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INTEGRATED NUMERICAL RESERVOIR MODELING COUPLED WITH GEOPHYSICAL MONITORING TECHNIQUES

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ABSTRACT

A new R & D project to develop novel techniques for monitoring and modeling reservoir mass and heat flows is described. Integrated reservoir modeling and simulation technology is being developed which will improve the quality of mathematical reservoir models by taking account of geophysical data sets such as changes in micro-gravity, self-potential, resistivity and seismic properties in addition to the conventional data sets usually employed in reservoir engineering studies. Computational feasibility studies of reservoir monitoring using geophysical survey techniques were performed based on a steady-state three-dimensional model of a hypothetical (but realistic and typical) geothermal reservoir system which was developed using a numerical reservoir simulator. Starting with this steady-state system, an exploitation strategy involving a 50 MW geothermal power station was devised and further numerical calculations were performed, which induced the changes in underground pressure, temperature, steam saturation and the underground flow pattern caused by 27 years of field operation. Then, various mathematical "postprocessors" were applied to this 27-year computed reservoir history to appraise changes that could be observed using various surface geophysical measurement techniques. Survey methods examined include surface microgravity, downhole microgravity profiling, electrical resistivity surveys, self-potential surveys and seismic surveys. The results suggest that these techniques have considerable promise. The development of various "postprocessors" and a database system were planned based on these feasibility studies.

1. INTRODUCTION

The New Energy and Industrial Technology Development Organization (NEDO – a Japanese Government agency) has carried out various projects over the years to promote geothermal development. Starting in 1997, NEDO undertook a new initiative: *Development of Technology for Reservoir Mass and Heat Flow Characterization,* which is broadly divided into two parts: (1) *Characterization of the Hydrological Properties of Fractures* and (2) *Monitoring and Modeling of Reservoir Mass and Heat Flows* (Horikoshi *et al,* 1998). The second part of the project involves several tasks:

(1) Gravity monitoring: to improve methods for measuring changes in gravity.
(2) Electrical and electromagnetic monitoring: to improve methods for measuring changes in SP and resistivity.
(3) Seismic monitoring: to improve methods for measuring changes in seismic properties.
(4) Integrated reservoir modeling and simulation techniques: to develop technology for integrated analyses of these data sets with conventional data, incorporating numerical reservoir modeling. In this way, more robust reservoir models can be developed to help optimize exploration strategies, guide field management, and make geothermal electricity more competitive.

This paper provides an overview of Task 4 (above) and describes the scope of work as well as the present developmental status of the various geophysical and geochemical postprocessors and other simulation-related software systems.

2. PROJECT OUTLINE

Fig.1 illustrates the overall concept. The general procedure for developing a numerical geothermal reservoir model is shown in the upper part of the figure. An appropriate conceptual model is first constructed by reviewing all of the data available from the field. Then, a numerical model based on the conceptual model is constructed and calibrated by (1) "natural-state simulation" (to match observed pre-production states) and (2) "history match simulation" (if exploitation history data are available). If more constraints (based on more field measurements) can be imposed upon the model during these calibration stages, more robust reservoir models of the present-state can be developed so that more precise forecasts of future reservoir performance can be made. The project consists of the following two subtasks:

(1) *Development of postprocessors and other related software* for calculating changes in gravity, self-potential, resistivity, seismic properties and geochemistry based on the numerical reservoir simulation model.
(2) *Development of reservoir modeling and simulation techniques* (incorporating results from the postprocessors) by performing modeling studies on actual fields, focusing in particular on "history matching" studies using models involving representations of fractured geothermal reservoirs.

The first subtask consists mainly of software development; the essential components are shown schematically in Fig 2. The system can be broadly subdivided into three parts: the reservoir simulator itself, the postprocessors, and the database system. In our development plan, the system is not monolithic; instead, it is being constructed in a modular fashion so that appropriate tools may be selected for each practical application. The postprocessors are independent of each other, and each tool may be used alone or in concert with others for reservoir modeling studies.

3. DEVELOPMENT STATUS

Here, we describe progress made to date – many of the software development efforts are still in the early stages.

3.1 Postprocessors

Before this project began, a gravity postprocessor for the STAR geothermal reservoir simulator had already been constructed (Ishido *et al.*, 1995, and Pritchett, 1995). A postprocessor to calculate surface self-potential (SP) had also been developed for the STAR to facilitate the calculation of the electrokinetic effects which result from geothermal field evolution (Ishido and Pritchett, 1999). The development of new postprocessors in this project is based to a significant degree on these existing postprocessors, and the existing gravity and SP postprocessors are also being enhanced. New postprocessors are being developed to calculate changes in subsurface electrical resistivity, seismic observables, and fluid geochemical composition (tracer concentrations).

Before starting software development and enhancement, we carried out a computational feasibility study of using various geophysical methods to characterize subsurface changes in geothermal systems, applying these postprocessors and other existing techniques (Pritchett *et al,* 2000). In the study, a steady-state three-dimensional model of a hypothetical (but realistic and typical) geothermal reservoir system was developed using the STAR numerical reservoir simulator. A calculation of the effects of producing 50 MW of electricity for 27 years was then carried out, causing the distributions of underground pressure, temperature, steam saturation, and the underground fluid flow pattern to evolve. Then, various mathematical postprocessors were applied to this computed reservoir production history to appraise the changes that might be observable using various surface measurement techniques. Survey methods examined include surface microgravity, downhole microgravity profiling, electrical resistivity surveys (both DC resistivity and MT surveys), self-potential surveys and seismic surveys.

The results of the feasibility study were encouraging, so the program to enhance existing postprocessors and develop new ones was undertaken. First, the existing STAR microgravity postprocessor was extended to permit forecasting the response of a subsurface downhole gravity meter (in addition to surface measurements). This new tool was applied to the same hypothetical reservoir described by Pritchett *et al*. (2000) to compute changes in downhole microgravity profiles (Pritchett, 1998). Fig. 3 shows the computed vertical distribution of microgravity change (relative to natural state conditions) in a monitor well located centrally in the production wellfield after 1000, 2000, 5000 and 10,000 days of field operation. These changes in gravity are mainly due to the intensification and migration of the underground steam zone caused by fluid production. The signal amplitudes in the downhole profiles substantially exceed their expressions at the ground surface. At 10,000 days, the gravity changes at the surface amounts to –949 microgals whereas the subsurface extrema are +1,320 microgals and –1,398 microgals (total range 2,718 microgals). This calculation indicates that it should be feasible to accurately delineate regions where production-induced subsurface boiling is taking place if it is possible to develop and deploy instrumentation to accurately measure downhole microgravity changes in operating geothermal fields.

We plan to develop "resistivity postprocessors" for calculating (1) production-induced changes in the distribution of subsurface electrical resistivity (which arise mainly from changes in temperature and steam saturation), and (2) the effects of these underground resistivity changes on the results of both conventional DC resistivity surveys and MT (or CSAMT) surveys. Pritchett *et al.* (2000) examined the changes that might be observed using a conventional earth-surface Schlumberger DC resistivity array, using a prototype STAR "testbed" DC resistivity postprocessor which will form the basis for future development of a general-purpose DC resistivity postprocessor. Existing techniques for 3-D forward modeling of MT/CSAMT surveys will be adopted for development of the MT resistivity postprocessor.

We have not yet developed a general-purpose postprocessor to predict operations-induced changes in seismic survey results based on reservoir simulations. As a first step, Stevens *et al.* (2000a) carried out a preliminary assessment of the feasibility of monitoring changes in a geothermal field using seismic methods. It appears that seismic monitoring of a geothermal reservoir is feasible, but careful design of the seismic experiment is essential if meaningful changes are to be observed. To facilitate efficient design of the seismic monitoring network and comparisons between calculations and observations, we plan to develop a seismic postprocessor to calculate the production-induced changes in propagation characteristics based on simulation results. To this end, the status of existing models for the effects of changes in temperature and steam saturation on seismic propagation characteristics of reservoir rocks has been reviewed (Nur and Dvorkin, 1999). Laboratory tests of typical geothermal reservoir rocks are presently being performed to provide practical data for these models.

A new geochemistry postprocessor has been developed for use with the STAR geothermal reservoir simulator (Pritchett, 1999). The purpose of the new postprocessor is to facilitate the simulation of tracer experiments in operating geothermal fields. Both "natural" tracers (such as chloride, isotopes, etc.) and "artificial" tracers (such as organic dyes, rare gases or radioactive tracers emplaced in the reservoir using injection wells) may be treated. The tracers are collected by one or more production wells. The mass fractions and cumulative production of each tracer in the output flow stream may be evaluated as functions of time, either in the gross fluid mixture or in the separated water or separated steam. The flows from individual wells may be analyzed, flows from groups of wells (such as those connected to a particular separator) may be treated together, or the entire field-wide discharge may be appraised as a unit. These "tracers" may be adsorbed on rock surfaces, may experience thermal, chemical or radioactive deterioration at the user's option, and will partition between the liquid and vapor phases according to temperature-dependent user-specified partition functions.

3.2 Simulator and Related Software

In the NEDO program, the reservoir simulator itself is considered to be "existing technology" – we are not undertaking the development of a new reservoir simulator. The various postprocessors to be developed are, however, completely dependent upon output from reservoir simulation calculations, and the reservoir simulator occupies a central position in the system (Fig. 2). The STAR general-purpose multiphase multi-dimensional unsteady geothermal simulator (Pritchett, 1995) was chosen as the core simulator at the beginning of the project, since the existing gravity and SP postprocessors had been already developed for the STAR. The STAR code was initially designed for operation on computers using the UNIX operating system. Now that powerful and inexpensive PC's have become available, to facilitate efficient reservoir modeling using the various postprocessors the STAR system has been converted to permit operation in a Microsoft Windows (95, 98, NT etc.) environment as well. Patnaik *et al.* (2000) describe the operating procedures for the STAR system, and discuss this conversion. The STAR usage on the PC is now functionally equivalent to operation in UNIX.

To make the capabilities of the postprocessors being developed under this project available to users of reservoir simulators other than the STAR, "interface" codes to couple the postprocessors with other popular geothermal reservoir simulators are also being developed. The TOUGH2 code developed by Pruess (1991) and the SING2 code developed by NEDO (1991) are the principal candidates. Such an interface code reads output from the reservoir simulator and creates a new output file designed to mimic the special-purpose STAR output file which drives the postprocessors. An interface between the postprocessors and the TOUGH2 code was developed during fiscal year 1998 based on consultations with Pruess (1999). As a result, the existing gravity and SP postprocessors can now be used for TOUGH2 reservoir simulations, so long as certain restrictions on the TOUGH2 computational grid geometry are observed.

3.3 Database System

A database system is being developed that both stores archival geothermal data and supports geothermal reservoir modeling calculations. The database will maintain field data and help to organize and review input and output data from calculations. The initial design of the system is being developed using the basic functionality of GEOSYS (Stevens *et al.*, 1995), a geothermal database system originally developed for UNIX workstations. The system is being redesigned, extended to support information and displays developed in reservoir modeling studies (especially in the "history match simulation" phase), and converted to Microsoft Windows (95/98/NT). Stevens *et al.* (2000b) describe the overall architecture of the system, basic functionality, database structure, graphical displays, and development of low level database access functions.

The database system is being developed using the incremental prototype development method, which means that the system gradually evolves in a series of design/development cycles. The first stage of the database development has focused primarily on development of low level database access functions and prototyping to resolve design issues relating to database access, graphical displays, and user interface. The use of ActiveX Data Objects (ADO) allows the system to run using either a local Microsoft Access database or a client-server relational database such as Oracle or SQL with no changes to the code.

4. SUMMARY

Integrated reservoir modeling and simulation techniques are being developed to improve mathematical reservoir models by supplementing the conventional data sets (pressures, temperatures, discharge enthalpies etc.) usually used to constrain the modeling process with additional measurements acquired using geophysical techniques. Computational feasibility studies of geophysical reservoir monitoring have been performed, with encouraging results. Development of various computational "postprocessors" and a database system has been undertaken based on these feasibility studies.

The gravity postprocessor has been extended to permit the simulation of the response of a subsurface gravity meter. Various other postprocessors, simulator-related codes and a database system are also being developed. Application of these techniques to real operating geothermal fields is planned in the near future.

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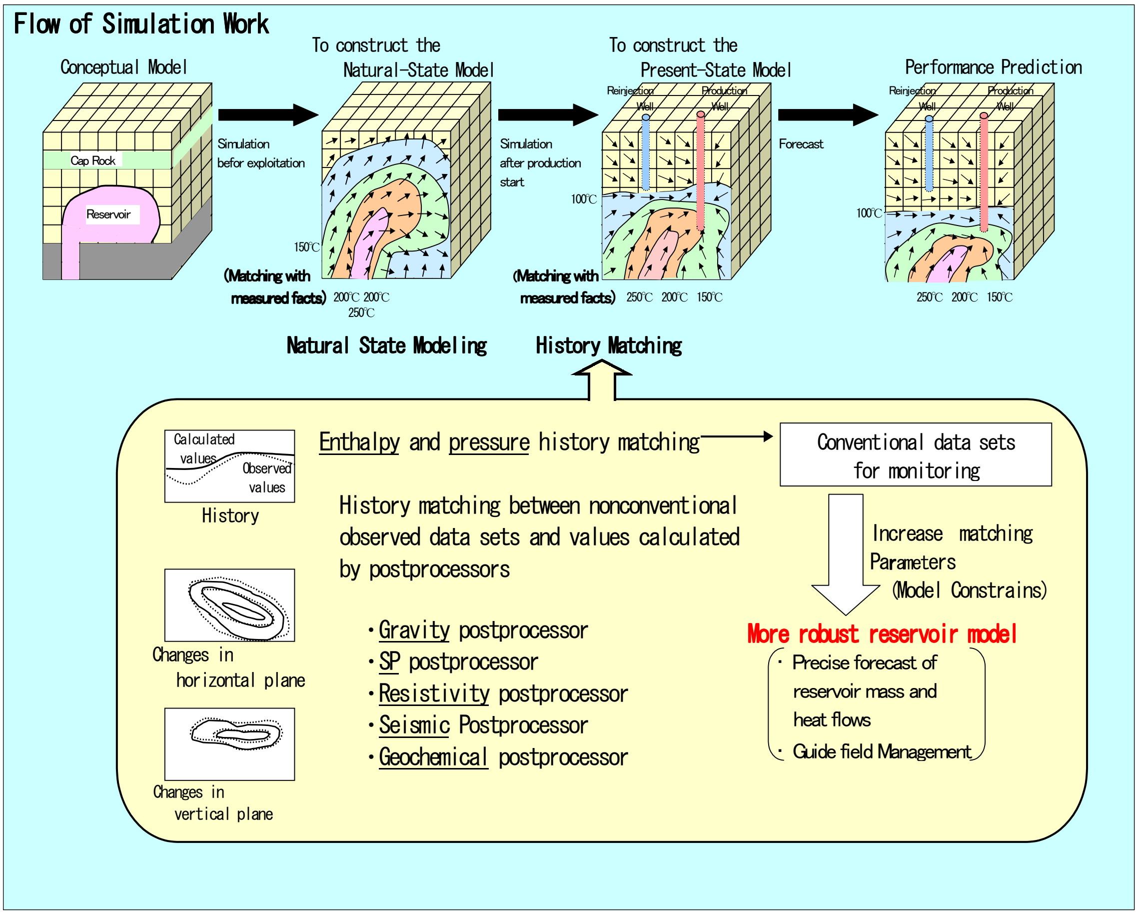

Figure 1. Integrated reservoir modeling and simulation technique

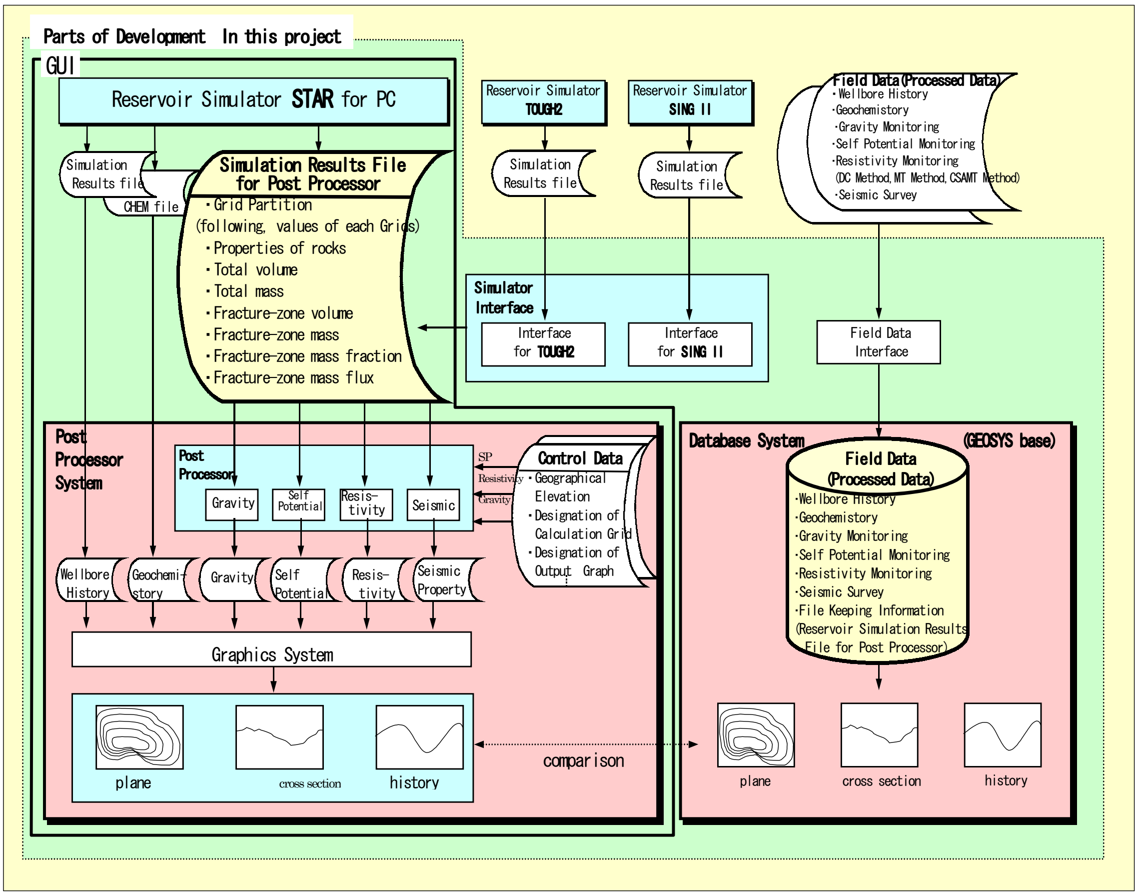

Figure 2. System components to be developed in the project.

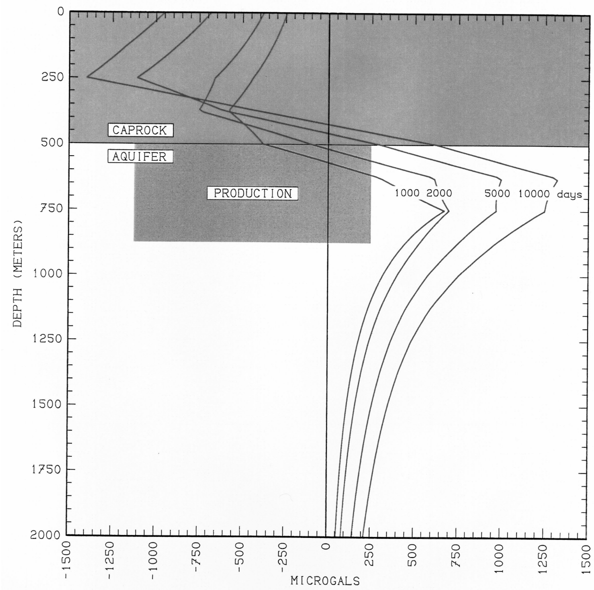

Figure 3. Computed downhole gravity change from natural state in monitor well located in center of production wellfield. The dark rectangle indicates the vertical extent over which production well feedpoints are considered to be distributed for computational purposes.