STAR: A GEOTHERMAL RESERVOIR SIMULATION SYSTEM

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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 boundary conditions, and realistic earth structure upon the finite-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 geothermal reservoir simulator computer program (together with various supporting utility programs and program libraries) which was designed specifically from the outset for geothermal applications. STAR treats unsteady multi-phase (vapor, liquid, precipitate, hydrocarbon) multicomponent (H_2O, CO_2, NaCl, *etc.*) transport of fluid mass and of heat in multidimensional heterogeneous geologic media. STAR and its predecessors (QUAGMR, MUSHRM, CHARGR, THOR, STAR) represent over twenty years of development of 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 for 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 of geothermal reservoirs over thousands of years (see for example Riney *et. al.*, 1977; Yasukawa and Ishido, 1990; Pritchett *et. al.*, 1991; Yano and Ishido, 1993) and reservoir-scale history-matching calculations and forecasts of future reservoir capacity (Bertani and Cappetti, 1995; Pritchett and Garg, 1995). One of the earliest accomplishments 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 graphics 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 715/735, Silicon Graphics Iris/Indigo 4000/4500, and similar systems). STAR is also available for use on a 486/Pentium PC 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 CalComp, 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 minimum effort.

3. NUMERICAL TECHNIQUE

The STAR simulator solves a set of simultaneous nonlinear partial differential equations expressing the conservation of fluid mass and of 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 spatial scheme which sharply reduces "numerical dispersion" 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,y), 2-D axisymmetric (r,z) 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 useful for specialized problems such as well-test 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 "thickness" 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 permits the representation of local discontinuous features such as cracks and dikes. Boundary condition options include: (1) "impermeable" boundaries (insulated, 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 (pressure and temperature). 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 ofthe distributions of rock properties in typical heterogeneous geothermal reservoirs. STAK uses a two-step procedure. First, a series of individual "formations" is defincd. each with a unique set of rock properties. Then. the various "formations" are assigned to individual computational grid blocks. Fur most 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 (I)thermal properties (heat capacity. conductivity. thermal expansivity), (2) mechanical properties (density. porosity, elastic moduli) and i3) flow properties (absolute permeabilities, relative permeabilities, capillary pressure relations, dispersion coefficient, adsorption behavior).

The elastic moduli and thermal expansivities define how the local porosily change, in response to underground pressure and temperature changcs. based on linear thermoelasticity. A non-linear "irreversible crushup" model is also availahle. Changes in porosity, in turn. can induce local temporal changes in permeability; a technique for specifying such relations is incorporated in STAR

The relative permeability to each fluid phase depends upon hoth saturation and temperature, in general. Capillary pressure functions are also both saturation and temperature dependent. A formulation for adsorption (sometimes called "vapor pressure lowering") is incorporated; adsorption is believed to be an important fluid storage mechanism in some vapor-dominated geothermal reservoirs (Hsieh and Ramey, 1983; Bertani and Cappetti. 1995).

5. FRACTURES

Geothermal reservoirs are frequently found in intensely fractured cocks. it is aften insufficient to treat the ruck as a simple porous medium, particularly if shan time scales are of interest. The STAR simulator provides for three different descriptions of local fluid/heat flow in the rock. Thew three descriptions ("porous medium", "impermeable matrix" and "permeable matrix") can be freely intermixed within a single calculation: some grid blocks ma) be treated as containing a simple porous mcdium 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 hlocks of "country rock' (or "matrix") separated hy relatively small but highly permeable "fracture zones". The average sizc of the hlocks of country rock (or "fracture spacing") is assumed tu he small in comparison with dimensions of interest (*i.e.*, the size of the reservoir; each computational grid hlock is treated as containing numerous fractures) All large-scale (interblock) tluid motion takes place within the fracture system. In the "impermeable matrix" model. the blacks of country look are completely impermeable, but unsteady heal 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 (low permeability. high storage) as wcll 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 Pruess and Narasimhan (1985).

In both cases, the matrix hlock.: are represented by on equivalent spherical rock body subdivided computationally into concentric "shells" to represent the unsteady mass/heat tlow. In this manner, the transient processes taking place within the individual blocks of country rack may be described hy a one-dimensional sub-grid treatment. A matching condition is imposed at the perimeter of the assembly of spherical shells with local conditiuns within the fractures. Each of the spherical shells within a representative hlock 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 zone. Each macroscopic computational grid block which is not treated as a "porous medium" contains cuch 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", "HOTH2O", "WATGAS" and "BRNGAS") are most useful for ordinary (hydrothermal) geothermal applications.

"WATSTM" treats pure H_2O using fits to steam-table data, and can describe compressed liquid water, superheated steam and/or two-phase water/steam mixtures. "WATGAS" incorporates, in addition to H_2O, a user-specified incondensible gas (such as CO_2 or CH_4); 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 H_2O/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 350°C and for pressures to around one kilobar. Using WATSTM, the user does not need to provide additional fluid constitutive 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 CO_2, CH_4 and air (gases) and for NaCl (solids).

The recently-developed "HOTH2O" package may become more useful with the completion of several "deep drilling" projects now underway around the world. Like "WATSTM", "HOTH2O" is restricted to pure-H_2O 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.

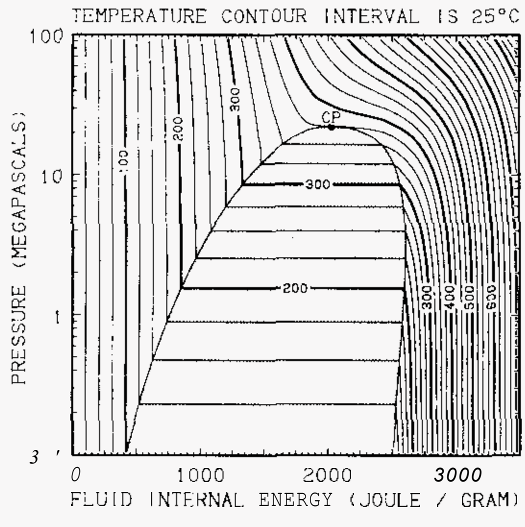

Figure I. Relations among pressure, temperature and specific internal energy from the HOTH2O fluid constitutive package Two-phase (water/steam) region shaded. "CP" = critical point.

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, CO_2, *etc.*), thesc "passive tracers" are sufficiently dilute that their presence does not significantly influence the thermomechanical properties of the Huid (density. viscosity, compressibility, heat capacity, *etc.*). Thus. the "tracer" distribution has no effect on the fluid/heat tlow pattern itself (but of course the tluid flow pattern has a profound effect on the tracer distribution). This simplification permits the inclusion of multiple tracer species within a STAR calculation at little additional computing cost. The user must supply the pertinent tracer properties (partition functions among the phases. deterioration/decay rate?. adsorption data. *etc.*, usually as functions of temperature) as part ofthe STAK input data set. These "tracers" can he useful in keeping track of water masses in natural-state simulations, in designing and interpreting tracerexperiments, 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 fisld has been developed using STAR. the next step is usually to (1) history-match the exploitation ofthe field to date (if any cuch history exists). and (2) perform forecasts of the future performance of the field. To facilitate 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 isenthalpic conditions within the h o w hole, and assumes that the liquid and vapor phases low upward without significant interphase "slip". Single- and two-phase pipe friction is treated using a formulation developed by Dukler, *et. al.* (1964) Ordinarily, these assumptions will suffice, hut 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 hrine

Groups of production anti injection wells may h: assigned to "geothermal power stations" (incorporating separators. turbines, condensers, flash-tanks, *etc.*), and power-station operating constraints may by user-supplied Several power-station models (single-flash, double-flash, pressurized Injection. atmospheric injection, separate condensate injection, *etc.*) are availahle (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.

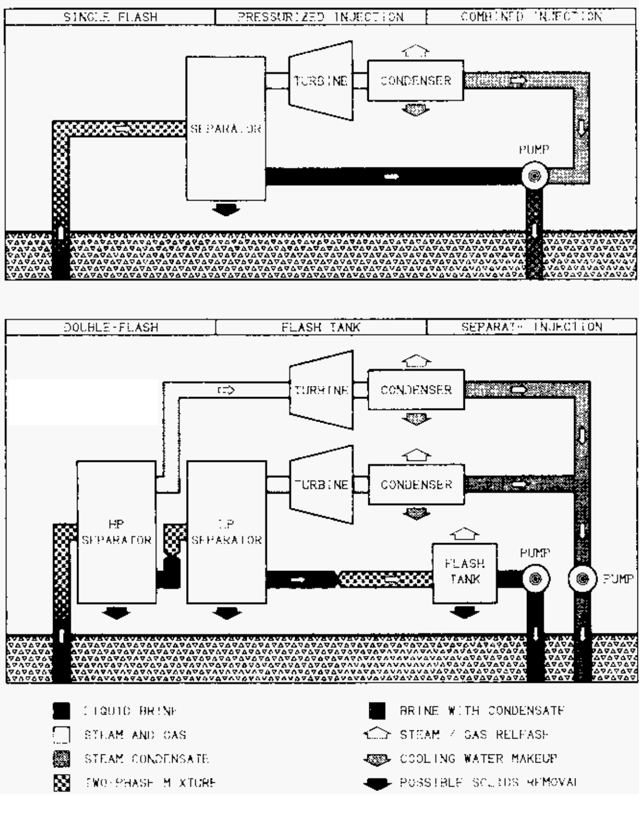

Figure 2. Examples of power station models available in STAK.

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-unitized situations.

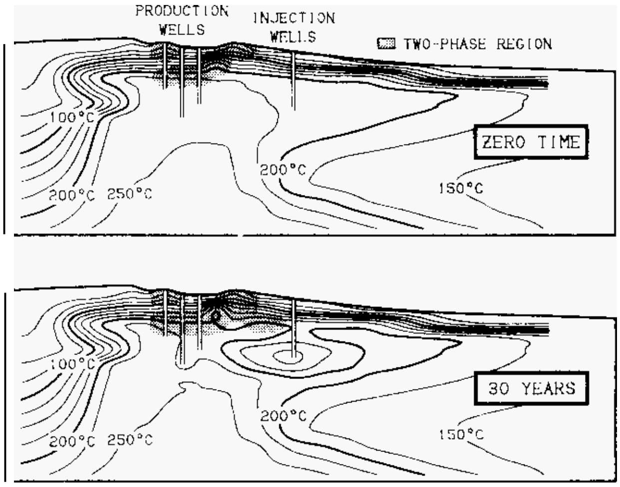

Figure 3. Changes in underground temperature and steam zone due to 30 years of operation of the Oguni geothermal field in Japan—STAR calculation for 250 tons/hour of steam production. Contour interval is 25°C.

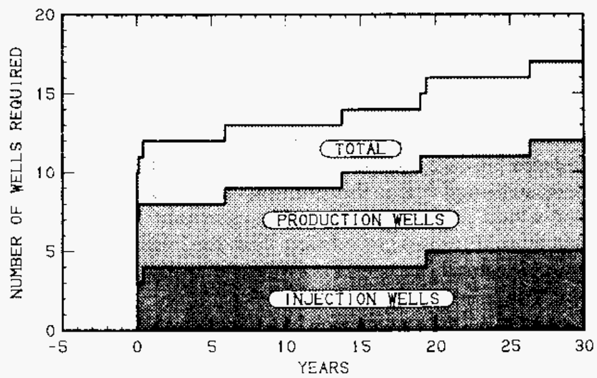

Figure 4. Computed drilling requirements for 30 years of field operation (Oguni model).

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.), point values (such as temperature at a point), powerplant performance histories, 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 feedpoint 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 he impossible to appraise several competing model.; 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 hy the extent to which thcy reproduce underground distributions of temperature and pressure (as measured in shut-in wells). Sometimes, surface discharge; (hot springs) and pressure-transient information are also availahle for matching. If the field has hren exploited for a significant time, one may impose the measured well mass discharge/ injection rate histones and compare computed discharge enthalpies and change? 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 resurveys to detect and characterize changes in microgravity due to changes in underground mass (decreases due to production and expansion of the steam zone; increases due to injection and cooling from injected brine and from cold-water recharge) are strongly related to change? in mass-in-place 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 Pederson, 1988).

For this purpose, a computational/graphical postprocessor has hccn 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 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 reservoir recharge caused hy production-induced pressure decline. Figure 5 show such a calculation. in which production of fluid in the northwest corner of the study area has resulted in local gravity decreases, but has 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 thii general type are planned for future years.

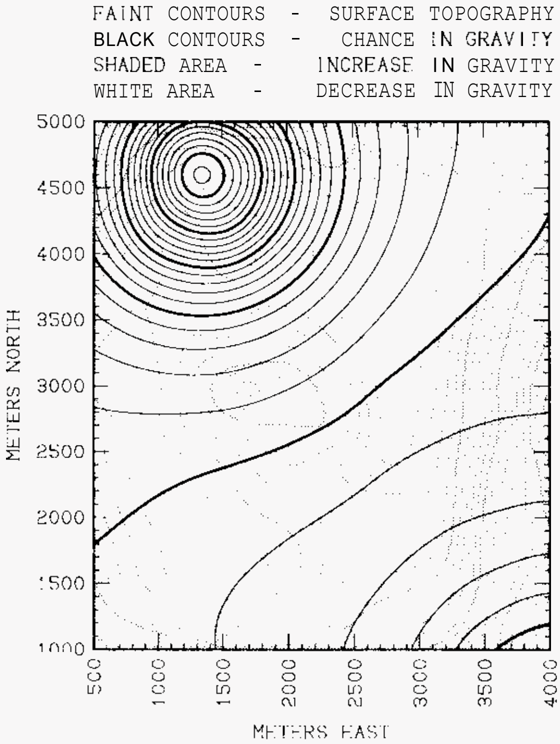

Figure 5. Calculated changes in surface microgravity (5 milligal contour spacing) after 22 years of hypothetical field operation.

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