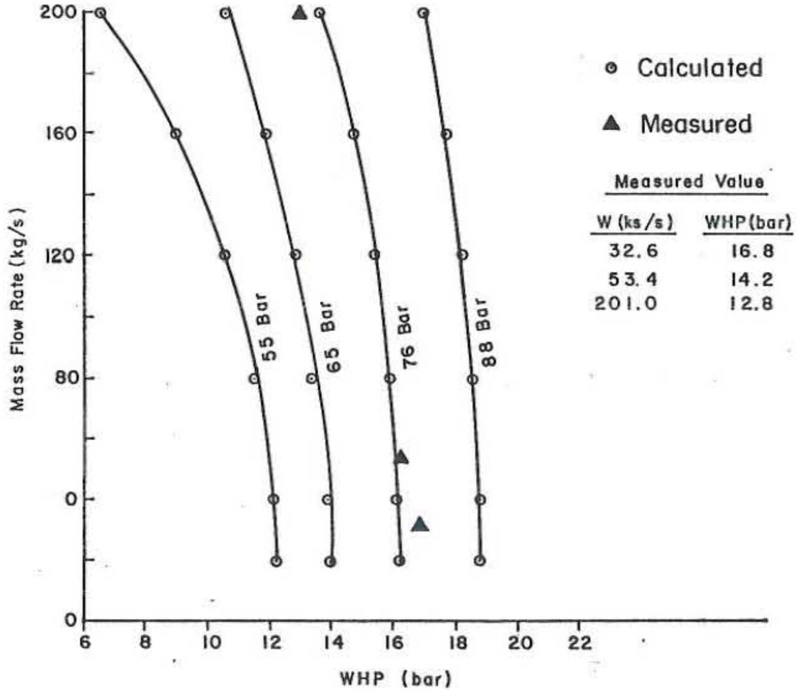


Figure 5. Deliverability curves for SG-11 for different reservoir pressures

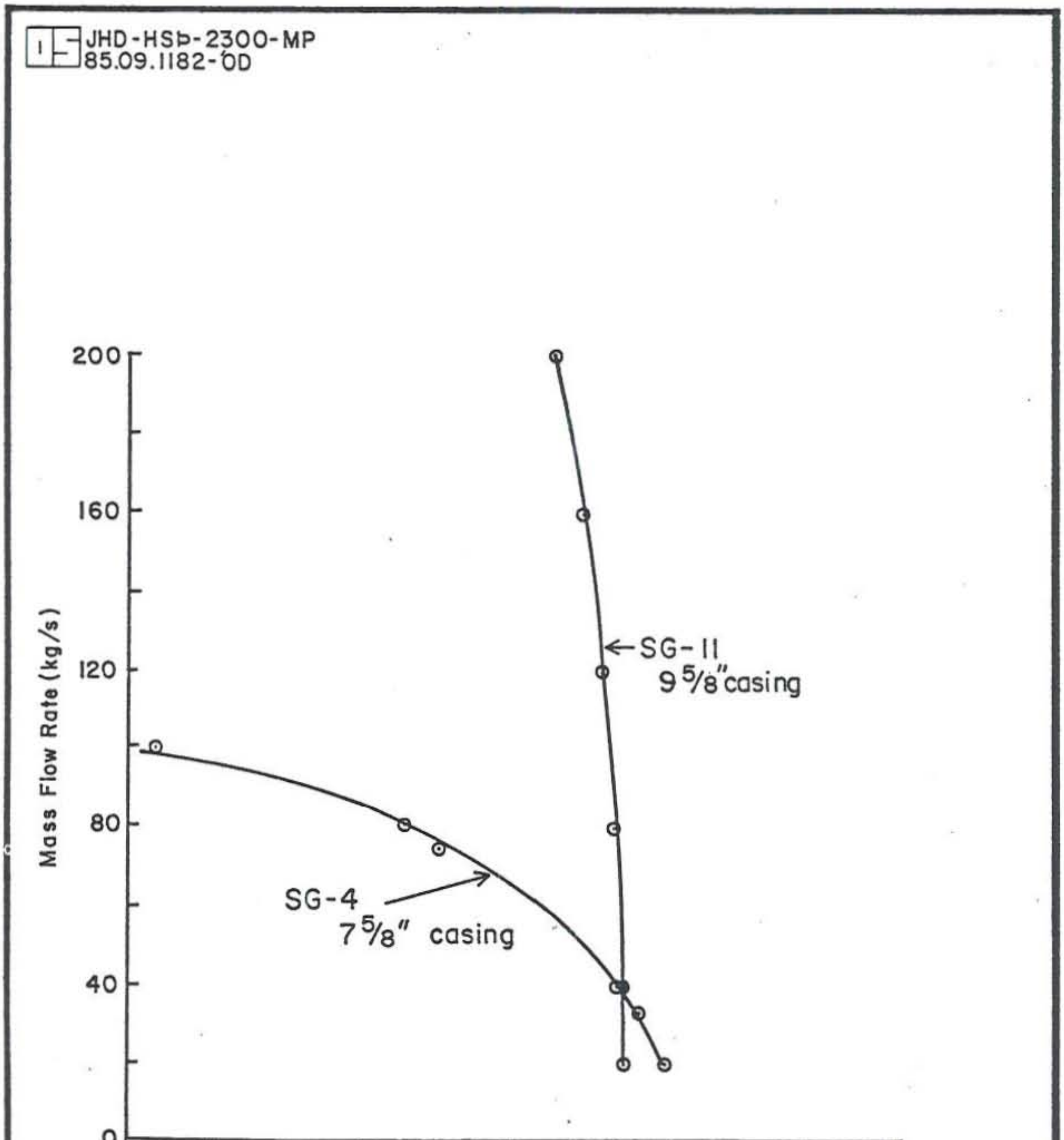


Figure 6. Effect of Casing Size on the Output Curves of geothermal Wells

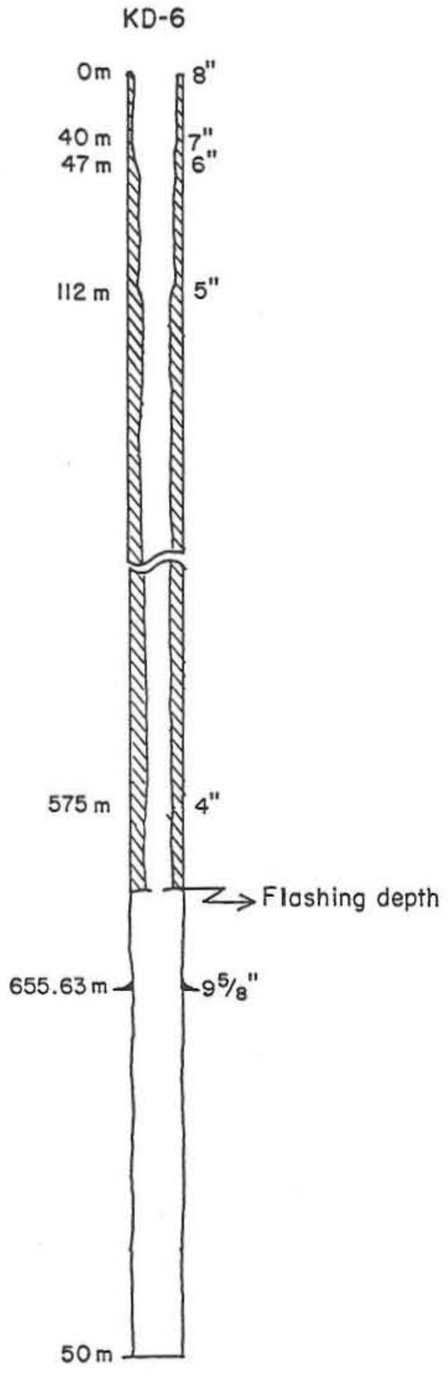


Fig.7 Scaling thicknesses measured by go-devil in kizildere well no 6

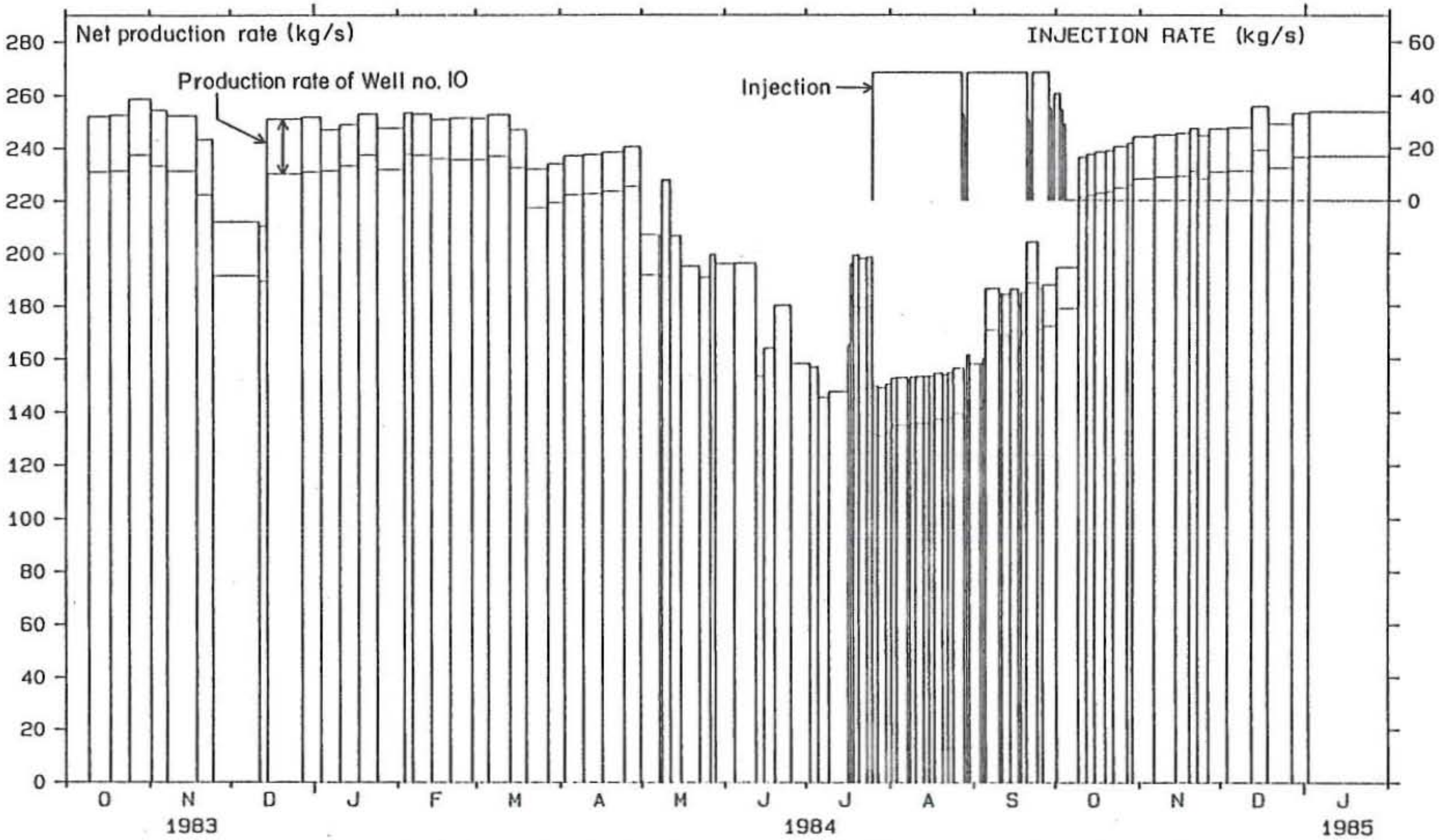


Figure 8. Net Production and Injection rates with time

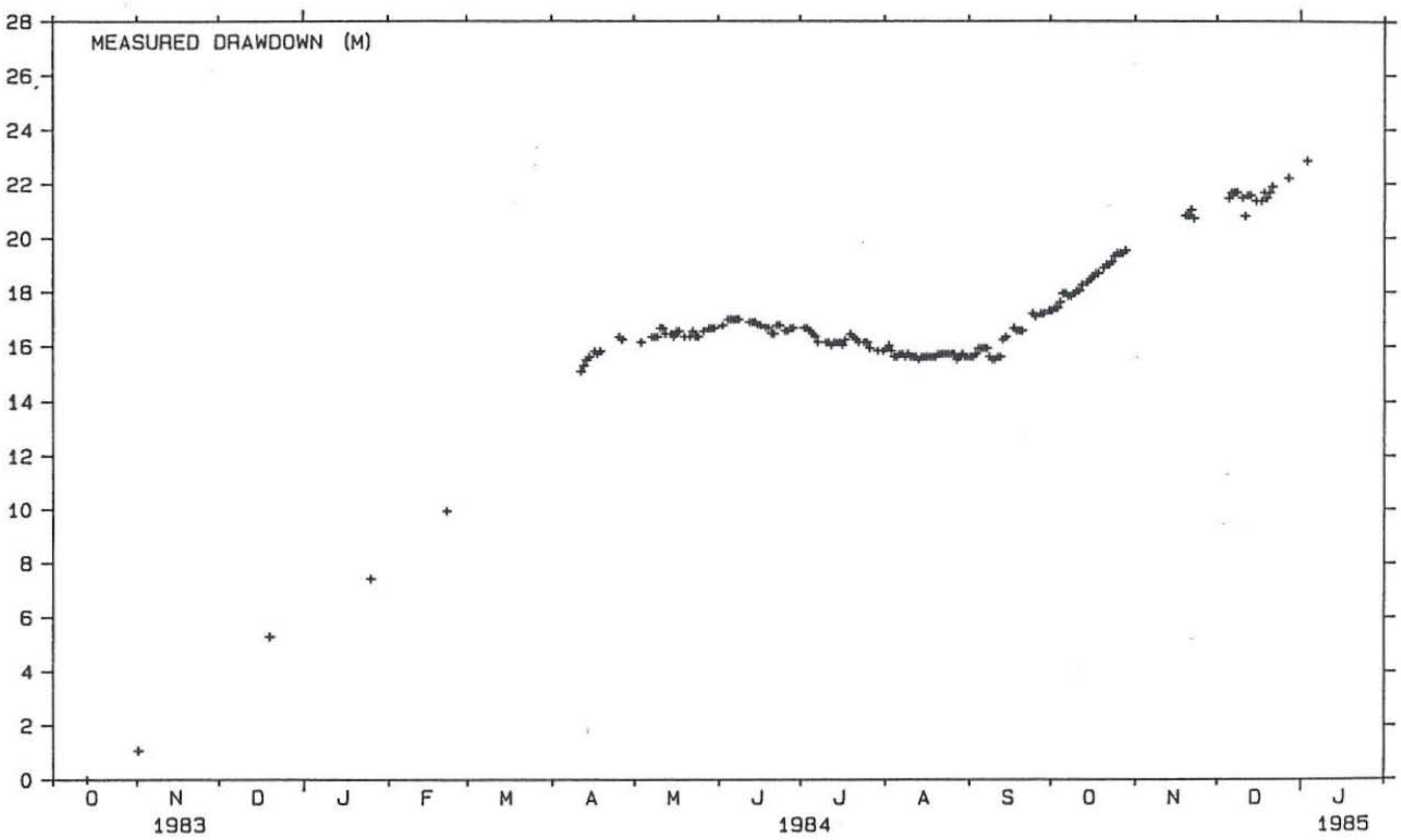


Figure 9. Drawdown with time

JHD-HSÞ-2300-MP
85.09. 1105-ÓD

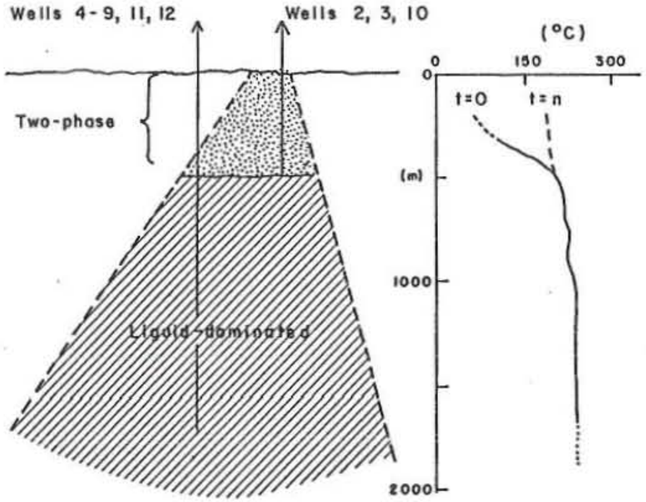


Figure 10. Conceptual Model of the Svartsengi Reservoir

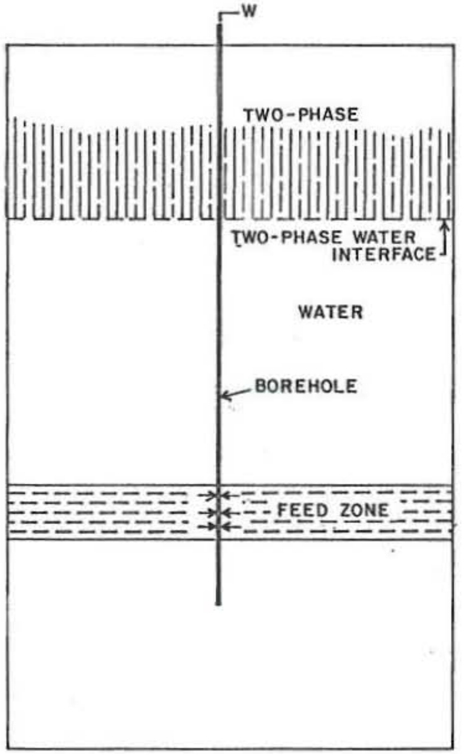


Figure 11. Schematic Representation of Steam Model of the Svartsengi Reservoir

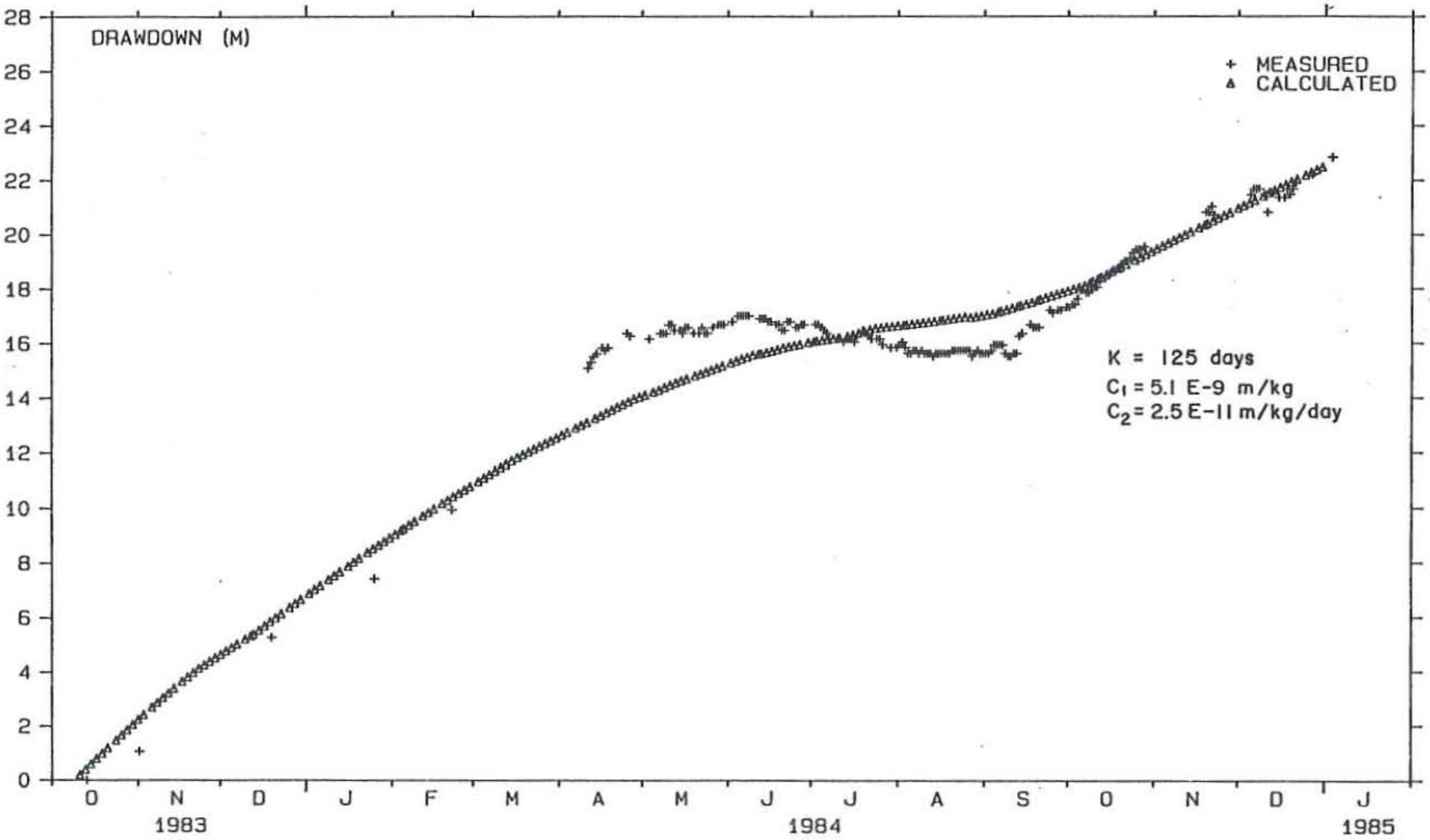


Figure. 12. Measured and Fitted Drawdown from Steam Model

APPENDIX A. PROGRAM LISTING OF WELLBORE SIMULATOR

```
      PROGRAM IKIFAZ
C*************************************************************************
C       INPUT PARAMETERS                                                 *
C*************************************************************************
C                                                                        *
C  ITYPE   : TO HAVE LISTS ENTER A NUMBER OTHER THAN '0'                 *
C  DZ1     : INCREMENT LENGTH IN TWO-PHASE SECTION,          (M)         *
C  TYPEZ   : INCREMENT LENGTH IN THE OUTPUT,                 (M)         *
C  ZA      : DEPTH OF AQUIFER,                               (M)         *
C  ZT      : REFERENCE DEPTH,IF FROM WELLHEAD, ENTER '0'     (M)         *
C  TEM     : AQUIFER FLUID TEMPERATURE,                      (C)         *
C  N       : NUMBER OF CHANGES IN THE WELLBORE DIAMETER                  *
C  ZZ(N)   : LENGTH OF SECTIONS HAVING DIFFERENT DIAMETERS,  (M)         *
C  DD(N)   : DIAMETER OF THE WELLBORE IN EACH SECTION,       (CM)        *
C  FLAM(N) : ABSOLUTE ROUGHNESS FACTOR FOR EACH SECTION,     (M)         *
C  PAA     : AQUIFER PRESSURE,                               (BAR)       *
C  DZ3     : INCREMENT LENGTH IN SINGLE PHASE SECTION,       (M)         *
C  CCO2    : DOWNHOLE CO2 CONCENTRATION,                     (PPM)       *
C  CNACL   : SALT CONCENTRATION,                             (PPM)       *
C  CTURB   : TURBULENCE COEFFICIENT,                         (BAR/(KG/S)2)*
C  FLOW    : TOTAL MASS FLOW RATE,                           (KG/S)      *
C  ITOUT   : MEAN ANNUAL TEMPERATURE                         (C)         *
C  GRAD1   : GEOTHERMAL GRADIENT IN SECTION '1'              (C/M)       *
C  GRAD2   : GEOTHERMAL GRADIENT IN SECTION '2'              (C/M)       *
C  Z1      : THE DEPTH IN THE CHANGE OF GEOTHERMAL GRADIENT  (M)         *
C  CON     : THERMAL CONDUCTIVITY OF THE ROCK                (W/MK)      *
C  DIF     : THERMAL DIFFUSIVITY OF THE ROCK                 (M2/DAY)    *
C  PTIME   : THE TIME ELAPSED AFTER THE WELL PUT ON                      *
C            PRODUCTION                                      (DAY)       *
C  KK      : TO RUN THE PROGRAM WITH HEAT LOSS                           *
C            ENTER '1'                                                   *
C*************************************************************************
C       INPUT FILE SHOULD BE IN THE FOLLOWING ORDER                      *
C*************************************************************************
C       ITYPE                                                            *
C       DZ1,TYPEZ,ZA,ZT,TEM                                              *
C       N                                                                *
C       ZZ(I),DD(I),FLAM(I)  where I=1,N                                 *
C       PAA,DZ3,CCO2,CNACL,CTURB,FLOW                                    *
C       ITOUT                                                            *
C       GRAD1,GRAD2,Z1,CON,DIF,PTIME                                     *
C       KK                                                               *
C*************************************************************************
      COMMON X,V,B,HSTAR,VS,VL,VG,HL,HG,G
      DIMENSION ZZ(10),DD(10),FLAM(10)
      character*8 FIELD,NAME,DATE
      character*32 fname
      G=9.8167
      type '(a)',' ENTER NAME OF FIELD,WELL NAME,DATE'
      accept '(4a)', FIELD,NAME,DATE
      type '(a,$)',' write name of datafile:'
      accept '(a)',fname
      open(unit=1,file=fname,type='old')
      type '(a,$)',' write name of outfile:'
      accept '(a)',fname
      open (unit=2,file=fname,type='new',carriagecontrol='list')
      Write (2,8) FIELD,NAME,DATE
    8 FORMAT(' NAME OF FIELD:',2X,A8//' WELL NAME     :',2X,A8//
     1' DATE OF CALC :',2X,A8//)
   10 READ(1,701,END=20) ITYPE
      READ(1,702) DZ1,TYPEZ,ZA,ZT,TEM
      READ(1,701)N
      READ(1,703) (ZZ(I),DD(I),FLAM(I),I=1,N)
      READ(1,702) PAA,DZ3,CCO2,CNACL,CTURB,FLOW
      READ(1,701) ITOUT
      READ(1,702) GRAD1,GRAD2,Z1,CON,DIF,PTIME
      READ(1,701) KK
  701 FORMAT(I4)
  702 FORMAT(6F10.0)
  703 FORMAT(3F10.0)
      TURBUL=CTURB*FLOW**2
      PA=PAA-TURBUL
      WRITE(2,803) PAA,TURBUL,PA,CCO2,CNACL
  803 FORMAT(' SINGLE-PHASE(WATER) SECTION:'/,30('-')//
     1' Pa (BARS)',7X,'=',F8.3//' (dp)turb (BARS) =',F8.3
     2//' Pwf (BARS)',6X,'=',F8.3//' CCO2 (ppm)',6X,'=',F8.1//
     3' CNACL (ppm)',5x,'=',F8.1////)
C--------------------------------------------------------------------
C     CALL SUB PROGRAM FOR PRESSURE AND TEMPERATURE PROFILES
C--------------------------------------------------------------------
      CALL U07SN5(ZA,ZT,N,ZZ,DD,FLAM,PA,FLOW,PT,ITYPE,
     1TYPEZ,DZ1,DZ3,CCO2,CNACL,TEM,ITOUT,GRAD1,GRAD2,
     2Z1,CON,DIF,PTIME,KK)
      WRITE(2,801) PT
  801 FORMAT(//,' WHP (BAR)= ',F10.2)
   20 STOP
      END
C--------------------------------------------------------------------
C     SUBPROGRAM TO CALCULATE PRESSURE AND TEMPERATURE PROFILES
C--------------------------------------------------------------------

      SUBROUTINE U07SN5(ZA,ZT,IN,ZZ,DD,FLAM,PA,FLOW,PT,ITYPE
     1,TYPEZ,DZ2,DZ3,CCO2,CNACL,T,ITOUT,GRAD1,GRAD2,
     2Z1,CON,DIF,PTIME,KK)
      COMMON X,V,B,HSTAR,VS,VL,VG,HL,HG,G
      REAL*8 FLKIND,BUBB,SLUG,ANNU
      DATA IBLANK,ISTAR/' ','*'/
      DATA BUBB,SLUG,ANNU/'BUBBLY','SLUG','ANNULAR'/
      DATA C1,C2,C3/0.21913E-6,0.17816E-3,0.0653665/
      DIMENSION ZZ(1),DD(1),FLAM(1)
C--------------------------------------------------------------------
      LOGICAL LTYPE
      LTYPE=(ITYPE.NE.0)
C--------------------------------------------------------------------
C     INITIALIZATION
C--------------------------------------------------------------------
      FRIC=0.
      POT=0.
      III=IBLANK
      DZ1=DZ2
      NINT=0.
      N=IN
C--------------------------------------------------------------------
C     SATURATION PRESSURE OF PURE WATER
C--------------------------------------------------------------------
      PS=EXP(C1*T**3-C2*T*T+C3*T-4.96087)
C--------------------------------------------------------------------
```

```
C       CORRECTION FOR SALT CONCENTRATION
C-----------------------------------------------------------------------
        CM=CNACL/58500.
C-----------------------------------------------------------------------
C       ENTHALPY OF LIQUID PHASE
C-----------------------------------------------------------------------
        HL=HLP(T,CM)
C-----------------------------------------------------------------------
C       ENTHALPY OF VAPOR PHASE
C-----------------------------------------------------------------------
        HG=HGP(T)
C-----------------------------------------------------------------------
C       SPECIFIC VOLUME OF LIQUID PHASE
C-----------------------------------------------------------------------
        VL=VSW(T,HG,HL)
C-----------------------------------------------------------------------
C       SPECIFIC VOLUME OF VAPOR PHASE
C-----------------------------------------------------------------------
        VG=VSG(PS,T)
C-----------------------------------------------------------------------
C       THE DIFFERENCE IN THE VAPOR PRESSURE DUE TO SALT
C       CONCENTRATION
C-----------------------------------------------------------------------
        DPS=(0.8314*(T+273.15)/(VG-VL)*CM/55.56)*1E-2
C-----------------------------------------------------------------------
C       PARTIAL PRESSURE OF CARBON DIOXIDE
C-----------------------------------------------------------------------
        ALF=(5.4-3.5*(T/100.)+1.2*(T/100.)**2)*1E-9
        PCO=CCO2*1E-11/ALF
C-----------------------------------------------------------------------
C       FLASH PRESSURE (BAR)
C-----------------------------------------------------------------------
        PSTAR=PS-DPS+PCO
C-----------------------------------------------------------------------
C       FLASHING DEPTH
C-----------------------------------------------------------------------
        CALL U07VA1(ZA,PA,ZZ,DO,FLAM,FLOW,DZ3,CNACL,IN,T,
       1TS,PSTAR,VG,VL,DPS,CM,G,ZSTAR)
        Z=ZSTAR
        P=PSTAR
        PSP=PS-DPS
        PC1=PCO
        T1=T
        T2=T1+5
        J=0
        N=IN
C-----------------------------------------------------------------------
C       TWO PHASE CALCULATIONS
C-----------------------------------------------------------------------
C       INITIAL CONDITIONS AT TWO-PHASE SECTION
C-----------------------------------------------------------------------
        HG=HGP(T)
        HSTAR=HLP(T,CM)
        HL=HSTAR
        VSTAR=VSW(T,HG,HL)
        VSTAR=VSTAR*1E-3
        VISF=VIS(CM,T)
        PACC=0.0025
        Q=HSTAR*1E3-ZSTAR*G
        TEMPZ=AINT(Z/TYPEZ+1.)*TYPEZ
        DZ=-(Z-AINT((Z-1.)/DZ1)*DZ1)
  10    IF(N.LE.1) GO TO 20
        IF(Z.GT.ZZ(N-1)) GO TO 20
        N=N-1
        GO TO 10
  20    D=DD(N)/100.
        FLAMDA=FLAM(N)
        FLOWA=FLOW/(D*D*0.78539816)
        REYN=FLOW/(VISF*D*1.27324)
        FFACT=((-2*ALOG10(FLAMDA/(3.7*D)+(7/REYN)**0.9))**2)**-1
        FLOWA2=FLOWA**2
        EKIN=0.5*FLOWA2*VSTAR**2
        PFLUX=FLOWA2*VSTAR
        VL=VL*1E-3
        V1=VL
        V2=VL
        V3=VL
        V4=VL*1.2
        VEFF=VL
        POT=G/VL
        X=0.
        B=0.5*FFACT*FLOWA2/D
        U=HSTAR*1E3
        ALPHA=0.
        IF(.NOT.LTYPE) GO TO 30
        WRITE(2,620) FLOW,PA,HSTAR,PSTAR
 620    FORMAT(//' TWO-PHASE SECTION:'/19('-')//' Wt (Kg/s)',7X,
       1'=',F8.3//' Pwf (BARS)',6X,'=',F8.3//' H (KJ/Kg)',
       27X,'=',F8.3//' Pflash (BARS)',3X,'=',F8.3////)
        WRITE(2,670)
 670    FORMAT(' ',T2,'DEPTH(M)',T12,'P(BAR)',T19,'PC(BAR)',T27,'DPC(BAR)',
       1T36,'D(CM)',T44,'DRNS',T52,'DPT',T59,'DPPOT',T68,'DPACC',T77,
       2'DPFRIC',T86,'H(J/g)',T94,'TEMP(C)',T104,'Ft',T109,
       3'SLIP',T116,'VOID',T124,'TYPE'/130('-')//)
C-----------------------------------------------------------------------
C       NEW CALCULATION STEP
C-----------------------------------------------------------------------
  30    IF(N.LE.1) GO TO 40
        IF(Z.GT.ZZ(N-1)) GO TO 40
        M=1
        IGO=1
        GO TO 300
  35    FLOWAO=FLOWA
        FLAMDA=FLAM(N)
        D=DD(N)/100.
        VISF=VIS(CM,T)
        REYN=FLOW/(VISF*D*1.27324)
        FFACT=((-2*ALOG10(FLAMDA/(3.7*D)+(7/REYN)**0.9))**2)**-1
        FLOWA=FLOW/(D*D*0.78539816)
        FLOWA2=FLOWA**2
        B=0.5*FFACT*FLOWA2/D
        DZ=0
        PFLUXO=PFLUX*FLOWA/FLOWAO
        GO TO 70
  40    FLOWAO=FLOWA
        IGO=2
        IF(-DZ.EQ.0.) GO TO 300
        IF(Z.GT.TEMPZ) GO TO 45
        GO TO 300
  45    PFLUXO=PFLUX
```

```
 50     DZ=-(Z-AINT((Z-1.)/DZ1)*DZ1)
        IF(N.LE.1) GO TO 65
        IF(Z+DZ.GT.ZZ(N-1)) GO TO 70
        DZ=-(Z-ZZ(N-1))
 65     IF(Z+DZ.GT.ZT) GO TO 70
        DZ=-(Z-ZT)
 70     U=Q+(Z+DZ)*G
        DP=POT*DZ+FMOM*DZ
        PSP=PSP+DP*1E-5
        PSPF=PSP
        IF(DZ.EQ.0) DP=(X*X*VG/ALPHA+(1-X)**2*VG/
        1(1-ALPHA))*(FLOWAO**2-FLOWA**2)
        NINT=0
        XLAST=X
        DDP=DP
        ISTOP=0
        POTO=POT
        FRICO=FRIC
 210    NINT=NINT+1
        PPDP=P*1E5+DP
        IF(X.EQ.0.) GO TO 212
        IF(DZ.EQ.0) GO TO 212
        IF(PPDP.GE.0.3116E6) GO TO 211
        DZ1=DZ1/2.
        IF(DZ1.LT.1) GO TO 90
        X=XLAST
        GO TO 50
C ----------------------------------------------------------------
C       CALL SUB PROGRAM TO CALCULATE NEW TEMPERATURE
C-----------------------------------------------------------------
 211    CALL NEWTEM(X,VG,VL,T1,T2,PPDP*1E-5,CM,PCO,T)
        HG=HGP(T)
        HL=HLP(T,CM)
        VL=VSW(T,HG,HL)
 212    VG=VSG(PSPF,T)
        IF(DP.EQ.0) GO TO 230
        EKIN=0.5*FLOWA2*V4*V4
C-----------------------------------------------------------------------
C       CALL SUB PROGRAM FOR HEAT LOSS
C-----------------------------------------------------------------------
        IF(KK.NE.1) GO TO 213
        CALL HEATLOSS(Z,DZ,ITOUT,GRAD1,GRAD2,Z1,T,CON,DIF,D,PTIME,HE)
 213    X=(U-EKIN-HL*1E3+HE/FLOW)/((HG-HL)*1E3)
        IF(DZ.EQ.0) GO TO 215
        IF(X.GT.0) GO TO 214
        ALPHA=0.
        V1=VL
        V2=VL
        V3=VL
        V4=VL
        GO TO 216
C-----------------------------------------------------------------
C       CORRECTION OF CARBON DIOXIDE PARTIAL PRESSURE
C-----------------------------------------------------------------
214     AT=(5.4-3.5*(T/100.)+1.2*(T/100.)**2)*1E-9
        RATIO=(1+(44*1E-3*VG*X)/(AT*8.314*(T+273.15)))**-1
        PC=PCO*RATIO
        DPCO2=PC-PC1
215     ALPHA=U07TP5(PPDP*1E-5,X,VL,VG,FLOWA,D,ALPHA)
        C1=ALPHA
        C2=1.-ALPHA
        B1=X/C1
        B2=(1-X)/C2
        V1=1./(C1/VG+C2/VL)
        C1=C1*B1
        C2=C2*B2
        V2=C1*VG+C2*VL
        CC1=C1*B1
        CC2=C2*B2
        V3=CC1*VG+CC2*VL
        CC1=CC1*B1
        CC2=CC2*B2
        V4=SQRT(CC1*VG*VG+CC2*VL*VL)
        VEFF=U07TP4(X,ALPHA,VL,VG)
216     POT=G/V1
        FRIC=B*VEFF
        DPPOT=(POT+POTO)*0.5*DZ
        DPFRIC=(FRIC+FRICO)*0.5*DZ
        PFLUX=FLOWA2*V3
        DPMOM=PFLUXO-PFLUX
        PSPF=PSP+(DPPOT+DPFRIC+DPMOM)*1E-5
        DPOLD=DP
        DP=DPPOT+DPFRIC+DPMOM+(DPCO2-DPCO2O)*1E5
        DDPOLD=DDP
        DDP=DP-DPOLD
        IF(ABS(DDP/DP).LE.PACC) GO TO 230
        GO TO 210
230     IF(DZ.EQ.0) GO TO 232
        P=P+(DPPOT+DPMOM+DPFRIC)*1E-5+DPCO2-DPCO2O
        D1=D1+DPPOT+DPMOM+DPFRIC+(DPCO2-DPCO2O)*1E5
        GO TO 233
232     P=P+DPMOM*1E-5
        D1=D1+DPMOM
233     DPCO2O=DPCO2
        D2=D2+DPPOT
        D3=D3+DPMOM
        D4=D4+DPFRIC
        IF(DZ.NE.0) FMOM=DPMOM/DZ
        IF(DZ.EQ.0) FMOM=FMOM*FLOWA/FLOWAO
        Z=Z+DZ
C-----------------------------------------------------------------
C       CALL SUB PROGRAM FOR HEAT LOSS
C-----------------------------------------------------------------
        IF(KK.NE.1) GO TO 231
        CALL HEATLOSS(Z,DZ,ITOUT,GRAD1,GRAD2,Z1,T,CON,DIF,D,PTIME,HE)
231     X=(U-EKIN-HL*1E3+HE/FLOW)/((HG-HL)*1E3)
        IF(Z.GT.ZT) GO TO 30
90      IF(DZ1.GE..1) GO TO 100
        PCRIT=(HSTAR**1.102*FLOWA)**1.04167*3.029E-13
        WRITE(2,660) PCRIT
660     FORMAT(' JAMES' CRITICAL PRESSURE=',F7.2,' (BARS)')
        GO TO 110
100     IGO=3
        GO TO 300
110     PT=P
        RETURN
300     IF(.NOT.LTYPE) GO TO 360
C---------------------------------------------------------------
C       DETERMINATION OF FLOW REGIME
C---------------------------------------------------------------
```

```
      VGOVL=VG/VL
      IF(X.GT.1.) GO TO 306
      X1X=X/(1-X)
      A1A=ALPHA/(1-ALPHA)
      IF(X.GT.0) GO TO 302
      S=1.
      GO TO 304
302   S=X1X/A1A*VGOVL
304   QX=A1A/(A1A+VGOVL)
      BETA=X1X/(X1X+1/VGOVL)
      GO TO 308
306   S=VGOVL
      QX=1.
      BETA=1.
308   R1=V1/V2
      R3=V3/V2
      R4=V4/V2
      REFF=VEFF/V2
      HBAR=X*HG+(1-X)*HL
      FR=FLOWA2/G/D*V2*V2
      IF(BETA.LT.0.15) GO TO 320
      IF(BETA.LT.0.55) GO TO 310
      IF(BETA.LT.(-0.0085*FR+0.9962)) GO TO 330
      GO TO 340
310   IF(BETA.LT.(-FR*0.02+1.85)) GO TO 330
      GO TO 340
320   FLKIND=BUBB
      GO TO 350
330   FLKIND=SLUG
      GO TO 350
340   FLKIND=ANNU
350   IF(Z.GT.ZA) III=ISTAR
C-------------------------------------------------------------------
C     CALCULATIONS ARE COMPLETED
C     PRESSURE AND TEMPERATURE VALUES AT THE END OF INCREMENT
C-------------------------------------------------------------------
      D1=D1*1E-5
      DPPO1=D2*1E-5
      DPMO1=D3*1E-5
      DPFRI1=D4*1E-5
      D5=D1-(DPPO1+DPMO1+DPFRI1)
      IF(J.EQ.0) GO TO 380
C-------------------------------------------------------------------
C     CALL SUB PROGRAM TO CALCULATE NEW TEMPERATURE
C-------------------------------------------------------------------
      CALL NEWTEM(X,VG,VL,T1,T2,P,CM,PCO,T)
380   IF(J.EQ.1) PC1=PC
      WRITE(2,650) Z,P,PC1,D5,DD(N),X,D1,DPPO1,DPMO1,DPFRI1,HBAR,
     1T,FFACT,S,ALPHA,FLKIND
650   FORMAT(' ',T2,4F8.3,F6.2,2F8.3,3F9.4,2X,F7.2,F7.1,F8.4,2F7.3,3X,A8)
      IF(Z.LE.TEMPZ) TEMPZ=TEMPZ-TYPEZ
      IF(M.EQ.1) N=N-1
      M=0
      D1=0.
      D2=0.
      D3=0.
      D4=0.
      J=1
      DPCO20=0.
360   GO TO(35,45,110) IGO
      END
C-------------------------------------------------------------------
C     SUB PROGRAM FOR TWO PHASE MULTIPLIER
C-------------------------------------------------------------------
      FUNCTION U07TP4(X,ALPHA,VL,VG)
      X2=((1-X)/X)**2*VL/VG
      X1=SQRT(X2)
      C=1+X*VG/(X*VG+(1-X)*VL)-ALPHA
      F2=1+C/X1+1/X2
      U07TP4=F2*VL*(1-X)**2
      RETURN
      END
C-------------------------------------------------------------------
C     SUB PROGRAM FOR VOID FRACTION
C-------------------------------------------------------------------
      FUNCTION U07TP5(P,X,VL,VG,FLOWA,D,ALPHA)
      FR=(FLOWA*VL)**2/D/9.8067
      ALPHA1=(0.833+0.05*ALOG10(P))/(1+(1-X)/X*VL/VG)
      BETA=X*VG/(X*VG+(1-X)*VL)
      ALPHA2=BETA-0.71*BETA*SQRT(1-BETA)*FR**(-0.045)*(1-P/221.2)
      ALPHA=AMAX1(ALPHA1,ALPHA2)
      U07TP5=ALPHA
      RETURN
      END
C-------------------------------------------------------------------
C     SUB PROGRAM FOR LIQUID PHASE ENTHALPY
C-------------------------------------------------------------------
      FUNCTION HLP(T,CM)
      REAL A(4,3)
      DATA ((A(I,J),J=1,3),I=1,4) /9633.6,-4080,286.49,166.58,
      168.577,-4.6856,-0.90963,-0.36524,0.0249667,0.17965E-2,
      20.71924E-3,-0.49E-4/
C     ENTHALPY OF MIXING
      SUM=0.
      DO 3 I=1,4
      SUM1=0.
      DO4 J=1,3
4     SUM1=SUM1+A(I,J)*T**(I-1)*CM**(J-1)
3     SUM=SUM+SUM1
      HM=4.184/(1000+58.44*CM)*SUM
C     ENTHALPY OF PURE WATER
      HW=0.12453E-4*T**3-0.45137E-2*T*T+4.81155*T-29.578
C     ENTHALPY OF PURE SALT
      HS=0.0715948*(-0.83624E-3*T**3+0.16792*T*T-25.9293*T)
      X1=1000/(1000+58.44*CM)
      X2=58.44*CM/(1000+58.44*CM)
      HLP=X1*HW+X2*HS+CM*HM
      RETURN
      END
C-------------------------------------------------------------------
C     SUB PROGRAM FOR VAPOR PHASE ENTHALPY
C-------------------------------------------------------------------
      FUNCTION HGP(T)
      HGP=-0.81257E-2*T*T+3.65228*T+2388.4
      RETURN
      END
```

```
C-----------------------------------------------------------------------
C       SUB PROGRAM FOR LIQUID PHASE SPECIFIC VOLUME
C-----------------------------------------------------------------------
        FUNCTION VSW(T,HG,HL)
        DATA C1,C2,C3,C4,C5/-0.315154,-1.203374E-3,7.48908E-13
        1,0.1342489,-3.946963E-3/
        TSS=14.9652*(T+273.15)**2/(HG-HL)*CM/55.56
        F=374.12-T-TSS
        VSW=(3.1975+C1*F**(1./3)+C2*F+C3*F**4)/
        1(1+C4*F**(1./3)+C5*F)*1E-3
        RETURN
        END
C-----------------------------------------------------------------------
C       SUB PROGRAM FOR VAPOR PHASE SPECIFIC VOLUME
C-----------------------------------------------------------------------
        FUNCTION VSG(P,T)
        VSG=1./(100*P/(-0.1296E-2*T*T+0.6325*T+121.05))
        RETURN
        END
C-----------------------------------------------------------------------
C       SUB PROGRAM FOR VISCOSITY
C-----------------------------------------------------------------------

        FUNCTION VIS(CM,T)
        A=0.3324E-1*CM+0.3624E-2*CM*CM-0.1879*CM**3
        B=-0.3961E-1*CM+0.0102*CM*CM-0.702E-3*CM**3
        C=20-T
        D=C/(96+T)*(1.2378-1.303E-3*C+3.06E-6*C*C+
        12.55E-8*C**3)
        MT=1002*10**D
        G=A+B*D
        VIS=MT*(10**G)*1E-6
        RETURN
        END

C-----------------------------------------------------------------------
C       SUB PROGRAM FOR THE CALCULATIONS IN SINGLE-PHASE
C-----------------------------------------------------------------------

        SUBROUTINE U07VA1(ZA,PA,ZZ,DD,FLAM,FLOW,DZ3,CNACL,IN,T,
        1TS,PSTAR,VG,VL,DPS,CM,G,ZSTAR)
        DIMENSION ZZ(IN),DD(IN),FLAM(IN)
C-----------------------------------------------------------------------
C       DENSITY OF WATER
C-----------------------------------------------------------------------
        HROL=DEN(CM,VL)
        WRITE(2,1005)
1005    FORMAT(T5,'DEPTH(m)',T19,'P(bar)',T32,'Vel(f)',T43,'Ffactor
        1',T55,'D(cm)',T68,'DPWAT.',T80,'DPPOT',T91,'DPFRIC',T100,
        2'FLOW(kg/s)',T111,'TEMP(C)',T122,'PFLASH'/130('-')//)
        N=IN
        P=PA
        Z=ZA
        VISF=VIS(CM,T)
        M=1
        J=2
        DZ=Z-AINT(Z/DZ3)*DZ3
        Z=Z-DZ
1010    IF(N.LE.1) GO TO 1020
        IF(J.EQ.2) GO TO 1020
        Z=Z-DZ
        IF(Z.LT.ZZ(N-1)) GO TO 1060
        GO TO 1020
1060    Z=Z+DZ
        DZ=Z-ZZ(N-1)
        J=1
        GO TO 1010
1020    D=DD(N)/100.
        P=P*1E5
        FLAMDA=FLAM(N)
        VVATN=FLOW/HROL/(D*D*0.78539816)
        REPT=HROL*VVATN*D/VISF
        FFACT=((-2*ALOG10(FLAMDA/(3.7*D)+(7/REPT)**0.9))**2)**-1
        DPPOT=-(HROL*G*DZ)
        DPFRIC=-(FFACT*HROL*VVATN**2/2/D*DZ)
        DPVATN=DPPOT+DPFRIC
1030    P=P+DPVATN
        IF(P.LE.(PSTAR*1E5)) GO TO 1050
        P=P*1E-5
        DPPOT=DPPOT*1E-5
        DPFRIC=DPFRIC*1E-5
        DPVATN=DPVATN*1E-5
1080    WRITE(2,1040) Z,P,VVATN,FFACT,DD(N),DPVATN,DPPOT,DPFRIC,
        1FLOW,T,PSTAR
1040    FORMAT(8F12.3,F10.2,F9.1,F12.3)
        IF(J.EQ.1) GO TO 1070
        IF(M.EQ.1) J=0
        IF(J.EQ.0) GO TO 1006
        DZ=Z-AINT(Z/DZ3)*DZ3
        M=1
        IF(N.LE.1) GO TO 1090
        GO TO 1010
1090    Z=Z-DZ
        GO TO 1020
1070    N=N-1
        D=DD(N)/100.
        FLAMDA=FLAM(N)
        VNEW=FLOW/HROL/(D*D*0.78539816)
        REPT=HROL*VNEW*D/VISF
        FFACT=((-2*ALOG10(FLAMDA/(3.7*D)+(7/REPT)**0.9))**2)**-1
        DPVATN=(VVATN-VNEW)**2*HROL/2
        P=(P*1E5+DPVATN)*1E-5
        DPVATN=DPVATN*1E-5
        VVATN=VNEW
        DPPOT=0.
        DPFRIC=0.
        M=0
        J=3
        GO TO 1080
1006    DZ=DZ3
        M=0
        IF(N.LE.1) GO TO 1090
        GO TO 1010
1050    P=P-DPVATN
        DPVATN=ABS(DPVATN)
        Z=Z+DZ
        DZSTAR=(P-PSTAR*1E5)/DPVATN*DZ
        ZSTAR=Z-DZSTAR
        IN=N
        RETURN
```

```
      END
C-----------------------------------------------------------------------
C     SUB PROGRAM FOR DENSITY OF LIQUID PHASE
C-----------------------------------------------------------------------

      FUNCTION DEN(CM,VL)
      DATA C1,C2,C3,C4,C5/-167.219,448.55,-261.07,-13.644,13.97/
      VL=VL*1E3
      F=C1+C2*VL+C3*VL*VL+((C4+C5*VL)*10.224/(3.195-VL)**2)
      DEN=(1000+CM*58.44)/(1000*VL+CM*F)*1E3
      RETURN
      END

C-----------------------------------------------------------------------
C     SUB PROGRAM FOR HEAT LOSS CALCULATIONS
C-----------------------------------------------------------------------

      SUBROUTINE HEATLOSS(Z,DZ,ITOUT,GRAD1,GRAD2,Z1,T,CON,DIF,D,TIME,Q)
      FOT=ALOG(4*SQRT(DIF*TIME)/D)-0.29
      DZZ=-DZ
      IF(Z.LT.Z1) GO TO 1
      IF(Z.GT.Z1.AND.(Z-DZZ).LT.Z1) GO TO 3
      TR=Z1*GRAD1+(Z-Z1-DZZ/2)*GRAD2+ITOUT
      GO TO 2
1     TR=ITOUT+GRAD1*(Z-DZZ/2)
2     Q=6.283185*CON*(TR-T)/FOT*DZZ
      RETURN
3     Z11=Z-Z1
      TR1=(Z-Z1-Z11/2)*GRAD2+Z1*GRAD1+ITOUT
      Q1=6.283185*CON*(TR1-T)/FOT*Z11
      Z22=DZZ-Z11
      TR2=GRAD1*(Z1-Z22/2)+ITOUT
      Q2=6.283185*CON*(TR2-T)/FOT*Z22
      Q=Q1+Q2
      RETURN
      END

C-----------------------------------------------------------------------
C     SUB PROGRAM TO CALCULATE TEMPERATURE
C-----------------------------------------------------------------------

      SUBROUTINE NEWTEM(X,VG,VL,T1,T2,P,CM,PCO,T)
      DATA C1,C2,C3/0.219138-6,0.178168-3,0.0653665/
      FT(TA)=P-EXP(C1*TA**3-C2*TA*TA+C3*TA-4.96087)+
     1(0.8314*(TA+273.15)/(VG-VL)*CM/55.56)*1E-2-
     2PCO*(1+(44*1E-3*VG*X)/(((5.4-3.5*(TA/100.)+
     31.2*(TA/100.)**2)*1E-9)*8.314*(TA+273.15)))**-1
1     T=T1-(T1-T2)*FT(T1)/(FT(T1)-FT(T2))
      IF(ABS(T-T1).LE.0.01) RETURN
      T2=T1
      T1=T
      GO TO 1
      END
```

APPENDIX B.1. COMPUTER OUTPUTS FOR SVARTSENGI 4 WITHOUT CALCITE DEPOSITION

NAME OF FIELD: SVARTSENGI
WELL NAME : SG-4
DATE OF CALC : 16-09-85

SINGLE-PHASE(WATER) SECTION:

Pa (BARS) = 88.000
(dp)turb (BARS) = 3.812
Pwf (BARS) = 84.188
CCO2 (ppm) = 500.0
CNACL (ppm) = 21000.0

| DEPTH(m) | P(bar) | Vel(f) | Ffactor | D(cm) | DPWAT. | DPPOT | DPFRIC | W(kg/s) | T(C) | PFLASH |
|---|---|---|---|---|---|---|---|---|---|---|
| 1000.000 | 82.214 | 1.348 | 0.018 | 19.368 | -1.975 | -1.958 | -0.017 | 33.00 | 240.0 | 33.739 |
| 900.000 | 73.986 | 1.348 | 0.018 | 19.368 | -8.228 | -8.156 | -0.072 | 33.00 | 240.0 | 33.739 |
| 800.000 | 65.758 | 1.348 | 0.018 | 19.368 | -8.228 | -8.156 | -0.072 | 33.00 | 240.0 | 33.739 |
| 700.000 | 57.530 | 1.348 | 0.018 | 19.368 | -8.228 | -8.156 | -0.072 | 33.00 | 240.0 | 33.739 |
| 600.000 | 49.302 | 1.348 | 0.018 | 19.368 | -8.228 | -8.156 | -0.072 | 33.00 | 240.0 | 33.739 |
| 500.000 | 41.074 | 1.348 | 0.018 | 19.368 | -8.228 | -8.156 | -0.072 | 33.00 | 240.0 | 33.739 |

TWO-PHASE SECTION:

Wt (Kg/s) = 33.000
Pwf (BARS) = 84.188
H (KJ/Kg) =1037.213
Pflash (BARS) = 33.739

| DEPTH | P | PC | DPC | D | X(%) | DPT | DPPOT | DPACC | DPFRIC | H(J/g) | T(C) | Ff | SLIP | VOID | TY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 410.9 | 33.73 | 1.27 | 0.00 | 19.37 | 0.0 | 0.000 | 0.000 | 0.000 | 0.000 | 1037.2 | 240.0 | 0.0185 | 1.00 | 0.00 | BU |
| 400.0 | 32.40 | 0.77 | -0.50 | 19.37 | 0.4 | -1.335 | -0.803 | -0.018 | -0.004 | 1037.1 | 238.5 | 0.0185 | 1.12 | 0.15 | SL |
| 362.0 | 29.78 | 0.35 | -0.41 | 19.37 | 1.4 | -2.624 | -2.165 | -0.007 | -0.029 | 1036.7 | 234.5 | 0.0185 | 1.19 | 0.40 | SL |
| 362.0 | 29.79 | 0.35 | 0.00 | 24.45 | 1.4 | 0.006 | 0.000 | 0.006 | 0.000 | 1036.7 | 234.5 | 0.0148 | 1.19 | 0.40 | SL |
| 300.0 | 27.04 | 0.19 | -0.15 | 24.45 | 2.6 | -2.746 | -2.569 | -0.004 | -0.013 | 1036.1 | 229.4 | 0.0148 | 1.28 | 0.57 | SL |
| 200.0 | 23.85 | 0.11 | -0.08 | 24.45 | 4.2 | -3.192 | -3.082 | -0.005 | -0.023 | 1035.1 | 222.7 | 0.0148 | 1.45 | 0.68 | SL |
| 100.0 | 21.34 | 0.07 | -0.03 | 24.45 | 5.5 | -2.510 | -2.443 | -0.004 | -0.027 | 1034.2 | 216.8 | 0.0148 | 1.63 | 0.74 | SL |
| 0.0 | 19.20 | 0.05 | -0.02 | 24.45 | 6.6 | -2.139 | -2.084 | -0.004 | -0.031 | 1033.2 | 211.4 | 0.0148 | 1.84 | 0.78 | SL |

WHP (BAR)= 19.20

where; TY : Type of flow in two-phase,
BU : Bubble flow, SL : Slug flow and AN : Annular flow

NAME OF FIELD: SVARTSENGI
WELL NAME : SG-4
DATE OF CALC : 16-09-85

SINGLE-PHASE(WATER) SECTION:

Pa (BARS) = 88.000
(dp)turb (BARS) = 12.184
Pwf (BARS) = 75.816
CCO2 (ppm) = 500.0
CNACL (ppm) = 21000.0

| DEPTH(m) | P(bar) | Vel(f) | Ffactor | D(cm) | DPWAT. | DPPOT | DPFRIC | W(kg/s) | T(C) | PFLASH |
|---|---|---|---|---|---|---|---|---|---|---|
| 1000.000 | 73.804 | 2.410 | 0.018 | 19.368 | -2.012 | -1.958 | -0.055 | 59.00 | 240.0 | 33.739 |
| 900.000 | 65.420 | 2.410 | 0.018 | 19.368 | -8.384 | -8.156 | -0.228 | 59.00 | 240.0 | 33.739 |
| 800.000 | 57.036 | 2.410 | 0.018 | 19.368 | -8.384 | -8.156 | -0.228 | 59.00 | 240.0 | 33.739 |
| 700.000 | 48.652 | 2.410 | 0.018 | 19.368 | -8.384 | -8.156 | -0.228 | 59.00 | 240.0 | 33.739 |
| 600.000 | 40.269 | 2.410 | 0.018 | 19.368 | -8.384 | -8.156 | -0.228 | 59.00 | 240.0 | 33.739 |

TWO-PHASE SECTION:

WL (Kg/s) = 59.000
Pwf (BARS) = 75.816
H (KJ/Kg) =1037.213
Pflash (BARS) = 33.739

| DEPTH | P | PC | DPC | D | X(%) | DPT | DPPOT | DPACC | DPFRIC | H(J/g) | T(C) | Ff | SLIP | VOID | TY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 552.1 | 33.74 | 1.28 | 0.00 | 19.37 | 0.0 | 0.000 | 0.000 | 0.000 | 0.000 | 1037.2 | 240.0 | 0.0184 | 1.00 | 0.00 | BU |
| 500.0 | 31.38 | 0.55 | -0.73 | 19.37 | 0.1 | -2.356 | -1.508 | -0.066 | -0.050 | 1037.0 | 237.1 | 0.0184 | 1.14 | 0.25 | SL |
| 400.0 | 26.37 | 0.17 | -0.38 | 19.37 | 3.0 | -5.017 | -4.326 | -0.051 | -0.263 | 1036.0 | 228.0 | 0.0184 | 1.31 | 0.52 | SL |
| 362.0 | 25.00 | 0.13 | -0.04 | 19.37 | 3.6 | -1.362 | -1.200 | -0.015 | -0.111 | 1035.6 | 225.2 | 0.0184 | 1.38 | 0.65 | AN |
| 362.0 | 25.03 | 0.13 | 0.00 | 24.45 | 3.6 | 0.031 | 0.000 | 0.031 | 0.000 | 1035.6 | 225.3 | 0.0143 | 1.37 | 0.66 | SL |
| 300.0 | 23.23 | 0.10 | -0.03 | 24.45 | 4.5 | -1.805 | -1.714 | -0.009 | -0.048 | 1035.0 | 221.3 | 0.0143 | 1.48 | 0.70 | SL |
| 200.0 | 20.75 | 0.07 | -0.03 | 24.45 | 5.8 | -2.479 | -2.350 | -0.012 | -0.086 | 1034.0 | 215.4 | 0.0143 | 1.68 | 0.75 | AN |
| 100.0 | 18.60 | 0.05 | -0.02 | 24.45 | 7.0 | -2.151 | -2.022 | -0.011 | -0.100 | 1033.1 | 209.7 | 0.0143 | 1.90 | 0.78 | AN |
| 0.0 | 16.66 | 0.04 | -0.01 | 24.45 | 8.1 | -1.944 | -1.805 | -0.011 | -0.116 | 1032.1 | 204.2 | 0.0143 | 2.18 | 0.80 | AN |

WHP (BAR)= 16.66

NAME OF FIELD: SVARTSENGI
WELL NAME : SG-4
DATE OF CALC : 16-09-85

SINGLE-PHASE(WATER) SECTION:

Pa (BARS) = 88.000
(dp)turb (BARS) = 19.688
Pwf (BARS) = 68.313
CCO2 (ppm) = 500.0
CNACL (ppm) = 21000.0

| DEPTH(m) | P(bar) | Vel(f) | Ffactor | D(cm) | DPWAT. | DPPOT | DPFRIC | W(kg/s) | T(C) | PFLASH |
|---|---|---|---|---|---|---|---|---|---|---|
| 1000.000 | 66.267 | 3.064 | 0.018 | 19.368 | -2.046 | -1.958 | -0.088 | 75.00 | 240.0 | 33.739 |
| 900.000 | 57.743 | 3.064 | 0.018 | 19.368 | -8.523 | -8.156 | -0.367 | 75.00 | 240.0 | 33.739 |
| 800.000 | 49.220 | 3.064 | 0.018 | 19.368 | -8.523 | -8.156 | -0.367 | 75.00 | 240.0 | 33.739 |
| 700.000 | 40.697 | 3.064 | 0.018 | 19.368 | -8.523 | -8.156 | -0.367 | 75.00 | 240.0 | 33.739 |

TWO-PHASE SECTION:

WL (Kg/s) = 75.000
Pwf (BARS) = 68.313
H (KJ/Kg) =1037.213
Pflash (BARS) = 33.739

| DEPTH | P | PC | DPC | D | X(%) | DPT | DPPOT | DPACC | DPFRIC | H(J/g) | T(C) | Ff | SLIP | VOID | TY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 618.4 | 33.74 | 1.28 | 0.00 | 19.37 | 0.0 | 0.000 | 0.000 | 0.000 | 0.000 | 1037.2 | 240.0 | 0.0183 | 1.00 | 0.00 | BU |
| 600.0 | 31.62 | 0.59 | -0.69 | 19.37 | 0.7 | -2.124 | -1.278 | -0.104 | -0.055 | 1037.0 | 237.4 | 0.0183 | 1.14 | 0.24 | SL |
| 500.0 | 26.30 | 0.17 | -0.42 | 19.37 | 3.0 | -5.312 | -4.381 | -0.086 | -0.423 | 1036.0 | 227.9 | 0.0183 | 1.31 | 0.60 | AN |
| 400.0 | 22.78 | 0.10 | -0.07 | 19.37 | 4.7 | -3.523 | -2.888 | -0.064 | -0.498 | 1035.0 | 220.3 | 0.0183 | 1.50 | 0.70 | AN |
| 362.0 | 21.61 | 0.08 | -0.02 | 19.37 | 5.3 | -1.169 | -0.921 | -0.021 | -0.212 | 1034.6 | 217.5 | 0.0183 | 1.58 | 0.73 | AN |
| 362.0 | 21.68 | 0.08 | 0.00 | 24.45 | 5.3 | 0.065 | 0.000 | 0.065 | 0.000 | 1034.7 | 217.7 | 0.0142 | 1.58 | 0.73 | AN |
| 300.0 | 20.18 | 0.07 | -0.02 | 24.45 | 6.1 | -1.499 | -1.382 | -0.012 | -0.090 | 1034.1 | 213.9 | 0.0142 | 1.71 | 0.75 | AN |
| 200.0 | 17.98 | 0.05 | -0.02 | 24.45 | 7.3 | -2.193 | -1.993 | -0.018 | -0.164 | 1033.1 | 208.1 | 0.0142 | 1.94 | 0.79 | AN |
| 100.0 | 15.98 | 0.04 | -0.01 | 24.45 | 8.5 | -2.009 | -1.788 | -0.017 | -0.192 | 1032.1 | 202.2 | 0.0142 | 2.23 | 0.81 | AN |
| 0.0 | 14.08 | 0.03 | -0.01 | 24.45 | 9.8 | -1.895 | -1.642 | -0.017 | -0.227 | 1031.1 | 196.0 | 0.0142 | 2.60 | 0.82 | AN |

WHP (BAR)= 14.08

APPENDIX 3.2. COMPUTER OUTPUTS FOR SVARTSENGI 4 WITH CALCITE DEPOSITION

NAME OF FIELD: SVARTSENGI
WELL NAME : SG-4
DATE OF CALC : 17-09-85

SINGLE-PHASE(WATER) SECTION:

Pa (BARS) = 88.000
(dp)turb (BARS) = 2.744
Pwf (BARS) = 85.256
CCO2 (ppm) = 500.0
CNACL (ppm) = 21000.0

| DEPTH(m) | P(bar) | Vel(f) | Ffactor | D(cm) | DPWAT. | DPPOT | DPFRIC | W(kg/s) | T(C) | PFLASH |
|---|---|---|---|---|---|---|---|---|---|---|
| 1000.000 | 83.286 | 1.144 | 0.018 | 19.368 | -1.970 | -1.958 | -0.012 | 28.00 | 240.0 | 33.739 |
| 900.000 | 75.078 | 1.144 | 0.018 | 19.368 | -8.208 | -8.156 | -0.052 | 28.00 | 240.0 | 33.739 |
| 800.000 | 66.870 | 1.144 | 0.018 | 19.368 | -8.208 | -8.156 | -0.052 | 28.00 | 240.0 | 33.739 |
| 700.000 | 58.662 | 1.144 | 0.018 | 19.368 | -8.208 | -8.156 | -0.052 | 28.00 | 240.0 | 33.739 |
| 600.000 | 50.454 | 1.144 | 0.018 | 19.368 | -8.208 | -8.156 | -0.052 | 28.00 | 240.0 | 33.739 |
| 500.000 | 42.245 | 1.144 | 0.018 | 19.368 | -8.208 | -8.156 | -0.052 | 28.00 | 240.0 | 33.739 |
| 410.000 | 34.858 | 1.144 | 0.018 | 19.368 | -7.387 | -7.341 | -0.047 | 28.00 | 240.0 | 33.739 |
| 410.000 | 34.877 | 3.244 | 0.054 | 11.500 | 0.013 | 0.000 | 0.000 | 28.00 | 240.0 | 33.739 |
| 400.000 | 33.855 | 3.244 | 0.054 | 11.500 | -1.021 | -0.816 | -0.205 | 28.00 | 240.0 | 33.739 |

TWO-PHASE SECTION:

Wt (Kg/s) = 28.000
Pwf (BARS) = 85.256
H (KJ/Kg) =1037.213
Pflash (BARS) = 33.739

| DEPTH | P | PC | DPC | D | X(%) | DPT | DPPOT | DPACC | DPFRIC | H(J/g) | T(C) | Ff | SLIP | VOID | TY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 398.9 | 33.74 | 1.28 | 0.00 | 11.50 | 0.0 | 0.000 | 0.000 | 0.000 | 0.000 | 1037.2 | 240.0 | 0.0540 | 1.00 | 0.00 | BU |
| 350.0 | 28.79 | 0.28 | -0.10 | 11.50 | 1.8 | -4.946 | -2.797 | -0.163 | -0.989 | 1036.7 | 232.7 | 0.0540 | 1.22 | 0.47 | SL |
| 350.0 | 28.82 | 0.28 | 0.00 | 24.45 | 1.8 | 0.028 | 0.000 | 0.028 | 0.000 | 1036.7 | 232.3 | 0.0150 | 1.21 | 0.46 | SL |
| 300.0 | 26.75 | 0.19 | -0.09 | 24.45 | 2.8 | -2.070 | -1.966 | -0.002 | -0.008 | 1036.2 | 228.8 | 0.0150 | 1.29 | 0.57 | SL |
| 200.0 | 23.59 | 0.11 | -0.08 | 24.45 | 4.3 | -3.160 | -3.062 | -0.003 | -0.017 | 1035.3 | 222.1 | 0.0150 | 1.45 | 0.68 | SL |
| 100.0 | 21.09 | 0.07 | -0.04 | 24.45 | 5.6 | -2.505 | -2.448 | -0.003 | -0.020 | 1034.3 | 216.2 | 0.0150 | 1.63 | 0.74 | SL |
| 0.0 | 18.94 | 0.06 | -0.02 | 24.45 | 6.8 | -2.141 | -2.096 | -0.002 | -0.023 | 1033.3 | 210.7 | 0.0150 | 1.84 | 0.78 | SL |

WHP (BAR)= 18.94

NAME OF FIELD: SVARTSENGI
WELL NAME : SG-4
DATE OF CALC : 17-09-85

SINGLE-PHASE(WATER) SECTION:

Pa (BARS) = 88.000
(dp)turb (BARS) = 5.324
Pwf (BARS) = 82.676
CCO2 (ppm) = 500.0
CNACL (ppm) = 21000.0

| DEPTH(m) | P(bar) | Vel(f) | Ffactor | D(cm) | DPWAT. | DPPOT | DPFRIC | W(kg/s) | T(C) | PFLASH |
|---|---|---|---|---|---|---|---|---|---|---|
| 1000.000 | 80.695 | 1.593 | 0.018 | 19.368 | -1.982 | -1.958 | -0.024 | 39.00 | 240.0 | 33.739 |
| 900.000 | 72.439 | 1.593 | 0.018 | 19.368 | -8.256 | -8.156 | -0.100 | 39.00 | 240.0 | 33.739 |
| 800.000 | 64.182 | 1.593 | 0.018 | 19.368 | -8.256 | -8.156 | -0.100 | 39.00 | 240.0 | 33.739 |
| 700.000 | 55.926 | 1.593 | 0.018 | 19.368 | -8.256 | -8.156 | -0.100 | 39.00 | 240.0 | 33.739 |
| 600.000 | 47.670 | 1.593 | 0.018 | 19.368 | -8.256 | -8.156 | -0.100 | 39.00 | 240.0 | 33.739 |
| 500.000 | 39.414 | 1.593 | 0.018 | 19.368 | -8.256 | -8.156 | -0.100 | 39.00 | 240.0 | 33.739 |

TWO-PHASE SECTION:

Wt (Kg/s) = 39.000
Pwf (BARS) = 82.676
H (KJ/Kg) =1037.213
Pflash (BARS) = 33.739

| DEPTH | P | PC | DPC | D(CM) | X(%) | DPT | DPPOT | DPACC | DPFRIC | H(J/g) | T(C) | Ff | SLIP | VOID | TY |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 431.3 | 33.74 | 1.29 | 0.00 | 19.37 | 0.0 | 0.000 | 0.000 | 0.000 | 0.000 | 1037.2 | 240.0 | 0.0185 | 1.00 | 0.00 | BU |
| 410.0 | 31.51 | 0.57 | -0.71 | 19.37 | 0.7 | -2.224 | -1.468 | -0.028 | -0.022 | 1037.0 | 237.3 | 0.0185 | 1.14 | 0.25 | SL |
| 410.0 | 31.37 | 0.57 | 0.00 | 11.50 | 0.7 | -0.147 | 0.000 | -0.147 | 0.000 | 1037.0 | 237.0 | 0.0540 | 1.14 | 0.25 | SL |
| 400.0 | 30.15 | 0.38 | -0.19 | 11.50 | 1.3 | -1.221 | -0.559 | -0.045 | -0.429 | 1036.9 | 235.1 | 0.0540 | 1.18 | 0.38 | SL |
| 350.0 | 25.41 | 0.15 | -0.23 | 11.50 | 3.4 | -4.733 | -1.988 | -0.161 | -2.354 | 1036.4 | 226.1 | 0.0540 | 1.34 | 0.62 | AN |
| 350.0 | 25.49 | 0.15 | 0.00 | 24.45 | 3.4 | 0.075 | 0.000 | 0.075 | 0.000 | 1036.4 | 226.3 | 0.0147 | 1.33 | 0.61 | SL |
| 300.0 | 23.92 | 0.12 | -0.03 | 24.45 | 4.2 | -1.572 | -1.522 | -0.003 | -0.016 | 1035.9 | 222.9 | 0.0147 | 1.41 | 0.66 | SL |
| 200.0 | 21.25 | 0.08 | -0.04 | 24.45 | 5.5 | -2.667 | -2.586 | -0.005 | -0.036 | 1034.9 | 216.7 | 0.0147 | 1.58 | 0.74 | SL |
| 100.0 | 18.98 | 0.06 | -0.02 | 24.45 | 6.8 | -2.266 | -2.197 | -0.005 | -0.042 | 1034.9 | 210.9 | 0.0147 | 1.78 | 0.76 | SL |
| 0.0 | 16.97 | 0.05 | -0.01 | 24.45 | 8.0 | -2.013 | -1.946 | -0.004 | -0.048 | 1033.0 | 205.2 | 0.0147 | 2.01 | 0.79 | AN |

WHP (BAR)= 16.97