MODELING FLOW IN A JOINTED GEOTHERMAL RESERVOIR

Daniel Swenson, Robert DuTeau, and Timothy Sprecker

Mechanical Engineering Dept., Kansas State University, Manhattan, KS 66506

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ABSTRACT

A coupled model of rock deformation, fluid flow, and heat transfer has been developed and used to simulate the Hot Dry Rock (HDR) geothermal reservoir at Fenton Hill, New Mexico. The goal of the model (GEOCRACK) is to address such questions as: the number and spacing of wells for optimal heat mining, the effects of low impedance flow paths (short-circuiting), the effects of operating the reservoir in different circulation modes (steady state or periodic pressurization), and the long term thermal performance of the reservoir.

Simulations of the Fenton Hill HDR reservoir show the model correlates with actual flow rates under differing pressure conditions, replicates reservoir tracer behavior, and reproduces the transient reservoir behavior observed. The model also simulates the heat transfer behavior of an HDR reservoir and can therefore be employed to examine the long term behavior and energy availability from an HDR resource. The model predicts reservoir impedance to drop significantly due to the thermal contraction of rock and the adjacent joints opening as heat is mined from the reservoir.

1. INTRODUCTION

A Hot Dry Rock (HDR) geothermal reservoir is an engineered system that can be developed in areas where the rock is hot, but does not contain transportable water. It is created by drilling a well into a body of hot crystalline rock, forming an artificial geothermal reservoir by pumping water down under pressures high enough to open natural joints in the rock, and subsequently drilling one or more production wells into the reservoir zone. During operation, fluid circulates around a closed loop, removing heat from the rock at depth and transporting it to the surface. An HDR system has the potential for steady, long-term energy production.

To establish closed loop circulation the rock must be relatively impermeable, with fluid flowing in an array of joints that connect the injection and production wells. These joints open under the influence of injection pressure, but are essentially closed otherwise. Such a system, will have minimal fluid leakage beyond the pressure-stimulated region. It is believed that conditions to establish pressurized closed-loop flow are not unusual at depths of 3-6 km. This has been the experience at the Fenton Hill, NM, test site operated by Los Alamos National Laboratory (Brown, 1993; Duchane, 1993).

Although it is impossible to completely know the state of the reservoir at depth, modeling can help in the successful design of such a system. This paper describes a fully coupled fluid flow/rock deformation/heat transfer model of a jointed reservoir. The model includes rock deformation, nonlinear joint contact, a joint permeability that is a cubic function of joint opening, heat transfer by fluid transport, conduction and thermal contraction of the rock, and viscosity dependence on temperature.

The coupling is incorporated in the model by discretely modeling the joints and rock blocks using the finite element method. The fluid and structural models are nonlinear and tightly coupled (especially for transient calculations where fluid can be stored in the joints), making it necessary to formulate the model such that both the pressures and the displacements are solved simultaneously. The result of this formulation is that coupling terms are introduced between the fluid and structure models which speed convergence of the problem. Newton-Raphson iteration is performed until the nonlinear equations converge. Because the coupling with the heat transfer is not as tight, a staggered-step approach is used, where iteration is performed between the fluid/structure solution and the heat transfer solution.

2. SUMMARY OF FINITE ELEMENT DERIVATIONS

Full details of the finite element model development are given in Swenson, et al. (1994) and Sprecker (1994); only a summary will be given here.

2.1 Rock and Joint Model

The continuum (rock) elements are derived following standard elasticity finite element practice (Hughes, 1987). The assembled element contributions are the global structural stiffness matrix $\mathbf{K}_s$, displacements $\mathbf{u}$, and the global force vector $\mathbf{f}$, or:

$$\mathbf{K}_s\mathbf{u} = \mathbf{f} \tag{1}$$

Interface elements are used to represent the nonlinear relationship between joint opening and joint stress. As such, they impose surface tractions on the continuum elements that are a function of the joint opening. The "Bed-of-Nails" model (Gangi, 1978) is used to represent the relation between joint opening and joint stress,

$$a = a_o\left[1-\left(\frac{\sigma}{\sigma_c}\right)^m\right] \tag{2}$$

where a is the joint opening, a_o is the zero stress joint opening, σ is the joint stress, σ_c is the stress at which the joint is assumed to be closed and m is a constant. In this model, as the joints close, they become stiffer; as they open, they become softer.

2.2 Fluid Model

The flow is assumed to be one-dimensional (planar) in a fluid flow path. The joint conductivity, k_p, is given by the cubic law,

$$k_p = \frac{a^3}{12\mu f} \tag{3}$$

where a is the joint opening, μ is the dynamic viscosity, and f is a frictional loss factor. Standard finite element development gives the assembled global equations for the fluid flow model as,

$$\mathbf{K}_p\mathbf{p} = \mathbf{q} - \mathbf{S}\frac{\partial \mathbf{a}}{\partial t} \tag{4}$$

where $\mathbf{K}_p$ is the global permeability matrix, $\mathbf{p}$ is the nodal pressure vector, $\mathbf{q}$ is the vector of specified flow rates, $\mathbf{S}$ is the joint opening storage matrix and $\partial \mathbf{a}/\partial t$ is the joint opening velocity vector. Including the storage term allows the solution of quasi-static transient problems, where the inertia of the fluid is neglected, but fluid is stored in the opening joints.

2.3 Heat Transfer Model

In a similar way the equations for heat transfer are obtained. An implicit time integration is used. The assembled equations for the structure are:

$$\left[\mathbf{K}_S^{th} + \mathbf{H}_S + \mathbf{C}_S\right]\mathbf{T}_S - \mathbf{H}_S\mathbf{T}_{Fh} = \mathbf{C}_S\mathbf{T}_S^p \tag{5.a}$$

Both conduction and heat transport are included in the fluid heat transfer equations

$$\left[\mathbf{K}_F^{th} + 2\mathbf{H}_F + \mathbf{C}_F + \mathbf{E}_F\right]\mathbf{T}_F - \mathbf{H}_F\mathbf{T}_{Sh} = \mathbf{C}_F\mathbf{T}_F^p \tag{5.b}$$

where. $\mathbf{K}^{th}$ is the conduction matrix. $\mathbf{H}$ is the surface film coefficient matrix, $\mathbf{C}$ is the heat capacitance matrix. $\mathbf{E}$ is the heat transport matrix. $\mathbf{T}$ is the temperature vector, with the subscript h indicating nodes with film coefficients and the superscript p indicating temperatures at the previous converged solution.

2.4 Coupling of the Models

The above derivations provide rhree sets of coupled equation, (equations 1.3. and 5). The coupling arises as follows:

- $\mathbf{f}$. the load on the structure. includes loads on the rock blocks due to the fluid pressures in the joints, $\mathbf{p}$.
- K,, the fluid permeability matrix of the joints. depends on the cube of the joint openings, which are functions of displacements. $\mathbf{u}$.
- $\partial\mathbf{a}/\partial t$, the joint opening velocity. depends on the displacements. $\mathbf{u}$. and the time step.
- the viscosity of the fluid is a function of the fluid temperatures. $\mathbf{T}_F$.
- The temperatures cause thermal strain, (shrinkage in the structure)
- The heat transport in the temperature solution includes the fluid flow rates calculated in the fluid solution

The goal of the solution procedure is to find solutions for the iimultaneoui equations that also satisfy the coupling between the sets of equations.

The coupling between the structure and the fluid equations is very strong, since only small changes in opening can change the flow and fluid storage terms significantly. Experience solving the structure/fluid problem showed that convergence was very slow using a staggered-step approach. where the equations are solved separately and information is passed between them until convergence. An alternate formulation. where both pressures and displacements are solved simultaneously, introduces coupling terms between the fluid and structure models tha! provide additional information to the solution and speed convergence to the solution. The coupling between the structure/fluid and the heat transfer problem is less strong. The temperatures in the problem change over a relatively long time. so a staggered step approach is satisfactory for the structure/fluid coupling to the heat transfer solution.

The unified formulation for the structure/fluid solutions was developed using a Newton-Raphson approach. In general. for a Sewton-Raphson scheme, the goal is to zero n functions of n unknowns. For the structure. the functions to be zeroed are derived from the summation of forces on each structural node. For the fluid. the functions to be zeroed are derived from the summations of flow at each node. Combined. these provide the required number of functions and unknowns to formulare the problem. The final matrix formulation is then:

$$\begin{bmatrix} \left(\dfrac{\partial\sum \mathbf{f}}{\partial \mathbf{u}}\right) & \left(\dfrac{\partial\sum \mathbf{f}}{\partial \mathbf{p}}\right) \\ \left(\dfrac{\partial\sum \mathbf{q}}{\partial \mathbf{u}}\right) & \left(\dfrac{\partial\sum \mathbf{q}}{\partial \mathbf{p}}\right) \end{bmatrix} \begin{bmatrix} \Delta \mathbf{u} \\ \Delta \mathbf{p} \end{bmatrix} = -\begin{bmatrix} \sum \mathbf{f} \\ \sum \mathbf{q} \end{bmatrix} \tag{161}$$

nhere $\mathbf{u}$ and $\mathbf{p}$ are the unknown displacement and pressure vectors and $\sum \mathbf{f}$ and $\sum \mathbf{q}$ are the summation of forces and floas at edch node The submatrix $\left(\dfrac{\partial\sum \mathbf{f}}{\partial \mathbf{u}}\right)$ is the standard stiffness matrix for the structure ($\mathbf{K}_S$ of equation 1). while the submatrix $\left(\dfrac{\partial\sum \mathbf{q}}{\partial p}\right)$ is the standard permeability matrix for the fluid probleni ($\mathbf{K}_P$ of equation 4) The other two submatrices are coupling matrices between displacements and pressure\. They are derived by force equilibrium at the structure nodes and conservation of mass a! the fluid nodes. These derivations provide the Jacobian needed for Newton-Raphson iteration. For each iteration this is reevaluated and the residual loads and flows calculated. The resulting set of equations is then solved to ohtain increments in displacements and preisures that are used io update the solution. This is continued until convergence of the structure/fluid solution. The flows and displacements are then pasied to the heat transfer solution and the new updated temperature\ are then used for another set of iterations of the structure/fluid solution. Typically. convergence is reached after three or four global iterations between the structure/fluid and the heat transfer problem. An implicit time integration is then used to move to the next time step

The above soltition scheme has been implemented in a program called GEOCRACK. GEOCRXCK was developed to provide an interactive graphics environment to allow the user to specify and monitor the problem in a simple. reliable way. All user interaction with the analysis is through the graphic display and a menu. The menus allow the user to specify the solution method. modify the mesh, define boundary conditions. specify material properties and examine results. The interactive nature of GEOCRACK unifies the traditionally separate tasks of preprocewng. analysis. and postprocessing.

3.0 VERIFICATION

Two verification problems will be used to illustrate the solution capability of GEOCRACK. The first problem is the analysis of transient fluid flow into a single joint. The second is transient heat removal by fluid heat transport from a conducting block.

Wijesinghe. (1986). soli ed the coupled deformation and one-dimensional fluid flow problem for a single joint loaded with a normal stress. He used a cubic law permeability and constant joint stiffness. His solution was obtained as a semi-analytical similarity solution and demonstrates the essential aspects of a coupled transient problem: fluid storage in the joint. permeability dependence on joint opening. and the effect of joint stiffness.

We have solved the same problem using GEOCRACK. The joint is 25 meters long. with a joint stiffness of 1.0×10^{11} N/m. The fluid viscosity is 1.0×10^{-4} N-s/m^2. There is an initial joint opening of 1.0×10^{-5} m. At time zero. the pressure at rhe left is increased to 0.9 MPa. The joint respond,. allowing flow into the joint. A comparison with the results of Wijesinghe is shonn in Figure 1 (Note. the openings are a linear function of pressure. so the same normalized curves can be used for pressure and displacement.) As can be seen. the agreement is excellent.

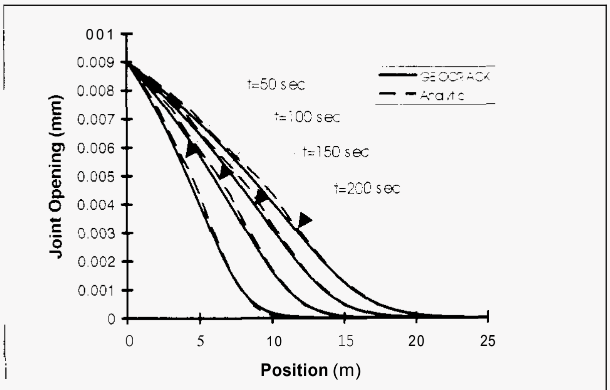

Figure 1: Single joint transient response

The second verification problem is transient heat removal from a block by fluid transport. The problem represents flow in a single joint through a block with finite width and semi-infinite height. The block is at a uniform initial temperature and the flow rate and entrance temperature of the fluid are constant. The analytic solution has been published by Carslaw and Yeager, 1959.

The problem was solved analytically and by GEOCRACK using the following parameters for the rock: initial temperature=230 "C, ρ=2,7 16 kg/m^3, c_p=803 J/kg-°K, k=222,000 J/day-M-°K, width and height 10 m. For the fluid the properties were: entrance temperature=70 °C, ρ=950 kg/m^3, c_p=4300 J/kg-°K, k=0.0, fluid velocity=2000 m/day, and joint width= 0.5 mm.

Figure 2 shows the temperature contours at 50 days and Figure 3 shows a comparison of the calculated and analytic outlet temperature as a function of time. Again, the agreement is good.

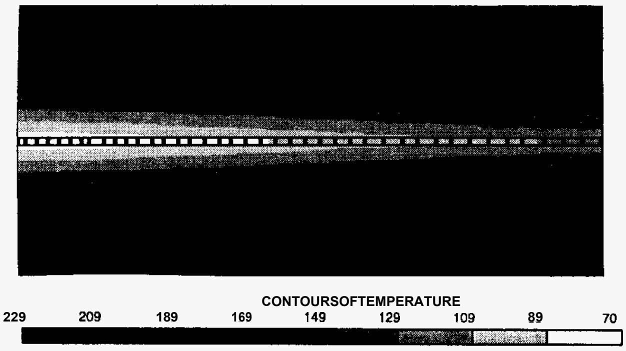

Figure 2: Verification problem temperature contours at 50 days

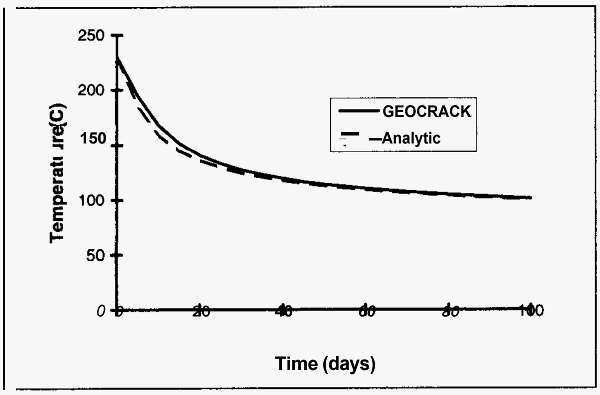

Figure 3: Verification problem, comparison of outlet temperatures

4.0 APPLICATION TO THE FENTON HILL RESERVOIR

GEOCRACK has been used to simulate and predict future thermal performance of the HDR reservoir at Fenton Hill. Data from Fenton Hill has been used to refine the construction of models and their input parameters. Although parameters such as in-situ stresses, fracture dimensions, joint orientations, and fracture spacing are not known precisely, models with reasonable in-situ stress regimes and relatively simple geometries exhibit behaviors analogous to the observed behaviors of the Fenton Hill reservoir.

4.1 Specification of Input Parameters

The fundamental inputs to the model such as reservoir size and well spacing were obtained from measurements of Fenton Hill. The dimensions used in the model correlate with the dimensions of the actual reservoir as indicated by microseismic events during hydraulic fracturing. Fluid volumes during slow pressurization without circulation, and reservoir permeabilities under different circulation pressure conditions were used to refine the nonlinear joint model inputs. Reservoir tracer and transient behavior data were also used to improve the construction of models, since that data suggests a wide distribution in the sizes and fluid residence times of flow paths.

Realistically, fluid is thought to channel within fractures, and different fractures may have significantly different permeabilities and storage capacities. Such ideas have led to the development of models with randomized distributions of flow path volumes. In GEOCRACK, flow paths of different permeabilities and fluid residence times are implemented by randomizing the distributions of fluid path depths. Instead of a single unit depth for fluid pathways in a model, many varying fluid depths can be randomly distributed. That is, the average fluid depth within a number of models may remain the same, but the position of flow paths with different fluid depths is randomized. The resulting set of models with randomized distributions must then be analyzed statistically since they exhibit significanlty different flow rates and flow distrbutions. In a sense, this is one way of considering the heterogeneity of the reservoir and implementing a pseudo-third dimension. However, because the model is 2-dimensional, a scaling factor is used to scale the volume of reservoir models to the volume of the Fenton Hill reservoir.

In models used for heat transfer calculations, the rock volume is correlated to the average fluid path depth so that the heat energy available from the rock is conducted through the surface area of the rock in contact with fluid. Unfortunately, due the the requirements for the equilibrium of forces on rock elements, a single unit depth of rock must be specified.

Table 1 specifies many of the values used to simulate Fenton Hill.

X length	620 m
Y width	150 m with symmetry
Z thickness	32 m (mean fluid height)
X and Y joint spacing	20 m
X in-situ stress	27.5 MPa
Y in-situ stress	15 MPa
Far-field stiffness	8,500 MPa/m
Far-field permeability	0
Gangi a0	0.185 mm
Gangi closure stress	45 MPa
Gangi exponent	0.33
Fluid roughness factor	1.5
Fluid viscosity	function of temperature
Fluid density	950 kg/m^3
Fluid heat capacity	4,300 J/kg-K
Fluid conductivity	57,000 J/day-m^2-K
Fluid film coefficient	57x10^6 J/day-m^2-K
Rock Temperature	300 to 200 °C (gradient)
Rock density	2,716 kg/m^3
Rock heat capacity	803 Jkg-K
Rock conductivity	222,000 J/day-m-K
Rock thermal expansion	7.5x[illegible]
Rock elastic modulus	85.12 GPa
Rock poisson's ratio	0.25

Table 1: Parameters used in the GEOCRACK Fenton Hill model

To evaluate the performance of the model, comparisons with Fenton Hill reservoir data were conducted and some of the results follow. Comparison shows that the basic physics simulated by the model accurately replicates the behavior of the actual reservoir at Fenton Hill. For example, in Figure 4 the transient pressures at the injection and production wells when the well-head valves are suddenly closed correlate well with the observed Fenton Hill data. In addition, since the pressure rise of the production well is much larger than the pressure drop at the injection well, this figure illustrates that most of the overall reservoir pressure drop occurs in the vicinity of the production well (DuTeau, 1993).

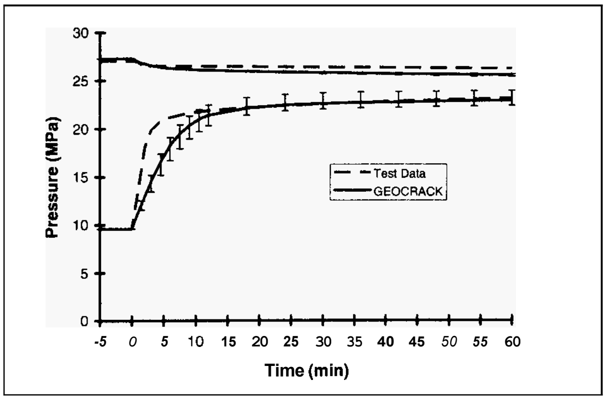

Figure **4:** Transient well-head pressure during the cessation of production flow.

Table 2 below shows that with the adjustment of Gangi parameters, GEOCRACK models Fenton Hill reservoir impedances fairly well and shows that reservoir permeability may by increased by increasing the level of hydraulic pressure exerted on the reservoir. Furthermore, the outlet flow rates are not highly sensitive to production well back-pressure. Both GEOCRACK and actual Fenton Hill data show that the level of outlet flow can be maintained even with a smaller driving pressure difference across the reservoir (Duteau and Brown, 1993).

	Injection Pressure	Production Pressure	Pressure Difference	Resultant Flow Rate
Fenton Hill	27.3 MPa	9.65 MPa	17.65 MPa	5.7 l/s
	27.3 MPa	12.4 MPa	14.9 MPa	5.7 l/s
	27.3 MPa	15.2 MPa	12.1 MPa	5.3 l/s
	22.4 MPa	9.65 MPa	12.75 MPa	3.8 Us
GEOCRACK	27.3 MPa	9.65 MPa	17.65 MPa	5.7 Us
	27.3 MPa	12.4 MPa	14.9 MPa	5.4 l/s
	27.3 MPa	15.2 MPa	12.1 MPa	5.1 l/s
	22.4 MPa	9.65 MPa	12.75 MPa	2.9 l/s

Table 2: Actual and modeled flows under different wellhead pressure conditions. (hydrostatic = 35.4 MPa)

As Table 2 reveals, the reservoir impedance is less well matched with Fenton Hill data in the lowered injection pressure case. This indicates the modeled joint openings do not provide enough permeability at lower pressures and the Gangi parameters input to the model may need some further adjustment near the production well.

With the incorporation of varying joint permeabilities the model also replicates reservoir tracer data. Initially, with the same unit depth assigned to all flow paths the model lacked the combination of short and long residence time flow paths needed to exhibit tracer responses similar to Fenton Hill. Different approaches, such as increasing the numbers of flow paths, or blocking flow paths could be used. The transient pressure response data, however, indicated the fractures at the inlet and outlet manifold into flow paths with much larger fluid capacities, so increasing the unit depths of flow paths was necessary for realistic tracer responses. Figure *5* shows the tracer response obtained by incorporating varying flow path dimensions in combination with a small percentage of blocked paths in order to obtain paths of many different fluid residence times. While the temporal changes during heat mining are not illustrated here, GEOCRACK models often show a divergence of flow into more fluid paths during heat removal. However, at higer flow rates models sometimes show a convergence of flow into fewer flowpaths. Actual tracer experiments at Fenton Hill showed a much more dynamic divergence of flow into an increasing number of fluid paths with more uniformly distributed flow (Rodrigues et al, 1993). A comparison of modeled tracer tests to actual tracer tests may suggest models with a greater number of more closely spaced flow paths should be used.

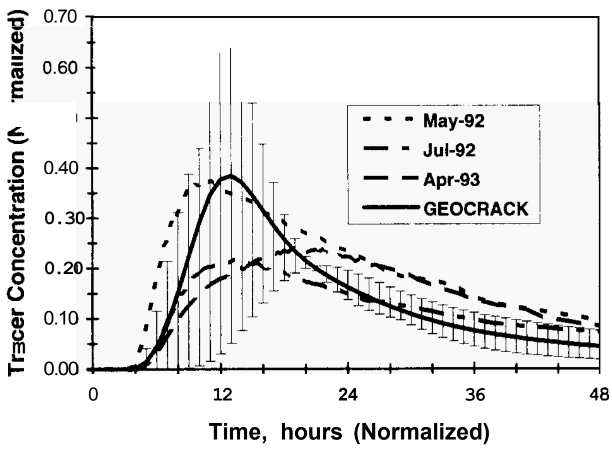

Figure 5: Comparison of a GEOCRACK tracer response to the data from a Fenton Hill tracer experiment.

4.2 Simulation of Fenton Hill Thermal Performance

Simulations were run to investigate the potential long term behavior of Fenton Hill (including the addition of a third well). The simulations were set up to represent the past circulation history of Fenton Hill and the anticipated continuation of flow testing with the eventual addition of a second production well. In the cumulative 270 days of the Long-Term Flow Test conducted at Fenton Hill in 1992 and 1993, no decline in the fluid temperature from the reservoir occurred.

Figure *6* shows the configuration of the modeled rock blocks and Figure 7 shows details of the finite element mesh around the injection well. As can be seen, a refined mesh is used to capture the temperature gradients as cold fluid is injected.

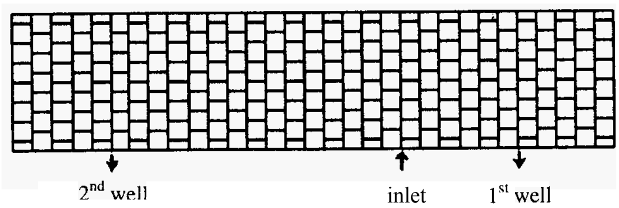

Figure *6:* Geometry used for analyses

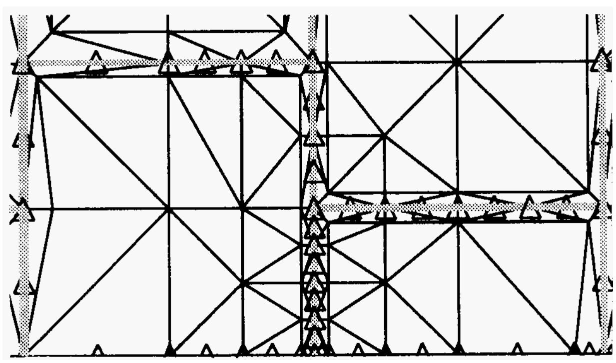

Figure 7: Details of mesh near injection well

In the analyses, a general pattern emerged that after approximately one year of operation, the permeability and flow through the reservoir began to increase. This is a result of cooling of the rock which opens the joints. Previous studies have shown that it is possible for thermal short-circuiting to occur if flow (heat transport) is allowed to increase beyond the rate at which heat can be conducted to the joint surfaces (Gringarten, et al., 1975; Robinson and Jones, 1987; DuTeau, et al., 1994). **As** a result, a sequence was followed which controlled flow in the reservoir. This sequence was chosen to represent possible long-term operation of the reservoir.

The first production well was run under pressure boundary conditions for the first 600 days (simulating past operation and one additional year of testing). From 600 to 1010 days, the first production well was held at a constant flow rate and the second production well started with **a** pressure boundary condition. From 1010 to 7000 days, the second production well flow rate was also held fixed at the 1010 day value. These conditions are illustrated in Figure 8.

4.3 Results

Because of the random blockages and fluid flow heights used in the model, several cases were run. With the randomization, flow rates varied considerably, with the standard deviation nearly 1/3 of the average flow rate. In most cases, the reservoir permeability steadily increased as heat energy was extracted and flow paths opened due to the thermal contraction of reservoir rock. In some cases, reservoir permeability decreased for a period of time as portions of flow paths opened and other portions of the same paths were forced to bear more of the in-situ stresses. Still others showed moderate but steadily decreasing long term permeabilities when significant blockages occurred between the injection and production positions in the modeled reservoir. In these cases the rock deformation due to thermal contraction steadily pinched-off joint openings and locally high stresses developed. Only by removing blockages, and therefore artificially simulating a new fracture opening in the reservoir, could the increasing stress gradients be relaxed enough to ensure continued convergence to solutions.

Previous tests at Fenton Hill also suggest that heat mining does impose locally high stress gradients which may result in joint movements that can be detected seismically. Such movements have, in fact, lowered reservoir impedance (Murphy et al, 1981). In general, the vast majority of model simulations showed drastically increased permeabilities after the removal of around 10% of the total available reservoir energy. Figure 8 illustrates this with a fluid temperature/pressure/flow rate history for a case with a temperature gradient between the well locations.

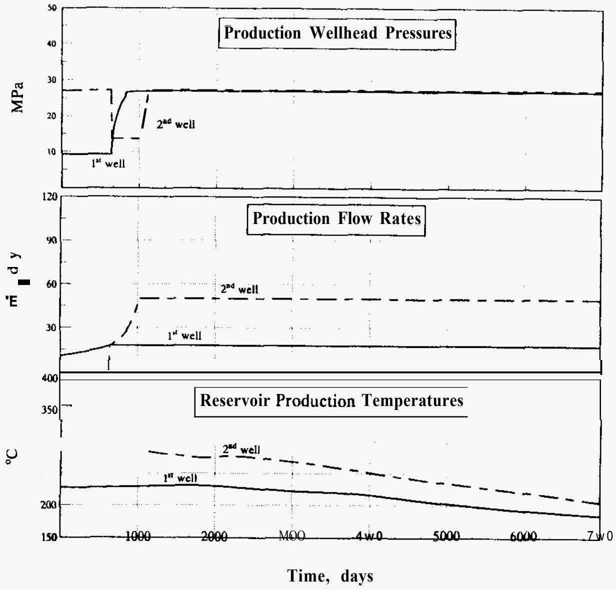

Figure 8: **A** typical reservoir history of one GEOCRACK model.

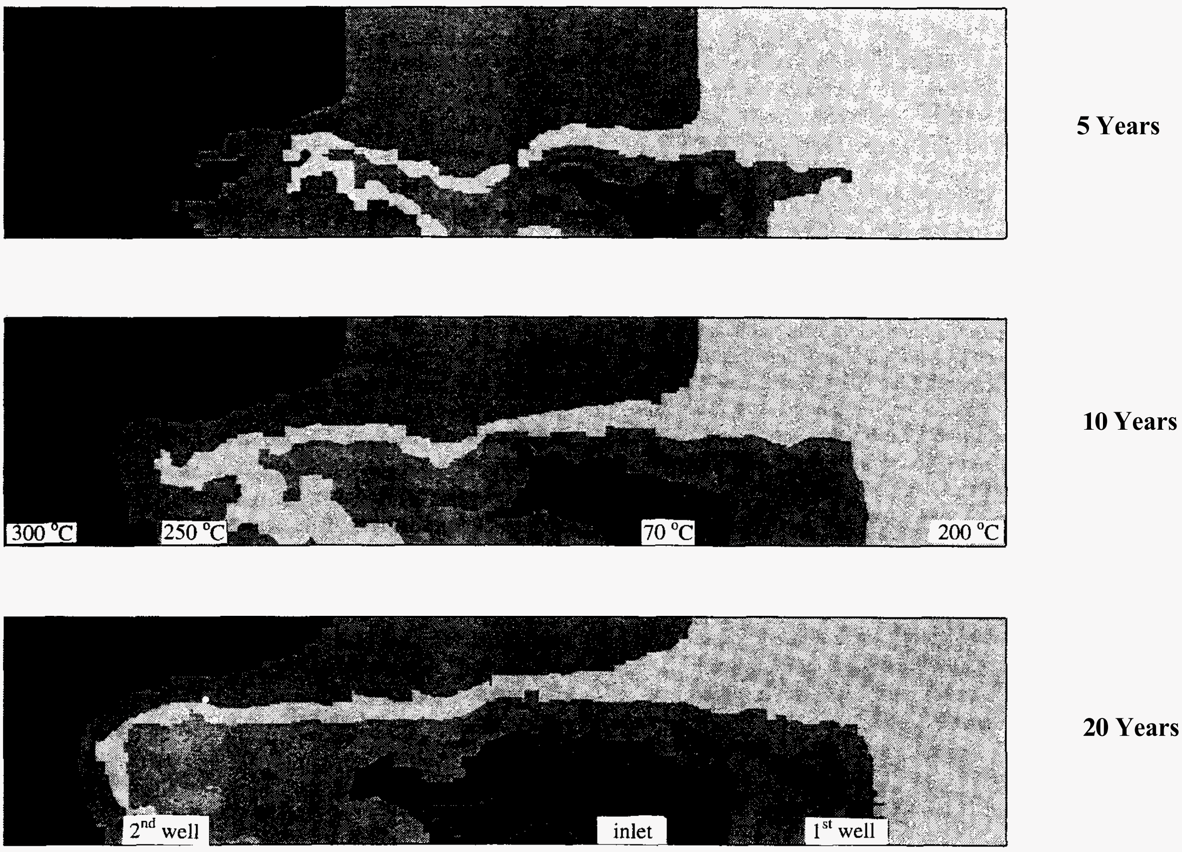

Figure 9: Temperature contours in reservoir during heat removal

Figure 9 shows the potential rock temperature distribution after 5, 10, and 20 years of reservoir circulation with the above flow history. Initially the rock temperature varied from 300 to 200 °C across the model from left to right with symmetry along the x-axis. After circulation, rock temperature contours vary from 70 °C at the inlet to 300 °C on the far left of the reservoir model. This figure indicates that a significant fraction of the heat energy of the modeled reservoir can be mined if the flow rate is controlled to sweep heat from the rock at a rate similar to the rate heat is conducted from the interior of the rock to the surface of the joints.

5.0 CONCLUSIONS

One of the fundamental purposes of a reservoir model is to predict thermal draw-down and reservoir longevity. Models, including GEOCRACK, show that longevity is dependent upon rock temperatures, flow path spacing, numbers of active flow paths, well spacing, and flow rates. Because well spacing and flow rates may be controlled to a much greater extent than the internal geometry of reservoir flow paths, GEOCRACK indicates that reservoir operators could engineer systems with extensive lifetimes and profitable thermal productivity by appropriate well spacing and limiting energy production rates.

Furthermore, since a large fraction of the pressure drop occurs near the production well(s) GEOCRACK indicates that wells may be spaced hundreds of meters apart without significantly more reservoir impedance than more closely spaced wells. Even though a large portion of the overall reservoir impedance occurs in the vicinity of the production well, joint opening due to cooling near the inlet allows higher pressure to extend nearer to the production well, thus increasing the flow rate at the outlet. As impedance declines over the lifetime of the reservoir, the pumping power required for the operation of a power plant should also decline drastically in the first few years of energy production.

As a caution, the model also indicates that a potential for short circuiting could become a danger if the flow rate is not controlled as reservoir permeability increases. In such cases the model shows that cooler flow paths take increasing fractions of the total flow. This would decrease the efficiency of heat mining since access to the volume of hot rock would decline.

Long term models of Fenton Hill show quite modest thermal draw-downs, with fluid outlet temperatures remaining above 200 degrees C for 20 years and more when total production flow rates are controlled at levels not exceeding an average of 34 l/s. Although much higher energy production levels may be possible, long-term models of higher production rates have not yet been run. The present model suggests there may be an optimal rate of energy production which balances reservoir thermal draw-down with the need to produce power at a rate sufficient to pay the initial capitol costs of reservoir development and power plant construction. In conclusion, GEOCRACK indicates that the HDR reservoir at Fenton Hill (and HDR reservoirs in general) has the potential to produce significant rates of energy production for many decades.

6.0 ACKNOWLEDGMENTS

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