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RESERVOIR ENGINEERING STUDIES OF THE MATSUKAWA GEOTHERMAL FIELD, JAPAN

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ABSTRACT

Since 1966, the Matsukawa geothermal power station has been in continuous and stable operation for twenty-six years. This has been due to proper maintenance of the power plant facilities and proper reservoir management. The reservoir management in Matsukawa includes monitoring of wells and reservoir performance, and reservoir engineering studies; analysis of the initial state and current state of the reservoir, modeling of the natural state of the reservoir, and history matching and reservoir performance prediction.

INTRODUCTION

Matsukawa was the first geothermal power plant in Japan, starting power production in October 1966, and is the only vapor-dominated geothermal field so far developed. The power plant has been continuously producing full power, 22MWe, almost 26 years.

Matsukawa is located about 600km north-east of Tokyo and about 50km north-west of Morioka, Japan. It is in the Hachimantai volcanic region, one of the most active volcanic regions in Japan. There are three geothermal power stations in this region, Matsukawa, Kakkonda and Ohnuma (Fig. 1).

The Matsukawa development and reservoir have been well documented. The history of the Matsukawa development, power production facilities and power generation history were recently summarized by Hanano et al. (1992). In this paper, we describe the most recent reservoir engineering study and the current reservoir management program applied at Matsukawa.

OUTLINE OF THE MATSUKAWA RESERVOIR

The Matsukawa geothermal reservoir has been studied previously (e.g. Akazawa and Muramatsu, 1988; Baba et al., 1970; Hanano and Matsuo, 1990; Hanano and Sakagawa, 1990; Hanano et al., 1991a, 1991b; Hayakawa et al., 1967; Mori, 1970; Nakamura and Sumi, 1967; Nakamura et al., 1970; Sumi, 1968, 1969; Sumi and Maeda, 1970; Yoshida, 1984; Yoshida and Ishizaki, 1988).

(1) Geological Setting

A geological cross section of Matsukawa is shown in Fig. 2. According to Akazawa and Muramatsu (1988), steam is produced mainly from faults and marginal fractures of the intrusive rock, at elevations ranging from 0 to 500m below sea level (approximately 800 to 1300m depth), in the Tamagawa Welded Tuffs and the Takinoue-onsen and Kunimitoge Formations.

(2) Physical Characteristics

Recent studies have shown that though the initial state of the Matsukawa geothermal reservoir was a vapor-dominated type as described by White et al. (1971) from a macroscopic point of view, the vapor-dominated zone in which the pressure profile is controlled by a steam column, was thin and existed in only the shallow part of the reservoir. The current production zone (800 to 1300m depth) was in a liquid zone below the vapor-dominated zone (Hanano and Matsuo, 1990). Thus, the early deep production wells produced wet steam with some hot water at first, but the fluid turned dry after six months to one year of production (e.g. Hanano and Matsuo, 1990). The current state of the Matsukawa reservoir has been studied mainly by pressure build-up tests (e.g. Hanano and Sakagawa, 1990). Based on these results, Hanano and Matsuo (1990) discussed a mechanism to produce dry superheated steam from such a liquid zone.

Hanano and Sakagawa (1990) interpreted the results of the pressure build-up tests, as well as the production records and the chemical data of produced steam. According to their study, steam flows from the south-west to north-east in the reservoir, and the only steam supply is from the south-west. Thus, the shut-in pressure is high in the south-west, where the production rate is high and the decline is low because of the proximity to the steam source. However, the shut-in pressure is low in the eastern and north-eastern part of the reservoir, where the production rate is low and decline is high because of the distance from the steam source. Thus, the eastern wells have a larger decline rate and larger degree of superheat. Recent shut-in pressure distribution is shown in Fig. 3.

From the above discussions, it is suggested that steam is supplied from the south-west along the Akagawa and Yunomori Faults. For such a reservoir pressure to stably exist as shown in Fig. 3 at a depth of 800 to 1300m, it is clear that there exists a low permeability barrier, consistent with the model of vapor-dominated systems by White et al. (1971), at least at the top and sides of the reservoir.

(3) Chemical Characteristics

Based on the report of Yoshida and Ishizaki (1988), we will summarize the chemical characteristics of the Matsukawa reservoir.

From the chemical characteristics of the produced steam, the wells in Matsukawa are divided into two groups; 1) wells M1, MN3 and M9 which are located in the eastern part, and 2) all other wells. M1, MN3 and M9 have a higher total gas concentration, higher CO_2 and NH_3 concentration and lower H_3BO_3 concentration than other wells. Following the lateral flow model of D'Amore and Truesdell (1979), the characteristics suggest that steam generally flows from the south-west to north-east in the Matsukawa reservoir, which is consistent with the results obtained by the pressure build-up tests. However, this does not necessarily mean that there is no other steam source other than that of the south-west. This rather suggests that the potential of other steam sources is much lower than that of the south-west. The model of D'Amore and Truesdell (1979) describes the flow of the natural state of vapor-dominated systems. However, this model can also be applied to a flow induced by exploitation as long as the flowing fluid is saturated steam (Hanano and Sakagawa, 1990).

The produced steam is of meteoric origin because there is an "Oxygen Shift". Analysis of tritium and carbon isotopes suggests that steam from M1, MN3 and M9 contains more newly formed meteoric-origin-steam than that of other wells. The He/Ar ratio and N_2/Ar ratio suggest that M1, MN3 and M9 have a stronger presence of volcanic gas than other wells. However, this does not necessarily mean that M1, MN3 and M9 have a greater supply of volcanic gas than other wells. This simply means that steam from M1, MN3 and M9 contains more volcanic gas in the mixing of old meteoric-origin-steam and volcanic gas.

The steam produced at Matsukawa thus consists of volcanic gas, old meteoric-origin-steam, and new meteoric-origin-steam. Mixing of these three components is controlled by the reservoir pressure balance shown in Fig. 3. That is, the south-western wells, which are closer to the main steam source, contain more old meteoric-origin-steam and have higher shut-in pressures, so that they have less volcanic gas and less new meteoric-origin-steam. However, M1, MN3 and M9, which are away from the main steam source, contain less old meteoric-origin-steam and have lower shut-in pressures, so that the ratio of volcanic gas is larger and there is more new meteoric-origin-steam. Accordingly, chemical characteristics of produced steam have a close relation to the physical characteristics of the Matsukawa reservoir.

NUMERICAL MODELING OF THE NATURAL STATE OF THE MATSUKAWA RESERVOIR

Natural state simulation is commonly applied for the study of heat and mass transport of undeveloped geothermal reservoirs (e.g. Bodvarsson et al., 1984; O'Sullivan et al., 1990). To test the feasibility of the discussions on the natural state of the Matsukawa geothermal reservoir made by Hanano and Matsuo (1990), a preliminary natural state simulation study was carried out (Hanano, 1992). The purposes of this modeling study were as follows:

1) To study whether the vapor-dominated system shown in Fig. 4 is attained as a natural state or not by simulating the reservoir behavior after the intrusion of a heat source with the real reservoir data.
2) To study whether dry superheated steam is produced or not after a certain period of production from the liquid zone by simulating the response of the reservoir of the above mentioned natural state to exploitation.

Since this was the first natural state simulation study at Matsukawa, a simplified two-dimensional cross-sectional porous model was employed accounting for the results of Ingebritsen and Sorey (1988). The grid mesh and the final model are shown in Fig. 5. This cross section is from south-west to north-east, the dominant lateral steam flow direction which was pointed out by Hanano and Sakagawa (1990). Temperature and water saturation distribution after 50,000 years' run are shown in Figs 6 and 7, respectively. The results obtained in this modeling study are summarized as follows:

1) Using conductive heat flux analyzed from temperature logging data, the numerical model reasonably reproduced the temperature and pressure distribution of the initial state described by Hanano and Matsuo (1990).
2) Production from this model led to production of superheated steam and confirmed that the initial state described by Hanano and Matsuo (1990) was feasible. Thus, the conceptual model of the initial state of the Matsukawa geothermal reservoir necessary for further modeling analyses was established.
3) Parameter studies indicated that without low permeability barriers of an order of $5x10^{-17}$ m^2 at least at the top and sides of the reservoir, the reservoir could not be vapor-dominated at the initial state and could not produce dry superheated steam after exploitation. This suggests that there is almost no fluid recharge from outside of the reservoir even after exploitation.
4) The relatively high natural conductive heat flux suggests that there is an intensive magmatic heat source not far from the bottom of the convective reservoir.
5) Parameter studies on bottom depth suggest that appropriate range of the simulation depth of permeabilities shown in Fig. 5 is from 2.5 to 3.0 km and that it is inappropriate to increase it to 4 km. This result, however, does not deny the possibility that the reservoir extends deeper than this depth. The hydrothermal convection would extend to a much deeper depth if a reservoir of very low permeability exists at great depth like that found in Kakkonda, Japan (e.g. Doi et al., 1988). However, this should be further studied by deep drilling.

RESERVOIR MANAGEMENT AT MATSUKAWA

It is well known that proper reservoir management is indispensable for stable geothermal power production. Imprudent geothermal development prevents effective energy extraction from the reservoir. Geothermal reservoir management has generally been summarized by Grant et al. (1982) and Gulati (1988). Actual reservoir management in The Geysers and Larderello has been described (e.g. Budd, 1973; Drenick, 1988; Barker et al., 1989; Neri, 1990; Enedy et al., 1990). Here we describe the reservoir management in Matsukawa.

There are five factors which affect decline of steam production in geothermal fields.

1) Reservoir pressure decline
2) Fluid enthalpy decrease
3) Insufficient fluid recharge from the outer area
4) Scale deposition and sealing in a wellbore and/or reservoir
5) Mechanical troubles in a wellbore

The reservoir pressure decline is caused by fluid production and is inevitable in geothermal developments if the fluid is not injected back into the reservoir. Thus, among these five factors, it is the most fundamental factor causing decline of geothermal well steam production.

Influences by the other four factors can be minimized as long as proper care and sufficient measures are taken. The fluid enthalpy decrease is the most harmful if thermal breakthrough of injected fluid occurs in liquid-dominated geothermal fields (e.g. Hanano et al., 1990). However, this damage can be minimized by careful planning and thoughtful development through detailed monitoring.

Insufficient fluid recharge is more important in liquid-dominated fields than in vapor-dominated fields, because vapor-dominated fields like Matsukawa essentially have a permeability structure which does not permit any fluid recharge. This factor has more influence on the decline of steam production over the entire field rather than that of individual production wells.

Scale deposition and sealing in wellbores and/or reservoirs happen under conditions of certain fluid chemical compositions. However, this is limited in particular liquid-dominated fields and is not common in vapor-dominated fields. Mechanical troubles in a wellbore can be avoided basically by careful drilling and completion of the well. Thus, the reservoir pressure decline is the most noteworthy among the five factors in the reservoir management of vapor-dominated geothermal fields.

The mechanism of decline of steam production in vapor-dominated geothermal fields is shown in Fig. 8. In vapor-dominated geothermal fields, the reservoir pressure is drawn down by steam production, causing a decrease in water saturation in the reservoir. This leads to a decrease in feed point pressure of production wells and results in decreases in steam production and/or well head pressure of the wells. Finally, this decrease in steam production of each well results in a decrease in steam production of the entire field. This is the mechanism of decrease in steam production of vapor-dominated geothermal fields. Thus, proper understanding of this mechanism is essential for better reservoir management in vapor-dominated geothermal fields.

Reservoir management begins with the understanding of the current state in any type of geothermal fields. Thus, it is very important to study the current state of the reservoir by monitoring of wells and the reservoir. A proper understanding of the initial state of the reservoir is also very important in judging whether the current state of the reservoir is in a favorable condition or not. Thus, it is very important to collect data not only after exploitation but also while the reservoir is in a natural state. The data being collected for reservoir management at Matsukawa is shown in Fig. 9.

A flow chart of reservoir engineering studies being carried out at Matsukawa is shown in Fig. 10. As seen in this figure, reservoir management at Matsukawa has been conducted through data acquisition, analysis of the initial state of the reservoir and analysis of the current state of the reservoir. In addition, a history matching study with a three-dimensional grid model has been conducted for model calibration for reliable reservoir performance prediction. Based on these reservoir engineering studies, the best development operations under the given conditions and circumstances have been conducted in Matsukawa.

The reservoir management criteria currently applied at Matsukawa is shown in Fig. 11. As seen in this figure, the current state of the wells and reservoir has been monitored continuously. This includes steam temperature and pressure at the well head, steam production rate, steam chemistry and reservoir pressure. Based on these data, the wells and reservoir are evaluated whether they are sound or not.

As long as they are in a favorable condition, the current production program is continued. However, if they show any sign of decline and/or trouble, a countermeasure which will solve the problem would be considered.

If the reservoir pressure decrease is very large and advances rapidly, it may suggest that the current steam production is too high and it would be better to reduce steam production. Fortunately, however, we have not had this case at Matsukawa.

If superheat of produced steam is notable in a major part of the field, it is better to consider the possibility of reinjection. Since this is the case in Matsukawa, we started reinjection experiment since March 1988. The results of early reinjection tests were reported by Hanano et al. (1991b). This reinjection has been beneficial and has slowed the decline of steam production of some wells other than those described by Hanano et al. (1991b).

Most vapor-dominated wells produce dry steam alone, but in some cases they produce some hot water. If this is a result of direct return of reinjected fluid, then the rate and place of reinjection should be reconsidered. Too much direct return of reinjected fluid cools fracture surfaces in the reservoir too much, making effective and long-term heat extraction impossible. Contrary, if this is a result of casing breaks and/or other mechanical wellbore troubles, the well would be abandoned and a replacement well should be considered in future.

In Matsukawa, a few wells have been producing small amounts of hot water prior to reinjection, which is believed to be a result of casing breaks in the shallow parts. In some cases, this hot water increased slightly after reinjection started. However, this hot water has been utilized for local direct use (Hanano et al., 1991b, 1992). Thus, this hot water problem is not very serious even now in Matsukawa. However, we have been conducting an extensive monitoring program, as described above, to avoid a serious thermal breakthrough problem. This is the reservoir management program currently applied at Matsukawa.

CONCLUDING REMARKS

The Matsukawa geothermal power plant has continued stable power production for 26 years. However, the superheat of the produced steam has been increasing slightly and average steam production of one well has been decreasing slightly. We thus continue efforts to maintain stable power production not only by proper maintenance of the power plant facilities but also by proper reservoir management.

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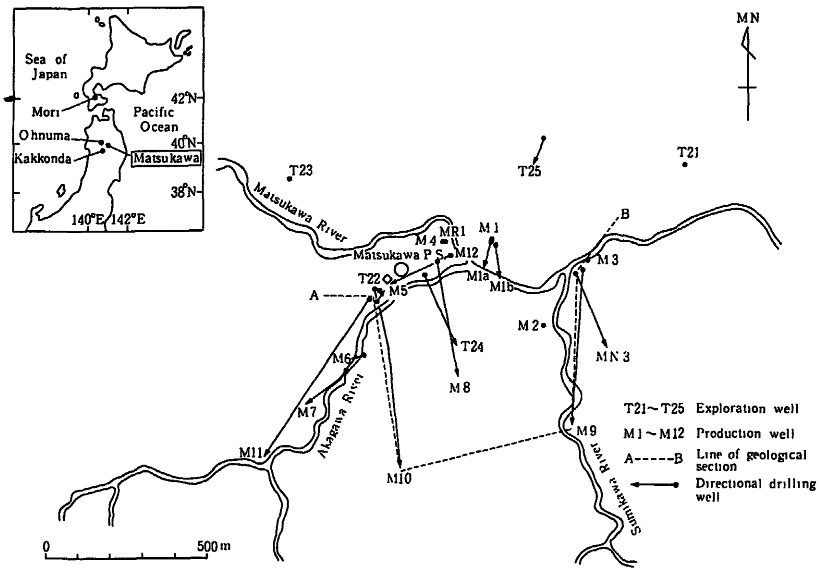

Fig. 1 Location of Matsukawa and wells (modified from Akazawa and Muramatsu, 1988).

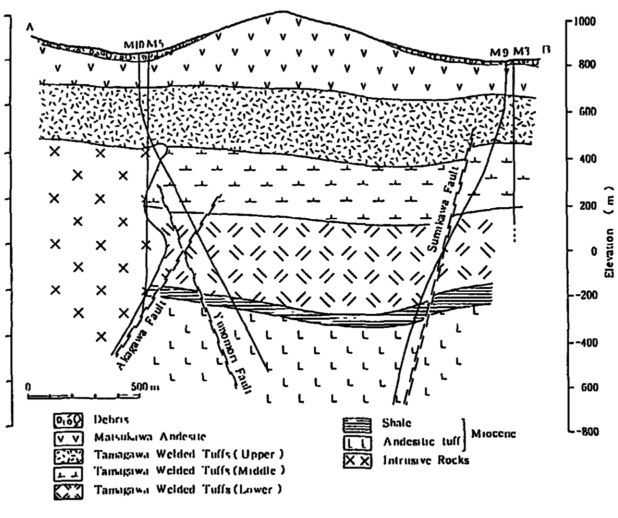

Fig. 2 Geological cross section of Matsukawa (after Akazawa and Muramatsu, 1988). Location of the cross section is shown in Fig. 1.

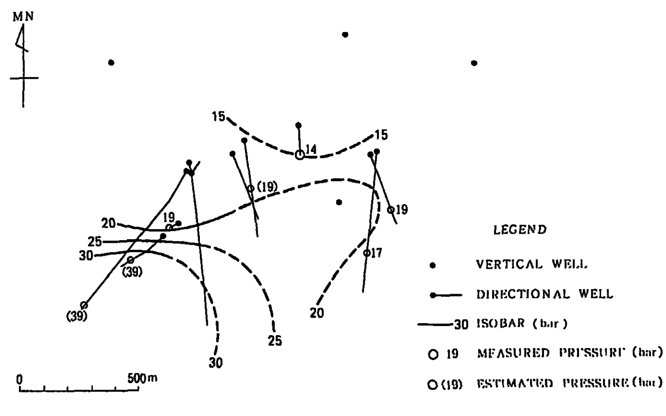

Fig. 3 Shut-in pressure distribution at feed points in October 1988 (after Hanano et al., 1989). Pressures are absolute.

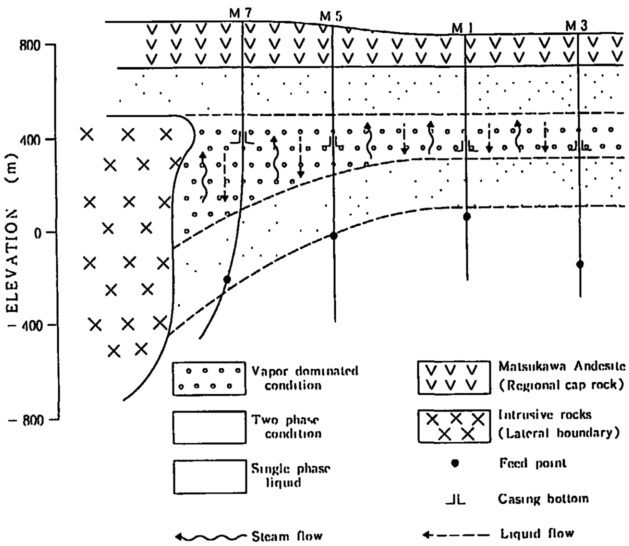

Fig. 4 Conceptual model of the initial state of the Matsukawa geothermal reservoir (after Hanano and Matsuo, 1990).

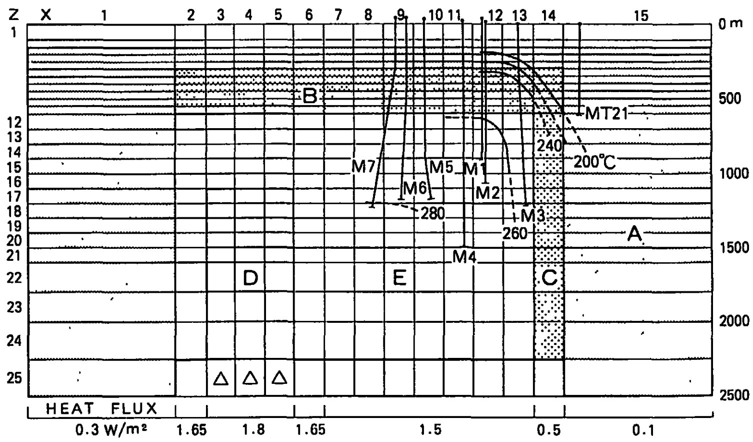

Fig. 5 Grid mesh with initial temperature distribution, along with permeability distribution (A = 5×10^{-17} m^2, B = 1×10^{-13} m^2, C = 5×10^{-14} m^2, D = 1×10^{-13} m^2, E = 1×10^{-15} m^2), location of mass input (Δ), and conductive heat input of the final model of natural state simulation of the Matsukawa geothermal reservoir (after Hanano, 1992).

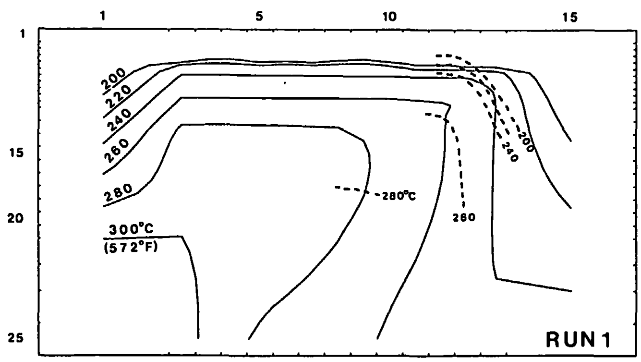

Fig. 6 Temperature distribution at 50,000 years of the final model, along with initial temperature distribution (dashed line) (after Hanano, 1992).

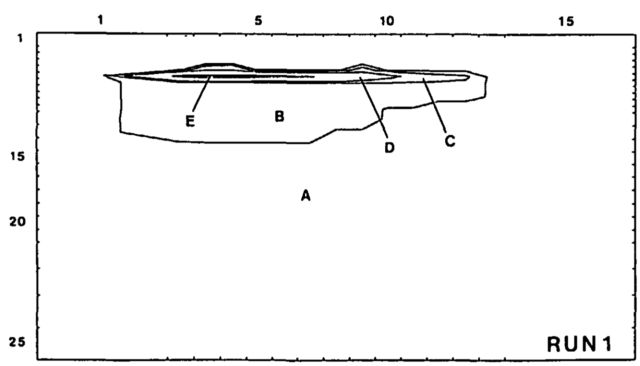

Fig. 7 Distribution of water saturation at 50,000 years of the best model (A : Sw=1.0 (k_{rs}=0.0), B : 0.95<Sw<1.0 (k_{rs}=0.0), C : 0.84<Sw<0.95 (k_{rw}>k_{rs}>0.0), D : 0.5<Sw<0.84 (0.99>k_{rs}>k_{rw}), E : Sw<0.5 (k_{rs}>0.99)) (after Hanano, 1992).

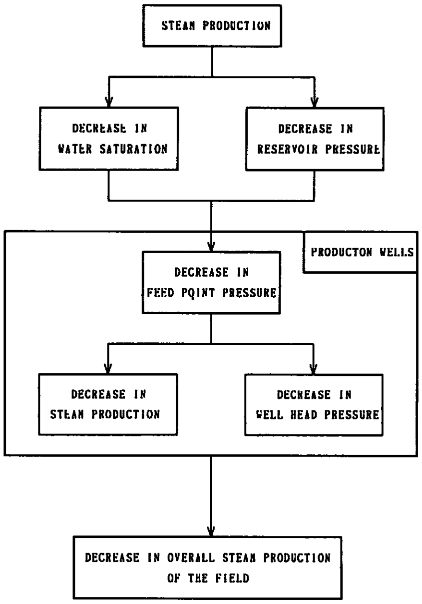

Fig. 8 Mechanism of decline of steam production in vapor-dominated geothermal fields.

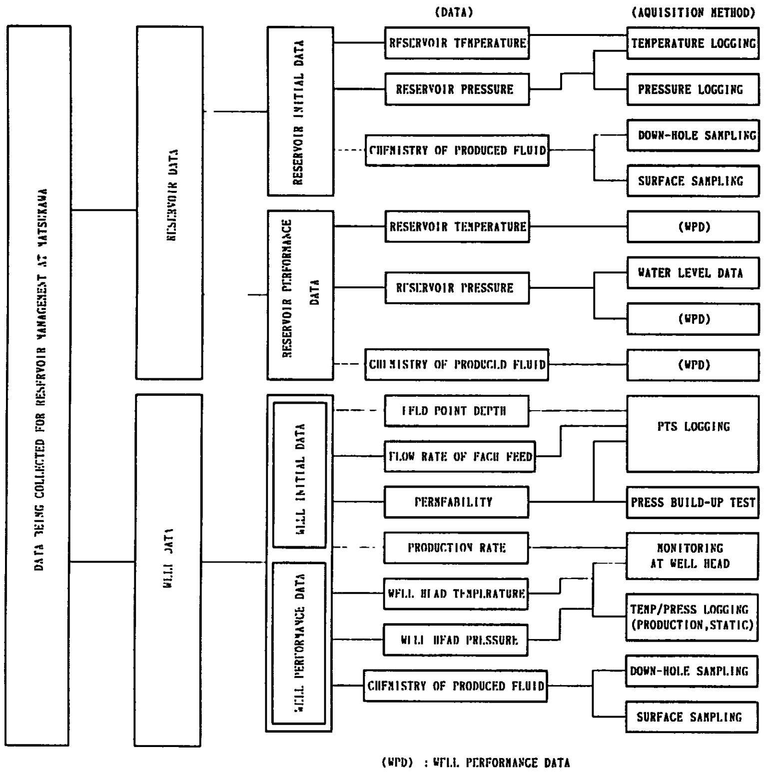

Fig. 9 The data being collected for reservoir management at Matsukawa.

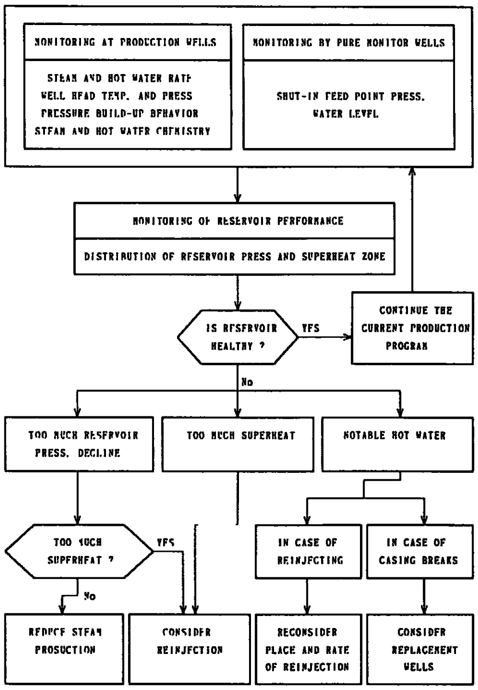

Fig. 11 Reservoir management criteria at Matsukawa.

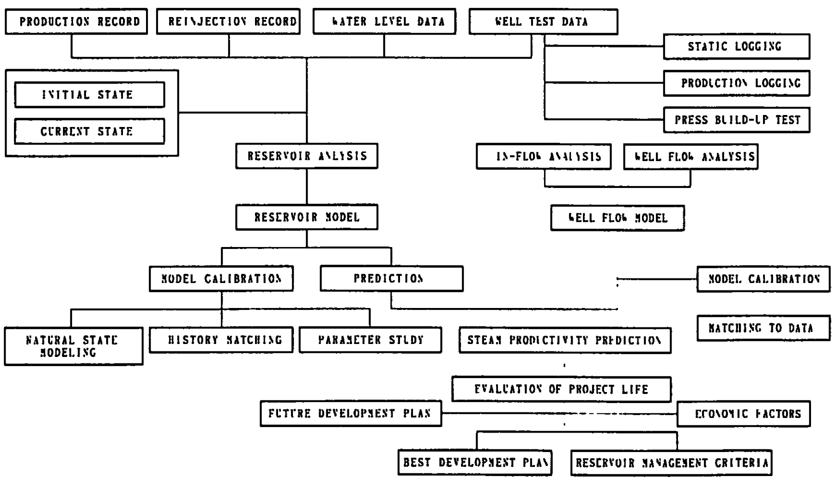

Fig. 10 A flow chart of reservoir engineering studies at Matsukawa.