COMPUTER PERFORMANCE MATCHING AND PREDICTION OF GEOTHERMAL RESERVOIRS

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ABSTRACT

The initial conditions (physical and chemical state) of a geothermal reservoir and its fluids are important information needed in geothermal reservoir engineering for determining the future productivity of the reservoir. An optimization scheme was employed to minimize the least squares function and determine the optimum initial conditions. Using the mass, energy, and volumetric balance equations, the initial parameters were obtained by matching the production data plot of average reservoir pressure versus cumulative mass produced for a compressed liquid, saturated liquid-steam, and superheated steam reservoir. Once a good curve match was attained, the performance projection of the geothermal reservoir was made at different production rates. A successful curve match was found to be highly dependent on the constraints chosen in the optimization scheme. Mass influx, as well as porosity also proved to be an influencing factor in the determination of the initial conditions. The computer prediction model is presently being used to assess reservoir conditions for the Hawaii Geothermal Project Well A, believed to be the hottest producing geothermal well in the world.

GEOTHERMAL RESERVOIR ENGINEERING: PERFORMANCE MATCHING AND PREDICTING

By Arthur S. Seki,[1] Bill H. Chen,[2] and Patrick K. Takahashi [3]

INTRODUCTION

It is becoming quite evident that the United States' stock of primary energy resources, oil and gas, are diminishing. By the turn of the century these natural resources may be completely depleted. The oil crisis a few years ago was evidence of the United States' dependency on foreign resources. It is therefore very important that the United States become as self-sufficient as possible in energy matters.

Research has already been directed to evaluate solar, wind, and ocean thermal differential as potential energy sources. Nuclear and geothermal plants are presently in operation. Of all energy sources currently available, geothermal energy requires the least capital cost per kilowatt [17].

The United Nations has played an important role in unifying geothermal technology. This was again recently demonstrated in May of 1975 when representatives from fifty-nine nations attended a ten-day conference on geothermal resources. Six distinct groups have contributed to the development of geothermal reservoir engineering in particular: Energy Research and Development Administration, Bureau of reclamation, United States Geological Survey, New Zealand government, Stanford University, and University of Hawaii.

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Congress adopted the Geothermal Steam Act in December of 1970, which established the development of the United States' geothermal resource as a national goal. With the new increased interest in geothermal energy, emphasis has been placed on the development of modern geological and reservoir principles to provide estimates of the reserves and the future productivity of geothermal fields [5].

Robert L. Whiting and Henry J. Ramey, Jr.[21] developed a mathematical computer model to match and predict the performance of a geothermal reservoir at Wairakei, New Zealand. To date, this has been the only major work of this type published. However, two other models of interest are the Brigham-Morrow [4] lumped parameter model of vapor-dominated systems and the Martin sealed model [10].

The objectives of our study was to develop a mathematical model to match the past performance of a geothermal reservoir, whether its physical state is compressed liquid, saturated liquid-steam, or superheated steam, and to predict future productivity. The computer model developed employs essentially the same material-energy balance equations used by Whiting and Ramey [21]. Special attention has been paid to the optimization technique used for matching reservoir performance and to the sensitivity analysis used to check the effect of the various controlling parameters.

Computer Models of Geothermal Reservoirs

Computer modeling for geothermal reservoirs may be divided into two general types: distributed-parameter models and lumped parameter models. A model in which the properties of the rock and/or the fluid (e.g. saturation, viscosity, pressure, etc.) are allowed to vary in space is called a distributed-parameter model. Numerical analysis is usually the method employed to solve this type of problem.

The lumped-parameter model offers one of the simplest means of describing the behavior of a geothermal system during exploitation, and was of primary interest to this study. In the lumped parameter model, the entire system is considered a perfect mixing cell for both mass and energy, so the spatial variation in concentration can be reduced to a single point in space. Instead of considering the internal distribution of mass and energy, attention is restricted to the total amounts generated within the system as well as those crossing the boundaries. Since time is the only independent variable, the system can be characterized mathematically by a set of ordinary differential equation or an equivalent set of algebraic expressions representing total mass and energy [22].

The best known lumped-parameter model of a producing geothermal reservoir is the Whiting-Ramey model. The system has a bulk volume containing vapor, water, and rock. Water may flow in from an adjacent aquifer or leak out of the system via steam vents, springs, wild wells, etc. The water influx is represented by a linear combination of terms each of which is the product of a theoretical time-dependent response function characterizing a certain aquifer flow geometry (hemispherical, linear, or radial) and pressure. These calculations further assume that the liquid inflow is isothermal with constant enthalpy. The energy balance calculation is based on the assumption that the system is in complete thermodynamic equilibrium. Additional assumptions made are that the heat loss is negligible, while the enthalpy of the produced and lost fluid is the same.

Basic Equations

Material Balance:

$$W_c = W_i - W_p - W_l + W_e \tag{1}$$

where W_c = current mass in reservoir, lb

W_i = initial mass in reservoir at start of production, lb

W_p = cumulative mass produced, lb

W_l = cumulative mass lost via springs, wild wells, etc., lb

W_e = cumulative liquid mass influx, lb

Energy Balance:

$$W_c H_c = V(1-\phi)\rho_r C_r (T_i - T_c) + W_i H_i - W_p H_p - W_l H_l + W_e H_e + Q_s \tag{2}$$

where H_c = average enthalpy of total fluids in reservoir, Btu/lb

H_i = average enthalpy of initial fluids in reservoir, Btu/lb

H_p = average enthalpy of produced fluids, Btu/lb

H_l = average enthalpy of lost fluids, Btu/lb

H_e = average enthalpy of liquid water influx, Btu/lb

V = reservoir bulk volume, ft^3

ϕ = formation porosity

ρ_r = formation density, lb/ft^3

C_r = specific heat of formation, Btu/lb-°F

T_c = current reservoir temperature, °R

T_i = initial reservoir temperature, °R

Q_s = cumulative net heat conducted into reservoir, Btu

Volumetric Balance:

$$V\phi = W_c[(1-X_c)V_f + X_c V_g] \tag{3}$$

where X_c = current steam quality in reservoir

V_f = specific volume of saturated liquid, ft^3/lb

V_g = specific volume of saturated vapor, ft^3/lb

Enthalpy Equation:

$$H = (1-X)H_f + X\, H_g \tag{4}$$

where H = fluid enthalpy of steam quality X, Btu/lb

H_f = enthalpy of saturated liquid, Btu/lb

H_g = enthalpy of saturated vapor, Btu/lb

In the most rigorous calculation scheme, for two phases, the current steam quality is calculated from the volumetric balance:

$$X_c = [(V\phi/W_c) - V_f]/(V_g - V_f). \tag{5}$$

The current enthalpy is solved from the enthalpy equation

$$H_c = (1-X_c)H_f + H_g X_c. \tag{6}$$

Now setting the energy balance to zero, the current temperature that satisfies equation (2) can be found

$$Y = W_i H_i - W_p H_p + W_e H_e - W_1 H_1 + V(1-\phi)\rho_r C_r (T_i - T_c) + Q_s - W_c H_c. \tag{7}$$

Once the current temperature is known, the corresponding pressure can be determined. From a set of past performance data, the corresponding pressures can be found using least squares fit. Figure 1 shows the path necessary to obtain the optimum initial conditions.

The compressed liquid reservoir equation is a simplified form of the mass-energy-volumetric balance equations used in the two-phase case:

$$V_1 = V_{1i}/[1 + (W_e/W_i) - (W_p/W_i) - (W_1/W_i)]. \tag{8}$$

where V_1 = specific volume of liquid water, ft^3/lb

V_{1i} = specific volume of liquid water at initial conditions, ft^3/lb

From the above equation, only the initial liquid specific volume and the various mass data are needed to determine the current liquid specific volume. Subprogram WASP (to be explained later) then is used to calculate the current pressure for the evaluation of the least squares value. A set of calculated pressures will be obtained from each set of production data.

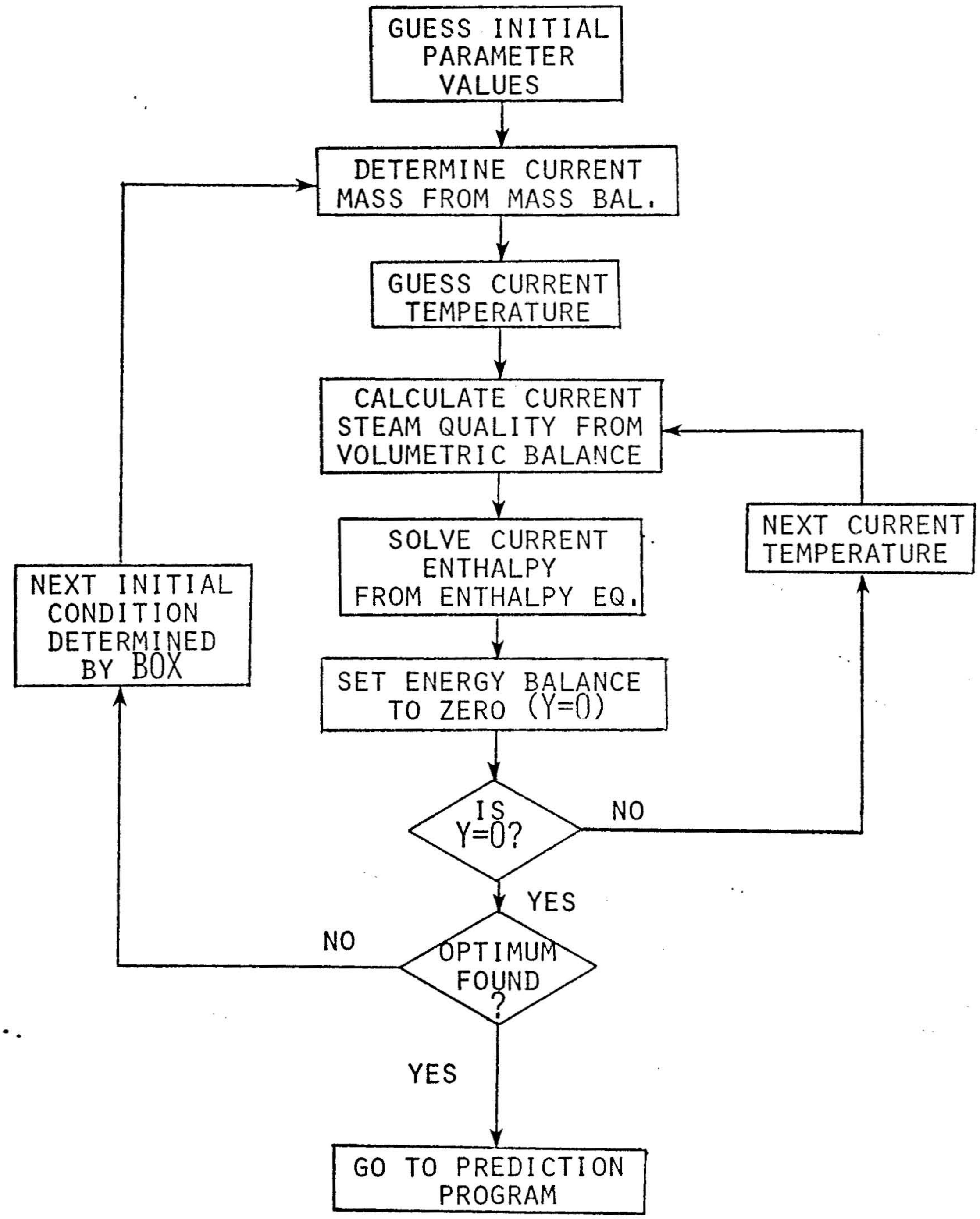

FIGURE 1. SATURATED LIQUID-STEAM RESERVOIR CALCULATION SCHEME

The superheated steam reservoir case is similar to the compressed liquid reservoir case. Since steam is a gas, the static reservoir pressure is handled in the usual gas reservoir engineering manner. This is based upon the mass balance equation (1) and a volumetric balance, which specifies that the volume of gas produced must equal the original mass of gas from the original pressure to the current pressure:

$$W_pV_v = W_i(V_v-V_{vi}) + W_eV_v-W_1V_v \tag{9}$$

where V_v = specific volume of vapor, ft^3/lb

V_{vi} = specific volume of vapor at initial conditions, ft^3/lb.

The specific volume terms, which are functions of temperature and pressure, can be expressed by the real gas law. The relationship of compressibility factor with temperature and pressure is

$$V_v = ZRT/pM \tag{10}$$

where Z = compressibility factor

R = gas law constant, 10.73 $(psia\text{-}ft^3)/(lb_{mole}\text{-}°R)$

T = reservoir temperature, °R

M = molecular weight of steam, 18 lb/lb_{mole}

P = reservoir pressure, psia.

Substituting equation (10) into (9) and rearranging it results in:

$$P/Z = (P_i/Z_i)[1+(W_e/W_i)-(W_p/W_i)-(W_1/W_i)] \tag{11}$$

where P_i/Z_i = initial (pressure/compressibility factor), psia

which is similar to the compressed liquid case. Only the various mass data and the initial (pressure/compressibility factor) are needed to obtain the current pressure.

Ramey [15] reported that if the actual field data are plotted (P/Z versus W_p) and a straight line results, the reservoir can be considered closed with no recharge. This straight line may be extrapolated to the abandonment pressure level to provide a measure of the ultimate recovery of steam. An extrapolation of zero pressure yields a measure of the initial mass of steam in place, W_i. Water influx usually results in a concave-upwards shape in the plot and pressure often stabilizes after a length of time.

Physical States of Water

In the use of Gibbs' phase rule, in order to specify the thermodynamic state of single phase water, two independent thermodynamic properties (i.e. temperature and pressure) must be specified. However, if two phases are present (e.g. saturated liquid-steam), specification of only one intensive property defines the system.

$$d_f = C - P + 2 \tag{12}$$

where d_f = degrees of freedom

C = number of components

P = number of phases.

It has been shown through thermodynamic analysis that a geothermal system initially yielding a single-phase fluid (either compressed liquid or superheated steam) will tend to deplete isothermally. However, once two phases form, a system should follow a variation of the vapor pressure curve appropriate for the fluids in the pore space [16].

Thermodynamics

The three initial geothermal fluid states--compressed liquid, saturated liquid-steam, and superheated steam--usually progress through well-defined paths during mass production. They will be covered in the order generally experienced.

The first case to be considered is compressed liquid, which lies entirely in the liquid region. Recall from Gibbs' phase rule that two intensive properties completely determine the thermodynamic state of the system. The path from compressed liquid to the saturation curve is essentially isothermal and isoenthalptic [21] until the vapor pressure curve is reached.

At the vapor pressure curve, according to Gibbs' phase rule, one intensive property determines this type of system. Although the thermodynamic condition is specified as liquid and vapor in equilibrium, the relative amounts cannot be determined unless other thermodynamic properties are known (e.g. enthalpy, steam quality, etc.). If saturated hot water was produced isothermally, there would be no reservoir pressure decline until all the fluid in the reservoir had vaporized. However, if the reservoir follows an isoenthalptic path, both pressure and temperature would tend to decrease.

The final case lies entirely in the vapor region. As in the compressed liquid phase, both initial pressure and temperature are needed to determine the initial condition. At initial superheated condition, the path of production of a typical geothermal steam reservoir would not truly be isothermal. However, the temperature decline would be too small to detect using normal field instruments.

Pressure Buildup Test

Of all the well test analyses, the pressure buildup test is the most important because it yields the static average pressure, $\overline{p}$, in the reservoir drainage area. If the production rates are known at various reservoir pressures, extrapolation into the future is possible.

Matthews and Russell [13] state the theoretical basis for the pressure buildup test using the following relation for an infinite boundary reservoir (nomenclature in Table 1):

Table 1. Practical and Darcy Units

Parameter	Practical Units	Darcy Units
t, time	hour (hr)	seconds (sec)
r, distance in radial direction	feet (ft)	centimeter (cm)
q, production rate	barrels/day (B/D)	cubic centimeter/second (cc/sec)
p, pressure	pounds/square inch (psi)	atmosphere (atm)
μ, fluid viscosity	centipoise (cp)	centipoise (cp)
k, formation permeability	millidarcy (md)	darcies
h, formation thickness	feet (ft)	centimeter (cm)
ϕ, formation porosity	--	--
c, fluid compressibility	volume/volume/pounds/square inch (vol/vol/psi)	volume/volume/atmosphere (vol/vol/atm)
r_w, well radius	feet (ft)	centimeter (cm)

adapted from [11]

$$P_{ws} = P_i + \left(\frac{q\mu}{4\pi kh}\right) \ln \left[\frac{\gamma^* \phi \mu c r_w^2}{4k(t+\Delta t)}\right] - \left[\frac{q\mu}{4\pi kh}\right] \ln \left[\frac{\gamma_* \phi \mu c r_w^2}{4k\Delta t}\right]. \quad (13)$$

where P_{ws} = well pressure after shut-in

P_i = initial pressure

t = time during well production

Δt = time after well is closed-in

γ^* = Euler's constant, 1.78

From the law of logarithms equation (13) then reduces to

$$P_{ws} = p_i - \left(\frac{q\mu}{4\pi kh}\right) \ln \left[\frac{(t+\Delta t)}{\Delta t}\right] \quad (14)$$

By applying the common logarithm and converting into practical units, equation (14) becomes

$$P_{ws} = p_i - \left(\frac{162.6\ q\mu B}{kh}\right) \log_{10} \left[\frac{(t+\Delta t)}{\Delta t}\right] \quad (15)$$

where B = formation volume factor.

Matthews and Russell [13] reported that an equation written for pressure behavior in an infinite reservoir may be immediately rewritten for a finite reservoir by substituting p^* for p_i. The variable p^* is defined as the well pressure at an infinite shut-in time, $(t+\Delta t)/\Delta t = 1$. Thus for a finite reservoir, a pressure build-up curve will decrease after a lengthy time period, as shown in Figure 2. The flattened section of the curve approaches the average pressure, $\overline{p}$, in the bounded reservoir while the straight line portion reaches the value of p^* at $(t+\Delta t)/\Delta t = 1$. In practice, a well will not be closed-in long enough to attain the condition represented by the flattened portion of the curve, but it is possible to estimate $\overline{p}$ from the extrapolated value of p^*.

Matthews, Brons, and Hazebroek [12] developed equations for $(p^* - \overline{p})$ versus time for drainage areas of various shapes. A plot of $(p^* - \overline{p})/(70.6\ q\mu\phi B/kh)$

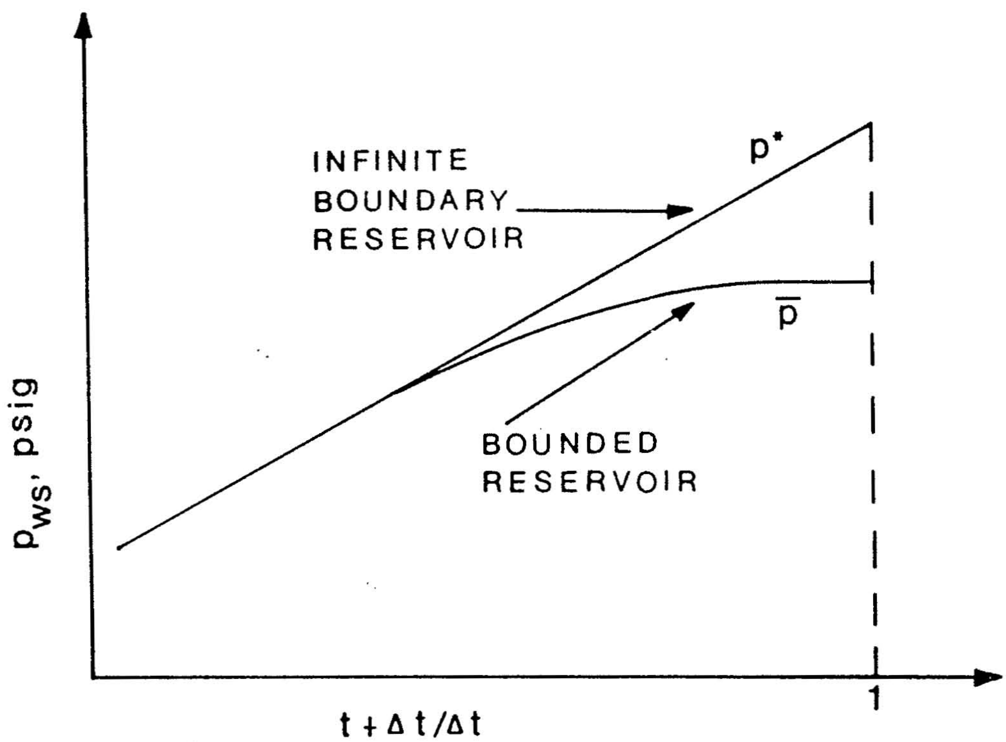

Figure 2. Pressure Buildup Curve for Infinite and Finite Boundary Reservoir [11]

versus 0.000264 $kt/\phi\mu cA$ for various locations of a well in a square boundary is shown in Figure 3. Plots of various boundary shapes and well locations are available [12].

The recommended procedure for determinig the average pressure is as follows:

1) Plot P_{ws} versus $\log_{10}$ $[(t+\Delta t)/\Delta t]$ to determine p* at infinite shut-in time. The graph is extrapolated to the point where $(t+\Delta t)/\Delta t = 1$ as illustrated in Figure 4.

2) t_{DA} is calculated from the following equation:

$$t_{DA} = 0.000264\ kt/\phi\mu cA \tag{16}$$

3) Use a pressure function plot, like Figure 3, with the appropriate drainage area and well location. Since p* is known, calculate $\overline{p}$.

It should be noted that to obtain a single $\overline{p}$ value, there must be production for at least one week or longer followed by a shut-in and buildup test, which will require about one month. Therefore, it may be three to six months before performance prediction can be attempted with any confidence.

Hot Water and Steam Properties

Geothermal fluids may contain salt, silica, calcium carbonate, potash, manganese, boron, iodine, bromine, lithium, sulfur, fluorine, potassium, arsenic, antimony, and other dissolved solids [20]. Dry steam reservoirs also produce noncondensable gases along with steam. The gases include carbon dioxide, hydrogen sulfide, ammonia, methane, and ethane. The presence of these noncondensable gases in a dry steam reservoir will affect the thermodynamic and transport properties of the produced fluid. Unfortunately, almost no experimental work seems to have been done on the properties of dry steam and noncondensable gas mixtures [16].

Mashima [11] reported that the salt water content of the underground water at Wairakei reservoir was less than 3% and the properties of dilute saline solutions

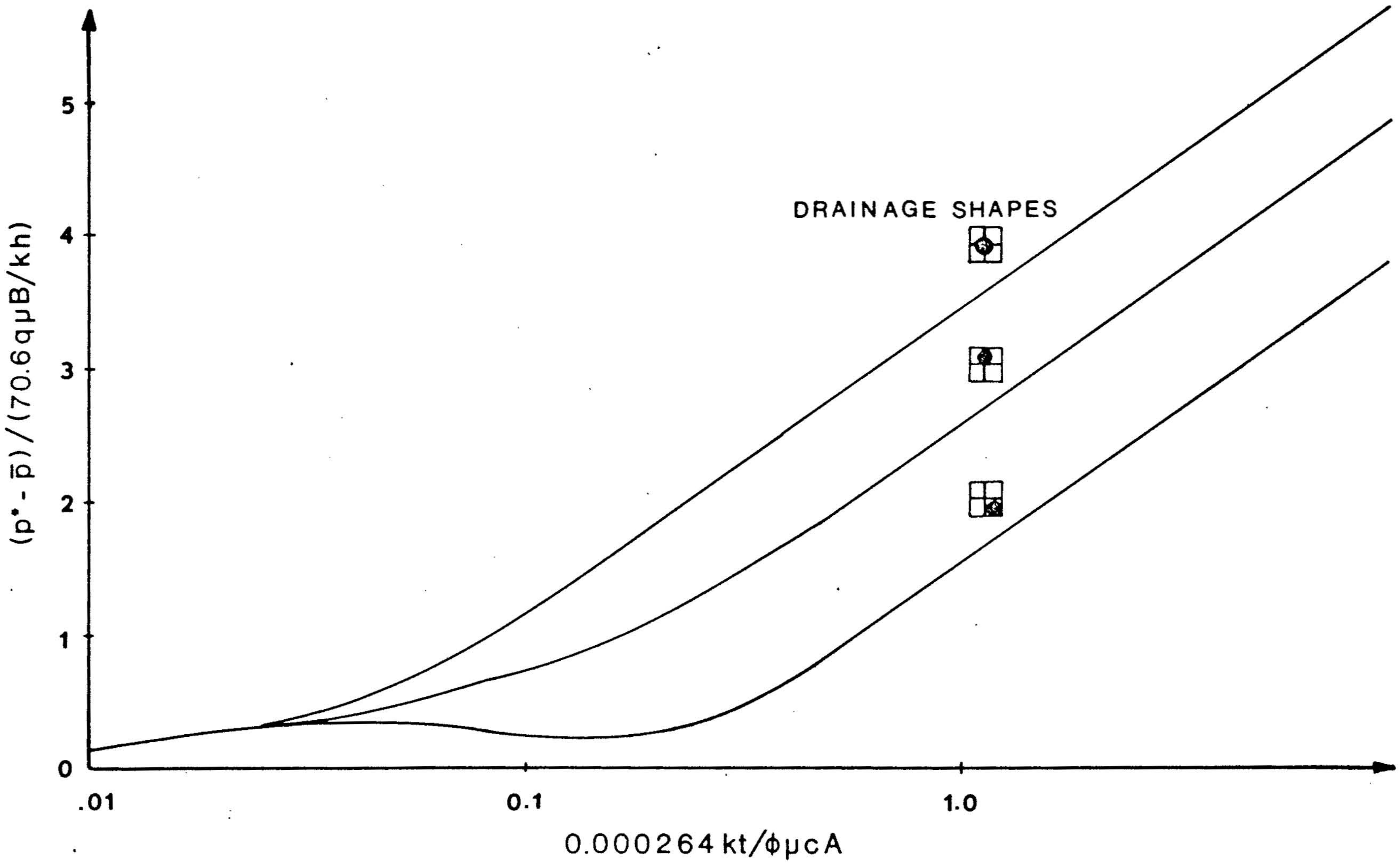

Figure 3. Pressure Function for Different Well Locations in a Square Boundary [12]

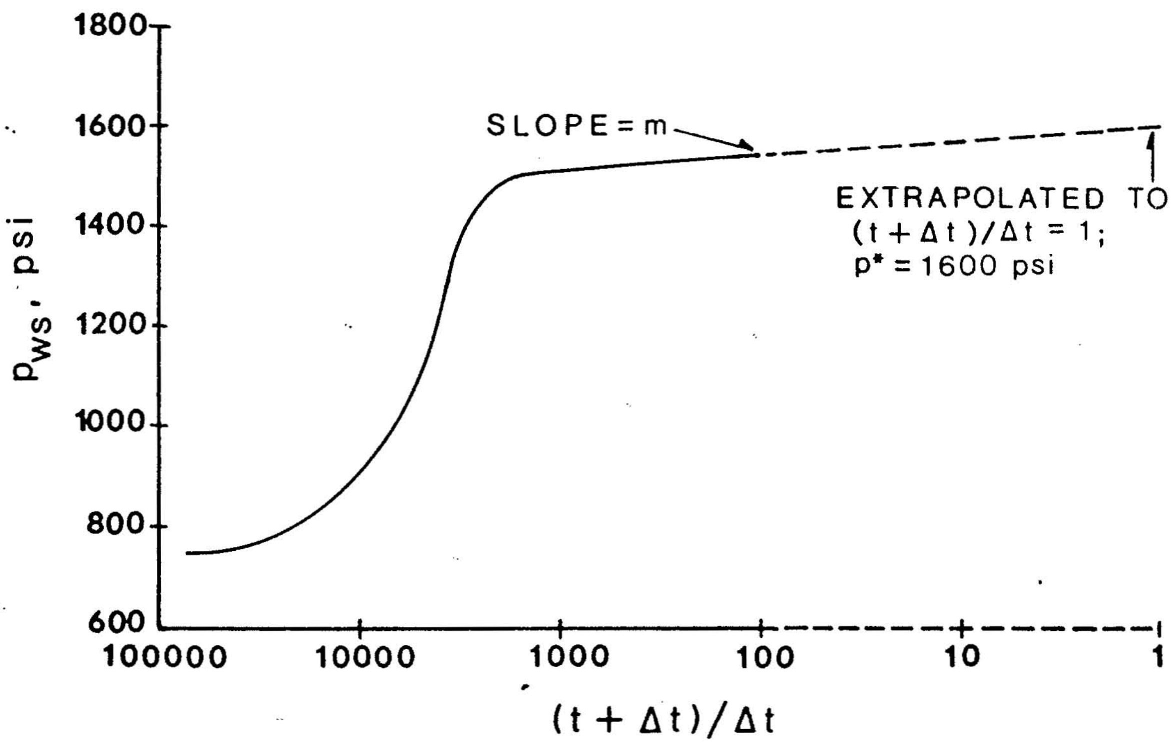

Figure 4. Sample Plot of Pressure Buildup Test [11]

are very close to the properties of pure water. However, Imperial Valley has as much as 30% dissolved solids by weight in the geothermal fluid [18].

Keeping these above points in mind, the true vapor pressure of water in a geothermal system may not necessarily be that presented in the steam tables. For a fixed pressure, the boiling temperature of water will be elevated by the presence of impurities. However, this effect is usually rather small. The difference according to Ramey [16], would probably not be measurable in a vapor-dominated geothermal system.

Based on the data in the literature, Chou [7] formulated the interpolated formula for vapor pressure, specific volume, enthalpy, and heat of vaporization of ordinary sea water in the temperature range of 32°F to 392°F for salinities of 0 to 120 ppt.

Although the effect of salts in solution and the lowering of vapor pressure due to capillary pressure could have modifying influences upon quantitative calculations, the presence of salts should not alter the general principles presented. For the first geothermal well in Hawaii, the dissolved solid content was considerably below 1%, so calculations could be performed with a high degree of confidence.

FORMULATION OF COMPUTER PROGRAM

Performance Matching and Prediction

In addition to the four basic equations (1), (2), (3), and (4) introduced in the previous chapter, the following assumptions about the reservoir and its conditions form the fundamental bases for this study:

1. The system is the fluid and rock in the reservoir, including the well.
2. Complete thermodynamic equilibrium exists.

3. Isothermal depletion in the single-phase reservoir during production.
4. The reservoir essentially contains pure water.
5. Mass influx, W_e, is treated as a single parameter. The mass influx was considered a saturated liquid at a constant influx temperature.
6. Thermal and hydraulic equilibrium exists in the reservoir.
7. Enthalpy produced, enthalpy lost, and current enthalpy are assumed to be equal ($H_p = H_l = H_c$). Heat loss in the well bore is neglected.
8. Heat capacity at constant pressure is essentially the same as at constant volume.

The operation of matching the past performance data using the material-energy balance to determine the initial conditions involves a least squares fitting technique. Basically, the calculated pressure is matched against the actual average reservoir pressure with time as represented by the cumulative production figures. The mass influx is initially considered negligible. A range of least squares fits is obtained by varying combinations of the unknown initial conditions. Once the optimum initial parameters are known, mass influx may be varied until the maximum allowable rate (i.e. largest possible mass influx rate that has a good curve fit) is determined. In the two-phase case influx temperature may also be altered. A least squares value of zero means a perfect fit has been obtained.

An optimization scheme, BOX, is employed to find the optimum initial conditions by minimizing the least squares function.

$$S = \sum^{N} (P_{actual} - P_{calc})^2 \qquad (17)$$

where S = least squares value

P_{actual} = actual average reservoir pressure, psia

P_{calc} = calculated pressure, psia

N = number of past performance data sets (data set = actual average reservoir pressure versus cumulative mass produced).

The initial parameters to be optimized in the three different cases are:

1. Compressed liquid reservoir
   a. initial pressure
   b. initial mass
2. Saturated liquid-steam reservoir
   a. initial temperature
   b. initial mass
   c. initial steam quality
3. Superheated steam reservoir
   a. initial (pressure/compressibility factor)
   b. initial mass

Chen [6] reported that the initial conditions obtained from performance matching may or may not be the real reservoir condition. Nevertheless, it is not necessarily important to have the correct model as long as the performance of the model and the reservoir is the same.

When the optimum initial conditions are known, computer program PRE can be used to predict the performance at different production rates. A thirty-year projection, which is standard in the utility field, was used.

Computer Analysis

Basically, the computer analysis consists of two separate programs: BOX and PRE. The BOX program is primarily an optimization scheme that minimizes the least squares function (performance matching) and locates the optimum initial parameters for a compressed, saturated liquid-steam, or superheated steam reservoir. Program PRE is used to predict the thirty-year performance of the geothermal reservoir at various production rates.

The use of BOX requires the user to supply the estimated ranges (i.e. upper and lower constraints) of each initial parameter. The success of finding the minimum least squares value (good performance match) and subsequent optimum initial parameters is highly dependent on the constraints chosen. Therefore, the general scheme for obtaining a good match is to vary the constraints.

Description of Computer Program BOX

The optimization scheme is based on the "complex" method developed by M.J. Box [3]. This method is a sequential search technique which has proven to be effective in solving problems with nonlinear objective functions subject to nonlinear inequality constraints. No derivatives are required. The procedure can be used to determine the global minimum, as the initial set of points are randomly scattered throughout the feasible region. Figure 5 illustrates a flow chart of the general optimization scheme.

Subroutine FUNK contains the objective function that is to be minimized. A set of independent variables (initial parameter) are transferred to this subroutine in an attempt to match the past performance of the geothermal reservoir. A flow chart of the general scheme is shown in Figure 6.

Description of Computer Program PRE

This computer program is used to make a thirty-year projection of the performance for a geothermal reservoir. The optimum initial conditions determined from

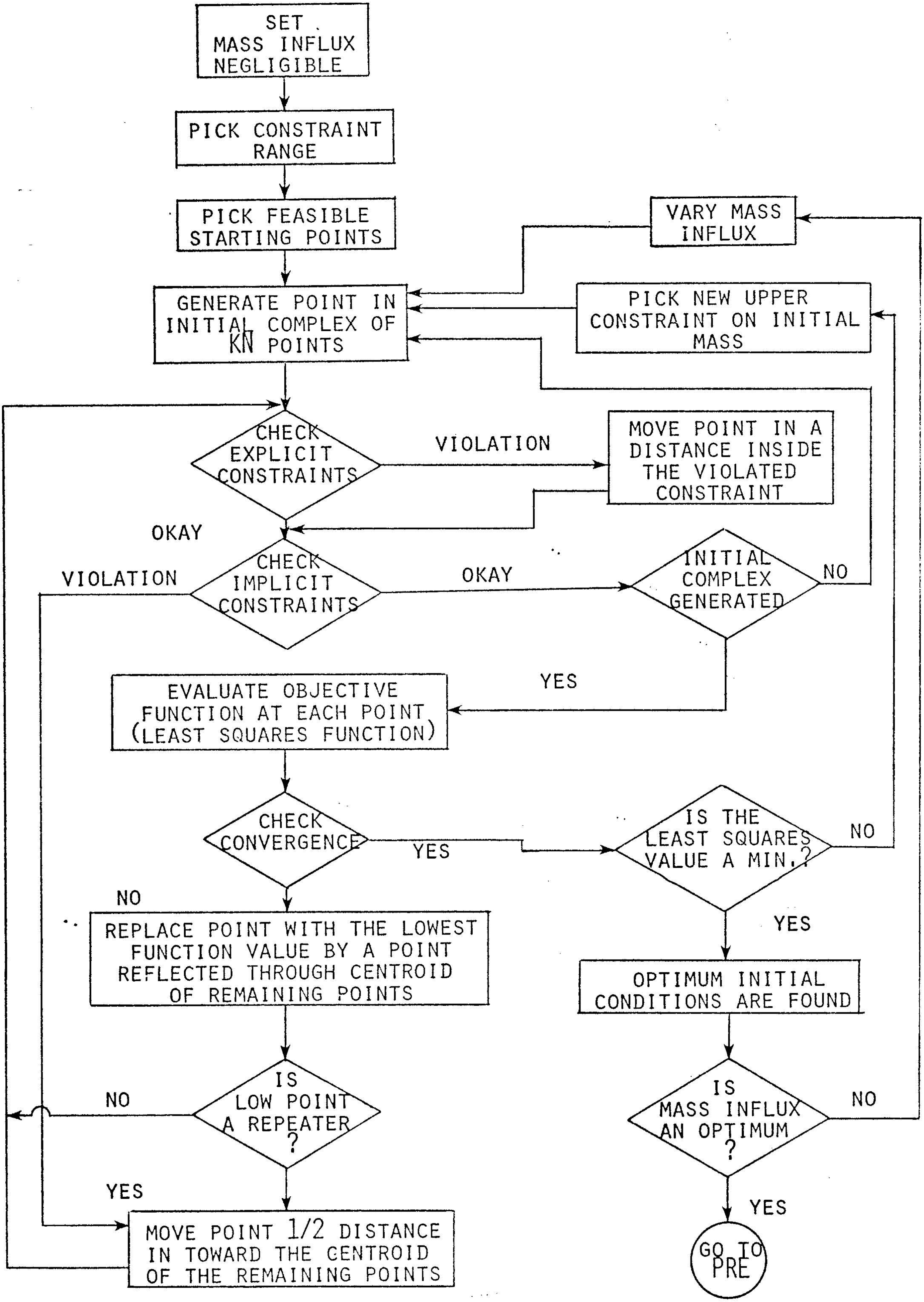

Figure 5. BOX Optimization Scheme
(Adapted from [9])

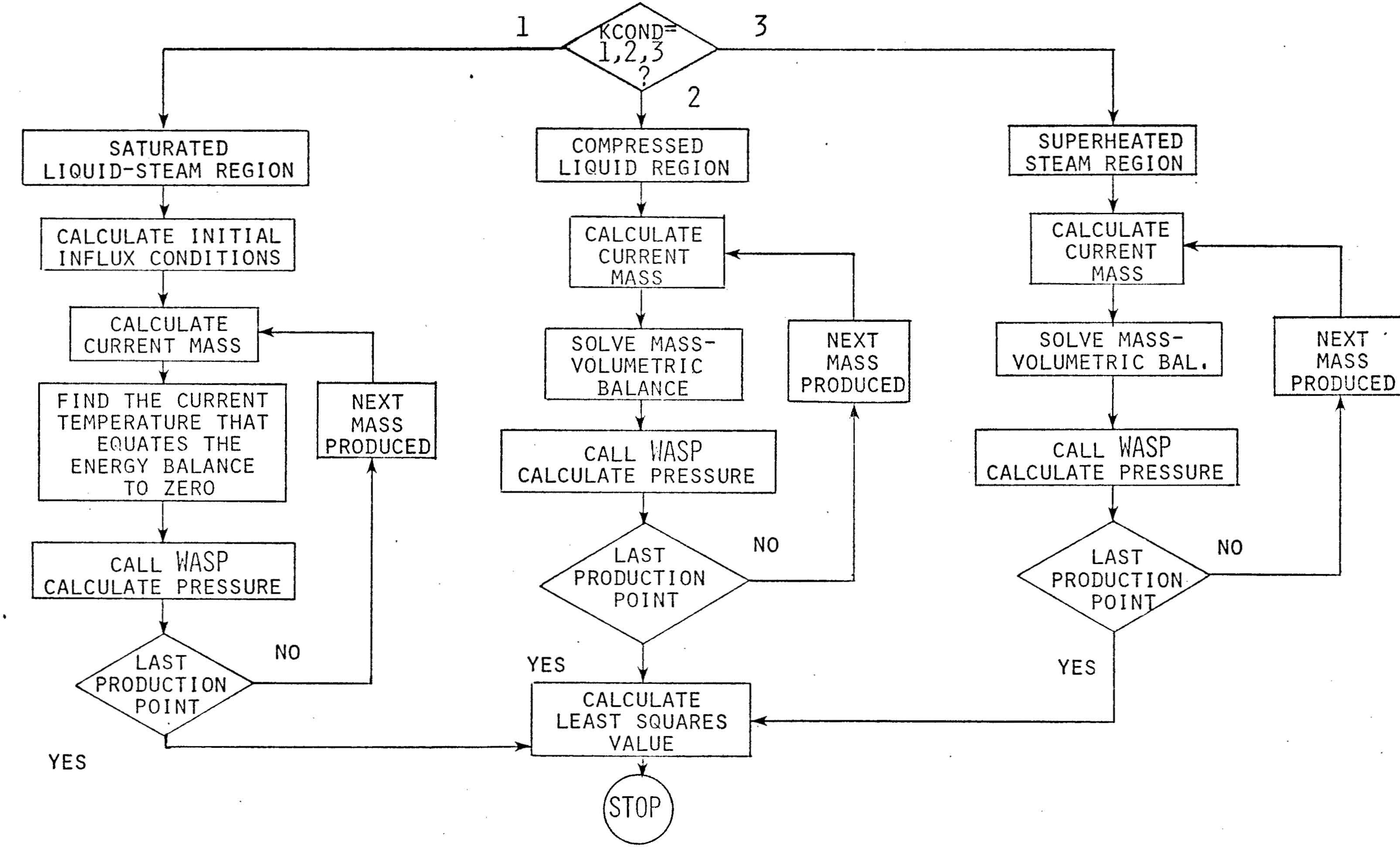

FIGURE 6. BOX -- SUBROUTINE FUNK LOGIC DIAGRAM

BOX are read into PRE. These values are used in the material-energy balance equations to match the performance of the geothermal reservoir, and the thirty-year projections are made at different production rates. In this routine, phase changes are accounted for in prediction and projection. Figure 7 displays the general logic of PRE.

Water and Steam Properties Subprogram (WASP)

WASP [8] was used to calculate the thermodynamic properties of water and steam. This subroutine, developed by the National Aeronautics Space Administration, accepts any combination of pressure, temperature or density as input conditions. In addition, pressure and either entropy or enthalpy are also allowable input variables. The properties available in any combination as output include, among others, temperature, pressure, density, enthalpy and specific heats.

To enable the use of WASP to calculate the thermodynamic properties of water and steam with a high degree of accuracy, the subprogram was operated in double precision. BOX and PRE, which made frequent calls to WASP, are also in double precision.

WASP appears in subroutine FUNK of both BOX and PRE quite frequently. In the two-phase section of each program, WASP was contained within a do-loop that conservatively made over 13,000 calls to WASP. This resulted in extreme expense. To reduce cost, general equations for the desired thermodynamic properties were determined by linear regression.

Results and Discussion

Reservoir performance data to test each case was difficult to obtain because private firms generally treat reservoir data as proprietory. However, with the assistance of James W. Mercer of the United States Geological Survey [14], five reels of microfilmed data from the Wairakei geothermal field was secured. A second set of production data was obtained with the help of R.S. Bolton [2], chief geothermal engineer with the Ministry of Works and Development in New Zealand [1]. The third and final set of production data was found in a publication by Henry J. Ramey, Jr. [15].

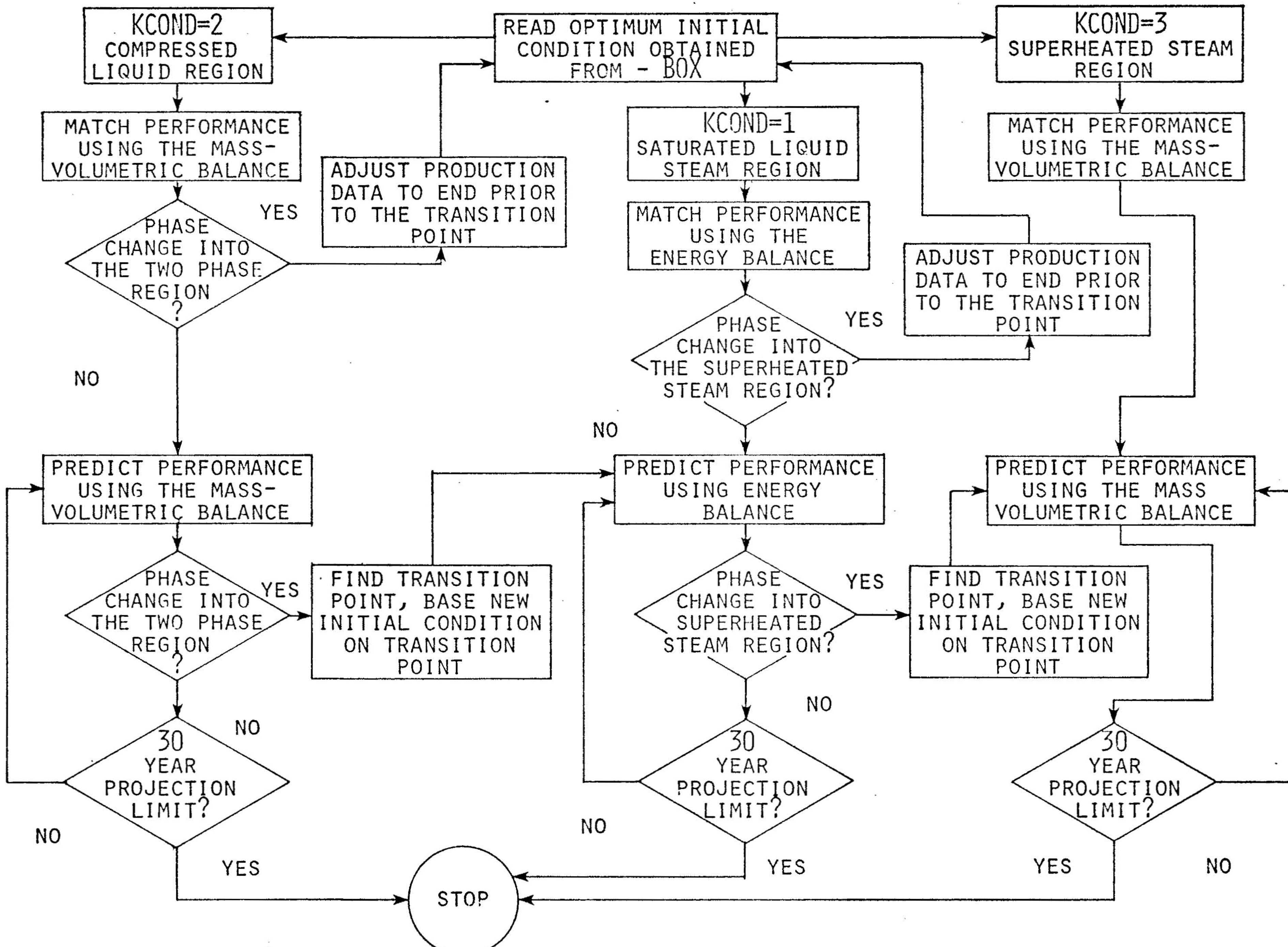

FIGURE 7. COMPUTER PROGRAM PRE LOGIC DIAGRAM

Table 2 displays the optimum initial conditions and minimum least squares value for the three geothermal reservoirs studied: compressed liquid, saturated liquid-steam and superheated steam. For the reservoirs studied it appeared that large mass influxes gave better curve fits. This was especially true for the compressed liquid case, in which the least squares value decreased from 105 to 80.

Whiting [19] tested the model on Wairakei data. He assumed negligible mass influx, mass loss, and heat loss. The following table shows the results of Whiting-Ramey model in comparison with the Hawaii Geothermal Project model. The values are essentially in agreement with each other.

Initial Parameter	Whiting-Ramey Model	HGP Model
Pressure	773.3	772.4
Mass	5.23×10^{14}	5.42×10^{14}

$W_l = W_e = Q_s = 0.0$

Henry J. Ramey, Jr. [15] reported that the usual gas reservoir engineering manner for predictions is made by extrapolating pressure/compressibility factor versus the cumulative production plot. Other information such as the initial conditions can also be obtained from this plot.

Initial Parameter	Ramey's Plot	HGP Model
P_i/Z_i	190.0	188.2
Mass	2.15×10^{11}	2.31×10^{11}

The optimum initial condition obtained from BOX are read into PRE for the predictions of future performance. A thirty-year projection was made using 60 psia as the abandonment pressure and 400°F as the influx temperature. Figures 8 and 9 reveal the pressure drops of seven different production rates for the compressed liquid case. A phase change occurs at about 487.16 psia, at which point production has little depletion and looks very optimistic. The saturated liquid-steam case also had a

Table 2. Optimum Initial Parameters of a Geothermal Reservoir

Reservoir Parameter	Without Mass Influx	With Mass Influx
Compressed Liquid:		
Initial Pressure	772.388130	773.879926
Initial Mass	$5.41981569 \times 10^{14}$	$4.87952480 \times 10^{14}$
Least Squares Value	105	80
Saturated Liquid-Steam:		
Initial Temperature	952.518912	952.739672
Initial Mass	$1.87592409 \times 10^{12}$	$1.77168640 \times 10^{12}$
Initial Steam Quality	0.078475	0.014552
Least Squares Value	8	4
Superheated Steam:		
Initial (Pressure/Compressibility)	188.162590	191.320409
Initial Mass	2.3119401×10^{11}	1.8274845×10^{11}
Least Squares Value	0	0

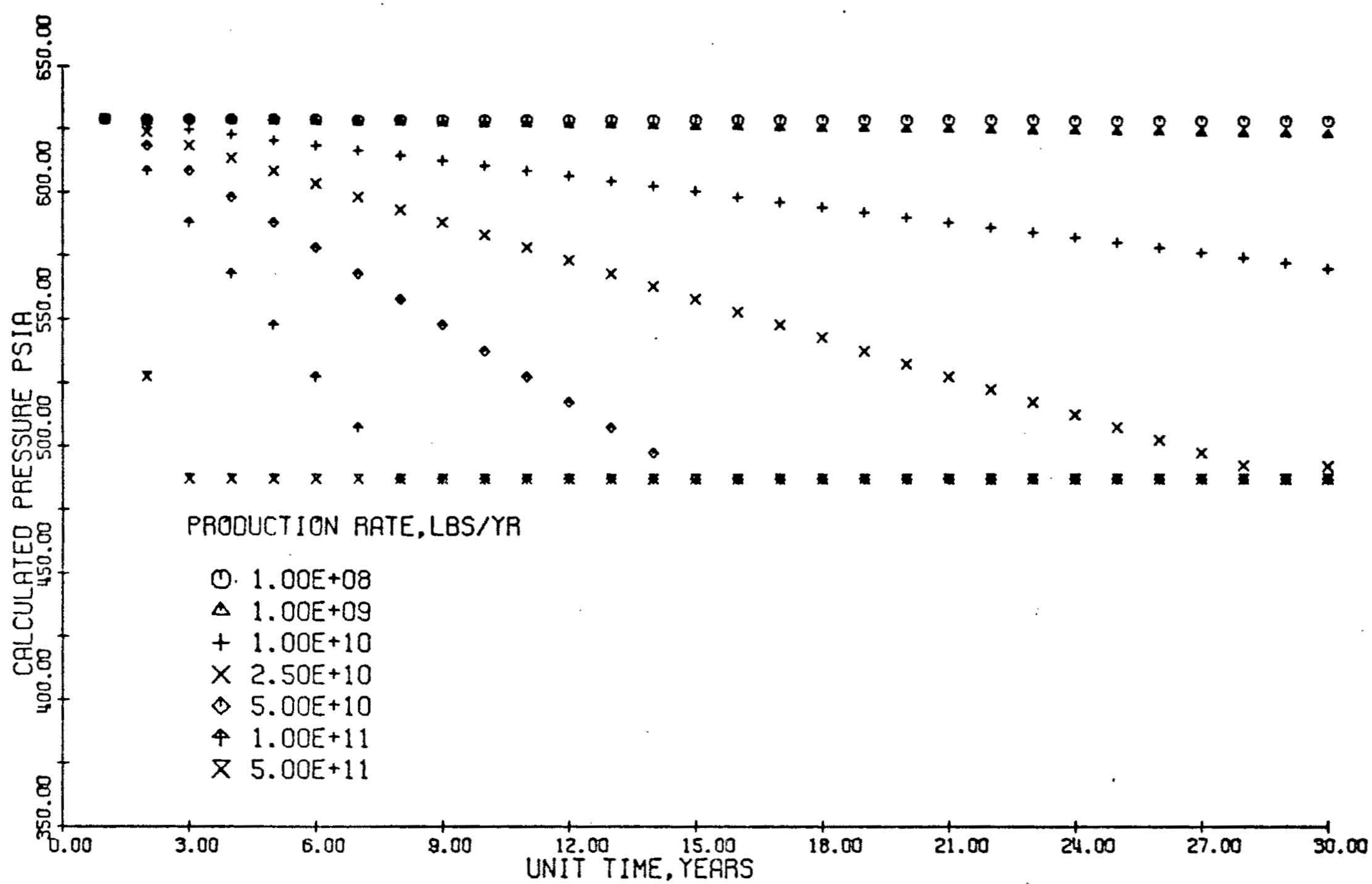

Figure 8. Performance Prediction of a Compressed Liquid Reservoir With the Mass Influx Rate = 1.0 lb/yr

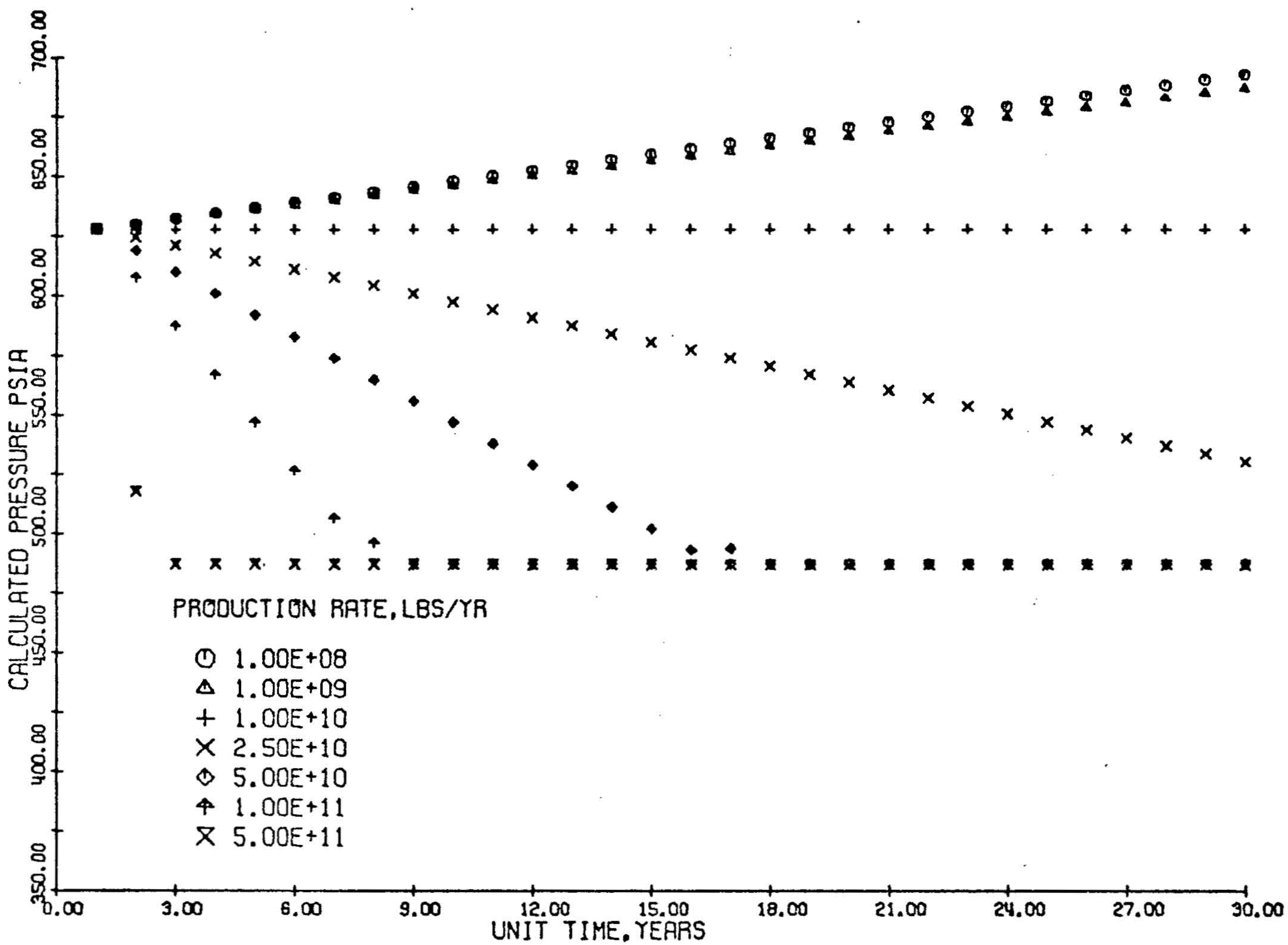

Figure 9. Performance Prediction of a Compressed Liquid Reservoir With the Mass Influx Rate = 1.0 X 10^{10} lb/yr

phase change but into the superheated steam region. This was displayed by the sudden drop in production presented in Figures 10 and 11. The superheated steam case was as expected. Depletion occurred when the production rate was greater than the influx rate. In general, a large mass influx rate into the field will have a positive effect on geothermal reservoir performance, if hot fluid only leaves the system from production.

Sensitivity Analysis

The parameters examined in the sensitivity analysis are the reservoir properties of the saturated liquid-steam case and the mass influx rate for all the reservoirs. The upper and lower constraints for each initial parameter of BOX were also checked. As mentioned before, the chances of finding the optimum initial conditions are highly dependent on the constraints chosen for each parameter. For example, this difficulty can be illustrated for compressed liquid reservoirs by Figure 12. The contour plot of the least squares equation as a function of initial pressure and initial mass reveals a narrow ridge which no doubt presented problems for the optimization technique in finding local minimums, but not global minimums. The other two cases also show similar contour patterns, which explain the high sensitivity of certain parameters.

Conclusions

The HGP model results for the optimum initial parameters for the compressed liquid case verified the results produced by the Whiting-Ramey model. The superheated steam use was compared with Ramey's plots. The optimum initial parameters determined by the HGP model confirmed Ramey's estimated values. The HGP model successfully projected the performance of the geothermal reservoirs at different production rates.

The optimum mass influx rates tended to have better curve fits in performance matching and greater life expectancies for the geothermal reservoir in performance projections than with negligible mass influx. A comparison of the optimum initial parameters for each case revealed that the differences are relatively insignificant, although the differences are evident in the prediction plots.

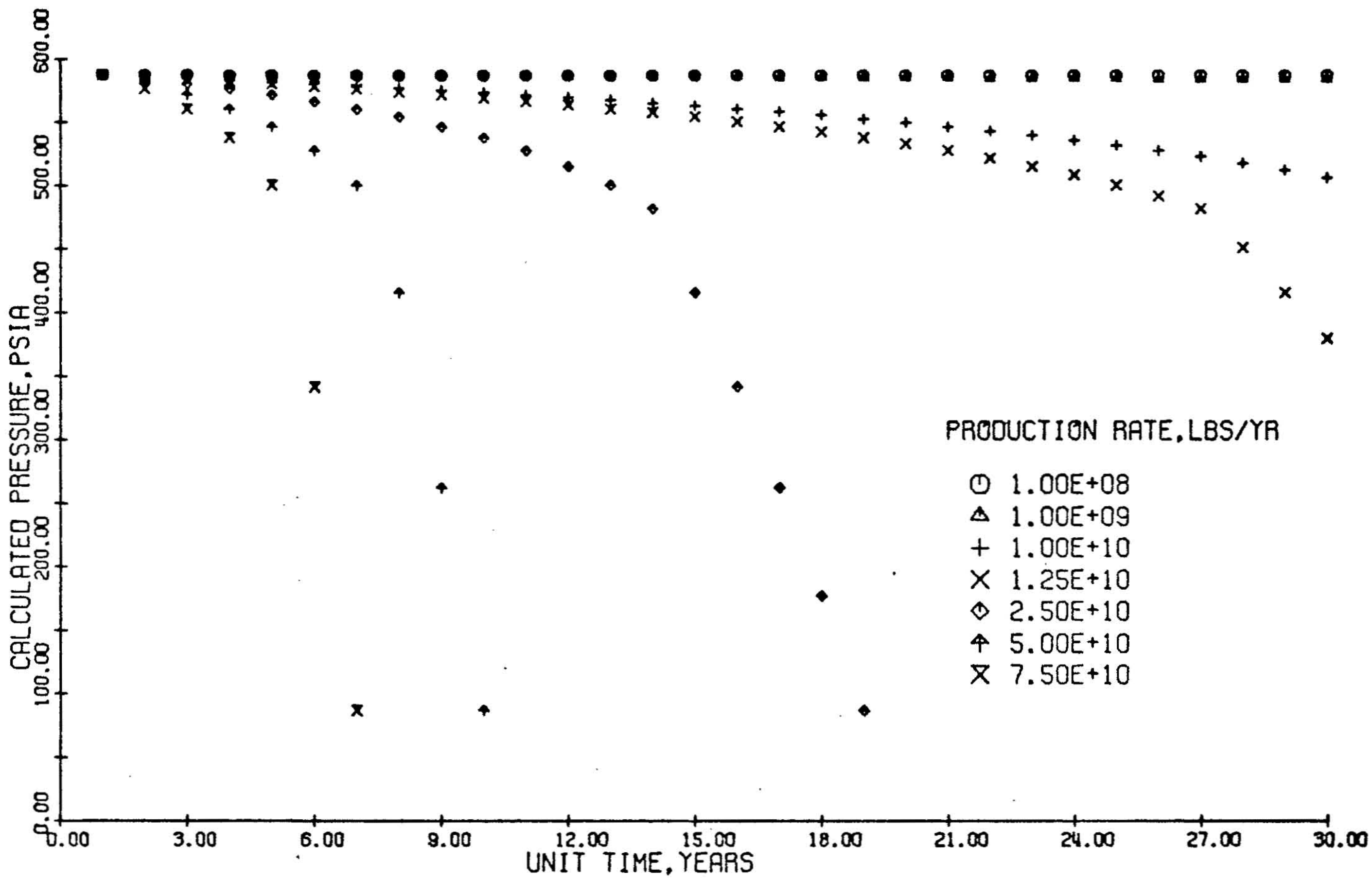

Figure 10. Performance Prediction of a Saturated Liquid-Steam Reservoir With the Mass Influx Rate = 1.0 lb/yr

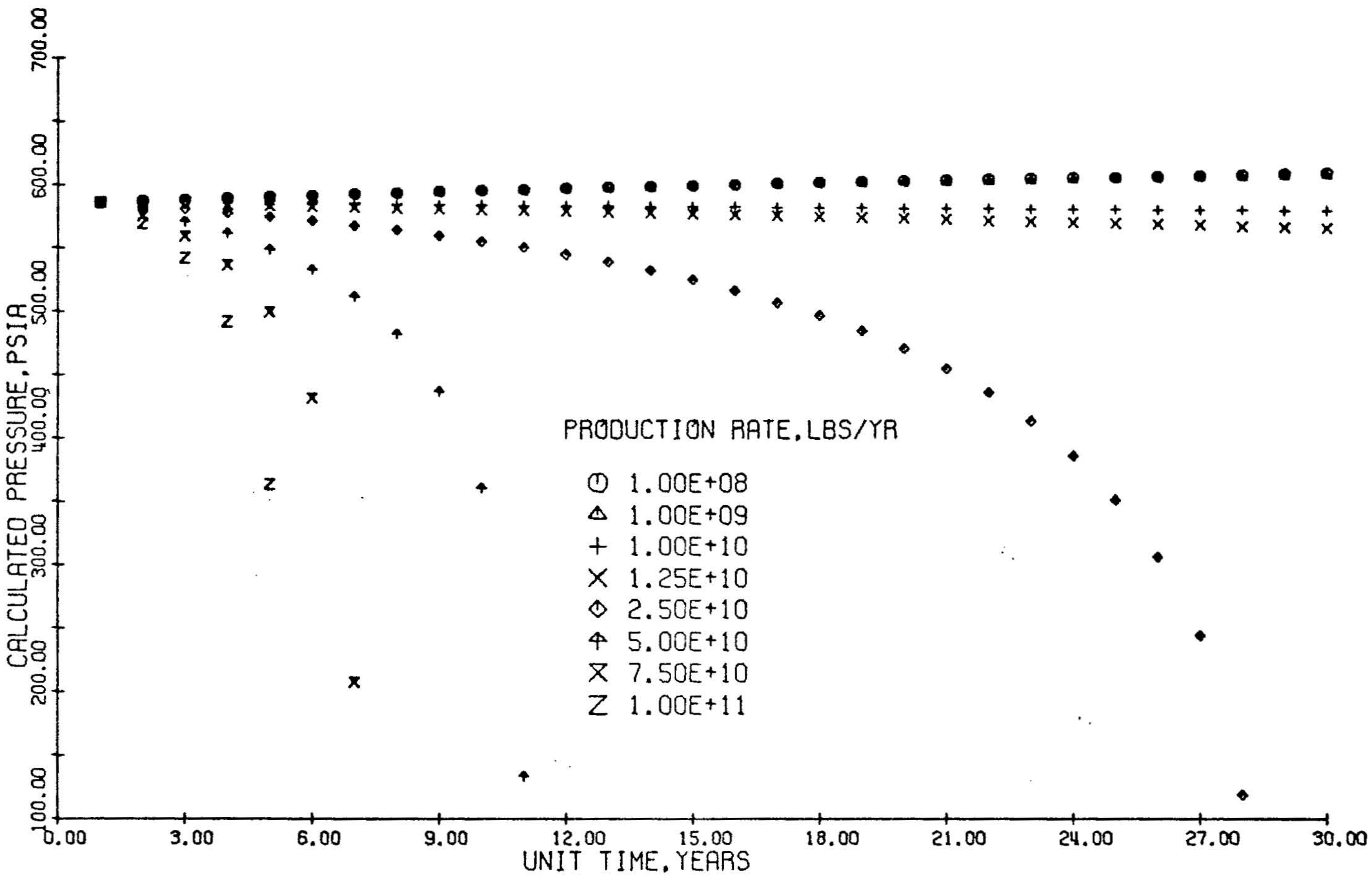

Figure 11. Performance Prediction of a Saturated Liquid-Steam Reservoir With the Mass Influx Rate = 1.0×10^{10} lb/yr (Starting at 2.0×10^{10} lb)

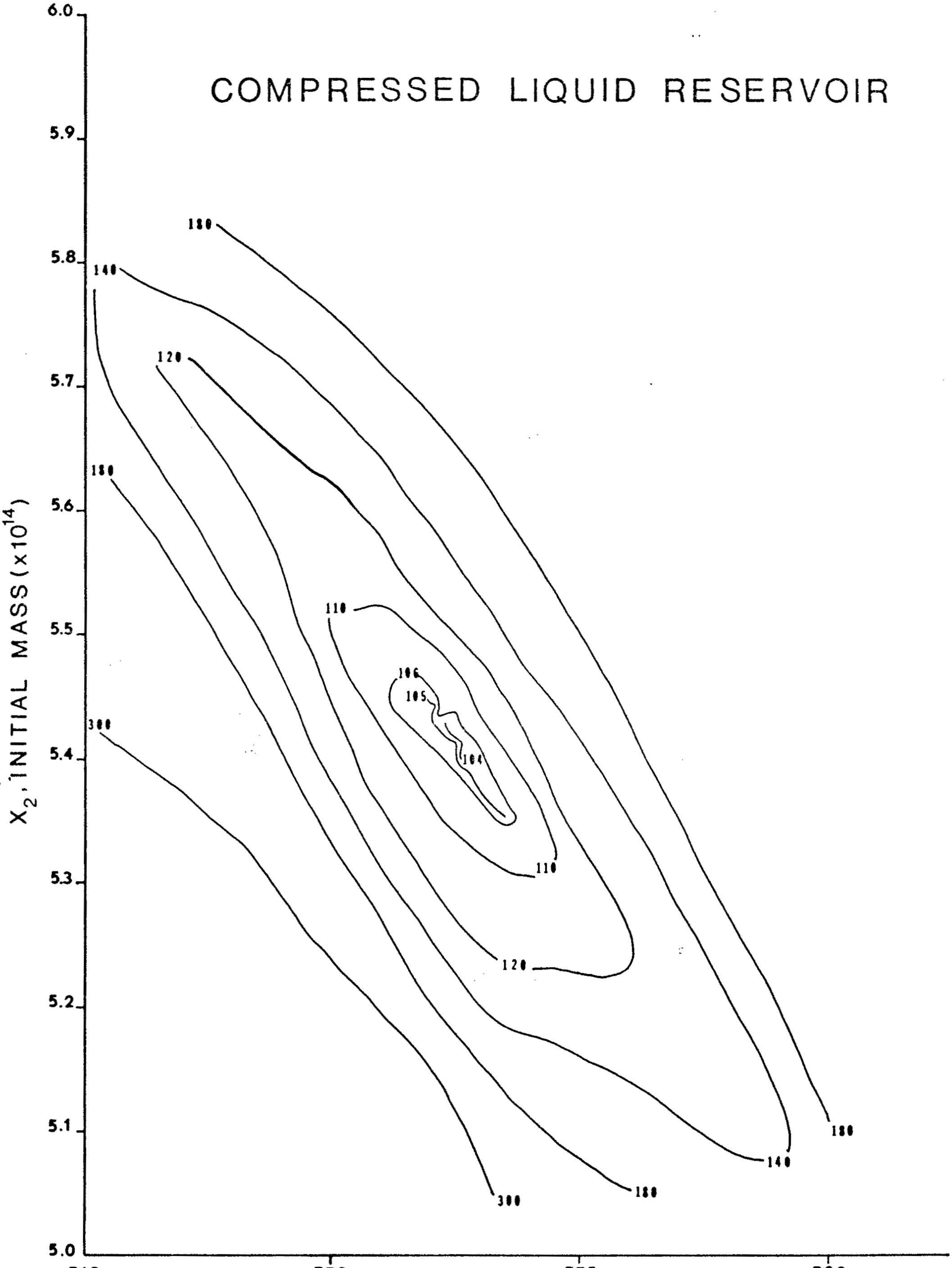

Figure 12. Contour Plot of Least Squares Function

It was found that the upper constraint of the initial mass parameter for each geothermal reservoir examined was the most sensitive parameter in the performance matching with BOX. The magnitude of the initial mass value (10^9 - 10^{11}) in comparison with values of the other initial parameters (1 - 10^2) may be the contributing factor to its relative sensitivity in the optimization scheme.

The developed computer model has the flexibility of predicting the performance of any geothermal reservoir, given the appropriate parametric conditions versus time. The next phase of this study will be the analysis of data obtained from Hawaii Geothermal Well A, said to be the hottest (358°C) geothermal well in the world, where recent studies indicated that 75,000 pounds per hour of fluid at 65% steam quality could be produced at a wellhead pressure of 375 psi. However, the results of this study will probably not be available until the middle of 1978.

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