PROCEEDINGS, Fourteenth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 24-26, 1989
SGP-TR-122

STABILITY OF TWO PHASE ZONES BELOW FISSURED CAPROCK

Y. Yano and T. Ishido

Geological Survey of Japan
Higashi 1-1-3
Tsukuba 305, Japan

INTRODUCTION

Many geothermal reservoirs contain two-phase (water/steam) flow regions under natural-state conditions. Vapor-dominated reservoirs are characterized by the predominance of such regions (and occasionally dry steam zones), but even liquid-dominated reservoirs frequently contain two-phase regions which overlie part or all of the liquid filled volume below. Production-induced reservoir pressure decline will cause the two-phase flow region to grow. Owing to compressibility effects, the response characteristics of two-phase regions and of liquid zones are very different. Consequently, it is important to properly understand the development and flow characteristics of reservoirs containing two-phase zones.

The purpose of this paper is to study the conditions required for the development of a two-phase zone in a particular Japanese geothermal reservoir. The complicated behavior of two-phase systems may now be treated using numerical simulation techniques. Ingebritsen (1987) examined three different kinds of vapor dominated reservoirs which can evolve in the natural state. He suggested that there are several basic types of two-phase zones which have different sizes and characteristic pressure profiles. The differences arise from differences in formation properties.

EVOLUTION OF A TWO-PHASE ZONE

As Ingebritsen (1987) demonstrated, even though small-scale two-phase regions may develop naturally in the absence of overlying confining beds, a caprock layer to prevent cold-water downflow is an essential prerequisite for the formation of large-scale two-phase regions. Hence, it is important to incorporate confining caprock layers in theoretical studies of the development of two-phase geothermal reservoirs.

In Japan, crustal motions and volcanic activity have created numerous faults and fracture zones in geothermal areas. If a vertical fracture penetrates the caprock overlying a two-phase region, steam may flow upward through the crack and create a fumarole at the surface. The liquid water within the two-phase region may flow either upward or downward, depending on the natural deep recharge rate which supplies the reservoir.

The Ginyu reservoir, located within the Kirishima thermal area in southern Japan, is characterized by a natural two-phase region below a caprock layer which is locally penetrated by a fractured zone through which steam flows upward to supply surface fumaroles (Kodama and Nakajima, 1988). The effective vertical permeability of the fractured area which penetrates the caprock must be at least ten millidarcies based upon measured fumarole heat output and observed underground pressures. Despite the relatively small volume of the two-phase region, its presence has a profound influence upon the response of the reservoir to a four-year history of well discharge (Kitamura, *et al.*, 1988). The role of the fissured zone as it influences the two-phase region and the underground pressure distribution proved to a critical issue in a recent numerical modeling study of the natural state of the Ginyu reservoir (Maki, *et al.*, 1988).

MODEL DESCRIPTION

In the interests of simplicity, for the present study we chose to represent the Ginyu reservoir as a two-dimensional vertical section as indicated in Figure 1; this rather simplified model incorporates many of the major structural features of the reservoir. Quantitative details concerning this representation are summarized in Table 1. The so-called "convective-radiative" boundary condition was imposed upon heat flow along the upper surface; a volumetric energy sink was imposed in each uppermost grid block of strength:

$$e(\text{watts/m}^3) = 1 - T_b/10 \qquad (1),$$

where T_b is the instantaneous block temperature in degrees Celsius. This is intended to represent an upward heat flux of:

$$H(\text{watts/m}^2) = K_{bl}(T_b - T_{air}) / L \qquad (2),$$

where L is the thermal boundary layer thickness, K_{bl} is the boundary layer thermal conductivity (taken as 5 watts/m°C), and T_{air} is air temperature. For most of the upper blocks, we adopted the particular values L = 1 meter,

T_{air} = 10°C. In the uppermost block containing the fissure itself, we used L = 10 m and T_{air} = 100°C to maintain two-phase conditions.

Numerical calculations were all performed using the THOR reservoir simulator (Pritchett, 1988), which is designed to solve multidimensional unsteady multi-phase problems in geothermal reservoir flow. Calculations were carried out using the CRAY computer system located at the RIPS computer center at Tsukuba.

NUMERICAL RESULTS

Figures 2 and 3 illustrate the computed results for a case in which the deep inflow rate was prescribed as 100 kg/s. The internal energy of the inflowing fluid is 1130 kJ/kg, corresponding to liquid water at 260°C. These illustrations show the situation at t = 4986 years, by which time a nearly steady state is reached. A small two-phase zone with high steam saturations has formed within the fissure and extends into the upper part of the reservoir. A less pronounced two-phase zone is also present near the surface below the lower-topography area to the left.

Presumably, if the deep inflow is insufficient, surface waters will flow downward through the fissure and escape from the system through the horizontal conduit. This critical flow rate may be estimated as:

$$M_{esc} \approx k_{horiz} A_{horiz} (P_a - P_b) \;/\; (\nu L_{horiz}) \quad (3),$$

where k_{horiz}, A_{horiz} and L_{horiz} are the permeability, cross-section area and length of the horizontal conduit. The kinematic viscosity of water is represented by ν. P_b is the boundary pressure (P_1) applied at the conduit outlet (see Figure 1) and P_a is the initial hydrostatic pressure below the fissure at the elevation of the conduit (8.5 MPa). For kinematic viscosity, a value appropriate for water at 200°C (1.5×10^{-7} m^2/s) was assumed. It may reasonably be assumed that, if the deep inflow rate (M_o) exceeds the above "escape" rate (M_{esc}), then fluid will flow upwards into the fissure; otherwise, downflow will occur. Using the above numerical values, a critical flow rate of 47 kg/s may be obtained; in the present calculation, M_o = 100 kg/s, resulting in upflow in the fissure.

The stable steam zone should increase in size if the inlet flow (M_o) is reduced. To investigate this possibility, we carried the above numerical calculation further in time, but reduced this parameter to 80 kg/s for the interval 5000 - 10,000 years and then imposed an additional reduction (to 60 kg/s) for the interval 10,000 - 15,000 years. The distribution of the two-phase region at about this point (14,960 years) is shown in Figure 4. As expected, two-phase flow has become more extensive. Further reductions in flow rate were imposed thereafter; M_o was reduced by 6 kg/s every 1000 years, reaching a final value of 30 kg/s at 19,000 years. Prior to 17,000 years, the input rate exceeds the above critical rate (47 kg/s) required to maintain upflow, and the two-phase region continues to grow. After this time, however, cold water begins to flow downward through the fissure collapsing most of the two-phase zone. Figure 5 shows the shrunken two-phase zone at 17,590 years (at which time M_o = 42 kg/s).

In the preceding calculations, the internal energy of the fluid entering the system at depth (1130 kJ/kg) was relatively low, corresponding to liquid conditions at about 260°C. Under these circumstances, as discussed above, the inflow rate must exceed a critical value (47 kg/s) to avoid downflow of cold groundwater into the reservoir through the vertical fissure. If, however, the deep recharge fluid is sufficiently energetic, it may be possible to sustain a stable two-phase region even at lower recharge rates.

To investigate this possibility, a calculation was performed with relatively low inflow rate (30 kg/s) but with a much higher inflow fluid internal energy (1810 kJ/kg). This value corresponds to saturated liquid water at near-critical conditions (20.3 MPa, 367°C). Since the pressure at the bottom of the computing volume is substantially lower, this condition amounts to the introduction of a two-phase mixture directly into the bottom surface of the computational volume. As Figure 6 shows, by 4954 years a stable situation was reached with a huge two-phase region filling much of the upper portion of the volume and extending downward to the hot fluid source.

Thus, if the input power is sufficient, a stable two-phase zone can occur even if the inflow rate is less than the critical value given by Equation (3). The reason is simply that, in the high-energy case, steam saturations become so high in the upper part of the two-phase region that the liquid phase becomes nearly immobile and the pressure distribution approaches vapor-static (instead of hydrostatic, as in the low-energy case). The effect is to reduce P_a in Equation (3) substantially, reducing the minimum flow rate required to sustain fissure discharge.

CONCLUSIONS

A two-phase zone may form in the upper part of a geothermal reservoir even if the caprock is penetrated by a vertical fissure, so long as either (1) sufficient deep fluid mass recharge is present, or (2) the deep input power is great enough. Two-phase zones sustained by high mass flow rates are qualitatively different from those created by high heat flow. In the high-mass-flow case, the two-phase zone is relatively small in size, and decreases in size as recharge rate increases above a certain critical value. So long as the inflowing fluid enthalpy is relatively modest (consistent with single-phase flow at depth), flow rates below the critical value will fail to create a two-phase region and cold water will flow downward through the fissure into the reservoir. The critical mass flow rate may be estimated using a simple algebraic model. On the other hand, if the inflowing fluid is sufficiently energetic (such that steam is injected directly into the reservoir from below), an extensive two-phase region may result even if the inflow rate is significantly less than the critical value; in this case, the two-phase region will be characterized by relatively low pressures, approaching vapor-static conditions.

REFERENCES

Ingebritsen, S. E. (1987), "Vapor-Dominated Zones within Hydrothermal Convection Systems," *Twelfth Workshop on Geothermal reservoir Engineering*, Stanford University, Stanford, California, SGP-TR-109, pp. 291-296.

Kitamura, H., T. Ishido, S. Miyazuki, I. Abe and R. Nobumoto (1988), "NEDO's Project on Geothermal Reservoir Engineering - A Reservoir Engineering Study of the Kirishima Field, Japan," *Proc. 13th workshop on Geothermal Reservoir Engineering*, Stanford University.

Kodama, M. and T. Nakajima (1988), "Exploration and Exploitation of the Kirishima Geothermal Field," *Jour. of Japan Geothermal Energy Assoc., Vol. 25, No. 3*, pp. 201 - 230 (in Japanese with English abstract).

Maki, H., T. Ishido, I. Abe, R. Nobumoto and Y. Oikawa (1988), "A Modeling Study of the Natural State of the Kirishima Field," *Proc. International Symposium on Geothermal Energy, 1988, Exploration and Development of Geothermal Resources,"* Kumamoto and Beppu, Japan, pp. 144-147.

Pritchett, J. W. (1988), "THOR User's Manual," SSS-IR-88-9408, S-CUBED, La Jolla, California, 109 p.

GEOMETRY

entire system:	width=2850m, height=1900m(right edge), thickness=500m
reservoir(A):	width=1050m, height=800m (along edge)
vertical conduit:	width=100m, center location=950m from right end
horizontal conduit:	height=100m, center depth=450m from surface
fissure:	width=50m

ROCK PROPERTIES (Symbols A-D are shown in Figure 1.)

Absolute permeability(m^2)(A:10^{-13}, B:4.0×10^{-14}, C:10^{-15}, D:2.0×10^{-17}).
Relative permeability: linear functions with residual liquid saturation=0.3, residual steam saturation=0.05.
Rock grain heat capacity(Joules/kg°C) = 1000(all).
Rock grain thermal conductivity(watts/m°C) = 2.5(all).
Rock grain density(kg/m^3) = 2700(all).
Porosity A=B:0.1, C=D:0.01

BOUNDARY CONDITIONS AND SOURCE/SINK

Sides:	insulated for both heat and mass except for horizontal conduit. P_1 in Figure 1 is 4.6×10^6 pascals.
Surface:	convective-radiative condition (see text). pressure = 1.013×10^5 pascals.
Bottom:	heat flux (2HFU for left 1100m, 5HFU for right 1750m except for vertical conduit). Hot water supply into vertical conduit: fluid internal energy=1.13×10^6 (Joules/kg) for models in Figures 2-5, see text for mass (M_o).

INITIAL CONDITIONS

Pressure:	hydrostatic pressure.
Temperature:	conductive profile according to heat flux from bottom.

Table 1: Parameters used for the numerical simulation.

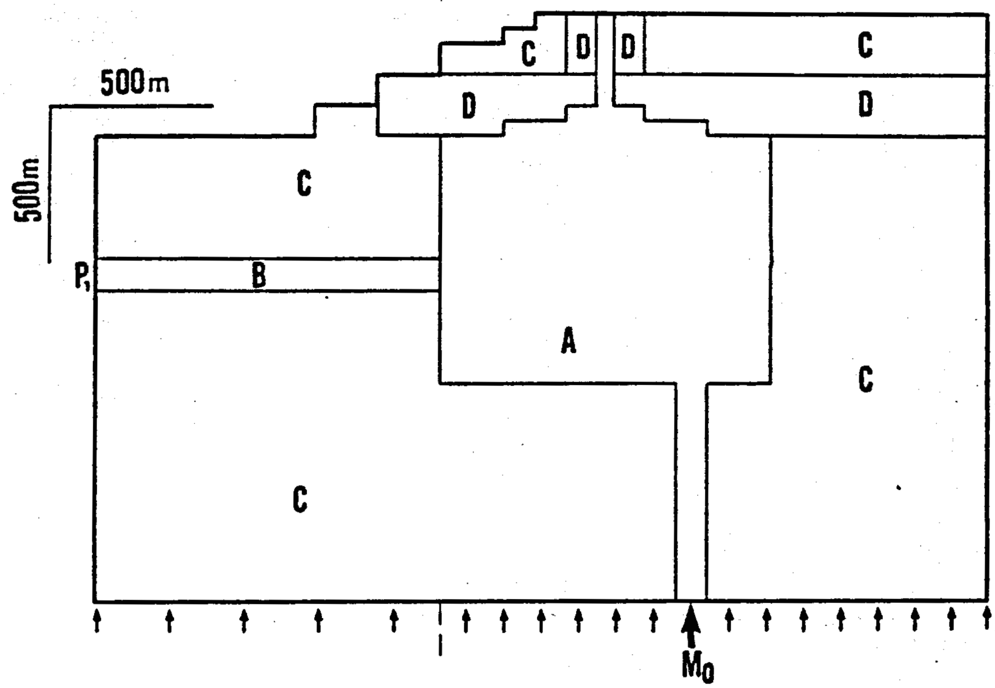

Figure 1. Two-dimensional model used for numerical simulation. Letters A,B,C and D indicate the rock type. See Table 1 for formation parameters.

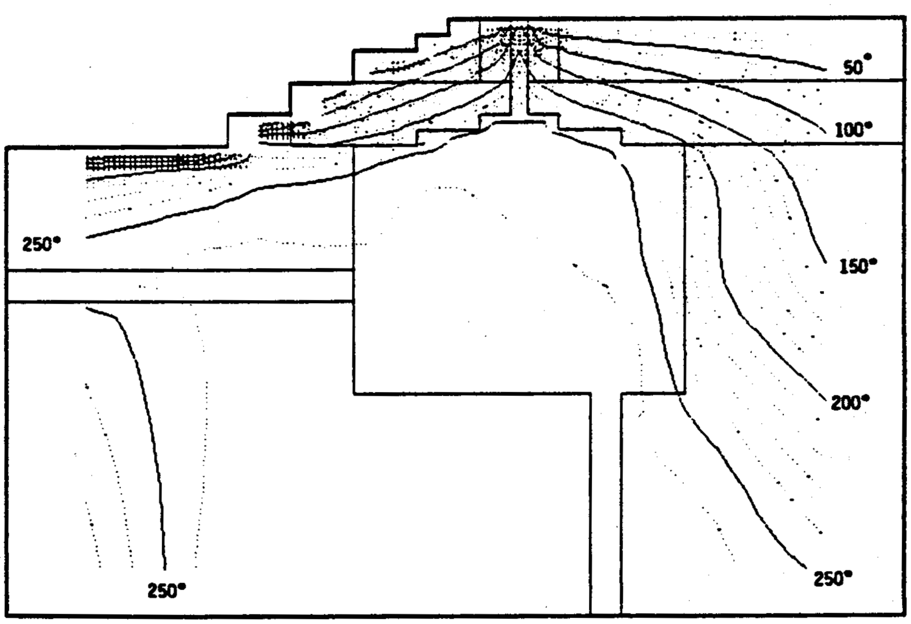

Figure 2. Computed temperatures at 4986 years for M_o = 100 kg/sec.

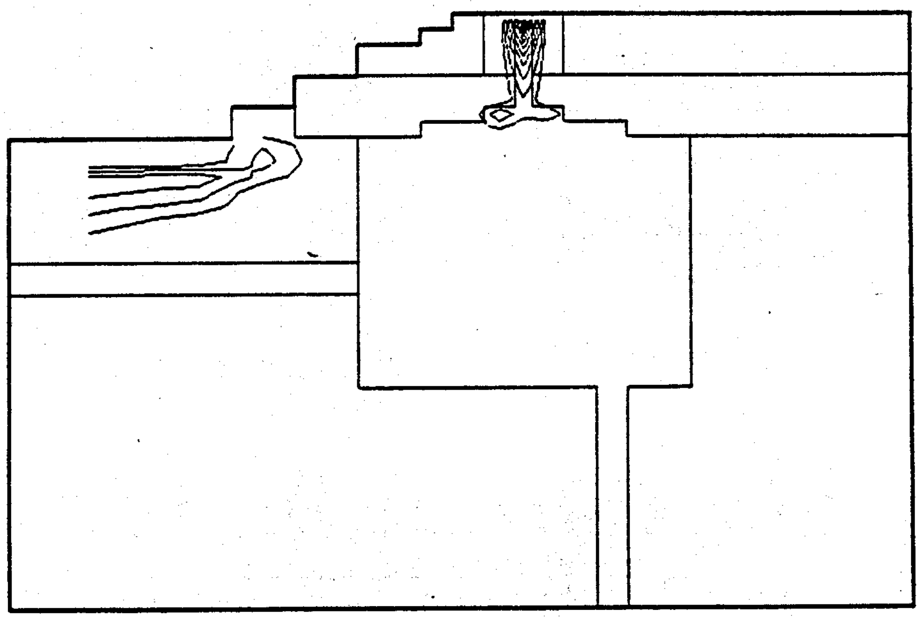

Figure 3. Computed steam saturation at 4986 years for M_o = 100 kg/sec. Contour interval is 0.05.

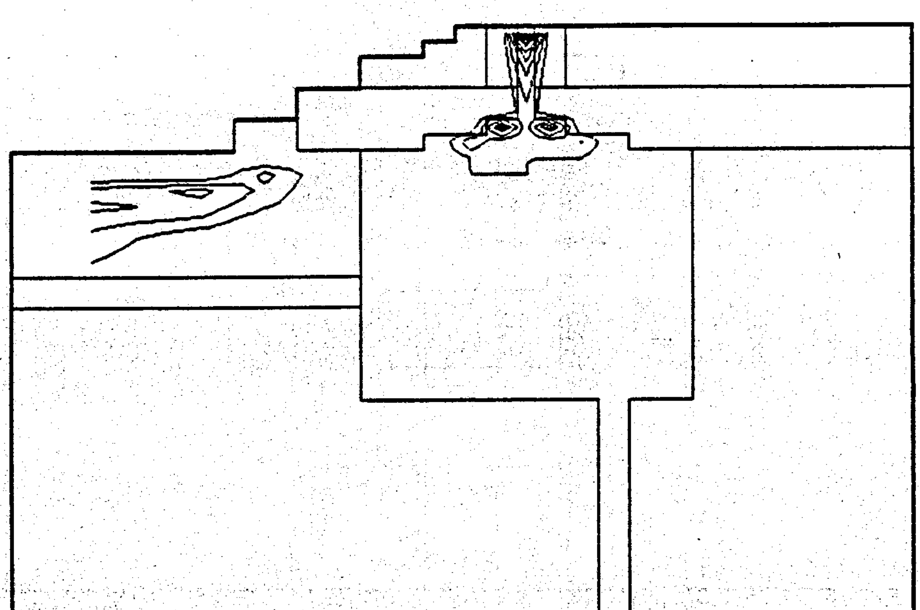

Figure 4. Computed steam saturation at 14,960 years with reduced mass input (M_o = 60 kg/sec).

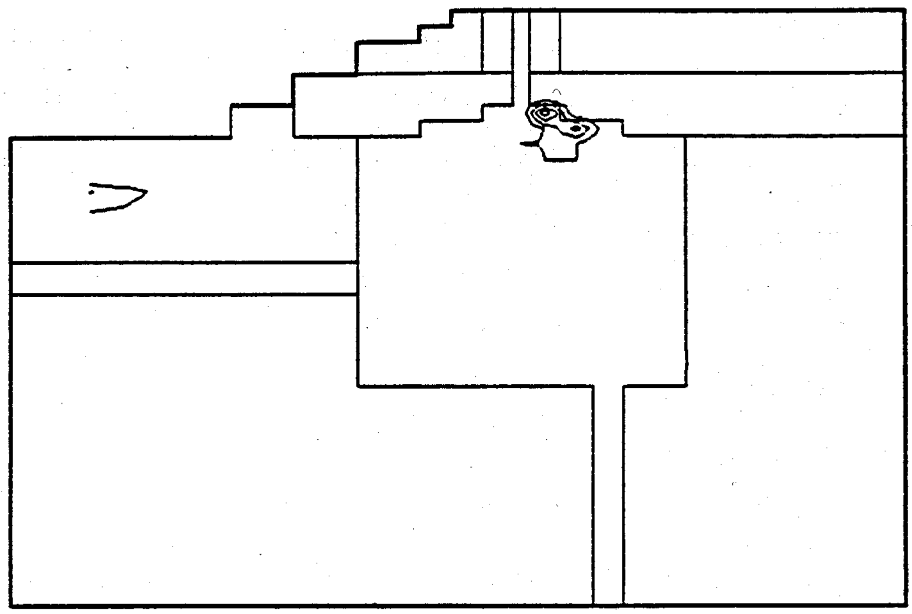

Figure 5. Steam saturation at 17,590 years.

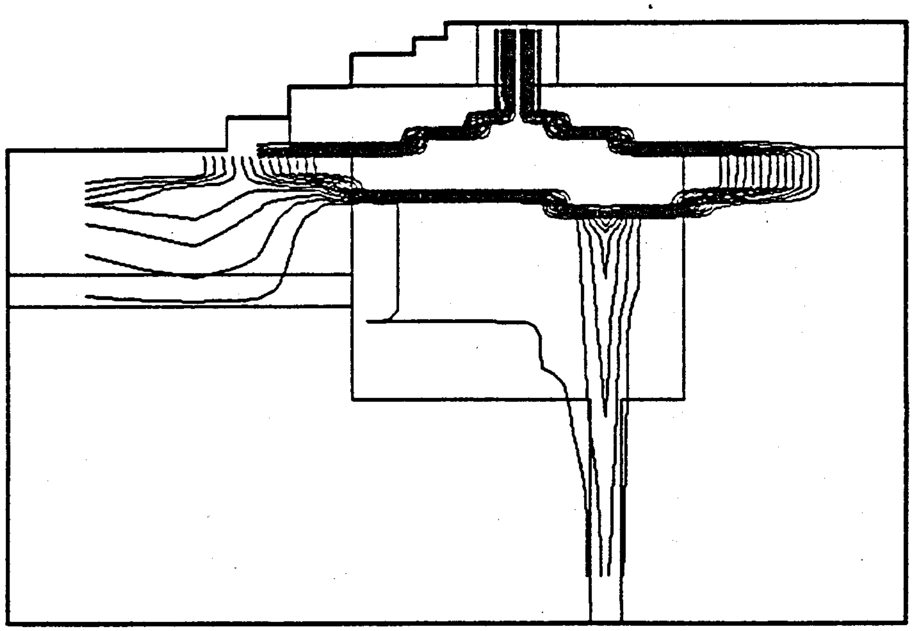

Figure 6. Computed steam saturation at 4954 years with small mass input (M_o = 30 kg/sec) of high internal energy (1810 kJ/kg) fluid.