STAR: A GEOTHERMAL RESERVOIR SIMULATION SYSTEM

Key words: modeling, multi-phase, compositional, three-dimensional, fractured, reservoir simulator

ABSTRACT

The STAR simulation system is the fifth generation in a series of general and flexible computational tools for simulating multiphase, multicomponent transport of fluid mass and heat in three-dimensional geologic media. STAR can operate in one-dimensional slab, cylindrical or spherical geometry, two-dimensional Cartesian or axisymmetric geometry, or three-dimensional Cartesian geometry. Considerable flexibility is provided for imposing various grid shapes, different types of auxiliary conditions, and realistic earth structure upon the fine-difference grid. The code uses a fully implicit iterative technique to simultaneously solve the highly nonlinear equations expressing the overall heat balance and the multicomponent, multiphase mass conservation relations. The thermodynamic description of the multiphase multicomponent fluid in the pores/fractures of the rock is incorporated as a modular computer-accessible equation-of-state package selected from the STAR program library. Postprocessors are incorporated in the system to facilitate the graphical presentation of computed results and to perform auxiliary calculations of the effects of reservoir phenomena upon other observable parameters such as the distribution of gravity anomaly.

1. BACKGROUND

The STAR geothermal reservoir simulation system consists of a generic thermal reservoir simulator computer program (together with various supporting utility programs and program libraries) which was designed specifically for the purpose of simulating geothermal applications. STAR treats unsteady multi-phase (vapor, liquid, precipitate, hydrocarbon) multidimensional (H, O, CO, NaCl, etc.) transport of fluid mass and heat in multicomponent, multi-phase (gas, liquid, water, brine) processes. The STAR system is based on preceeders (QUAGMIRE, MUSHRM, CHARGFR, THOR, STAR) representing over 30 years of experience in developing geothermal reservoir engineering software; each generation in this family of codes represents an expansion of capability and the incorporation of new features.

The STAR family of simulators has been in routine use for many years in geothermal reservoir simulation studies. These range in scope from relatively small-scale studies of nonlinear effects around wells during pressure-transient testing (Garg and Pritchett, 1988 and 1989; Ishido et al., 1992) to long-term calculations of the evolution of the natural-state geothermal reservoirs. A good example is the recent study of hydrothermal systems in 3-D (Rist, 1993) and reservoir-scale history-matching calculations and forecasts of future reservoir capacity (Carter et al., 1995; Pritchett and Garg, 1995). One of the earliest accomplishments of STAR was to replicate the results of a small-scale laboratory experiment involving transient two-phase flow within a rock core sample (Garg et al., 1975). A predecessor of STAR was also successfully tested in the landmark "DOE Code Comparison Project" (Sorey, 1980).

2. COMPUTING ENVIRONMENT

A major objective in the design of the STAR system was to maximize portability. Therefore, STAR is written in the ANSI standard Fortran 77 language, and all source code is always delivered with the STAR system, including the postprocessors. The system has been successfully installed worldwide on diverse computer systems including Cray supercomputers, IBM mainframes, and a variety of smaller systems. The preferred environment is Unix/X-Windows operating on high-performance desktop workstations (Sun SPARCstation, IBM RISC-6000, Hewlett-Packard 731/735, Silicon Graphics Iris/Indigo 400/4500, and similar systems).STAR is also available for use on a 386-Pentium II platform using the Microsoft Windows 3.1 operating system.

Special-purpose postprocessors make extensive use of graphical techniques to display computed results from STAR simulations. Hardcopy graphics may be produced using "Postscript" printers, versions of the graphics library are also available for several other hardcopy plotting devices including CDEComp, Versatek, Tektronix, and a few older machines. Console graphics displays have been implemented for several systems, including X-Windows/Motif, SunView, and MS-Windows. The graphical interface is designed specifically to be readily adaptable to a wide variety of device drivers with minimal effort.

3. NUMERICAL TECHNIQUE

The STAR simulator solves a set of simultaneous nonlinear partial differential equations expressing the conservation of fluid mass and energy using a finite-difference method. The principal unknown variables (functions of position and time) are fluid pressure, fluid specific internal energy, and fluid composition. STAR uses fully implicit techniques to avoid time step size limitations. Convection is treated using a second-order/second-order scheme which sharply reduces "numerical dissipation" errors.

STAR uses a finite-difference computational grid (with variable block spacing) to represent the reservoir geometry. Any of six coordinate systems may be specified: one-dimensional slab (x), one-dimensional radial (r), one-dimensional spherical (r), 2-D planar (x,z), 2-D axisymmetric (r,x) and 3-D Cartesian (x,y,z). Three-dimensional Cartesian geometry is usually used for most practical large-scale reservoir simulation applications, but the other coordinate systems are sometimes used for specialized problems such as well testing simulation or theoretical studies (for example, Garg et al., 1975; Sorey, 1980; Garg and Pritchett, 1988). In 1-D slab geometry, the "cross-section area" may be specified arbitrarily as a function of x. Similarly, the "thick-ness" in 1-D radial and 2-D Cartesian geometries may be arbitrary functions of position.

To facilitate the treatment of systems of irregular shape, provision has been made for any grid block(s) to be "tagged" "void". Each of the non-void grid blocks contains one or another of the various rock formations designated by the user. Any face of any grid block may represent a reservoir boundary of any of several types. This includes internal grid block interfaces, which permit the representation of local discontinuities such as cracks and fractures. Boundary condition options include: (1) "impermeable" boundaries (isothermal, prescribed temperature, prescribed heat flux, or conductive) and (2) "permeable" boundaries (prescribed pressure, prescribed mass flux, or pressure-transient). For the prescribed heat flux and prescribed mass flux boundaries, the prescribed fluxes may be specified as functions of local instantaneous conditions (temperature and pressure). For "permeable" boundary conditions, the user specifies the heat content (enthalpy) and composition of any inflowing fluid.

4. ROCK PROPERTIES

The spatial distribution of pertinent formation properties (porosity, permeability, etc.) as functions of position must be prescribed within
the reservoir volume. To facilitate the specification of the distributions of rock properties in typical heterogeneous geothermal reservoirs, STAGS uses a two-step procedure. First, a series of individual "formations" is defined, each with a unique set of rock properties. Then, the various "formations" are assigned to individual computational grid blocks. For more practical problems, only a few discrete "formations" (each characterized by a unique set of properties) are required. This two-step procedure therefore substantially simplifies the task of assigning rock properties to the various grid blocks.

Several models are available in STAR for describing the behavior of the rock. For each "formation", the user specifies (1) thermal properties (heat capacity, conductivity, thermal expansivity); (2) mechanical properties (density, porosity, elastic moduli); and (3) flow properties (absolute permeabilities, relative permeabilities, capillary pressure relations, dispersion coefficients, adsorption behavior).

The elastic moduli and thermal expansivity define how the local porosity change, in response to ambient pressure and temperature, affect local temperature changes in permeability. A technique for specifying such relationships is incorporated in STAR.

The relative permeability to each fluid phase depends upon both saturation and temperature. In general, capillary pressure functions are also available. A formulation for adsorption (sometimes called "vapor pressure lowering") is incorporated. Adsorption is a mechanism to be used in an important fluid storage mechanism in some vapor-dominated geothermal reservoirs (Hsieh and Ramsey, 1983; Beratan and Cappelli, 1995).

5. FRAC TURES

Geothermal reservoirs are frequently found in intensely fractured rocks. It is often inefficient to treat the rock as a single porous medium, particularly, if short time scales are of interest. The STAR simulator provides for three different descriptions of local fluid heat flow in the rock. These three descriptions ("porous medium", "impermeable matrix" and "permeable matrix") can be freely intermixed within a single calculation; some grid blocks may be treated as containing only a single porous medium while others use either of the MINC-type double-porosity models ("impermeable matrix" or "permeable matrix").

Both of these double-porosity models assume that, on a local scale, the reservoir consists of relatively impermeable blocks of "country rock" (or "matrix") separated by relatively small but highly permeable fracture zones. The average size of the blocks of country rock (or fracture spacing) is assumed to be small in comparison with dimensions of interest (i.e., the size of the reservoir and such computational grid blocks are treated as containing fracture zones). All large-scale (block scale) fluid motion takes place within the fracture system. In the "impermeable matrix" model, the blocks of country rock are completely impermeable, but unsteady heat conduction takes place within the rock blocks and heat transfer occurs between the edges of the matrix blocks and the fluid in the fracture zones. In the "permeable matrix" model, unsteady mass and heat flow both occur within the country rock blocks (high permeability, high storage) as well as within the fracture system (high permeability, low storage), and across the country rock/fracture zone interface. The "permeable matrix" model is essentially equivalent to the MINC technique first proposed by Pmns and Narasimhan (1985).

In both cases, the matrix block representatives are represented by an equivalent spherical rock body subdivided computationally into concentric "shells" to represent the localized mass heat flow in this manner, the transient processes taking place within the individual blocks of country rock may be described by a one-dimensional sub-grid treatment. A matching condition is imposed at the perimeter of the assembly of spherical shells with local conditions within the fractures. Each spherical shells within a representative block of country rock is assigned the same fraction of the block volume, which provides the desired high resolution near the perimeter of the assembly, adjacent to the fracture zones. Each macroscopic computational grid block which is not treated as a "porous medium" contains such a representative assembly of spherical "shells". The classical Warren-Root double-porosity fracture model is thus equivalent to the "permeable matrix" model with only one shell in the assembly.

6. BRINE AND STEAM PROPERTIES

Another essential ingredient is a description of the constitutive behavior of the fluid phases occupying the pore spaces and fractures. Using STAR, the fluid properties (relations among pressure, temperature, enthalpy, composition, saturation, viscosity, density, etc.) required for reservoir calculations are provided by one or another of the ten different "constitutive packages" available with the system. The user selects which of these descriptions is to be used during problem setup. Of these ten packages four ("WATSTM", "WATHEO", "WATGAS" and "BRNGAS") are most useful for ordinary (hydothermal) geothermal applications.

"WATSTM" treats pure H2O using fits to steam-table data, and can describe compressed liquid water, superheated steam and two-phase water/steam mixtures. "WATGAS" incorporates, in addition to H2O, a user-specified incondensible gas (such as CO2, or CH4); this gas may be present in the free gas phase and/or dissolved in the liquid. The "BRNGAS" package adds a "dissolved solid" (such as NaCl) to the H2O/gas mixture; the salt may be dissolved in the liquid phase or, at high concentrations, a solid precipitate may form. "WATSTM", "WATGAS" and "BRNGAS" are validated for temperatures to 500°C and for pressures to around one kilobar Using WATSTM, the user does not need to provide additional fluid data; internal fits to steam-table data are employed. With WATGAS and BRNGAS, the user must define the properties of the additional materials (incondensible gases, dissolved solids). "Default" properties are available for CO2, CH4, and air (gases) and for NaCl (solids).

The recently-developed "WOTH2O" package may become more useful with the completion of several "deep-drilling" projects now underway around the world. Like "WATSTM", "WOTH2O" is restricted to pure H2O systems, but the range of validity extends to 800°C (far beyond the critical point; see Figure 1). Ordinarily, however, unless the high-temperature capability is really needed, the "WATSTM" package should be used to save computer time.

Figure 1. Relations among pressure, temperature, and specific internal energy from the WOTH2O fluid constitutive package. Two-phase (water/steam) region shaded. "CP" = critical point.

Provision has been made in STAR for the incorporation of "passive tracers". It is assumed that, unlike the materials described by the "constitutive packages" (NaCl, CO2, etc.), these "passive tracers" are sufficiently dilute that their presence does not significantly influence the thermomechanical properties of the fluid (density, viscosity, compressibility, heat capacity, etc.). Thus, the "tracer" distribution has no effect on the fluid heat flow pattern itself (but of course the fluid flow pattern has a profound effect on the tracer distribution). This simplification permits the inclusion of multiple tracer species within a STAR calcula-
tor at a little additional computing cost. The user must supply the pertinent trace properties (partition functions among the phases, deterioration/decay rates, adsorption data, etc.) usually as functions of temperature as part of the STAK input data set. These "tracers" can be useful in keeping track of water masses in natural-state simulations, in designing and interpreting trace experiments, and to represent dilute components which, although unimportant hydrodynamically, may significantly influence other measurable reservoir properties (electrical conductivity, for example).

7. GEOTHERMAL PRODUCTION OPERATIONS

Once an adequate model of the "natural-state" of a geothermal field has been developed using STAK, the next step is usually to (1) history-match the exploitation of the field to date, (if any such history exists), and (2) perform forecasts of the future performance of the field. To facilitate these calculations of this type, STAK incorporates features to simulate the effect of field production operations. Production wells may be imposed within the computational grid; the "well performance functions" (relations among bottomhole pressure, bottomhole enthalpy, bottomhole composition, wellhead pressure, and discharge rate) may be specified directly by the user, or alternatively STAR's internal "wellbore model" may be employed to establish these relationships automatically. The "wellbore model" assumes that the wells are free-flowing (not pumped), assumes enthalpy conditions within the well, and assumes that the liquid and vapor phases flow upward without significant interphase "slip". Single- and two-phase pipe friction is treated using a formulation developed by Dukler, Pl. u. (1964). Ordinarily, these assumptions will suffice, but if necessary (for example, for the pumped wells often used to supply binary power stations), well performance characteristics may be calculated externally and supplied to STAK as input data. Injection wells are treated similarly; the fluid within injection boreholes is treated as a single-phase liquid brine.

Groups of production and injection wells may be assigned to "geothermal power stations" (incorporating separators, turbines, condensers, flash tanks, etc.), and power-station operating constraints may be user-supplied. Several power-station models (single-flash, double-flash, pressurized injection, atmospheric injection, separate condensate injection, etc.) are available (see Figure 2) as well as a generalized formulation for unconventional systems (such as binary plants). If desired, the simulator will automatically "drill" make-up wells from time to time as required to maintain a specified steam supply history.

These features are useful both for history-matching studies and for forecasts of future reservoir performance and probable drilling requirements. Figure 3 illustrates changes in underground temperatures induced by thirty years of production and injection operations in a STAR forecast of the performance of the Oguni geothermal prospect in southern Japan (Pritchett and Garg, 1995). Figure 4 shows the corresponding drilling requirements to maintain 250 tons per hour of steam production. Multiple independent "power stations" may be incorporated within a single calculation if desired, to appraise potential interference effects between different operators in non-unified situations.

Figure 3. Changes in underground temperature and steam zone due to 30 years of operation of the Oguni geothermal field in Japan—STAR calculation for 250 tons/hour of steam production. Contour interval is 25°C.

Figure 4. Computed drilling requirements for 30 years of field operation (Oguni model).

8. PRE- AND POST-PROCESSORS

An extensive suite of utility programs and graphics postprocessors is included as part of the STAR system. Tools for specifying fluid properties for the more elaborate fluid constitutive packages are available, as well as fluid property "interrogation" utilities to facilitate problem design. A "generator" procedure to assemble a custom-configured version of STAR for a particular application (1-D, 2-D or 3-D fluid description, etc.) is also a part of the system.

Graphics postprocessors are available to produce (1) "snapshot" plots (contour plots, vector plots, and x-y plots of the "state-of-the-system" at fixed instants of time, pressure, temperature, saturation, mass flux, etc.), and (2) "history" plots of variables as functions of time such as spatially-integrated quantities (mass, energy, steam volume, etc.) or point values (such as temperature at a point). Powerplant performance histo-
ries, well production rates, and so on. Other graphics postprocessors facilitate visualization of the geological structure imposed, comparisons between computed and measured temperature profiles in wells, comparisons between computed and measured shut-in well heatpoint pressure distributions, and the like.

9. 'GEOPHYSICS' POSTPROCESSORS

Non-uniqueness is a persistent problem in geothermal reservoir modeling and simulation. If field data are sparse, it may be impossible to appraise severa competing models; for the system. As the total amount of information from the field increases, models become more definite and reliable. Traditionally, numerical models of geothermal fields are evaluated by the extent to which they reproduce underground distributions of temperature and pressure (as measured in shut-in wells). Sometimes, surface discharge; hot springs; and pressure-transient information are also available for matching. If the field has been exploited for a significant time, one may impose the measured well mass discharge/injection rate histories and compare computed discharge enthalpies and changes in reservoir pressure and temperature with measurements. Generally speaking, however, virtually all numerical reservoir models are underconstrained.

One promising approach to augment the data collected during field exploitation is to monitor the reservoir from the surface using techniques which have traditionally been employed in the past mainly for geophysical exploration. In particular, periodic gravity surveys to detect and characterize changes in microgravity due to changes in underground mass (due to production and expansion of the steam zone), injections due to injection and cooling of injected brine and from cold-water recharge, are strongly related to changes in the reservoir (Hunt, 1988). Comparison of measured gravity change with the consequences of a proposed numerical reservoir model can help evaluate and refine the model (Atkinson and Pedersen, 1988).

For this purpose, a computational/graphical postprocessor has been developed for calculating and displaying changes in surface microgravity due to the computed changes in the underground mass distribution during a STAR simulation. This feature is useful in the experiment design (Ishido et al., 1995), and offers the potential of a powerful new history-matching technique. Unlike comparisons with point measurements of pressure and temperature in wells, changes in gravity arise from the integrated effect of mass redistributions throughout the reservoir. Therefore, they offer the possibility of direct evaluation of models for increases in natural gravity recharge caused by production-induced pressure decline. Figure 5 shows such a calculation, in which production of fluid in the northwest corner of the study area has resulted in local gravity decreases, but also caused the invasion of the area by cold (dense) groundwater from the southeast, increasing gravity in that area.

Other geophysical exploration tools also offer potential for monitoring reservoir changes during exploitation. Work is presently in progress to develop a similar STAR postprocessor to calculate changes in "self-potential" at the ground surface caused by the evolution of the underground flow field. Additional postprocessors of this general type are planned for future years.

10. REFERENCES


