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FRACSL CODE DEVELOPMENT AND CORRELATION OF EAST MESA TEST RESULTS

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ABSTRACT

The FRACSL flow and transport code is under development as part of an effort to improve reservoir characterization techniques. The present version simulates a two-dimensional, isothermal reservoir composed of a global fracture network imbedded in a porous media.

FRACSL simulates the hydraulic response of a reservoir to injection or backflow. The code simulates the movement of injected tracers within the reservoir by adding advective and random dispersive motions of discrete particles.

FRACSL has been benchmarked against theoretical flow and transport responses in simple systems. It has been used to simulate a benchscale physical model and to correlate flow and dispersion data from the East Mesa Hydrothermal Injection Test Program. Correlation of East Mesa data has provided an estimate of an anisotropic hydraulic conductivity, a natural drift in the reservoir, and dispersivity.

NOTATION

σ	standard deviation of longitudinal or transverse dispersive movement, ft
D	longitudinal (L) or transverse (T) dispersivity, ft
V	flow velocity, ft/day
D_t	time increment, days
h	head, ft
Q	volumetric flow-rate, ft^3/day
b	thickness of porous layer, ft
k	hydraulic conductivity, ft/day
θ	porosity
r	effective distance from the well, ft
a	fourth root of the ratio of the hydraulic conductivity in the y direction to the conductivity in the x direction
S	specific storage ft/ft
t	time, days
C	tracer concentration $[ft^3]^{-1}$
C_o	injected tracer concentration $[ft^3]^{-1}$
erfc	complimentary error function
$\bar{r}$	average radius of initially injected tracer, ft.

INTRODUCTION

In 1981 EG&G Jdaho, together with the University of Utah Research Institute (UURI), initiated the Hydrothermal InjectSon Research Program for the Department of Energy, Division of Geothermal and Hydropower Technology. The program goal is to develop improved methods for reservoir characterization. The program will enhance the reservoir engineers' ability to evaluate, develop and utilize a geothermal system. The program's focus is on the study of the injection of spent geothermal fluids. Research efforts consist of a series of highly instrumented field studies with supporting laboratory and theoretical work. Field studies consist of injection and backflow tracer tests to determine the usefulness of single-well testing for the charatterization of reservoirs. Laboratory efforts consist of tracer transport studies in small physical models.

A comprehensive reservoir simulatbr is the central tool used to interpret and utilize both field and laboratory data. This simulator must ultimately be capable of simulating hydraulics, solute transport and heat transport in a fractured reservoir. The FRactured media-Advanced Continuous Simulation Language (FRACSL) code is being developed to meet these needs.

FRACSL has two dominant characteristics: (1) It is a dual porosity model with discrete fractures imbedded in a homogenous porous medium, and (2) solute transport is simulated with discrete particles rather than by solving the advection-dispersion equation. A third major characteristic is the use of the Advanced Continuous Simulation Language (ACSL) (Mitchell and Gauthier, 1981) as a driver code. ACSL supplies the numerics to implement and solve the reservoir model.

The present version of FRACSL simulates hydraulics and solute transport within a two-dimensional fractured reservoir of Cartesian geometry. Thermal and chemical processes are not incorporated in FRACSL but are to be added in the future.

This paper presents the salient features of FRACSL and its major capabilities. Some comparisons of FRACSL simulations with theoretical results from a homogenous nonfractured reservoir and injection/backflow tracer tests from the East Mesa Known Geothermal Resource Area (KGRA) are included in this paper.

FRACSL CODE DESCRIPTION

FRACSL defines a reservoir model using a rectangular nodalization. The hydraulic properties of the porous media are lumped at the nodes. The fracture system is defined by high conductivity connections between adjacent nodes. The pressures at each node are solved from this description and the conservation of mass relationship for either transient or steady-state conditions. Boundary condition options include fixed pressure, fixed flow-rate, or fixed conductivity to a zero head source or sink.

Solute transport is modeled using the hydraulic solution as the driving function for movement of discrete particles. The solute transport portion of the code is based on a "random walk" approach originated by Eliason and Foote (1972) for modeling thermal transport. Random walk dispersion is simulated by adding a zero mean Gaussian movement to the deterministic convective transport.

The longitudinal and transverse dispersive movements each have a standard deviation given as:

$$\sigma = \sqrt{2 \cdot D \cdot V \cdot D_t} \qquad (1)$$

A property of this approach is that the net dispersive movement is independent of the time step size.

Solute particles are identified as being within either the porous media or a fracture. Solute particle transport in porous media is based on the following assumptions:

- Flow is laminar and described by the Darcy velocity
- The local pressure distribution is completely described by the pressure at the node closest to a particle and the eight adjacent nodes
- The media is homogeneous within the region bounded by the nine nodes.

Fitting the nine pressures about a particle to second order functions of position provides a local pressure gradient and local pressure curvature. The pressure gradiemt and curvature are used to determine a particle's velocity and the derivative of velocity with respect to distance. This procedure allows particles to move a large fraction of the nodalization distance in a single step.

Particle movement in the discrete fractures and the particle transfers between media were initially described by Miller (1983) and are currently being modified.

CAT[illegible] O HOMOGENEOUS POROUS MEDIA

As the first stage of determining the accuracy of the FRACSL code, calculations have been compared to analytic results for an infinite layer of homogenous porous material. Comparisons have been made for isotropic and anisotropic hydraulic conductivity conditions. The anisotropic conductivity case was performed because an anisotropic conductivity was assumed in the East Mesa simulations. These calculations and the East Mesa simulations were made with the model parameters listed in Table 1.

Pressure distributions for a constant drawdown rate were calculated for an isotropic conductivity condition and a conductivity nine times larger in the y direction than in the x direction. These calculations were performed for a well at the center of the grid and repeated for a well at the corner of the grid with identical results. For an isotropic conductivity Hoopes and Harleman (1967) give the radial variation of head as

$$h_{r_1} = h_{r_2} - \frac{Q}{2\pi bk} \ln \frac{r_1}{r_2} \qquad (2)$$

The anisotropic case can be derived by transforming coordinates such that $x' = ax$ and $y' = y/a$. In the transformed coordinates, the conductivity is isotropic and Equation 2 applies with:

$$\sqrt{a^2 x_i^2 + y_i^2/a^2}$$

TABLE 1. FRACSL MODEL PARAMETERS

Model size:	150' x 150' 11 x 11 nodes
Hydraulic conductivity:	7.9 ft/day or 23.7 in y direction 2.63 in x direction
Storage coefficient:	1×10^{-5}
Porosity:	0.25
Thickness:	1 ft
Flow rate:	462 ft^3/day

Comparison of FRACSL results with analytic solutions for isotropic and anisotropic hydraulic conductivities is given in Table 2. A head of zero was set at 200 ft for the isotropic case and at x equals 150 ft and y equals 150 ft for the anistropic case. The error terms are small considering the coarse (11 x 11) nodalization of the model.

Dynamic pressure responses were calculated for the same conditions using the relationship given in Equation 3 (Theis, 1935). Table 3 lists the head responses at a distance of 15 ft from the well.

$$h = \frac{2.3\,Q}{4\pi kb} \log\left(2.25\,\frac{kbt}{r^2 S}\right) \qquad (3)$$

The FRACSL results match very closely for the isotropic case. The anisotropic solution lags behind by 0.06 ft in the low conductivity direction and 0.08 ft in the high conductivity direction. This lag shows up initially and remains fairly constant over time indicating the rate of change of head is very close to the analytic solution. Solute transport was simulated under steady-state flow conditions. A slug injection test was simulated for isotropic conductivity conditions. The dispersivities were set to zero which resulted in an expanding circle of tracer particles. The radial position of the particles is given by

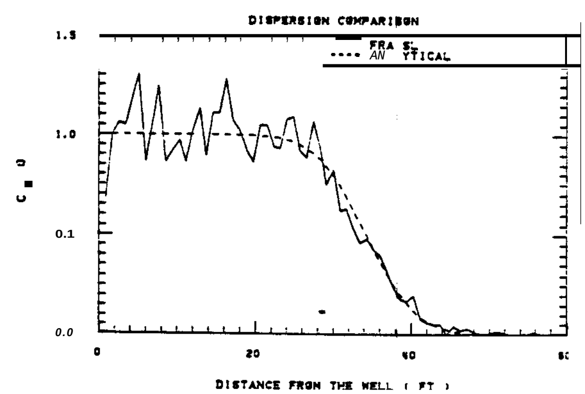
$$r = \sqrt{\frac{tQ}{b\pi\theta} + \left(r_{well}\right)^2} \qquad (4$$

Table 4 presents the results of these simulations.

The uncertainty given in the FRACSL results *is* the standard deviation of the particle position about the given radius. The particle deviations are preferential with greater errors along the axes and diagonals of the grid. The small deviation at 0.05 days is due to special handling of the region near the injection well. The delay and recovery of the particles at 0.25 days and 0.55 days, respectively, is due to the coarse nodalization. A second transport test accounting for dispersion was run with continuous particle injection. The longitudinal dispersivity was 0.6 ft and the transverse dispersivity was 0.2 ft. Bear (1972) defines the dependence of concentration on radial distance traveled by:

$$C/C_0 = 1/2\ \mathrm{erfc}\left(\frac{r-\bar{r}}{4/3\ D_L\ \bar{r}}\right) \qquad (5$$

Fiqure 1 shows C/C_0 as a function of distance from the well.



Fiqure 1. Comparison of FRACSL simulation to an analytical solution for radial flow from a well.

Figure 1 shows an excellent match to the theoretical results. It indicates that the deviations about the nominal radius apparent in Table 4 are small compared to the dispersive term. In Figure 1 the variability of the concentration near the well is a property of dispersion for the limited number of tracer oarticles used in the simulation.

TABLE 2. COMPARISON OF FRACSL AND ANALYTIC DRAWDOWNS

	Isotropic Case			Anisotropic Case					
r ft	Analytic Drawdown ft	FRACSL Drawdown ft	Error %	x ft	Y ft	r ft	Analytic Drawdown ft	FRACSL Drawdown ft	Error %
15	24.55	24.11	-1.8	0	15	8.7	32.15	31.93	-0.7
45	14.00	13.88	-0.8	45	0	77.9	11.70	11.63	-0.6
90	7.46	7.43	-0.4	0	150	86.6	10.72	10.84	+I. 1
212	-0.49	-0.54	-10.2	150	0	260.0	0.49	0.46	-6.1

TABLE 3. DYNAMIC PRESSURE RESPONSE

	Isotropic Conductivity		Anisotropic Conductivity: Low Conductivity Direction (x)		Anisotropic Conductivity: High Conductivity Direction (y)	
Time (days)	Analytic Pressure (ft)	FRACSL Pressure (ft)	Analytic Pressure (ft)	FRACSL Pressure (ft)	Analytic Pressure (ft)	FRACSL Pfessure (ft)
0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.01	20.32	20.36	15.21	14.62	25.43	24.64
0.02	23.54	23.56	18.43	17.78	28.65	27.84
0.05	27.80	27.83	22.69	22.04	32.91	32.13
0.08	29.41	30.01	24.88	24.38	35.09	34.48

TABLE 4. TRANSPORT OF A TRACER SLUG

Time (days)	Analytic Radius (ft)	FRACSL Radius (ft)	Error
0.0	0.0	0.0	0.0
0.05	5.46	5.44 ± 1×10^{-5}	-0.4
0.25	12.13	11.87 ± 0.3	-2.1
0.55	17.99	17.99 ± 0.4	0.0
1.05	24.84	24.21 ± 0.5	-2.6
2.05	34.73	34.23 ± 0.7	-1.4

SIMULATION OF EAST MESA TESTS

Tests conducted at East Mesa well 56-30 in 1983 and 1984 provided a base case data set of a porous media to verify FRACSL.

The reservoir surrounding this well is composed of layers of porous sandstone interbedded by relatively impermeable shale. While the reservoir contains near vertical faults, these are too distant to affect the flow distribution. Spinner logs taken during both injection and backflow indicate that the well has four major oroduction zones of equal production per foot of thickness. The model parameters used to simulate this well are given in Table 1. Two injection-quiescence-backflow tests were conducted. One test consisted of 12 hours injection, 12 hours quiescence and a backflow long enough to recover the injected tracer. In the second test the quiescence was lengthened to 6 months in order to evaluate the natural drift in the reservoir.

The returning tracer concentrations for the six month quiescence test peaked after a volume 7.5 times the injected volume was backflowed from the well. The delay in the returning tracer peak is an indication of a natural drift in the reservoir. Simulation of this test, incorporating natural drift requires an anisotropic conductivity to match the shape of the tracer return.

Figure 2 presents a comparison of slug concentration data and FRACSL results for the six month quiescent test. The ordinate of Figure 2 is the return concentration divided by the injected concentration. The abscissa is the cumulative number of injection volumes backflowed into the well. The FRACSL results were fit to a seventh order power series for the Figure 2 plot.

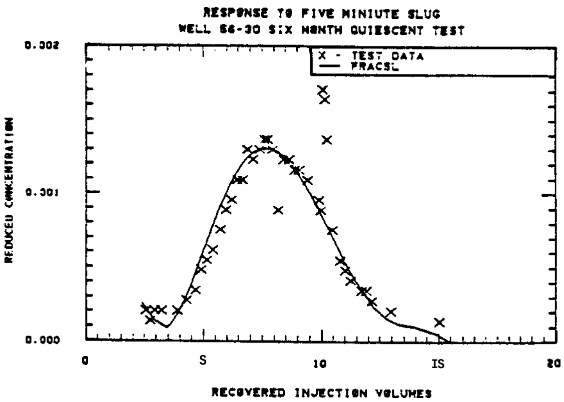


Figure 2. Comparison of FRACSL to an actual tracer and analytical recovery data from a six-month quiescent test at East Mesa.

The returning concentration of both slug and continuous tracers was matched by using a hydraulic conductivity ratio of nine to one, a longitudinal dispersivity of 0.17 ft and a transverse dispersivity of 0.06 ft. The simulation of the six month quiescent test required a 32 ft drift during the quiescent period and the nine to one conductivity ratio to match the peak return time.

The time to peak for the return concentration is affected by both the natural drift and anisotropic conductivity. The drift required to match the time of peak return changes with a changing conductivity ratio. The peak time is very sensitive to drift but not the hydraulic conductivity ratio, which is probably accurate to within 30%. The shape of the curve is quite sensitive to the dispersivity and changes of 10% are noticeable in the FRACSL results.

CONCLUSION

The FRACSL code is being developed to simulate hydraulic response and solute transport within a fractured reservoir. The validation against analytic and field results presented in this paper were limited to porous media applications. The hydraulic model uses a dual porosity approach and lumped parameter nodalitation. Solute transport is simulated with a discrete particle approach. The discrete particles are moved by calculating the local advection based on the hydraulic model results. Dispersion is simulated using a random walk perturbation about the deterministic advection.

Example simulations for an infinite homogeneous porous reservoir with both isotropic and anisotropic hydraulic conductivities have been compared to analytic solutions. The comparisons were for dynamic and steady-state pressure responses to a step in volumetric flow from a line source. The comparisons show good agreement with analytic results using a model with a small number of nodes.

Transport of a pulse injection of solute particles from a constant flow source was simulated without dispersion and compared to analytical results. A step input of tracer from a constant flow source was simulated using dispersion. These comparisons have shown that FRACSL is capable of closely simulating an unfractured homogeneous resevoir

The well tested at East Mesa is located in a well defined unfractured porous sandstone. FRACSL simulations provided a close match to measured test data. A hydraulic conductivity nine times as great in one direction than in the perpendicular direction and a longitudinal dispersivity of 0.17 along with a 32 ft drift were required to provide the match. Use of FRACSL has thus yielded an estimate of an anisotropic hydraulic conductivity, dispersivity, and a drift velocity from a comparison with field test data.

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