A POWER PLANT ORIENTED GEOTHERMAL SIMULATION MODEL

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ABSTRACT

To be useful for power plant planning and design, a simulation model must include both a geothermal reservoir and wells, maintaining constant wellhead pressure and varying flow. The well model allows for vertical single- or two-phase flow under steady state, and the reservoir model allows for horizontal axisymmetrical radial single- or two-phase non-isothermal flow under transient conditions. The simulation permits prediction of reservoir evolution on the basis of the first well test results, such as: (1) permeability, porosity, thickness, and (2) static pressure and temperature. The other required input is one of the following versus time: (1) wellhead pressure, (2) power plant output, or (3) wellhead flow. The output consists of the simulated history of pressure, saturation, and temperature fields (the latter both for rocks and fluid). The model has been tested against the actual behavior of a geothermal reservoir.

INTRODUCTION

The capability of predicting reservoir response under various power plant operating conditions is found to be a primary objective when determining power plant capacity. It is found, however, that most existing mathematical models for reservoir simulation determine either pressure field (single-phase model) or pressure, temperature, and saturation fields (2-phase model) at a given and constant rate of extraction. Furthermore, in these models pressure at the well is bottomhole pressure, and no relationship is stated between bottomhole and wellhead pressures.

One peculiarity of a geothermal power plant is to run at constant (or nearly constant) turbine inlet pressure, which also yields a nearly constant wellhead pressure. The fact that wellhead pressures of wells flowing to a power plant are not the same means only that wells are at different distances from the steam collector, not that the well is better because the pressure is higher.

Another peculiarity of a geothermal power plant is that plant production has priority over reservoir testing, making it difficult to run properly conventional tests on wells or even to make proper downhole measurements.

On these bases, a model was developed which could provide information about reservoir characteristics using as input only those data readily available without interfering with production, such as: (1) initial reservoir conditions (generally known because power plant priority had not been stated at early investigation times), and (2) well production history. A clear advantage of such a model is that it can be used both as an inverse model (trials) to determine reservoir characteristics from actual field behavior (flow and enthalpy history), and as a direct model to predict reservoir behavior under various operating conditions (wellhead pressure history).

The model consists of two parts: (1) a well simulator, and (2) a reservoir simulator, so that bottomhole pressure and temperature need not be measured (or stated), except at initial conditions ($t = 0$, flow $= 0$). Generally, at these conditions, bottomhole pressure is assumed to be uniform reservoir pressure.

The reservoir simulator allows for two-phase nonisothermal radial symmetrical flow with heat transfer from rock to fluid, under transient conditions; whereas the well simulator allows for steady-state adiabatic vertical flow. The reservoir can be layered, without crossflow. Steady-state flow in the well is justified by the different order of magnitude between the time constant in the well against that in the reservoir. (Fig. 1.)

THE WELL MODEL

The general equations governing vertical steady-state flow in a geothermal well can be written as follows:

Mass balance:
$$\rho_f cA = \dot{m} \tag{1}$$

Force balance:
$$\frac{cdc}{dz} + \frac{\lambda c^2}{2D} = - g - \frac{1}{\rho_f}\frac{dp}{dz} \tag{2}$$

Energy Balance:
$$dq + dR = du - \frac{p}{\rho_f^2}\, d\rho_f \tag{3}$$

We made the assumption that, at rates and times interesting for power plant production: (1) heat transfer from upward flow to surrounding rocks can be neglected ($dq = 0$), and (2) flow regimes can be characterized by a proper average figure of the friction parameter. Both assumptions have been supported by a number of comparisons between observed and simulated pressure profiles. It must be noted that flow is not assumed to be isoenthalpic and that the acceleration term is included in the balance. Results show for general behavior that enthalpy change is quite small, whereas the acceleration term is remarkably high and cannot be neglected. Equations are integrated along the well, using the Runge-Kutta method; dependent variables are pressure, temperature, and dryness.

THE RESERVOIR MODEL

The general equations for transient two-phase one-dimensional (radial) nonisothermal porous media flow can be written as:

Darcy flow + mass balance

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{r\rho_f k}{\mu}\frac{\partial p}{\partial r}\right) = \frac{\partial(\phi\rho_f)}{\partial t} \tag{4}$$

Energy balance for fluid

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{r\rho_f k}{\mu} e \frac{\partial p}{\partial r}\right) = \frac{\partial(\phi\rho_f e)}{\partial t} - \alpha_c(T_r - T_f) \tag{5}$$

Energy balance for rocks

$$\frac{dT_r}{dt} = -\frac{\alpha_c(T_r - T_f)}{c_{pr}\rho_r(1-\phi)} \tag{6}$$

The equations are integrated versus time using the Runge-Kutta method; dependent variables are pressure, temperature and dryness; the shape along the radii is guessed by proper interpolation of the functions. If a layered reservoir is used, pressures along the sandface are computed according to hydıostatic gradient.

Water properties are relevant to pure water, and are used in tabulated form with linear interpolation between adjacent points, which resulted in better precision and faster computation than with functions.

THE OVERALL MODEL

As previously mentioned, well and reservoir simulators are combined to form an overall model. The connection between the two is given by compatibility conditions: (1) the sandface pressure must be equal to the bottomhole pressure,* (2) flow through the sandface must be equal to flow within the wellbore, and (3) average enthalpy from reservoir layers must be equal to bottomhole enthalpy. Convergence iteration modifies pressures, assuming that the same flow is crossing the sandface at the well and passing inside the borehole. The model can be run according to three different procedures, depending on which of the following is to be given versus time: (1) wellhead pressure, (2) power plant output, or (3) well-head flow.

It can be noted that all of these conditions are relevant only to the surface, and no hypotheses are made (except for initial conditions) on reservoir temperature and pressure fields, whose evolution is the main output of the model. Some problems arose when choosing convergence criteria, mainly because of numerical instability or large computing times (Fig. 2).

*Editor's Note: this assumption appears to neglect a skin effect (wellbore damage, partial penetration, etc.). See also asterisk on next page.

APPLICATION TO A CLUSTER OF WELLS

In the case of a cluster of wells rather than a single well, the model still applies, with some modification to the concepts of sandface and bottomhole pressure. If we draw a circle including the cluster, it can be considered (from the reservoir point of view) to be a large single well whose sandface pressure is the pressure at this circle. From this circle to the well, there is a pressure drop which can be computed with steady-state equations if the Fourier number is greater than about 3, which, in practical cases, occurs at real times as small as one month or less. Using the sandface pressure as the bottomhole pressure, diminished by the steady-state drop, the cluster case is reduced again to the single well case.

SOME RESULTS

The model has been used as both an inverse and as a direct model. The model was tested comparing simulated results against actual field behavior. During this test, an interesting question arose regarding the capability of rocks to transfer heat to the fluid. In fact, the first simulation was made using the term $c_{pr}\rho_r(1-\phi)\ (\partial T_f)/\partial t)$ instead of $-\alpha_c(T_r-T_f)$ in Eq. 5, and deleting Eq. 6, which means we assume instantaneous thermal equilibrium between fluid and rocks. This assumption resulted in such a large heat transfer that production converted to dry steam after two years of operation. Since the known period was four years with no evidence of a large increase in enthalpy, we decided to introduce a heat resistance between the rocks and fluid. This can be explained physically by a flow pattern through some main channels and not through an ideal porous media. It is believed also that increased speed and lower mass transfer after boiling can justify this heat resistance. After the modification, results were satisfactory (see Fig. 4).

Another interesting question arose regarding the reservoir thickness to be used in the case of partial penetration. We found that the best match is obtained by adopting the total thickness in the outer area of the cluster while using the penetrated thickness*in determining pressure drop to the wells. However, this problem is still under study.

Simulation of future behavior of a geothermal field gives us the opportunity to note some particulars of the fluid production mechanism. Initial conditions were with pressurized water, and early evolution is according to constant compressibility equations. Once evaporation occurs, closed to the drilled area, main fluid production is by change in density in the evaporation area; the pressure profile in the liquid area flattens. Early increase in enthalpy is evident from the increase in power plant output, despite decreasing flow. After a transient period, bottomhole pressure is nearly a straight line with time (Fig. 5, a,b,c).

The overall model has also been split to use only the well model for a calibration of this part against known pressure and temperature profiles. Using the well model, the parameter λ of Eq. 2 was obtained by a fitting procedure for several wells. Figures for various wells settled in a narrow range, proving the model was satisfactory. However, the same procedure applied to profiles at different dates gave figures increasing with time. We interpreted this to be the possible occurrence of scaling in the casing, but due to lack of data, it was not possible to properly check this hypothesis (Fig. 6).

The model can be used to predict reservoir behavior under various conditions, allowing for single-phase (water or steam) and two-phase flow. We realize that simulation is somewhat approximate, but we consider its results to be very helpful when designing a power plant, since we can now determine: (1) the amount of reservoir energy which can be extracted at various power plant capacities, (2) which wellhead pressure can be maintained during the reservoir lifetime, and (3) what the flow decline rate and energy available at wellhead are at various wellhead pressures.

It is clear that solutions like these, even if taken with some care in their absolute figures, are extremely meaningful when used to compare alternative exploitation schemes. The application of the model to known cases elicited some interesting questions, making it evident that further study is needed to improve the capability of the model.

NOMENCLATURE

A = casing inner area (m^2)

C = fluid velocity (m/s)

Cpr = rock specific heat (J/kgK)

D = casing inner diameter (m)

e = enthalpy + kinetic energy (J/kg)

F = flow (kg/s)

g = acceleration of gravity (m/s^2)

h = layer thickness (m)

k = permeability (m^2)

$\dot{m}$ = mass flow (kg/s)

p = pressure (Pa)

q = transferred heat (J/kg)

r = radial coordinate positive outward (m)

R = work of frictional forces (J/kg)

t = time (s)

T = temperature (°C)

u = internal energy (J/kg)

z = vertical coordinate positive downward (m)

α_c = convection coefficient (W/m^3 °C)

Δ = increment (-)

ϕ = rock porosity (-)

λ = friction coefficient (-)

μ = viscosity (Pa s)

ρ = density (kg/m^3)

Subscripts

bh = bottomhole

f = fluid

r = rock

res = reservoir

sf = sandface

w = well

wh = wellhead

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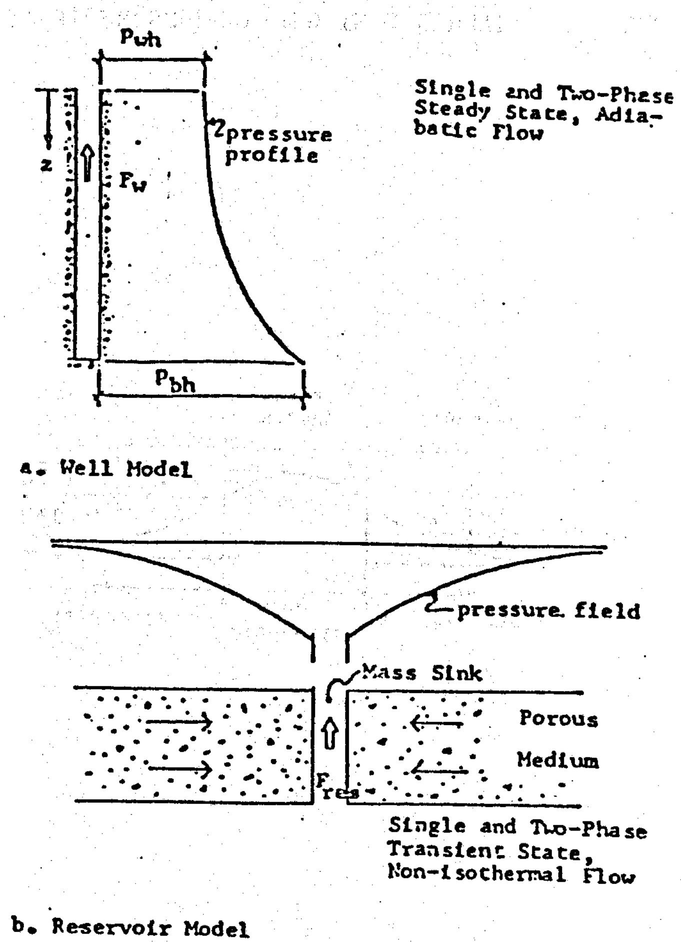


FIG. 1: COMPOSITION OF THE MODEL (WELL MODEL + RESERVOIR MODEL + COMPATIBILITY EQUATIONS = OVERALL MODEL)

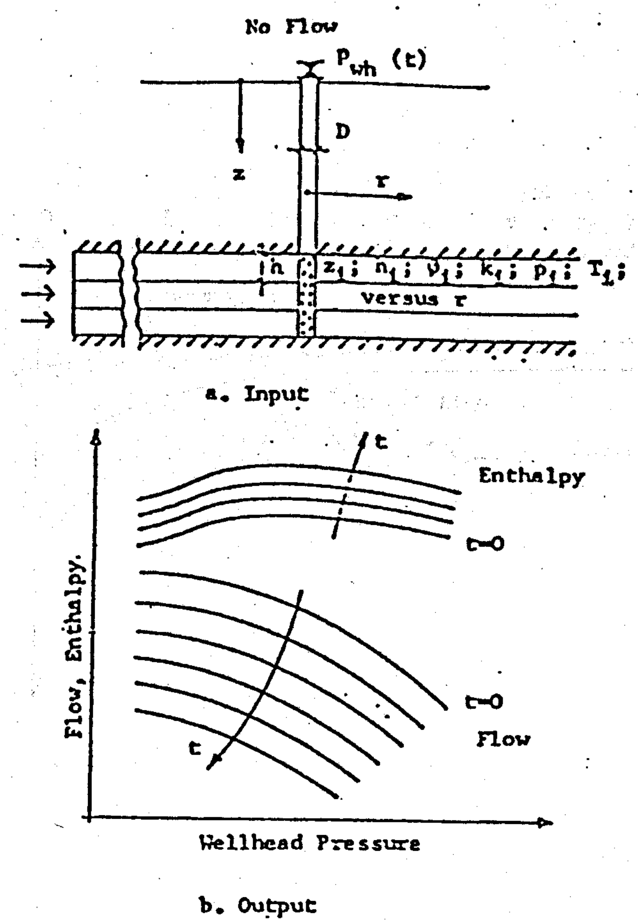


FIG. 2: INPUT AND OUTPUT OF SIMULATION MODEL (USED AS DIRECT MODEL)

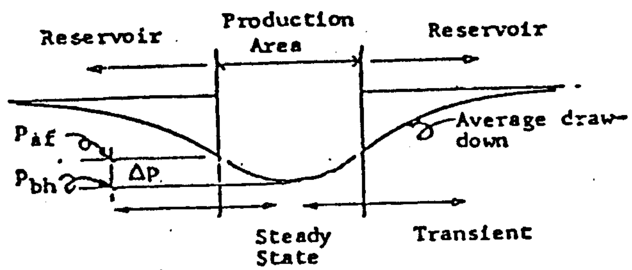


FIG. 3: PRESSURE FIELD IN A CLUSTER OF WELLS

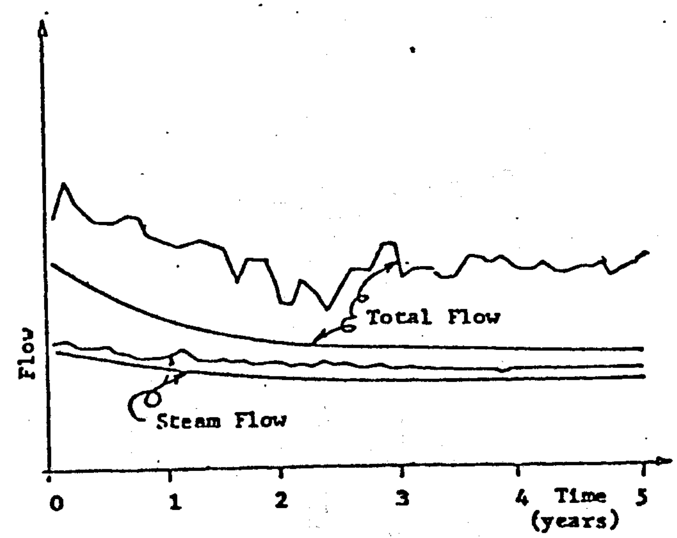
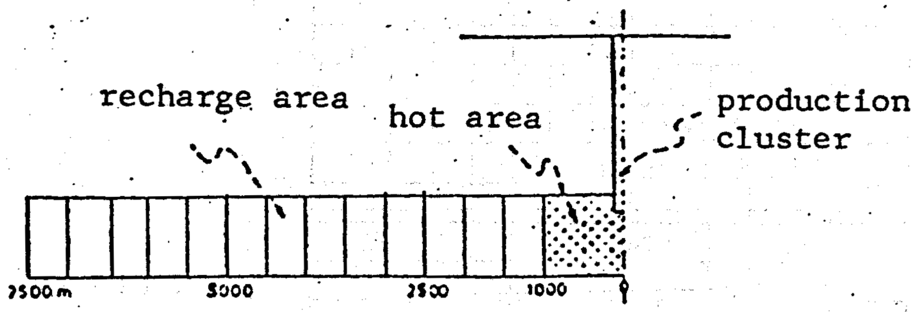


FIG. 4: COMPARISON OF SIMULATION AGAINST REAL BEHAVIOR

RESERVOIR MODEL (INPUT)



WELLHEAD PRESSURE HISTORY (INPUT)

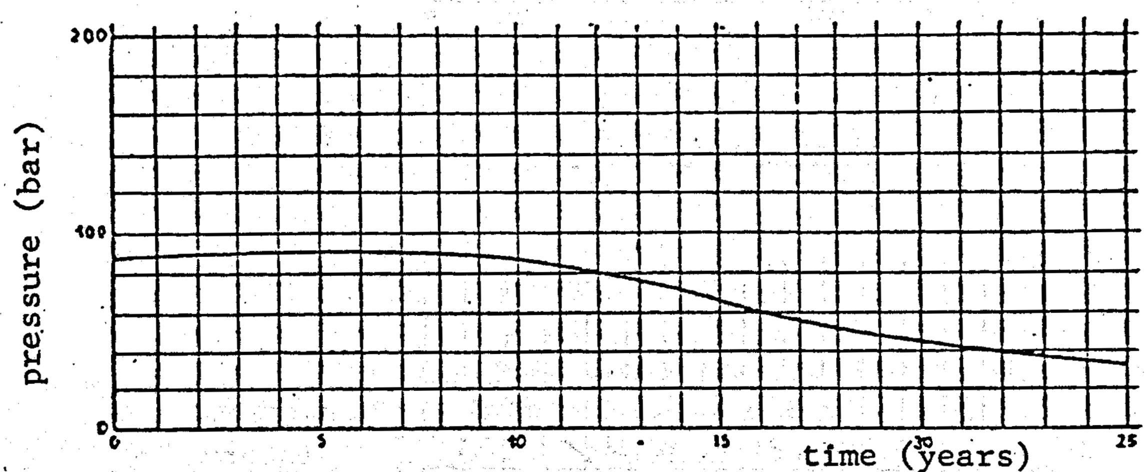
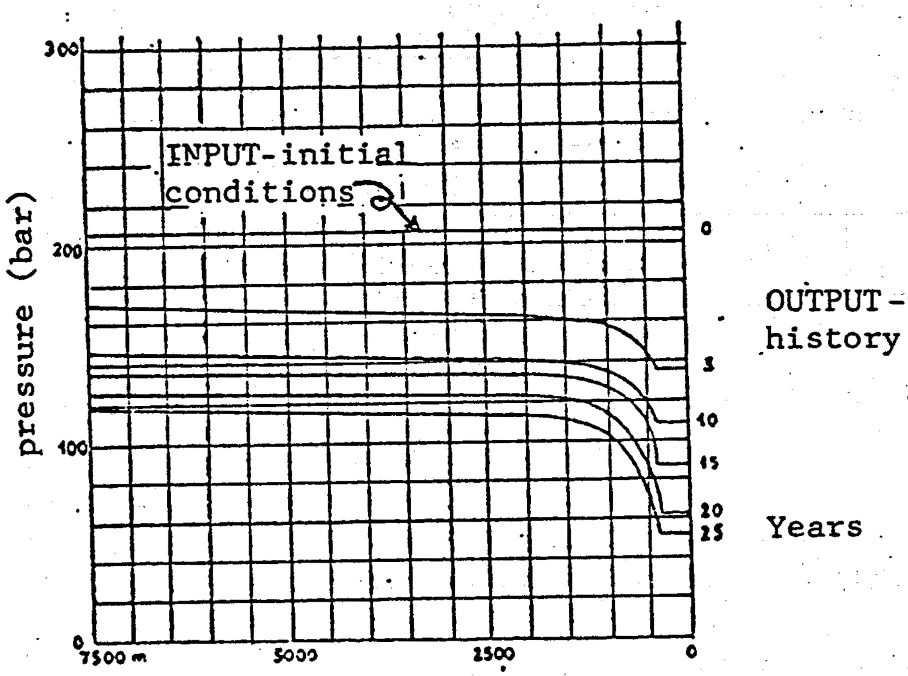


Fig. 5a - Overall Model - Main Simulation Input

PRESSURE FIELD



TEMPERATURE FIELD

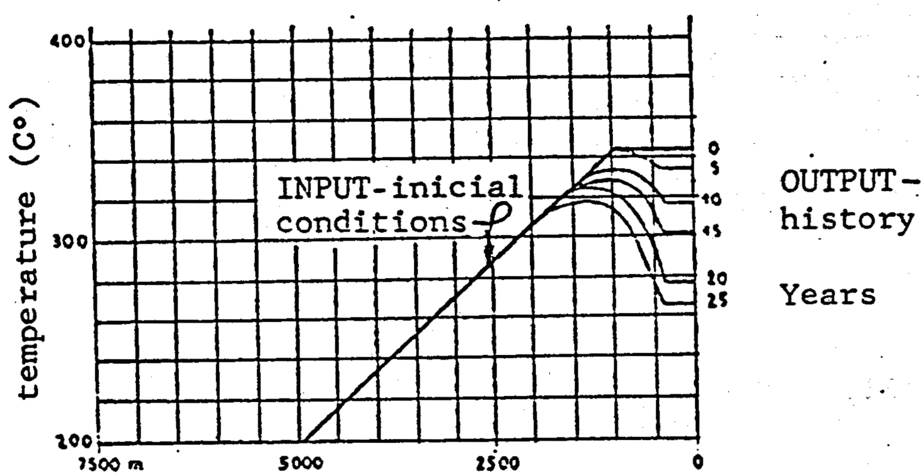


Fig. 5b - Overall Model - Simulation
Input and Output (Reservoir)

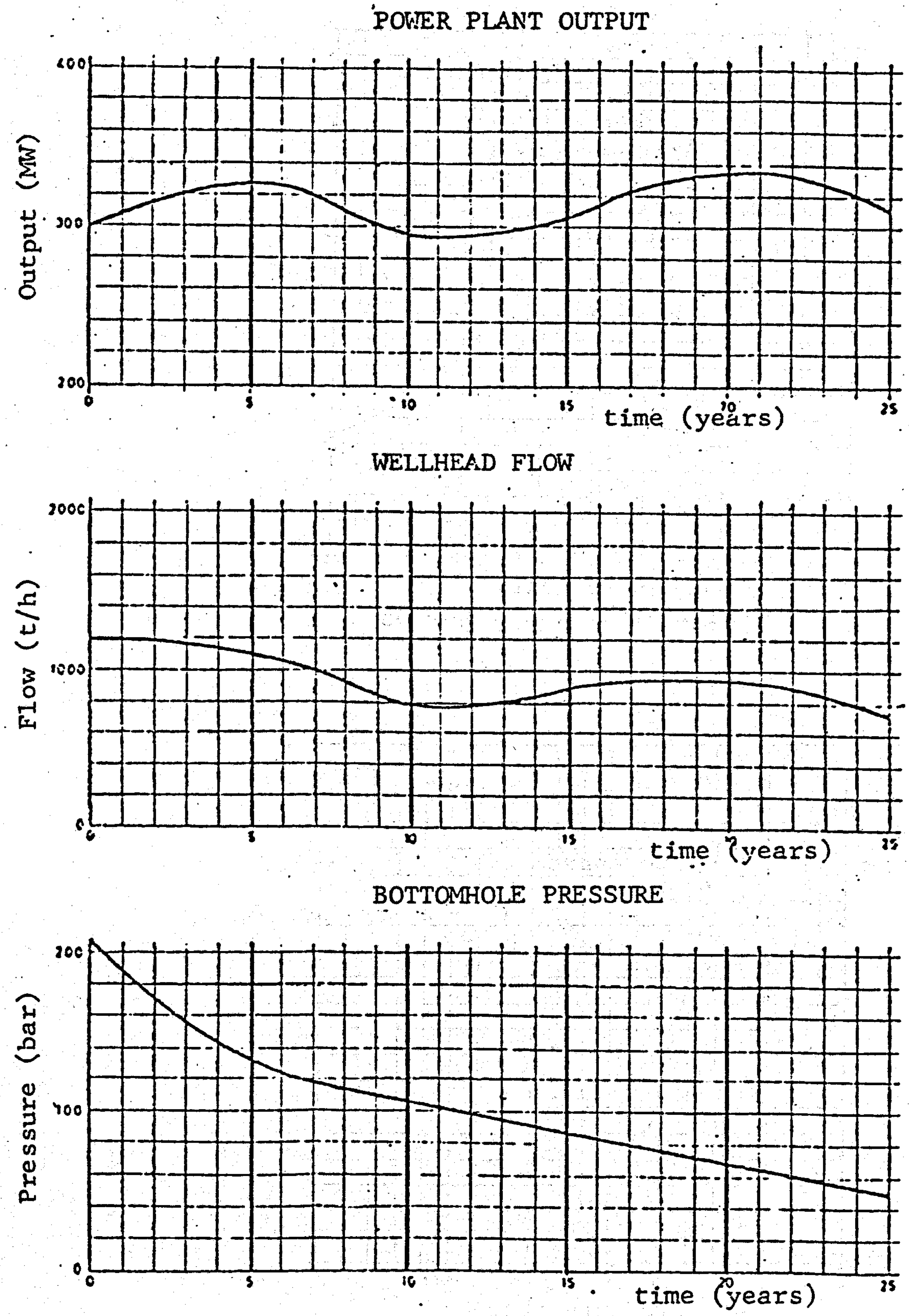
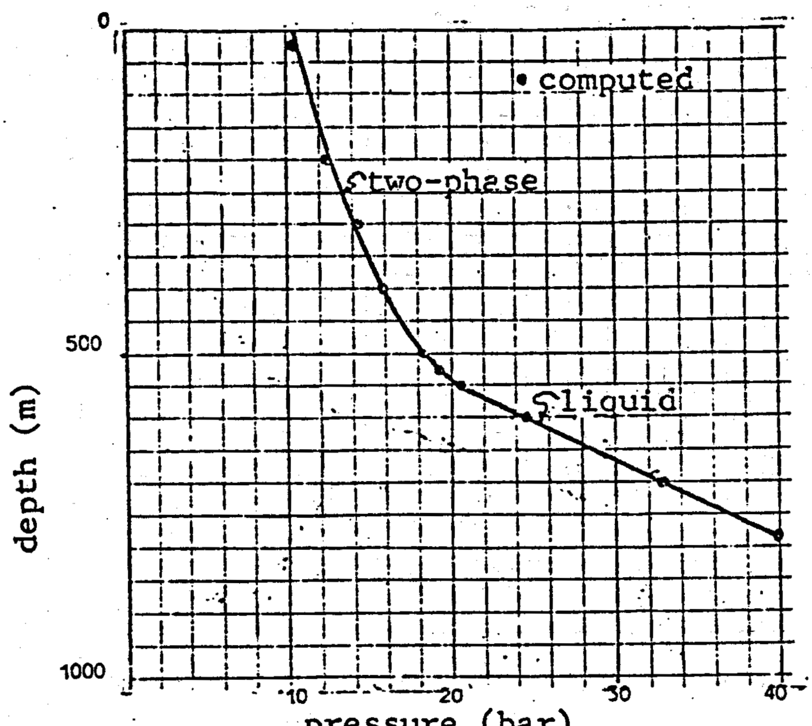
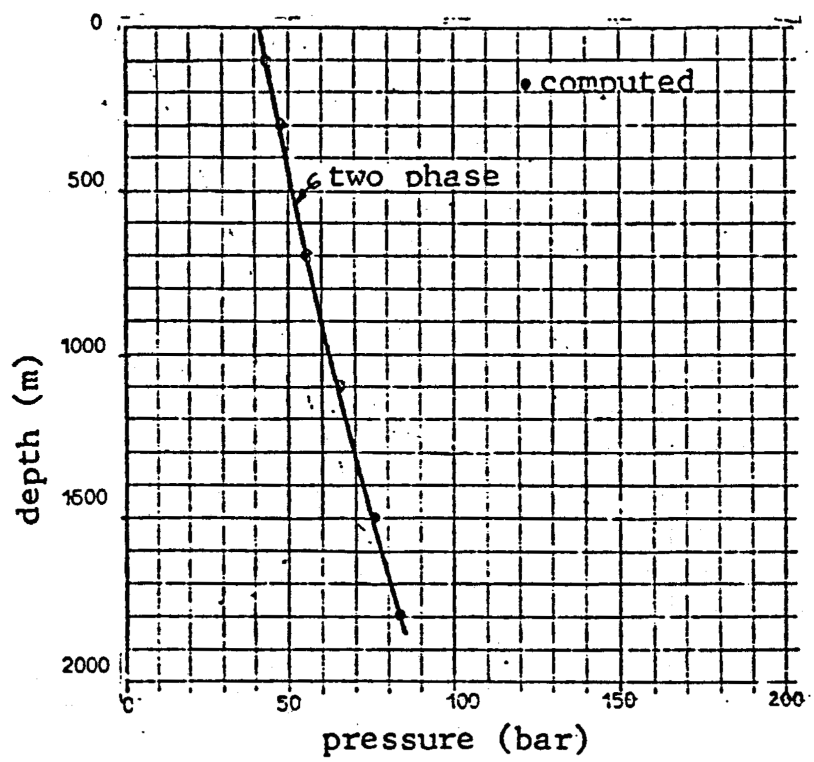


Fig. 5c - Overall Model - Simulation
Output (Well and Power plant)



a. Flash within the casing



b. Flash since bottomhole

Fig. 6: Well Model - Comparison of Predicted against Actual Pressure Profile