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A SUMMARY OF RECENT STUDY ON THE INITIAL STATE OF THE MATSUKAWA GEOTHERMAL RESERVOIR

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ABSTRACT

Feed point pressures of some of the earliest production wells in Matsukawa were reconstructed from water levels and temperature profiles measured during warm up of the wells immediately after drilling. Although most of the wells currently produce dry superheated steam, the reconstructed pressures indicate that the pressure gradient of the production zone was super-hydrostatic and was similar to that of Kakkonda, which is a liquid-dominated system. It implies that the current production zone of the Matsukawa reservoir was induced to produce dry superheated steam mainly by little water recharge and high heat flow.

INTRODUCTION

Geothermal development at Matsukawa was initiated by drilling of shallow exploration wells for the hot bath by the local administration in 1952. Most of the wells encountered the steam zone at around 300m deep, instead of the hot water. Electric power generation at Matsukawa was started in October 1966 by Japan Metals and Chemicals Co., Ltd. and has been continued successfully for more than twenty-three years.

According to Akazawa and Muramatsu (1988), steam is mainly produced from faults and marginal fractures of the intrusive rock, ranging from 0 to -500m above sea level (800 to 1300m deep). Location of the wells and geological cross section of Matsukawa are shown in Figs. 1 and 2 respectively.

Initial state of the main production zone of the Matsukawa geothermal reservoir was thought to be saturated water at boiling point temperature for depth, before the publication of White et al. (1971) (Hayakawa, 1967). Then, two phase condition similar to White et al. (1971) was assumed (Hirako, 1982). However, it has not been very well discussed.

Initial feed point pressures of some of the earliest production wells were reconstructed from water levels to consider its initial state. Results and discussions of the pressure data are summarized in this report.

RECONSTRUCTION OF FEED POINT PRESSURES

Due to the lack of real reservoir pressure data, it is impossible to accurately estimate the initial state of Matsukawa reservoir. This is because, no pressure logging was made before June, 1966 at Matsukawa. The first one was done at well M4 with the Kuster gauge during and after the discharge test (Baba et al., 1970), but no more pressure loggings were made except only a few cases at M4.

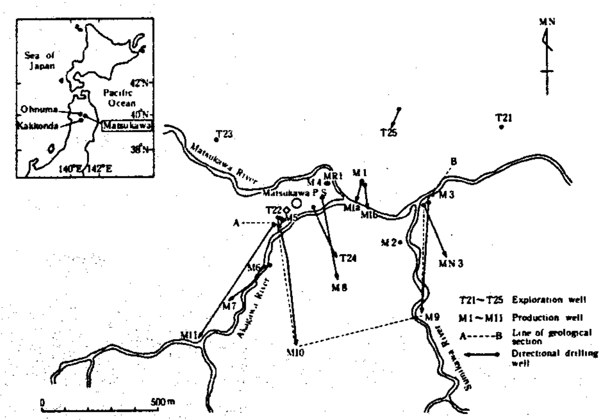


Fig. 1 Location of wells of Matsukawa (after Akazawa and Muramatsu, 1988).

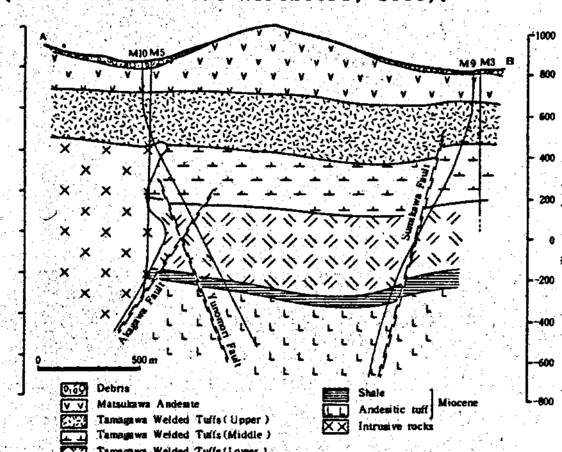
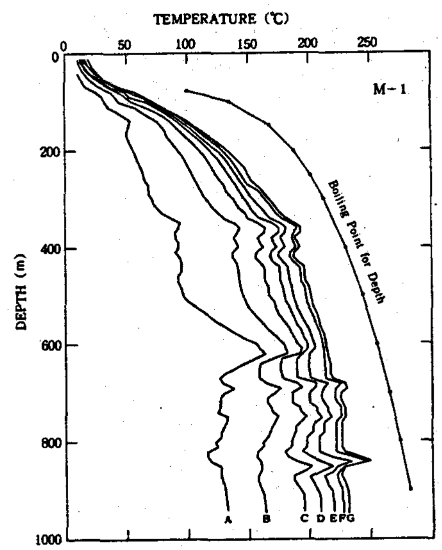


Fig. 2 Geological cross section of Matsukawa (after Akazawa and Muramatsu, 1988). Location of the cross section is shown in Fig. 1.

Reconstruction of feed point pressures from water level is commonly applied in liquid-dominated reservoirs. Celati et al. (1975) pointed out that feed point pressures reconstructed from water levels agree well with reservoir pressures even if in a vapor-dominated system.

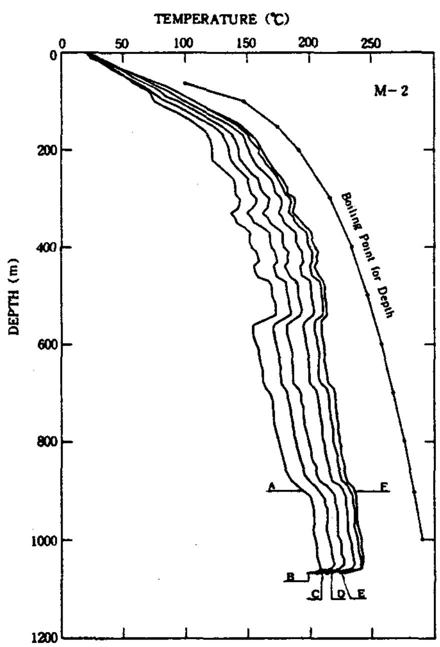
As widely applied, a pressure profile in a well can be estimated by integrating the density of the fluid over the depth, if the water level and temperature profiles are known, and if there is no internal flow in the well bore. This integration was done numerically downward from the water level to the bottom of the well. The density of the fluid was calculated at each step by the 1967 IFC Formulation for Industrial Use which appeared in 1980 SI JSME Steam Tables (Japan Society of Mechanical Engineers, 1981).

Feed point pressures reconstructed from temperature and water level data which are shown in Figs.3, 4 and 5, are shown in Table 1. Feed points shown in Table 1 are estimated mainly from lost circulation records and results of the temperature logging, but they are not confirmed by logging of flowing velocity, because the tool was not available at that time; moreover, any logging is practically impossible due to the lack of a top valve at the well head.



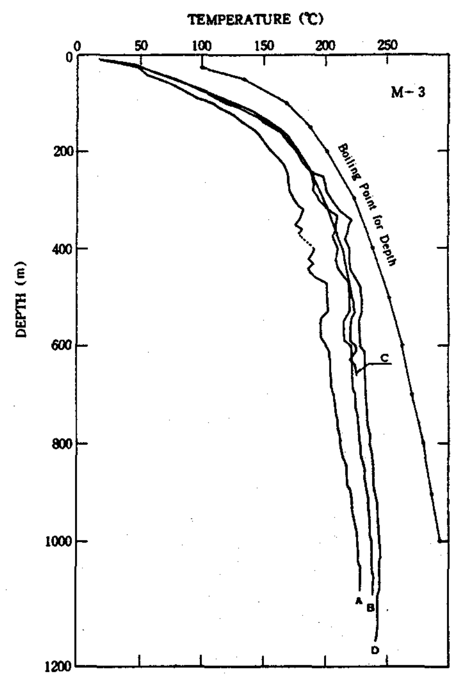
RUN	DATE	STANDING TIME(hrs)	WATER LEVEL(m)
A	Jan. 5, 1964	8	147
B	Jan. 6, 1964	26.5	110
C	Jan. 7, 1964	39.2	95
D	Jan. 8, 1964	73.2	91
E	Jan. 9, 1964	107	85
F	Jan. 11, 1964	147	77
G	Jan. 12, 1964	167	75

Fig.3 Temperature and water level build-up of M1 after the completion of drilling. The temperature data are taken from Takaki and Tanaka (1968). Boiling Point for Depth corresponds to Run G.



RUN	DATE	STANDING TIME(hrs)	WATER LEVEL(m)
A	July. 21, 1964	27.3	-
B	July. 22, 1964	46.8	-
C	July. 23, 1964	70.8	93
D	July. 25, 1964	119	-
E	July. 27, 1964	167	77
F	July. 29, 1964	214	61

Fig.4 Temperature and water level build-up of M2 after the completion of drilling. The temperature data are taken from Takaki and Tanaka (1968). Boiling Point for Depth corresponds to Run F.



RUN	DATE	STANDING TIME(hrs)	WATER LEVEL(m)
A	Dec. 30, 1964	79.2	25
B	Jan. 6, 1965	253	-
C	Jan. 10, 1965	350	-
D	Jan. 18, 1965	541	-

Fig.5 Temperature and water level build-up of M3 after the completion of drilling. The temperature data are taken from Takaki and Tanaka (1968). Boiling Point for Depth corresponds to Run A.

As seen in Table 1 and Figs.3 and 4, there are seven water level data for M1, three data for M2 and two data for M6. These water levels built up with standing times corresponding to warm up of water column in the well. Feed point pressures of the wells based on these water levels are closely estimated at each wells (Table 1). This indicates that the feed point pressures of the wells stabilized in very short time and that the estimated pressures are reasonably accurate. Thus, averaged pressures at the feed points are used for further discussion, if there are plural number of logging data (Table 1).

DISCUSSION

A relationship between feed point pressures and their elevations is shown in Fig.6. As seen in Fig.6, the feed point pressures are correlated reasonably well with their elevations except that of M7. This indicates that the feed points of M1, M2, M3, M4 and M6 have hydraulic communication with each other and are included in a single hydrothermal convection system. A straight line shown in Fig.6 is obtained by the least squares excluding the datum of M7. Reasons why the datum of M7 scatters from the line are discussed later.

The feed point pressures at Matsukawa and those at Kakkonda are plotted against their elevations in Fig.7. The data at Kakkonda are those of KA2, KB3, KC1, KC2, KC3, KD1, KD3, KE1 and KT205 (from unpublished data of Japan Metals and Chemicals Co., Ltd.). As seen in Fig.7, reservoir pressure profile at Matsukawa is parallel to that of Kakkonda, which is a well known liquid-dominated system.

The reservoir pressure profile shown as the straight line in Figs.6 and 7 represents density of the reservoir fluid. The reservoir pressure profiles of Matsukawa and Kakkonda correspond to the densities of saturated hot water of 217°C and 220°C, respectively. This implies that the production zone of the Matsukawa reservoir was filled with liquid at the initial state.

Table 1 Feed point pressures reconstructed from water levels.

well	feed point depth (m)	feed point elevation (m)	date	standing time (hours)	water level depth (m)	feed point pressure estimated (bar)	feed point pressure average (bar)
			Jan. 5, 1964	8	147	65.9	
			Jan. 6, 1964	26.5	110	67.3	
			Jan. 7, 1964	39.2	95	67.5	
M-1	840	+ 18	Jan. 8, 1964	73.2	91	67.1	67.0
			Jan. 9, 1964	107	85	67.0	
			Jan. 11, 1964	147	77	67.1	
			Jan. 12, 1964	167	75	67.0	
			July 23, 1964	70.8	93	86.6	
M-2	1,080	-246	July 27, 1964	167	77	86.1	86.6
			July 29, 1964	214	61	87.2	
M-3	1,040	-222	Dec. 30, 1964	79.2	25	88.5	
M-4	960	-122	Sep. 4, 1965	232	71	77.5	
M-6	970	-106	Jan. 19, 1969	76.8	75	79.9	79.5
			Jan. 20, 1969	103	73	79.1	
M-7	1,064	-185	Apr. 5, 1970	148	200	76.7	

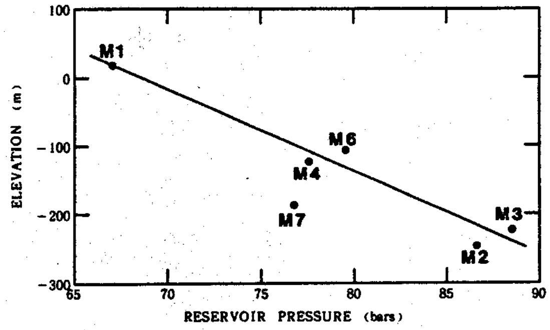


Fig.6 Feed point pressures at Matsukawa vs. elevations of the feed points. The line was obtained by the least squares excluding a datum of M7.

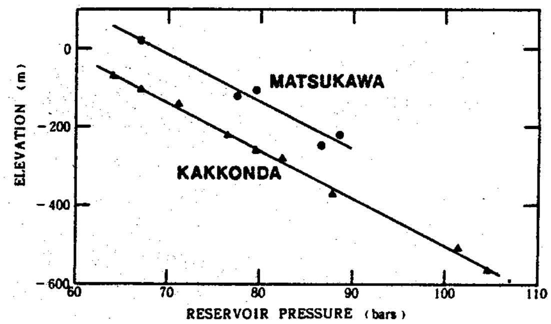


Fig.7 Feed point pressures at Matsukawa and Kakkonda vs. elevations of the feed points. Lines were obtained by the least squares.

Figs.8 to 11 represent temperature profiles of the longest standing times, saturation pressures corresponding to these temperature profiles, and the reservoir pressure profile estimated from water levels. As seen in Figs.8 to 11, the reservoir pressure is much higher than the saturation pressures. Estimated temperatures of 900m deep of M1, 1000m deep of M2 and 1100m deep of M3 by a modified Horner plot described by Roux et al. (1979) are 258, 263 and 252°C, respectively. Saturation pressures of pure water of these temperature are 45.4, 49.2 and 41.1 bars respectively, so that they are much lower than the estimated reservoir pressures. However, an effect of partial pressure of non-condensable gas, such as CO_2, should be considered.

Volume concentration of gases in the produced steam at an early stage of the production is approximately 0.2% and approximately 90% of the gases were CO_2 (such as Nakamura, 1967), so that partial pressure of CO_2 in reservoir fluid is evaluated to be 11 bars by the empirical equation of Malinin (1963), by assuming all of the gases were CO_2, the average reservoir temperature was 260°C, and produced fluid was steam alone. This value is the maximum to be expected. This is because, most of the earliest production wells at Matsukawa produced a considerable amount of hot water at the same time with steam at the beginning of the discharge (Fig.12), so that

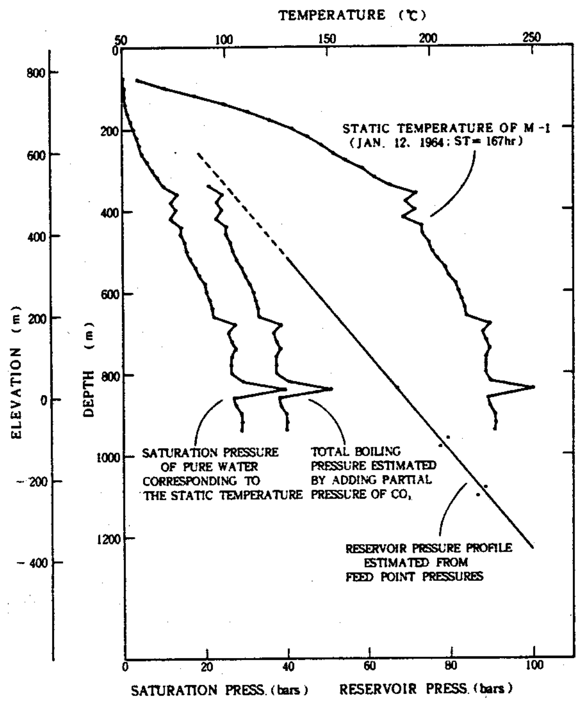


Fig.8 Static temperature of the longest standing times of M1, saturation pressure corresponding to the temperature, and the reservoir pressure profile estimated from the water level analysis.

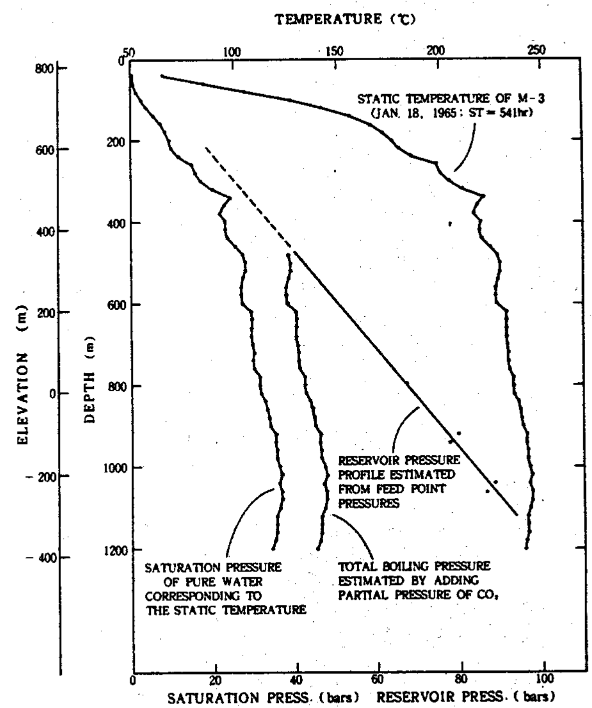


Fig.10 Static temperature of the longest standing times of M3, saturation pressure corresponding to the temperature, and the reservoir pressure profile estimated from the water level analysis.

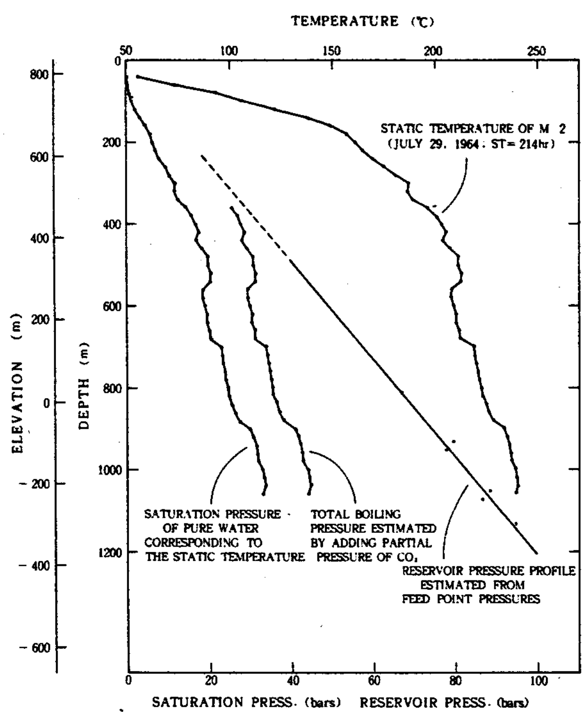


Fig.9 Static temperature of the longest standing times of M2, saturation pressure corresponding to the temperature, and the reservoir pressure profile estimated from the water level analysis.

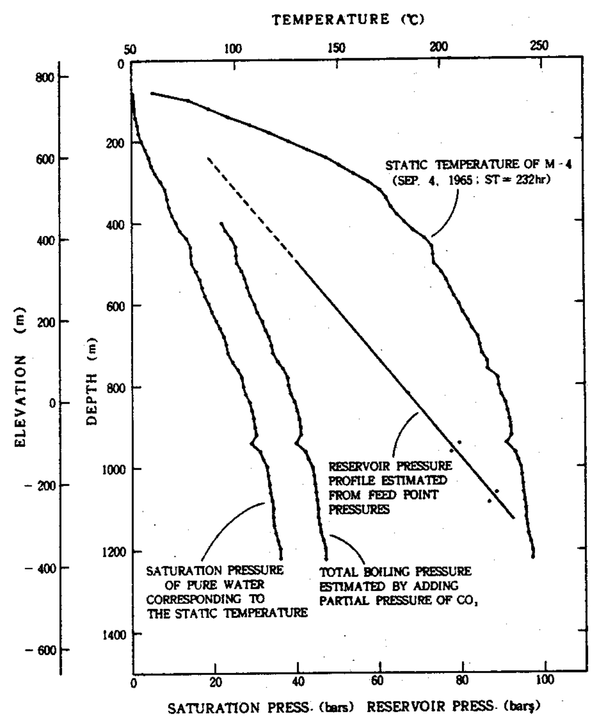


Fig.11 Static temperature of the longest standing times of M4, saturation pressure corresponding to the temperature, and the reservoir pressure profile estimated from the water level analysis.

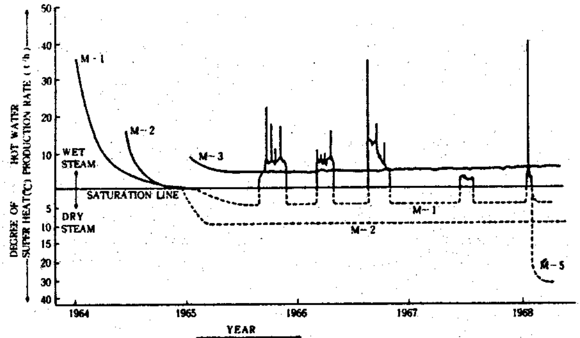


Fig.12 Discharge rate of hot water accompanied by steam from production wells at early stages of the production (after Miyamori, 1968).

the volume concentration of the CO_2 was lower than that used here. It must had been half of that used here. However, the hot water decreased with time and then the wells became to produce dry steam alone (Fig.12).

As seen in Figs.8 to 11, total boiling pressure estimated by adding the partial pressure of CO_2 to the saturation pressure of pure water corresponding to the static temperatures is much lower than the estimated reservoir pressures. Thus, it is probable that the production zone of the Matsukawa reservoir was filled with compressed liquid alone at the initial state.

Based on the results discussed above and the results of Pruess (1985), the mechanism how the produced fluid evolved from two-phase to dry steam is hypothesized as follows:

At the initial discharge, the reservoir fluid flashed in fractures in the vicinity of the wells, so that most of the wells produced wet steam with some hot water at first. Then the steam gradually became superheated due to the expansion of the flash front owing to less recharge both from the rock matrix and the surrounding formations due to the low matrix permeability and the existence of the low permeability barriers, and high heat flow from the surrounding formations. Thus, the primary cause of the evolution of produced fluid from two-phase to dry superheated steam at Matsukawa are thought to be the relatively little recharge both from the rock matrix and the surrounding formations due to the low matrix permeability and the existence of low permeability barriers at least both top and lateral sides, and the relatively high heat flow.

The relatively little fluid recharge from the surrounding formations at Matsukawa is clear from current reservoir pressure distribution obtained by pressure build-up tests (Fig.13). The current reservoir pressure is much lower than the initial reservoir pressure estimated here. Thus, there should be very large pressure difference, at least more than 30 bars, between current production zone and the surrounding area. Such a large pressure difference can exist only when fluid recharge from surrounding formation is low enough.

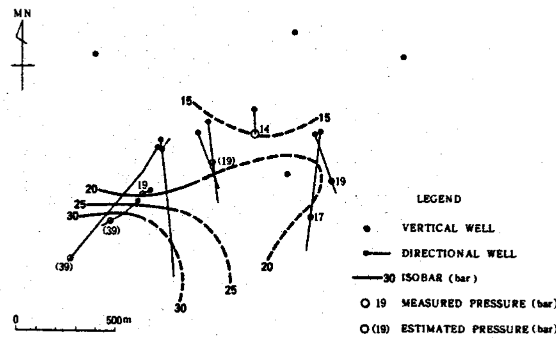


Fig.13 Shut-in pressure distribution at feed points in October, 1988 (after Hanano et al., 1989).

After Pruess and Narasimhan (1982), matrix permeability necessary to evolve a fractured liquid-dominated reservoir to produce dry superheated steam is in the order of $10^{-17}m^2$. This order of permeability is easily obtained through tests of fresh part of core samples. Thus, fluid recharge from the rock matrix is thought to be very little as long as the matrix does not have many micro-fractures.

The relatively high heat flow at Matsukawa is indicated from the temperature profiles shown in Figs.3 to 5. From these figures, an averaged temperature gradients in the cap rock of M1, M2 and M3, between approximately 50m and 150m deep, is approximately 0.816K/m. By multiplying 1.82W/mK, an averaged thermal conductivity of the core samples of this formation, conductive heat flux through the cap rock at Matsukawa is estimated to be $1.49W/m^2$. This value is mostly identical to $1.53W/m^2$, which was used to evolve vapor-dominated conditions in numerical simulations by Ingebritsen and Sorey (1988). According to Ingebritsen and Sorey (1988), this heat flow is of the same order as the measured surficial value at The Geysers. Thus, the heat flow at Matsukawa is high enough as The Geysers.

Surface elevation of Matsukawa is higher than that of Kakkonda by approximately 200m. Thus, reservoir pressure of Matsukawa is expected to be higher than that of Kakkonda by approximately 20 bars at the same elevation. However, difference of reservoir pressures of the same elevation of both areas is approximately 10 bars such as at -200m above sea level (Fig.7), implying that Matsukawa is relatively under-pressured by approximately 10 bars. Moreover, an extrapolated line of the reservoir pressure profile and the saturation pressures of the temperature profiles of M1 through M4 get closer around 300m to 400m deep (Figs.8 to 11). Considering the possibility of recovery of the temperature profile and error of the extrapolated line, it is likely that there existed a vapor-dominated condition which has a nearly vapor static pressure profile of more than 100m thick at around 300m to 400m deep at the initial state. After Ingebritsen and Sorey (1988), part of the liquid zones just above and below the vapor-dominated zone are two phase with rather limited steam saturation. Thus, it is consistent with results that early exploration wells encountered steam zone at around 300m, as described above. That is, the model of White et al. (1971) is still applicable to Matsukawa from a macroscopic point of view.

Muramatsu (1987) reported coexistence of liquid and gas inclusions in cuttings obtained from wells at Matsukawa. He also described that the inclusions must have been trapped during pyrophyllite had been formed. This fact seems to be inconsistent with results discussed above. However, Sumi (1972) described that geothermal activity at Matsukawa has risen and fallen repeatedly several times and the activity at the time when pyrophyllite was formed was quite vigorous, based on analysis of hydrothermal rock alteration. He also described that current geothermal activity is rather low compared with that at the time when pyrophyllite was formed. Thus, heat flow at the time when pyrophyllite was formed must had been much more than the current one, so that the vapor-dominated zone must had been thicker and must had been extended deeper than the current production zone. The gas inclusion must have been trapped under such condition.

As described above, the reservoir pressure datum of M7 scatters from the reservoir pressure profile estimated from another data (Fig.6). There seems to be two possible explanations of this phenomenon. The one is an effect of exploitation, because the power plant had been operating for four years when M7 was drilled, 1970, so that the reservoir pressure might had decreased slightly.

The other is an unequal thickness of vapor-dominated zone; its thickness might had been thicker around M7 than that around northeastern wells. This can be explained by its high temperature. M7 recorded 277°C at around the bottom. This temperature is close to 292°C, a saturation temperature of 76.7 bars, which is the estimated feed point pressure at the initial state for M7 (Table 1). M7 is thought to be a well which is one of the closest well to a steam source, because it has been maintaining high flow rate and shows small decrease (Hanano et al., 1989; Hanano and Sakagawa, 1990). Saturation pressure of pure water of 277°C is 61.3 bars, so that total boiling pressure of the reservoir fluid may be around 72 bars by assuming that the partial pressure of non-condensable gas is around 11 bars as described above. This pressure is close to the estimated feed point pressure, 76.7 bars, so that it is possible that the vapor-dominated zone of the southwestern area, which is thought to be close to the steam source, was thicker and extended nearly to the production zone.

The two explanations described above probably interact and affect, but the second one might have more affect. However, no matter what the reason was, it is highly probable that most of the current production zone was filled with single phase liquid at the initial state of the development from a physical point of view as described above. Conceptual model of the initial state of the Matsukawa geothermal reservoir discussed above is shown in Fig.14.

Donaldson and Grant (1981) had noticed that pressures at Matsukawa were hydrostatic rather than vapor controlled and thus it was liquid-dominated field, based on the temperature recovery data shown in Baba et al. (1970), which are the same ones as quoted in this report.

PROBLEMS TO BE STUDIED FURTHER

According to White et al. (1971), the liquid zone beneath the vapor-dominated zone should

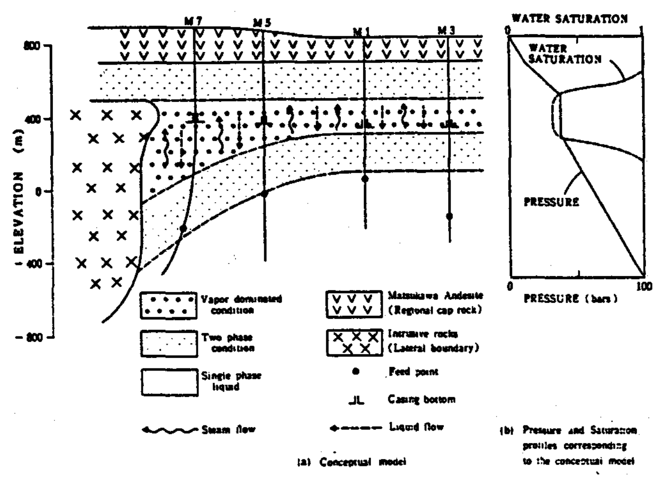


Fig.14 Conceptual model of the initial state of the Matsukawa geothermal reservoir. The pressure and saturation profiles are referred from Ingebritsen and Sorey (1988).

be brine, whose chloride concentration is high. However, chloride concentration of the hot water discharged with steam at the early stage of the production at Matsukawa was 5 to 15 mg/l (such as Sumi and Maeda, 1970). This value is too low to be thought of as brine, so that the hot water should be thought of condensate rather than brine. The reason why the condensate was distributed at such a depth, around 1000m deep which is much deeper than the depth of the estimated vapor-dominated zone, 300m to 400m, should be further explained in future.

CONCLUSION

(1) The reconstructed feed point pressures are correlated closely with their elevations. Although most of the wells currently produce dry superheated steam, the slope of the pressures is super-hydrostatic and is closely similar to that of Kakkonda, which is a liquid-dominated system.

(2) The reconstructed feed point pressures are much higher than the saturation pressure of 260°C, which is thought to be the average reservoir temperature before exploitation. Partial pressure of non-condensable gas is harmless to this result.

(3) It is highly probable that most of the current production zone of the Matsukawa geothermal reservoir, approximately 800m to 1300m deep, was filled with compressed liquid before the exploitation. However, there is a possibility that there existed a vapor-dominated condition of more than 100m thick at around 300m to 400m deep at that time, because the initial reservoir pressure at Matsukawa was under-pressured by approximately 10 bars.

(4) It is implied that the reservoir fluid flashed in fractures in the vicinity of the wells, so that most of the wells produced wet steam with some hot water at first, then the steam gradually became superheated due to the expansion of the flash front owing to less recharge due to the low matrix permeability and the existence of the low permeability barriers at least both top and lateral sides, and high heat flow from the surrounding formations.

(5) The existence of low permeability barriers is clearly seen in the current reservoir pressure distribution obtained by pressure build-up tests. In addition, the heat flux calculated from temperature gradient through the cap rock is high enough as The Geysers.

(6) However, very poor chloride concentration of the produced hot water implying condensate origin should be further explained in future.

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