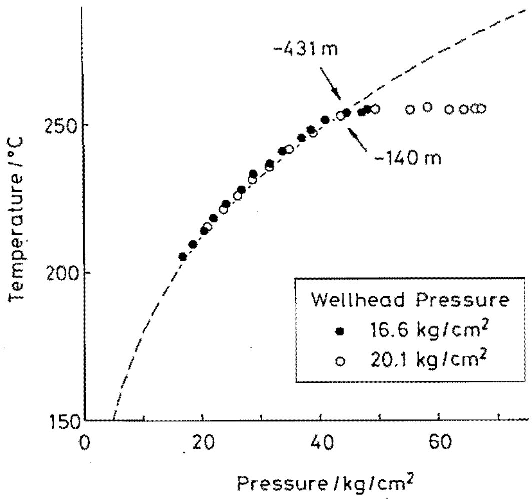

Fig. 7. Temperature-pressure relation of the fluid of Well 128 as a function of wellhead pressure.

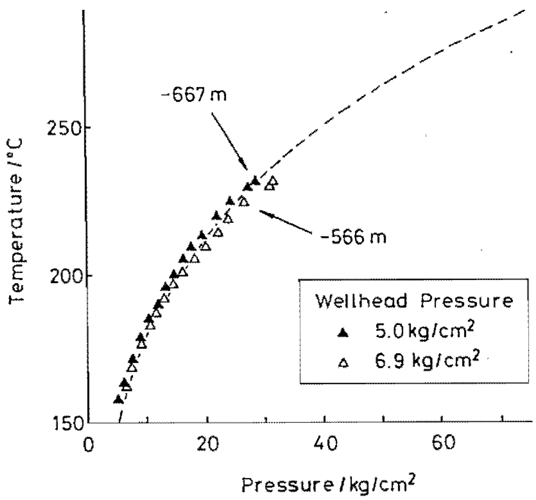

Fig. 8. Temperature-pressure relation of the fluid of Well 129 as a function of wellhead pressure.

The pressure and temperature were measured as functions of depth and wellhead pressure in Wells 128 and 129. The results are shown in Figs. 5 and 6 as well as the data under the static condition, respectively. Under the static condition, the temperature of Well 128 gradually increases with the depth. The lost circulation was observed only at the depth of 1141 m (-442 m above the sea level). These facts indicate that the fluid is supplied from the point. On the contrary, the mud water lost at many points during the drilling of Well 129. The static temperature of this well is oscillated. These imply that the hot fluid flows in the well from the deepest lost circulation point (1451 m; -639 m above the sea level), and that the cold fluid flows in the well from fractures occurring near the middle point of this well.

The temperature-pressure relation of Well 128 fluid (Fig. 7) is reduced from the data shown in Fig. 5. The temperature-pressure curve almost coincides with the vapor-pressure curve of pure water. When the wellhead pressure is 20.1 kg/cm^2, the fluid boils at -140 m. On the other hand, the boiling level is -431 m, when the pressure is 16.6 kg/cm^2. The feed point and the operating wellhead pressure of this well are -442 m (Fig. 3) and 11.5 kg/cm^2, respectively. These data imply that the two-phase fluid is supplied from the reservoir to the well. The temperature-pressure relation of Well 129 is shown in Fig. 8. The fluid boils at -566 m under the wellhead pressure of 6.9 kg/cm^2. On the contrary, the fluid consists of two phases through the whole well, when the pressure is 5.0 kg/cm^2. The feed point of this well is -693 m (Fig. 3). Accordingly, the two-phase fluid is also supplied in this well, because the operating wellhead pressure is 4.5 kg/cm^2 (Fig. 4).

The above stated facts suggest that the fluid of the Onikobe geothermal field boils in the reservoir, and that it flows into the production well as two-phase fluid.

Acknowledgments:This work is one of the national projects organized by NEDO (NEW ENERGY DEVELOPMENT ORGANIZATION). The measurement and the analysis were carried out with the assistance of many staffs of JMC (Japan Metals & Chemicals Co., Ltd) and EPDC (Electric Power Development Co., Ltd.). We greatly thank NEDO, JMC and EPDC.

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ON THE BEHAVIOR OF TWO PHASE GEOTHERMAL RESERVOIRS

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1. INTRODUCTION

Many geothermal reservoirs contain two-phase flow region under natural-state conditions. Vapor-dominated reservoirs are characterized by 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 result in the growth of the two-phase flow region. 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 typical Japanese geothermal reservoir. The complicated behavior of two-phase systems may now be treated using numerical simulation technique. 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 difference arise from differences in the formation properties.

2. 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.

3. MODEL DESCRIPTION

Figure 1 shows the particular geological setting selected for our numerical simulation study. The overall reservoir geometry, rock properties, boundary conditions, sink/source distributions and initial conditions used are summerized in Table 1.

The so-called "convective-radiative" boundary condition was imposed on heat flow along the upper surface. This was accomplished by imposing a volumetric energy sink 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 ℃), and T_{air} is air temperature. For most of the upper blocks, we adopted the particular values L = 1 meter, T_{air} = 10 ℃. In the uppermost block containing the fissure itself, we used L = 10 m and T_{air} = 100 ℃ 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.

4.NUMERICAL RESULTS

Figure 2 illustrates the computed results for a case in which the deep inflow rate (M_0) was prescribed as 100 kg/s. Initially, no steam is present; as Figure 2 shows, the inflowing fluid flows upward into both the horizontal conduit and into the upper vertical conduit which represents the fissure through the caprock. This situation represents the

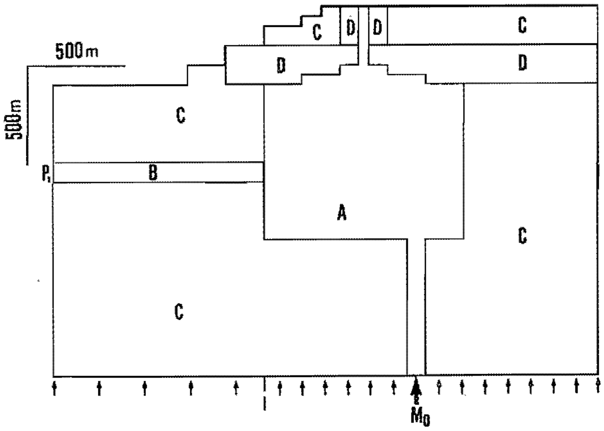

Fig.1 Two dimensional model used for numerical simulation. Letters A,B,C and D indicate the rock type. See table 1 for formation parameters.

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 Fig.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 saturation=0.3, residual steam saturation=0.05.
rock grain heat capacity(joules/kg C) = 1000(all).
rock grain thermal conductivity(watts/m ℃)= 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 Fig.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 enthalpy=1.13×10^6 (kJ/kg), see text for mass(M_0)

INITIAL CONDITIONS
pressure : hydrostatic pressure
temperature : conductive profile according to heat flux from bottom

Table 1 Parameters used for the numerical simulation.

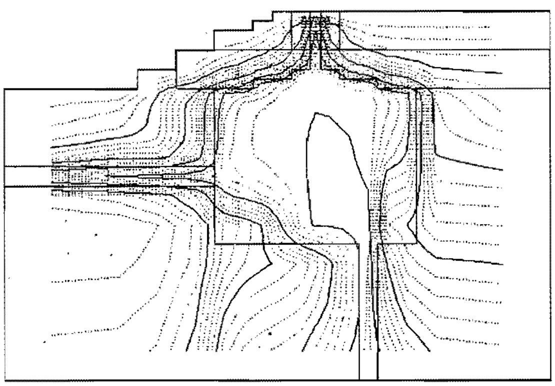

Fig.2 Computed temperatures at 186 years for M_0 = 100 kg/sec. The contour interval(bold lines) is 50 ℃.

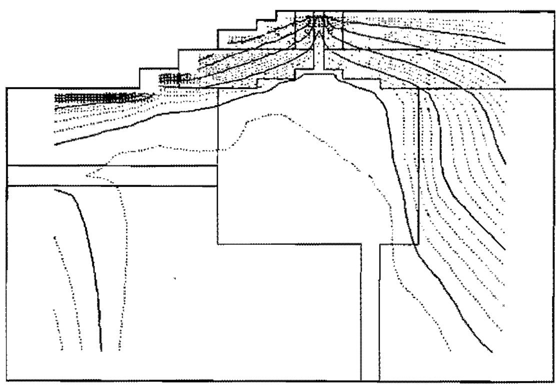

Fig.3.1 Computed temperatures at 4986 years for M_0 = 100 kg/sec.

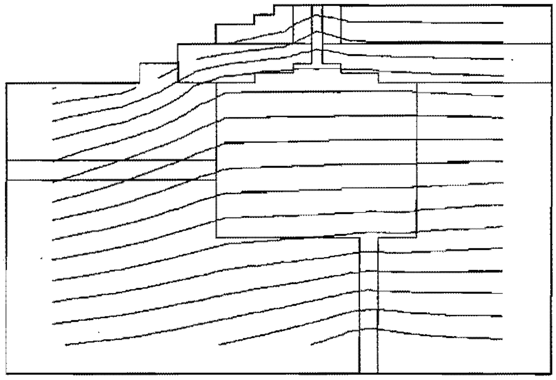

Fig.3.2 Computed pressure distribution at 4,986 years for M_0 = 100kg/sec. Contour interval is 1 MPa.

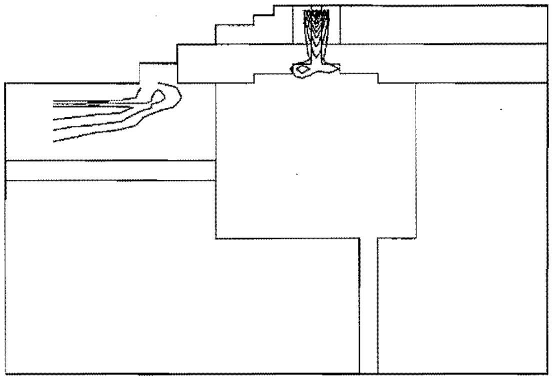

Fig.3.3 Computed steam saturation at 4,986 years for M_0 = 100 kg/sec. Contour interval is 0.05.

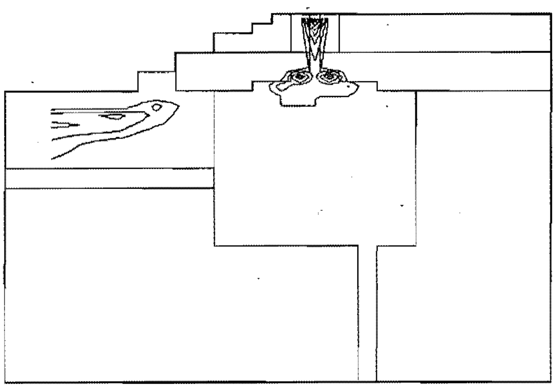

Fig.4 Computed steam .saturation at 14,960 years with reduced mass input(M_0 = 60 kg/sec).

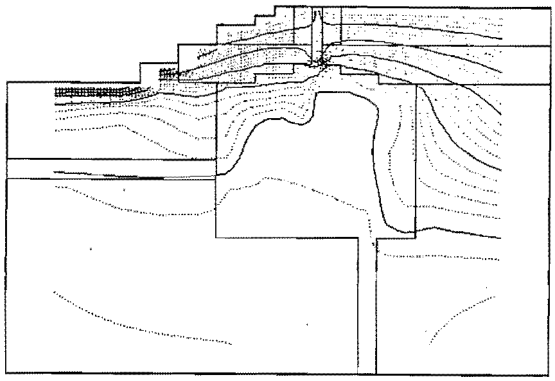

Fig.5.1 Computed temperatures at 17,590 years with mass input M_0 = 42 kg/sec.

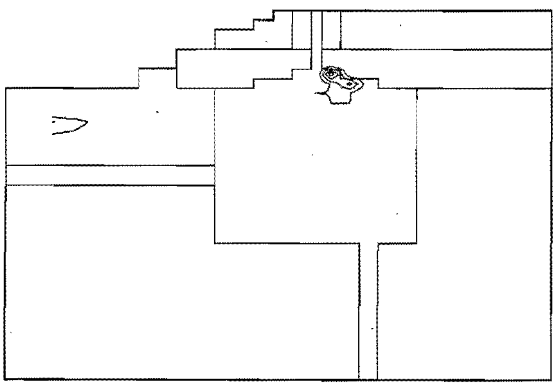

Fig.5.2 Steam saturation at 17,590 years.

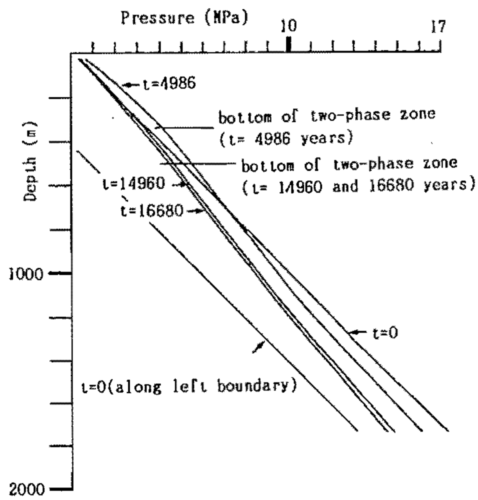

Fig.6 Vertical pressure profiles at the location of the fissure for t = 0, 4,986, 14,960 and 16,680 years. Hydrostatic pressure along left boundary of the model also illustrated.

state after 186 years; by this time, a small two-phase region has already formed within the fissure.

If there is no deep inflow(i.e. $M_0 = 0$), then surface waters will flow downward through the fissure and escape from the system through the horizontal conduit. This flow rate may be estimated as:

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

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 ℃ (1.5×10^{-7} m^2/s) was assumed. Now, it may reasonably be assumed that, if the deep inflow rate (M_0) 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_0 = 100 kg/s, resulting in upflow in the fissure.

After about 5000 years, a nearly steady state is reached (Figures 3.1-3.3). A small two-phase zone with high steam saturations has been 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. At this point, 20.7 kg/s of water and 5.6 kg/s of steam are flowing out the top of the fissure; 47.2 kg/s of water is also exiting through the horizontal conduit. These outflows represent 74 percent of the deep inflow(100 kg/s).

We expected that the steam zone created by 5000 years would increase in size if the inlet flow (M_0) were reduced. Hence, we changed this parameter to 80 kg/s for the interval 5,000 - 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_0 was reduced by 6 kg/s every 1000 years, reaching a final volume of 30 kg/s at 19,000 years. Prior to 17,000 years, the input rate exceeds the critical rate estimated above(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_0 = 42 kg/s).

Pressure-depth profiles below the fissure are shown in Figure 6. At 5,000 years, pressures within the two-phase region exceed initial pressures. At 14,960 and 16,680 years, however, the pressure has decreased relative to initial pressure even within the two-phase regions, owing to reduced inflow.

5. CONCLUSIONS

It has been shown that an extensive two-phase region may form at the top of a geothermal reservoir even if the caprock is penetrated by a permeable fissure, so long as sufficient upflow of hot water from below is present. At exceedingly high upflow rates, the two-phase region will be relatively small in size; if the upflow rate is less, the two-phase zone will be more extensive. If, however, the upflow rate is less than a certain critical value, the two-phase region vanishes and cold-water downflow will occur through the fissure. Simple algebraic models may be used to estimate this critical upflow rate.

Acknowledgments.
The authors would like to thank helpful review by J.W. Pritchett and S.K. Garg.

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