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THE *STAR* GEOTHERMAL RESERVOIR SIMULATION SYSTEM IN A *PC* COMPUTING ENVIRONMENT

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ABSTRACT

STAR, Maxwell's numerical reservoir simulator, solves a set of nonlinear partial differential equations which describe unsteady flow of fluid mass and heat in heterogeneous rock formations. STAR was initially written primarily in Fortran for UNIX workstations. Now that inexpensive and powerful PC's are available, the STAR simulator and related post-processing software have been converted for PC operation. First, all computational source code was moved to the PC platform and compiled with DIGITAL "Visual Fortran for Microsoft Windows" on a Pentium II machine. Non-standard features were identified and removed. The printed output was compared to that generated by a UNIX workstation for a suite of test problems, with favorable results. Next, STAR's internal graphics software was transferred to the PC. The lowest level graphics routines were replaced with C routines which use some of the Windows graphics primitives. With the completion of these two steps, operation of the software on a PC is now functionally equivalent to operation on a UNIX workstation, and existing UNIX users should have little difficulty running STAR on a PC. We plan to maintain both versions in the future.

1. INTRODUCTION

The STAR general-purpose multiphase multidimensional unsteady geothermal reservoir simulator (Pritchett, 1995) was initially designed for operation on computers which use the UNIX operating system (or related systems such as AIX or UNICOS). The code was written at Maxwell in Fortran 77 (with a few functions in C) and uses a specialized low-level graphics package to display computed results. STAR is also equipped with various computational post-processors to permit the interpretation of measurements from geophysical surveys of operating fields and their use in history-matching studies. Much of this latter capability has been developed with support from NEDO (the New Energy and Industrial Technology Development Organization) and GSJ (the Geological Survey of Japan), both agencies of the Japanese Government.

In recent years, powerful and inexpensive PC's have become available. Therefore, the STAR system (including the simulator itself and all associated computational and graphical pre- and post-processors) has been converted to permit operation in a Microsoft Windows (95, 98, NT etc.) environment as well. This conversion involves three distinct steps. First, all of the computational programs (pre-processors, reservoir simulator and post-processors) were moved to the PC and compiled with DIGITAL Visual Fortran. This conversion was tested by comparing computed results for a suite of test problems with results from the original UNIX implementation. In the second step the STAR graphics package was converted for PC operation by replacing the lowest level routines with C routines which use some of the Windows GDI (Graphical Display Interface) primitives to create images on the screen. Accordingly, operation of the new version of STAR in a PC environment is now functionally equivalent to operation in UNIX. The third step (still in progress) involves the development of a Graphical User Interface (GUI) to facilitate the smooth operation of the system. We also plan to take advantage of existing commercial software to enrich the graphical output capabilities of STAR.

2. USING THE STAR SYSTEM

STAR is not just a single computer program, but is instead an interrelated system of several computer programs that carry out different tasks in a mutually-supportive and internally consistent fashion. The principal programs in the system together with brief descriptions of their functions are listed in Table 1. Accordingly, solving a reservoir problem may involve several different computer runs using various programs in the system.

Figures 1, 2 and 3 summarize typical operating procedures. The interactive "Generator" program assembles the source code for the STAR reservoir simulation program according to the configuration of the problem at hand (Fig. 1). The user specifies dimensionality (1-D? 2-D? 3-D?), fluid equation-of-state selection, and parameters which dictate the sizes of internal computational arrays. The generator then accesses the STAR master program libraries, assembles Fortran/C source code to meet the specifications, and then compiles and links the source code creating custom-made executable files for the STAR simulator itself and for the "Snapshot" plotting post-processor. The "Simulator" may then be executed using user-prepared input data files, creating a number of large output files (Fig. 2) which in turn provide data needed to run the various post-processor programs (Fig. 3).

Post-processor programs include both display and report-generating utilities ("Snapshot", "Time-plot", "Power-station" etc. – see Table 1) and computational programs capable of calculating the effects of underground changes in the reservoir on quantities observable from the surface. These latter quantities include results of microgravity surveys, self-potential changes, DC resistivity surveys and MT soundings, changes in seismic surveys, and changes in the compositions of fluid samples obtained from wellheads and separators. The main purpose of the computational postprocessors is to provide a capability to computationally mimic ongoing reservoir monitoring operations in geothermal fields and thereby make numerical models of geothermal reservoirs more robust and reliable by reducing non-uniqueness and adding constraints for history-matching studies. Development of some of these computational post-processors is still in progress.

3. APPROACH TO CONVERSION

The STAR reservoir simulator itself and the various computational post-processors (microgravity, self-potential etc. – see Table 1) were actually very easy to implement on the PC since they are large but straightforward Fortran computational programs with few special or unusual requirements. The most difficult tasks were to revise (1) the code installation procedures, (2) the "Generator" program and (3) the JPLOT graphics module.

The STAR installation procedure is rather different on a PC compared to the UNIX environment, and the STAR "Generator" required substantial reconfiguration for PC operation. On a UNIX workstation, executing a custom script file installs all the pre/post-processor executables. On the PC however, advantage is taken of the "Developers Studio Environment" (DSE) provided by Microsoft, in which editing, compiling, linking, running and debugging are all done in one integrated environment. First, a "Win32 Console Application Project Workspace" is opened in the DSE and the appropriate source code from various directories is collected, compiled and linked. The resulting executable files are stored in a "bin" directory. Then the generator program is run from an MS-DOS window, very similar to the workstation environment.

STAR output graphics generation (both for screen display and for hardcopy) is accomplished by the JPLOT package (Pritchett and Alexander, 1986). Typically, each STAR computational or graphical post-processor creates an "intermediate graphics file" (IGF) which contains a sequence of JPLOT directives. The JPLOT directives are written in a meta-language which is unique to JPLOT. When the JPLOT program is executed using the IGF file as input, images are created in accordance with the directives in the IGF. The JPLOT computer-graphics plotting package originally arose from an attempt to create a relatively "site independent" plotting formalism useful in transporting large scale Maxwell simulators to various customers' facilities. In this spirit, JPLOT was organized in four separate subdirectories or levels. The lowest level routines are either Fortran or C functions which call device-dependent functions to perform the most basic graphic operations, such as drawing a line, changing pen color, filling and clipping, and so on.

For screen-display on the PC, a new Windows program was written in C. This program first sets up the window for viewing the plots and then passes control to Fortran. Since Windows uses a device-independent Graphical Device Interface (GDI), the program should run on any Windows PC, independent of display hardware. The new program makes use of Windows' "message-driven architecture". To generate hardcopy graphics, another JPLOT variant is provided which creates "postscript" files directly (not using "screen-dumps" or similar artifices), suitable for printing or for inclusion in other documents using a word processor or desktop-publishing package such as WordPerfect, Microsoft Word or PageMaker.

4. HARDWARE AND SOFTWARE

The state-of-the-art in PC hardware and software is advancing so rapidly that it is difficult to characterize a "typical" PC configuration. Most of the present development work was carried out on a PC with the following specifications, which are already obsolescent but may be regarded as a "minimum" configuration for running the STAR system. Machines with faster CPU's and larger amounts of RAM and hard disk will, of course, be more satisfactory for large-scale calculations. Note that Fortran and C compilers are required for STAR operation, since the "Generator" uses them.

Hardware:
Pentium II with 266 MHz MMX Processor
512K Cache
Phoenix BIOS
64 MB RAM
6 GB Hard Drive
SVGA 17" color monitor

Software:
Windows NT 4.0, Service Pack 3
Microsoft Developer Visual Studio 97
- Digital Visual Fortran Standard Edition 5.0A
- Visual C++ 5.0
- Visual Basic 5.0

5. OTHER RECENT DEVELOPMENTS

The STAR system has been extended and improved significantly since the previous status report at the last World Geothermal Congress (Pritchett, 1995). As noted above, the system has now been converted for PC operation. Substantial improvements have also been made to input and output capabilities, particularly graphical output. In recent years, effort has focused on developing "postprocessors" capable of simulating the effects of reservoir phenomena upon the results of repeat surveys using conventional exploration geophysical and geochemical techniques (see Table 1). The purpose is to provide additional constraints on the reservoir modeling process by, in effect, adding the capability to "history-match" these phenomena (Pritchett *et al.,* 2000). Five years ago, progress along these lines was limited to the "microgravity" postprocessor. Since that time, additional packages have been developed to examine effects of reservoir changes on the results of surface SP (self-potential) surveys (Ishido and Pritchett, 1996) and DC resistivity surveys. A capability has been added (the "chemistry" postprocessor) to facilitate comparisons between fluid sample compositions obtained at separators with computational results. Work is in progress to treat magnetotelluric and seismic survey measurements in a similar fashion. The following examples serve to illustrate some of these new capabilities.

In a typical natural geothermal system, various fluid masses are usually present which can be distinguished by their chemical composition. Chemical discriminators include dissolved substances such as NaCl, H_2S, and CO_2. As a geothermal field is produced for electrical power, long-term shifts in the compositions of the fluids withdrawn from the field are often observed as a result of migration of water masses from point to point. Moreover, tracer experiments are occasionally carried out in operating reservoirs, in which a slug of tracer is introduced into an injection well, and then the fluids withdrawn from nearby production wells are analyzed to detect and characterize the tracer "return". Fig. 4 shows results obtained using the chemistry post-processor for a synthetic STAR calculation. SF_6 tracer was injected in one injection well, and the produced fluids from four nearby production wells were introduced into a common separator and steam was separated at 0.5 Mpa absolute pressure. The separated steam was then analyzed for SF_6 content. The concentration shows a distinct early peak as SF_6 appears in the nearest production well followed by a second peak when it makes its way to a more distant well. During the 200-day sampling period, as shown in Fig. 4, SF_6 either never reaches the other two wells or is so diffused to be indistinguishable.

The electrical resistivity of a geothermal reservoir is usually lower than that of surrounding rocks owing to relatively high temperature and the presence of less resistive fluid conduits among the more resistive rock matrix. Consequently, for many years surface DC resistivity surveys (using Wenner, Schlumberger, dipole-dipole, etc. surface electrode arrays) have been used for geothermal prospecting and reservoir characterization. If such surveys are repeated from time to time during field exploitation, changes in results arising from reservoir changes may be detectable. Fig. 5 shows the computed percentage changes in the apparent DC resistivity distribution (observed by a conventional ground-surface Wenner DC survey using an electrode spacing of 300 meters oriented east-west) which should be expected after 50 years of 20 MW_e exploitation of the Oguni geothermal field in southern Japan. Underground resistivity increases mainly because of reservoir pressure decline, which causes boiling and an increase in underground (resistive) steam volume. Reservoir cooling by injection also plays a minor role.

As underground conditions evolve during the exploitation of a geothermal field, the natural distribution of electrical potential at the surface changes because of (1) changes in the underground distribution of electrical conductivity and (2) changes in the underground fluid flow pattern. Repeat "self-potential" surveys at the surface can therefore be used to help monitor the behavior of a geothermal field. Fig. 6 shows results obtained using the self-potential post-processor for a STAR calculation of the Onikobe geothermal field in southern Japan in the natural state (prior to the onset of electrical power production in 1975). The natural-state SP distribution at Onikobe is strongly influenced by local topography and the resulting natural southwesterly flows, which cause a substantial southward potential gradient. Similar calculations have been performed of the temporal changes in the self-potential distribution caused by fluid production and injection since that time. Results indicate that these temporal changes should be clearly observable. Unfortunately, verification of these results is not possible, since SP surveys were not carried out at the Onikobe field on a regular basis, and the field is now mature (Nakanishi, Pritchett and Yamazawa, 2000).

6. FUTURE PLANS

STAR, Maxwell's reservoir simulation code, has been transferred to a "Wintel" PC platform. STAR usage on the PC is now functionally equivalent to operation in UNIX. The next step is the construction of GUI (Graphical User Interface) tools to facilitate constructing input data sets, executing the simulator, running the post-processors and viewing the graphical and tabular output seamlessly from the same Windows environment. Various options will then be explored to incorporate commercially available graphics software for line, contour, perspective and 3-D plots to supplement STAR's existing native graphics capabilities.

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Table 1. Principal components of the STAR geothermal reservoir simulation system

PROGRAM	DESCRIPTION
Pre-Processors:	
GENERATOR Program	Interactive program which creates "Simulator" and "Snapshot" executable files according to user's specifications.
EOS-INQUIRE Programs	Utilities providing direct user access to the fluid property data in the equation-of-state library for problem design.
EOS-DATA Programs	Utilities permitting user modification of fluid equation-of-state data (definition of physical properties of dissolved solids and gases).
Reservoir Simulator:	
SIMULATOR Program	The "STAR" geothermal reservoir simulator.
Graphical-Post-Processors:	
SNAPSHOT Program	Creates line, contour and vector plots of spatial distributions of reservoir variables (pressure, temperature, saturation, composition, mass flux etc.) at fixed times.
TIME-PLOT Program	Creates plots of scalar point variables (individual grid-block values) and spatially-integrated quantities as functions of time.
EARTH-STRUCTURE Program	Graphical visualization tool for spatial distributions of rock properties, such as porosity, permeability, conductivity, and properties of the fracture system.
WELL-PRESSURE Program	Permits graphical comparison of measured well feedpoint pressure values with calculated reservoir pressure distribution.
WELL-TEMPERATURE Program	Facilitates comparisons between temperature profiles measured in wells and computed reservoir temperature distribution.
POWER-STATION Program	Creates graphical and printed reports on performance history of power stations, production and injection wells, makeup drilling, etc.
Computational-Post-Processors:	
CHEMISTRY Program	Computes temporal changes in compositions of samples taken from wellheads and separators based on results of the STAR reservoir simulation.
GRAVITY Program	Computes temporal changes in surface and downhole microgravity due to field operations based on reservoir simulation.
SELF-POTENTIAL Program	Computes temporal changes in self-potential distribution at the ground surface based on results of reservoir simulation.
DC-RESISTIVITY Program	Computes temporal changes which would be observed in surface DC resistivity surveys based on reservoir simulation.
*MT/CSAMT Program**	Computes observable temporal changes in magnetotelluric electrical resistivity soundings based on reservoir simulation.
*SEISMIC Program**	Computes observable temporal changes in seismic surveys due to changes in underground conditions according to reservoir simulation.
Low-Level Graphics Package:	
JPLOT Program	Reads meta-language IGF files written by graphical and computational post-processors and creates screen and hardcopy graphical displays.

* Program in development – not yet released.

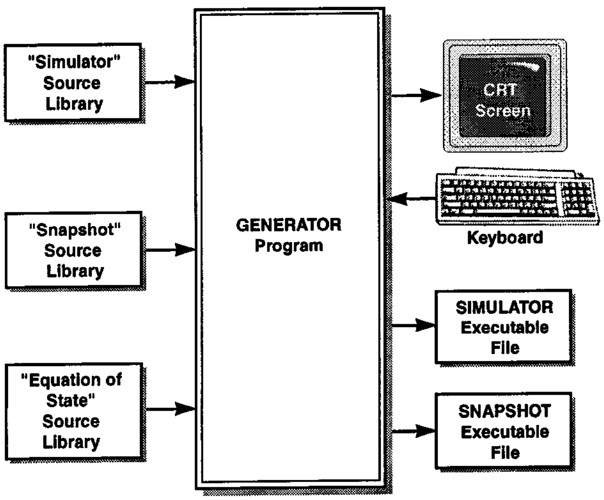

Figure 1: Operation of the STAR generator program.

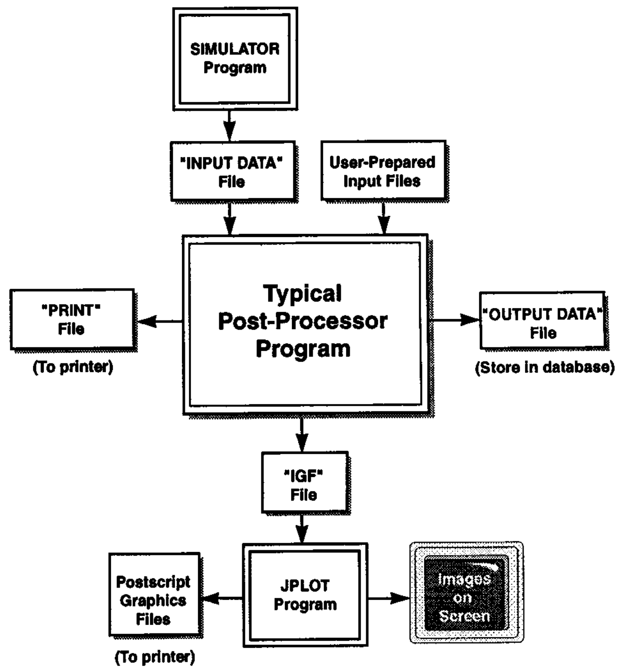

Figure 3: Operation of a typical post-processor program.

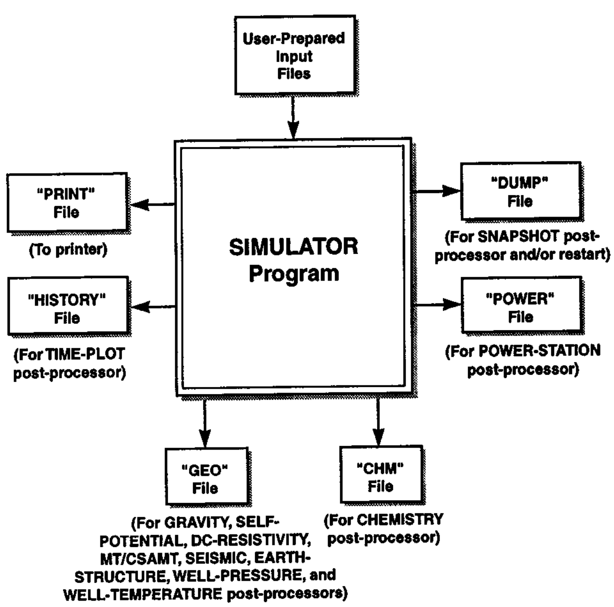

Figure 2: Operation of the STAR simulator program.

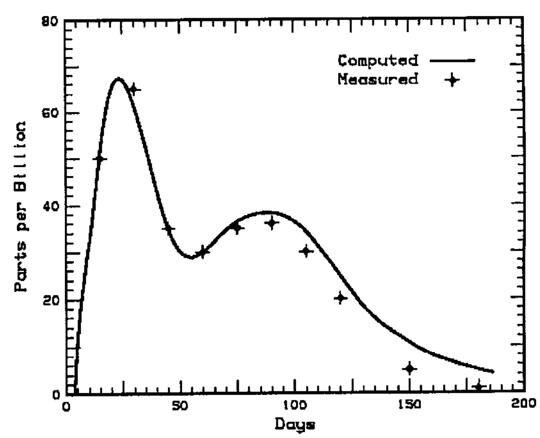

Figure 4: Mass fraction of SF_6 in separated steam (parts per billion) from common separator fed by four production wells. From a synthetic STAR calculation.

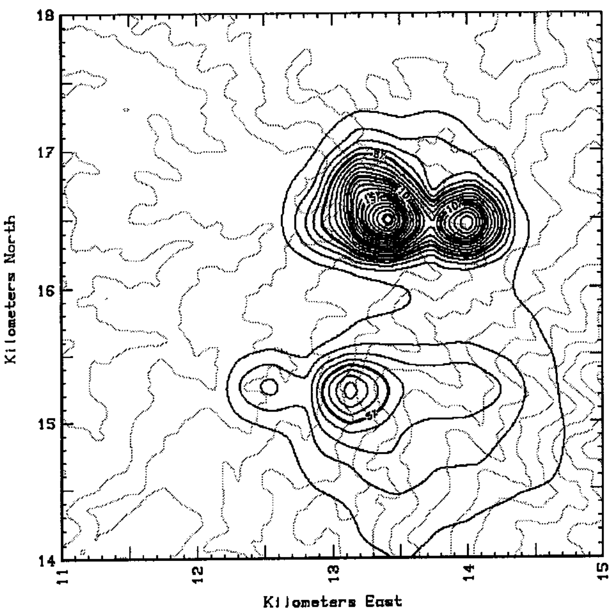

Figure 5: Predicted DC apparent resistivity percentage increase after 50 years of operation at the Oguni geothermal field, using a Wenner array with 300 m electrode spacing oriented east-west. Faint contours indicate local topography.

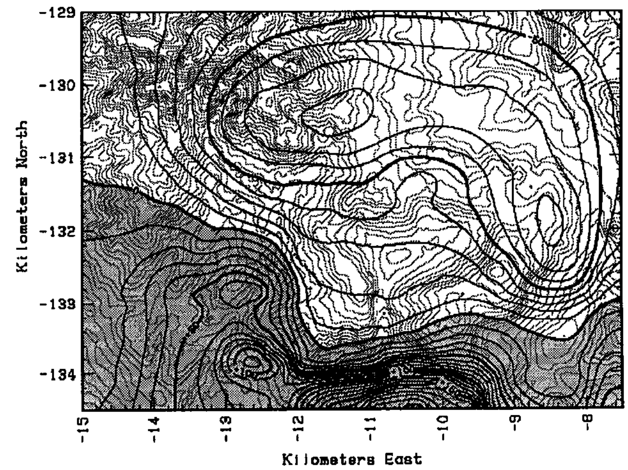

Figure 6: Computed electrokinetic self-potential distribution at the Onikobe geothermal field prior to plant startup (1975). Contour interval is 10 millivolts. Shaded area indicates regions of positive potential. Faint contours indicate local topography.