FEASIBILITY STUDY OF RESERVOIR MONITORING USING REPEAT PRECISION GRAVITY MEASUREMENTS AT THE SUMIKAWA GEOTHERMAL FIELD

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Abstract

In principle, repeat gravity surveys can help appraise changes in natural reservoir recharge in response to production-induced pressure decline. Unambiguous interpretation of gravity surveys (in isolation from other data) is, however, often impossible. One promising approach is to combine precision gravity survey measurements with numerical reservoir simulation studies. The synthesis of the two techniques is potentially capable of providing results which would be unobtainable using either technique alone. Preliminary numerical simulation studies (prior to full-scale field exploitation) have been used (1) to evaluate feasibility and **(2)** to design a specific gravity survey plan for the Sumikawa geothermal field. These results were processed to yield areal maps of "synthetic gravity anomaly change" corresponding to the changes in underground conditions calculated by the numerical reservoir model. Numerical simulation studies performed prior to full-scale development could be of significant utility in evaluating the feasibility and guiding the execution of the early field survey program. If a preliminary mathematical model of the reservoir is available, parametric calculations may be performed using that model to represent potential future exploitation effects. These calculations will provide preliminary estimates of how the distribution of fluid mass is liable to change within the reservoir volume. These results, in turn, may then be further processed to yield an areal map of "synthetic gravity anomaly change" corresponding to the changes in underground conditions calculated by the numerical reservoir model. Such a map (or maps, if various alternative reservoir models are available) would appear to be of substantial potential value for planning the field gravity survey program, and establishing appropriate locations for benchmarks in the local leveling network.

1. INTRODUCTION

Recent advances in precision gravity meters provide a powerful new technique to aid in geothermal reservoir management during exploitation. The general approach is as follows. Gravity surveys of the field are first performed prior to large-scale development to assess the gravity anomaly distribution in the natural state. Then, periodic re-surveys are performed and comparisons are made with earlier surveys. The purpose is to detect and characterize changes in the gravity anomaly distribution in and around the field as exploitation proceeds. Clearly, measurements of this type are pertinent to the assessment of natural recharge into the reservoir and how it increases in response to production-induced pressure decline (see e.g. Hunt, 1970, 1988; San Andres and Pedersen, 1993). The effect of pressure changes on inflow rates from the boundaries is very difficult to estimate, but is of obvious importance when appraising the useful lifetime of a field. Repeat gravity surveys offer significant promise in alleviating this uncertainty. Of course, the results of gravity surveys are difficult to interpret quantitatively in an unambiguous fashion if taken in isolation. One possibility which would appear to be very promising is to combine gravity survey measurements with numerical reservoir simulation studies. The synthesis of the two techniques is potentially capable of providing results which would be unobtainable using either technique alone.

A successful gravity survey program can yield diagnostic data suitable for verification of numerical reservoir simulation models and, by enhancing the reliability of the models, improve our ability to forecast future reservoir performance. In this paper, numerical simulation studies to assess the feasibility of repeat gravity surveys of the Sumikawa geothermal field are discussed. First, however, the Sumikawa geothermal reservoir must be introduced.

2. THE SUMIKAWA RESERVOIR

The Sumikawa geothermal field is located in the Hachimantai volcanic zone of the Sengan thermal area in northern Honshu, Japan. Exploratory studies have been in progress at Sumikawa since 1981 by Mitsubishi Materials Corporation (MMC) and Mitsubishi GasChemical Corporation (MGC); this comprehensive program incorporates a variety of geochemical and geophysical surveys and an extensive drilling investigation. The drilling program has revealed a complex geological structure and has made possible a very thorough pressure-transient testing program involving both short-term single-well and long-term multi-well pressure transient tests. These studies were first canied out jointly by MMC and NEDO (the New Energy and Industrial Technology Development Organization) from 1985 to 1989, and then by MMC and GSJ (Geological Survey of Japan) from 1990 to 1994.

The area depicted in Figure I is about **42** square kilometers; the Sumikawa field lies in the western part of the area, and may be regarded as centered around drilling pads A, **B,** C, D and E. A 50 MW geothermal power station is now under construction, with start-up scheduled for early **1995.** To the east, the Ohnuma geothermal power station has been producing about **10** MW of electricity for several years. Within the area, the ground surface averages about 1000 meters above sea level (ASL), but slopes sharply down from south (> 1300 m ASL near Mt. Yakeyama) to north (< 700 m ASL near the Akagawa hot spring area). The major geological formations in the area are as follows, in order of increasing depth:

"ST" Formation: Surface andesitic tuffs, lavas and pyroclastics of Recent origin.

"LS" Formation: Lake sediments; Pleistocene tuffs, sandstones, siltstones and mudstones.

"DA" Formation: Pliocene dacites, dacitic tuffs and breccias.

"**MV**" Formation: "Marine/Volcanic Complex"; interbedded Miocene dacitic volcanic rocks and "black shale" marine sediments.

"AA" Formation: Altered andesitic rocks which are apparently extensively fractured.

"GR" Formation: Crystalline intrusive rocks, mainly granodiorite and diorite.

The various pressure transient tests performed so far have helped to clarify the permeability structure of the Sumikawa reservoir (see e.g. Garg et al., **1991;** Ishido et al., **1992).** The "DA", "AA" and "GR" formations appear to be fairly permeable; the "LS" layer is an impermeable aquitard, and the "MV" formation, while permeable to horizontal fluid motion, acts as a barrier to vertical flow.

Several interference tests have been performed which involved discharging well **S-4** and recording downhole pressure changes in shut-in observation well **KY-1;** these wells are 1.1 km apart and both feed from a very permeable north-south channel within the "AA" layer. A "double porosity channel model" seems to be particularly appropriate for explaining both the short-term and long-term behavior observed in this series of tests (Ishido et al., **1992).** Analyses of the data yields the following quantitative results:

$$\omega = 0.2$$
$$\lambda^2/k_m = 10^{21}$$

here ω is the fracture-to-total storage ratio, λ is the fracture spacing and k_m is the permeability of the **matrix.**

3. PARAMETRIC CALCULATIONS OF FUTURE EXPLOITATION EFFECTS

Parametric calculations were performed using the mathematical model of the Sumikawa reservoir to predict system response to exploitation.

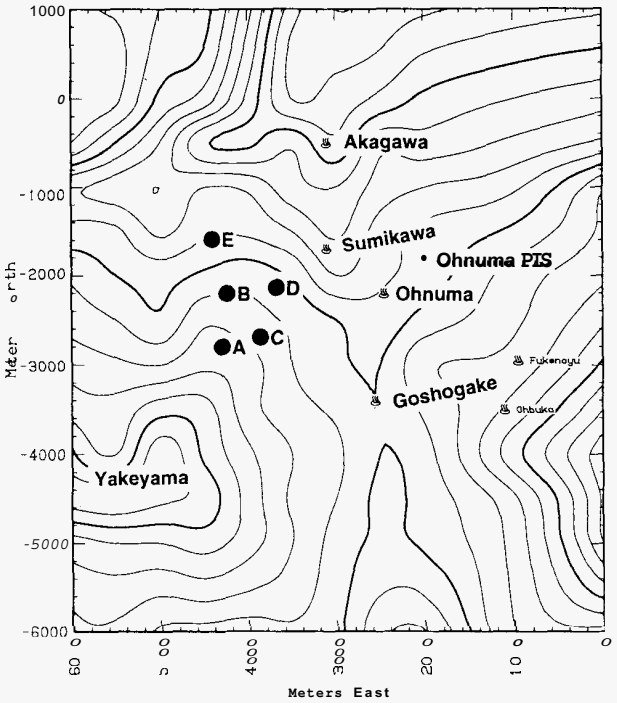


Figure 1. The Sumikawa/Ohnuma area, showing locations of drilling pads. Contour interval is 50 m RSL.

The results of these numerical calculations provide the spatial distribution of mass change within the reservoir volume. (Areal maps of "synthetic gravity anomaly change" corresponding to the calculated changes in underground conditions will be discussed in the next section.)

For this study, the STAR geothermal simulator (Pritchett, **1989,1993;** see also Pritchett, **1994)** was used to perform a 30-year forecast of the consequences of production and injection, starting from the "natural-state" model developed by Pritchett et al. **(1991)** as the initial conditions. In all cases (described below), all boundary conditions and rock properties (except for the "AA" formation) were the same as used to calculate the "natural-state". In each case, 500 tons per hour of steam at a fixed separator pressure of **5** bars was withdrawn — all separated liquid was maintained under pressure and reinjected at separator temperature together with a small amount of steam condensate. Since the average enthalpy of the produced fluid changes as time goes on, the total fluid production rate was varied as function of time so as to provide the desired constant steam supply.

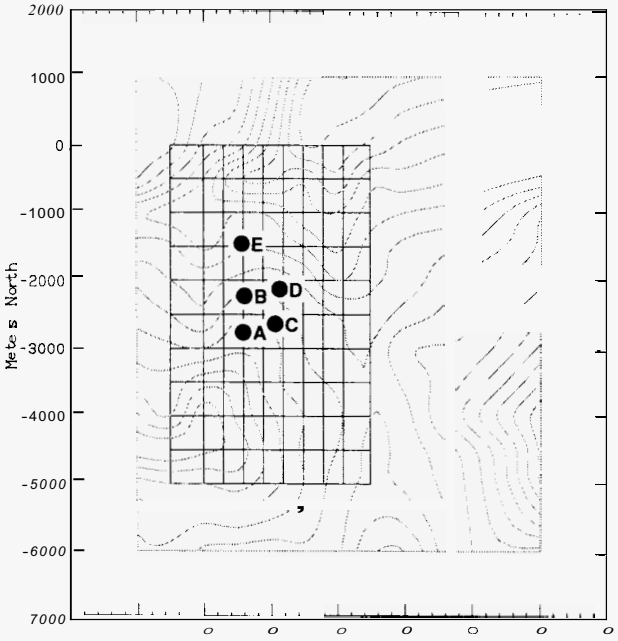
In the present performance predictions, a "MINC" representation (Pruess and Narasimhan, **1982)** was applied to "AA" formation (the main production zone) to represent the effects of fractured reservoir behavior. In the "double porosity (MINC) medium" representation, on the sub-grid scale the STAR simulator idealizes a "typical" block of country **rock (matrix) as a** sphere, surrounded by a concentric spherical shell of high-permeability material representing the fracture zone. **In** the present calculations, the matrix region was subdivided into **4** concentric spherical shells for numerical purposes. The following three cases an: considered:

Case **"A":** "AA" formation **is** a porous medium as in the "natural-state" model.

Case "B": "**AA**" formation **is** a "MINC" fractured medium. The MINC parameters are $\omega = 0.2$ and $\lambda^2/k_m = 10^{21}$ *(h* = 100 m and $k_m = 10^{-17}$ m^2) based upon the observations described in the previous section, and the global transmissivity and storativity are the same as Case "**A**".

Case "C": Similar to Case B, except the fracture spacing and the fracture zone permeability are both smaller (λ = 30 m, $k_m = 10^{-18}$ m^2).

The three-dimensional computational grid used in the present study (same as that used for the "natural-state" model) is shown in Figure 2; it consists of 10 grid blocks (each 500 meters in size) in the north-south direction, 9 grid blocks (300 to 500 meters in size) in the east-west direction, and a total of 16 vertical layers, ranging from 100 to 300 meters in vertical thickness. The horizontal grid area is 15 square kilometers, and the gnd extends vertically from -1600 m **ASL** (above sea level) to +1200 rn **ASL;** the total number of grid blocks



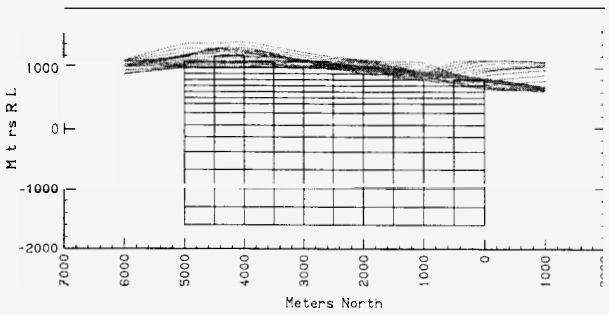


Figure 2b. North-south vertical section through grid blocks with east-west index i=2 (-5000 m E to **-4700** m E). Ground surface elevations along north-south sections are projected (dotted lines).

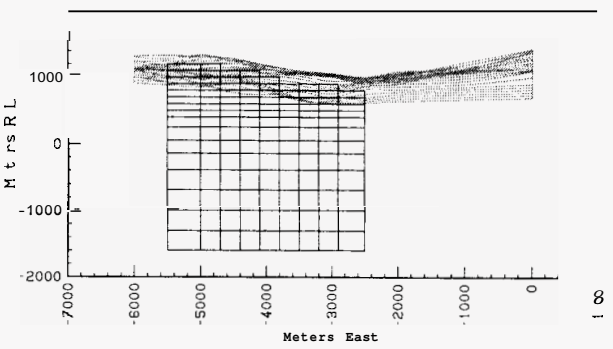


Figure 2c. East-west vertical section through grid blocks with north-south index j=2 **(-4500** m N to -4000 m N).

In all cases, production takes place near well pads **A,** B and C (Figure 2a). The feedpoints of the production wells were distributed between -1000 m **ASL** and **+50** m **ASL** in the "**AA**" formation and between -1600 m **ASL** and -1300 m **ASL** in the "GR" formation. Injection was assumed to take place (at wellhead pressures below 5 bars) near pads **D** and E between -700 m **ASL** and +250 m **ASL** in the "MV" and **"AA"** formations. The time-step size employed was 22.8 days for. Cases "**A**" and "B", and 5.7 days for Case "C".

As time goes on in each computed case, the average produced-fluid enthalpy tends to increase owing to the growth of the two-phase (water/steam) zone within the production area. Thus, for constant steam flowrate, the total fluid (water plus steam) required by the power station will tend to decrease with time. Figure 3 shows these trends for Cases **A,** B and C. Note, however, that small discontinuities occur at discrete times during these computed histories. These discontinuities arise from the "opening" of new makeup production wells required to maintain steam production.

The total fluid production rate for Case B exceeds that of Case **A,** whereas the total for Case C is less than Case **A.** This is because the average produced fluid enthalpy of Case C exceeds that of Case **A,** while the Case B enthalpy is less than Case **A.** The temporal evolution of the steam saturation and of the temperature within a grid block located centrally in the **"AA"** formation production zone - both in the fracture zone and within the country rock - are illustrated in Figure **4.** Figure 4a shows that the fracture-zone vapor saturation in Case B is less than in the "porous medium" case (Case **A),** whereas the Case C fracture-zone vapor saturation is the highest of all.

These differences in vapor saturation arise from the long time required for pressure and temperature equilibrium to become established between the fracture zone and the country rock in the matrix region. Under the two-phase conditions, the time required for pressure equilibration (τ_{pe}) **is** about **30** years for Cases B and C, due to the high compressibility of water/steam mixtures (seee.g. Pritchett and Garg, 1990). The times required for temperature equilibrium to

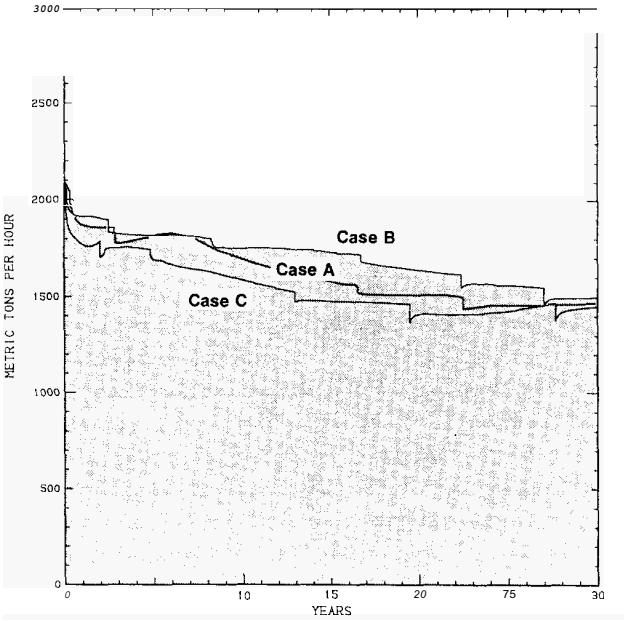


Figure 3. Change in total fluid production rate versus time.

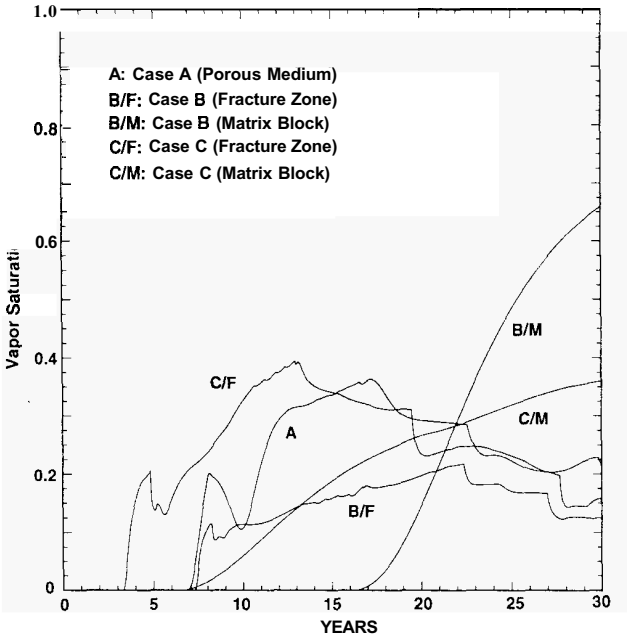


Figure 4a. Change in vapor saturation versus time within a grid block located centrally in the production zone.

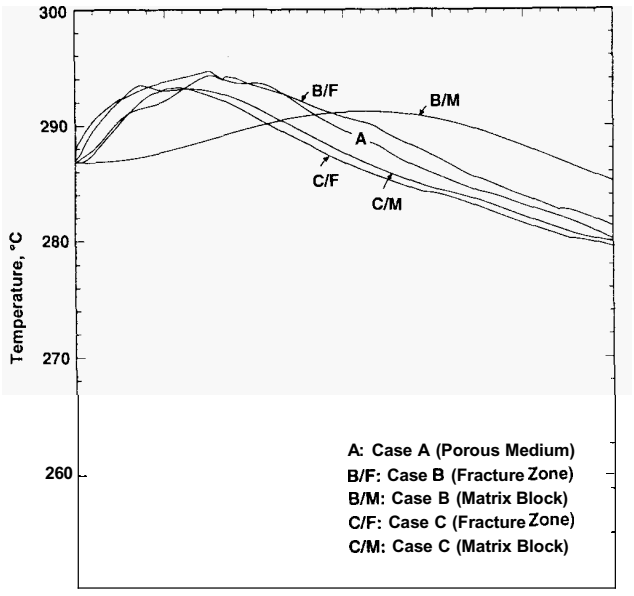


Figure 4b. Change in temperature versus time within the same grid block as Figure 4a.

be reached due to heat conduction acting alone (τ_{hc}) are about 30 years and 3 years for Cases B and *C*, respectively. In Case B, as seen in Figure 4b, the temperature of the fracture zone increases during the first seven years due to high temperature fluid inflow from the (southern) high temperature area. However, the country rock temperature increases only slowly since τ_{hc} is large; low-enthalpy fluids drain from the matrix block into the fracture zone, tending to suppress the formation of steam between 7 and **20** years. By contrast, in Case C, heat conduction within the matrix region plays a significant role. Two-phase conditions prevail throughout the block by about seven years. Since, in two-phasc flow, fluid pressures and temperatures are not independent but are constrained to lie along the saturation curve for steam/water mixtures, rapid heat conduction effects can influence the pressure distribution and thereby influence fluid convection, increasing the steam saturation in the fracture zone.

4. GRAVITY ANOMALY CHANGES

A computational/graphical postprocessor for the **STAR** code (Pritchett, 1989) was used to forecast gravity changes induced by the under-ground redistributions of fluid mass caused by geothermal operations according to the exploitation models described above. The results after 1, 10 and 30 years of field operation for Case **A** arc illustrated in Figure *5.*

In the early years of production (up to about *5* years) the increase in gravity associated with the reinjection wells is dominant, since reinjection takes place at shallower levels than fluid production. It should be possible to detect this gravity increase (–30 microgals, Figure 5a) even after only one year of operation. The anomaly continues to increase for about ten years; this **is** due to the long time required for the expansion of cold (denser fluid) injection front and the thermally-induced collapse of shallow two-phase zones.

At later times, the effects of fluid production become comparable to those of reinjection (Figure 5b), and gravity decreases dominate most of the area after **30** years (Figure 5c). Although the net fluid withdrawal is 400 ton/hr (500 ton/hr minus reinjected condensate) for all cases, the differences in total fluid production (Figure 3) and reinjection rates make substantial differences in gravity change among Cases **A,** B and C. The differences become very pronounced between 10 and 20 years of operation. The minimum gravity anomaly values at t = 10 years (owing to fluid withdrawal) are -70, -80 and *-55* microgals for Cases A, B and C respectively. In all cases, however, the negative anomaly arising from fluid production is large enough to be clearly identifiable after ten years of operation.

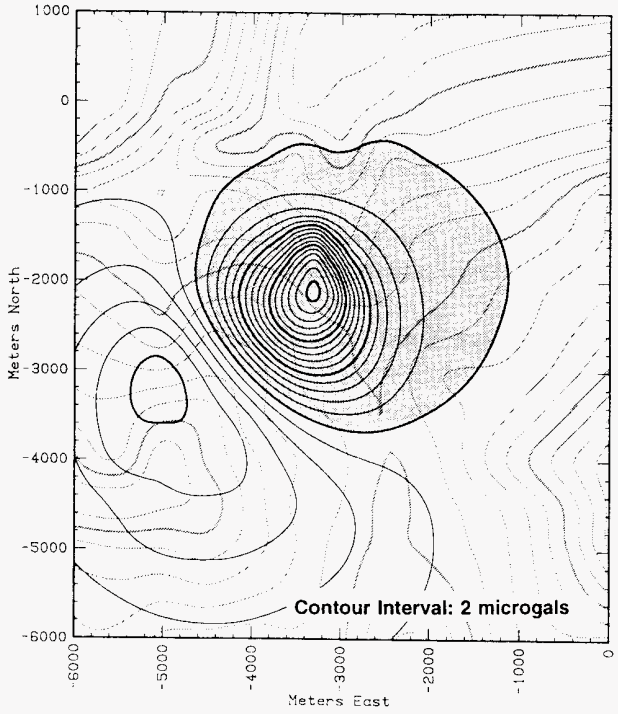


Figure 5a. Gravity change between 0 and 1 year for Case **A.** The change is positive over shaded area.

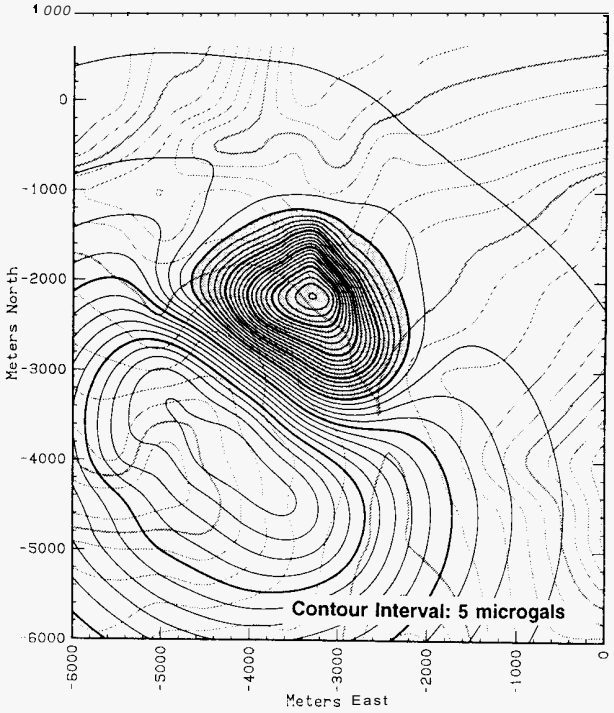


Figure 5b. Gravity change between 0 and 10 years for **Case A.**

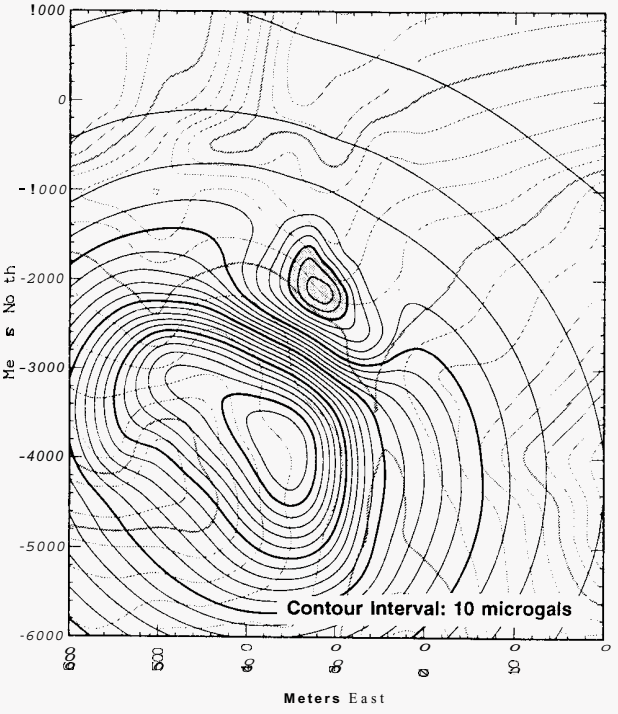


Figure 5c. Gravity change between 0 and 30 years for Case **A.**

The above-described forecast has been useful in designing a network of gravity stations for long-term monitoring of the Sumikawa field. Twenty-six benchmark locations have been selected and occupied in and around the Sumikawa area based on these calculations. Gravity measurements with a LaCoste & Romberg Model D gravity meter and levelings utilizing the GPS (global positioning system) have been carried out during the last three years to obtain the baseline "initial state" of the gravity field. Monitoring of shallow groundwater levels will begin in **1994.**

In history-matching studies, observed gravity changes may be compared with computed gravity changes arising from a particular mathematical reservoir model. Such comparisons would provide additional constraints on the history-matching process (analogous to comparisons between computed and observed underground pressure and temperature changes), and thus improve the quality of the resulting reservoir model. The mathematical models of the Sumikawa reservoir used in this study do not incorporate any increase in deep recharge in response to production-induced pressure decline. Gravity monitoring results from the Sumikawa field during the first decade of production should help improve the representation of the reservoir boundary conditions (particularly the deep recharge boundaries) under conditions of fluid withdrawal.

5. CONCLUDING REMARKS

Numerical models of geothermal reservoirs are never precise, owing to the problem of non-uniqueness. The difficulty increases as the amount of available relevant field data becomes smaller. For example, if only a few facts are known about the reservoir, a variety of theoretical reservoir models may explain these known facts equally well, but yield very different predictions of future potential. **As** the amount of field data available increases, of course, these uncertainties diminish. Thus, as time goes on, the understanding of the reservoir improves and forecasts become more reliable.

Typically, the data base upon which numerical reservoir models are constructed consists of (1) geophysical surveys of various types,

usually performed prior to development, (2) geological interpretations of underground structure, (3) downhole pressure and temperature surveys in shut-in wells, (4) flowing downhole surveys in wells, and *(5)* pressure-transient test results. Once exploitation begins in earnest, additional data become available such as temporal trends in downhole flowing pressure and enthalpy. These latter data may be used in "history-matching" studies.

Since the uncertainty in the predictions of numerical reservoir models is directly related to the amount of field data available against which the models can be tested, it is clear that the addition of repeat gravity survey data to the above list of pertinent field measurements is likely to improve the reliability of these forecasts. It is particularly noteworthy in this connection that, unlike most available data for history-matching, changes in gravity anomaly are the consequence of integrated effects (that is, the volumetric distribution of mass change) rather than simple point values (feedpoint pressures and temperatures in wells, for example). As such, they show considerable promise for appraising the volumetric properties of any proposed mathematical reservoir model. Since the future performance potential of a geothermal field depends mainly on volumetric properties of the field (for example, available quantities of mass and heat in place) and upon such quantities as pressure support by recharge through the reservoir boundaries, measurements of this type offer unique promise for improved reservoir assessment technology.

The application of improved geophysical and geochemical techniques to reservoir management is the objective of GSJ's "Study on Reservoir Dynamics" geothermal research program. We are also pursuing the development of improved field survey techniques and associated modeling studies involving other geophysical survey techniques and their application to reservoir performance monitoring, such as repeat self-potential surveys (see e.g. Ishido et al., 1989) in addition to gravity monitoring.

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