"MODELLING OF THE SOULTZ RESERVOIR: DIFFERENT APPROACHES AND POSSIBLE BENEFITS"

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ABSTRACT

This paper gives an overview of numerical models developed and used around the reservoir of Soultz-sous-Forêts. We focus here only on reservoir modeling numerical codes (no fracture/pore scale numerical code). The main mathematical features and physical processes taken into account, as well as an application example and major bibliography about each code are presented.

INTRODUCTION

Many numerical codes have been developed and used since the experiments began in Soultz-sous-Forêts, in 1989. Indisputable advances have been released in this domain during the past years. The modeling group, the last years chaired by T. Kohl, coordinates work of several scientific teams over Europe.

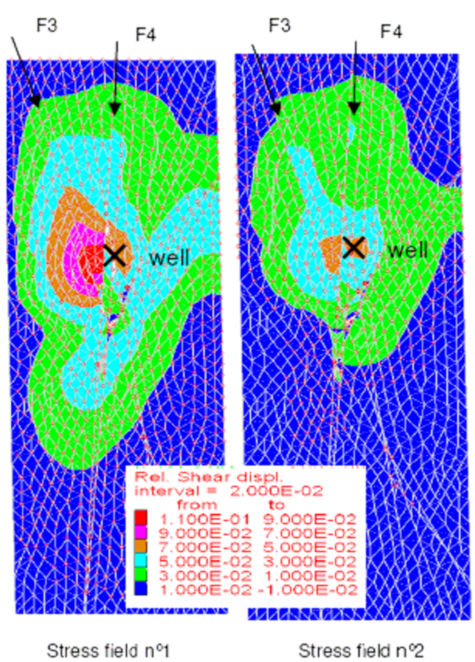
A state-of-the-art of modeling activities in Soultz is presented. Instead of adopting a classical scientific paper shape, we give here an overview of the different codes existing and used for scientific investigations in Soultz.

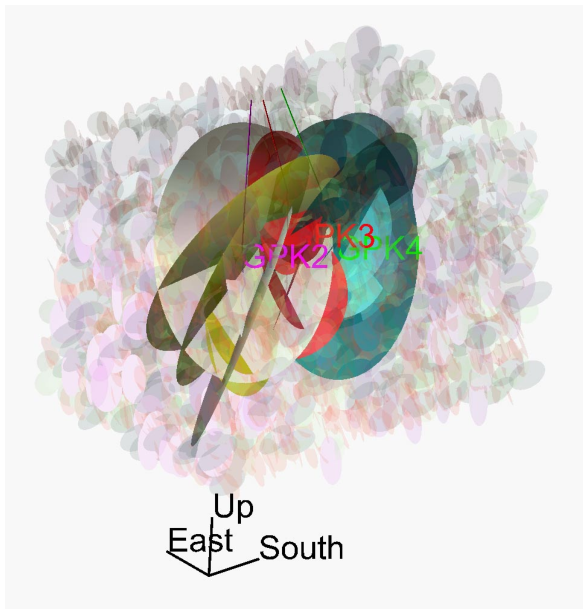
To that purpose, a form has been sent to recent contributors of the modeling group in order to shortly describe their numerical code. The main fields of the form that was sent are:

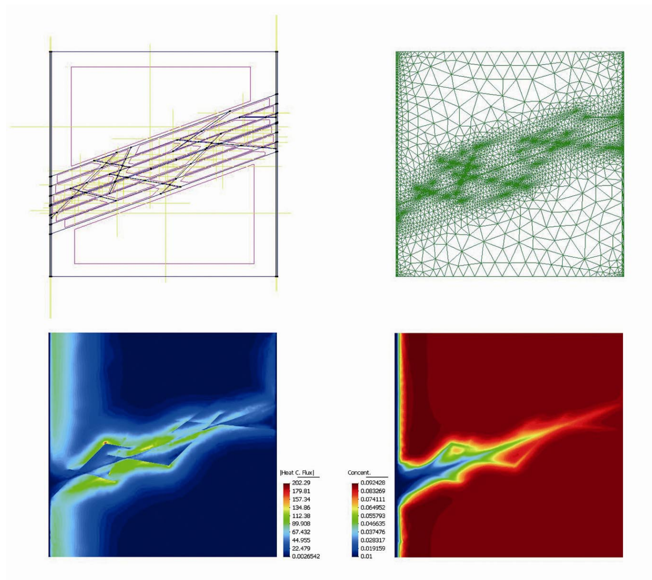
- Author(s)
- Institution
- Code
- Mathematical algorithm
- Physical Processes and interactions
- Special features
- One application example
- Future developments
- Benefits for Soultz Project
- References

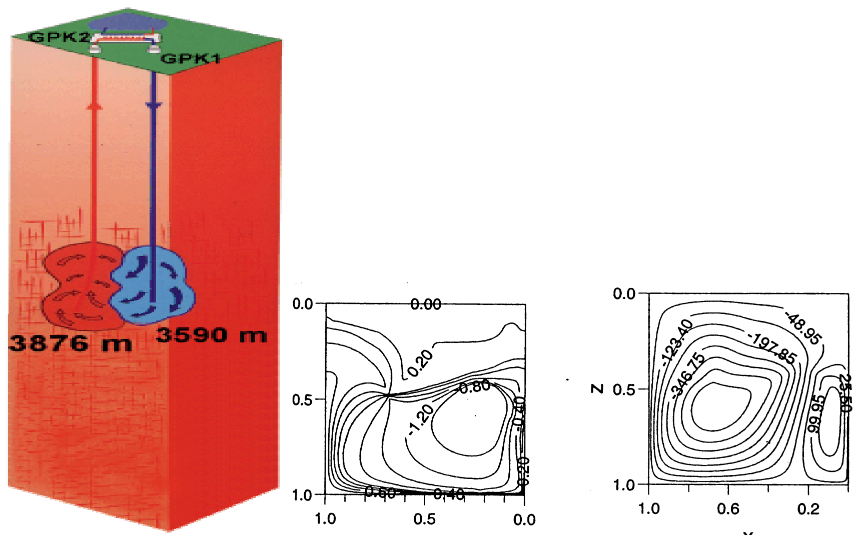
Each author that answered and filled in the form is an author of this paper. This overview is voluntarily limited to reservoir modeling codes. Many other codes (mainly fracture/pore scale simulation code, inverse modeling or economical modeling) were written and used but are voluntarily not referenced in the following pages.

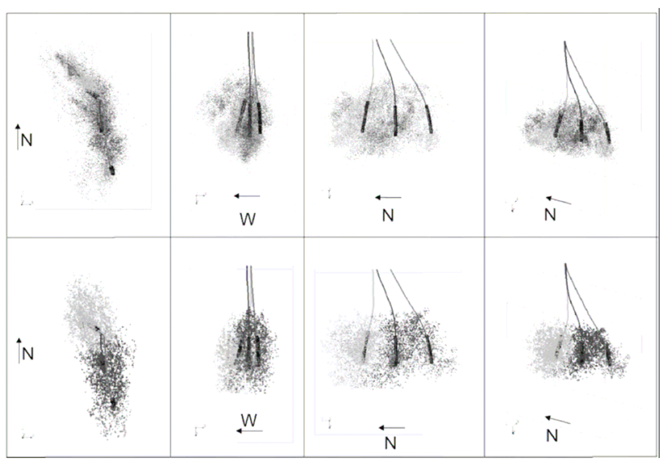
In the following, the codes are presented by alphabetical order of the code name.

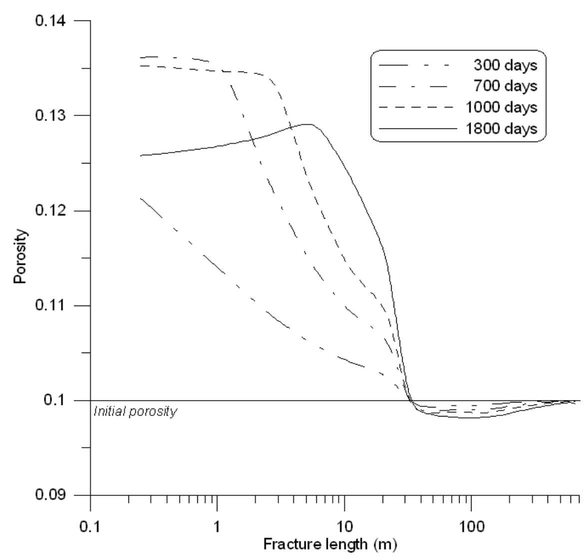
Author(s):	**Peter Cundall, Mark Christianson, Jose Lemos, Branko Damjanac**
Institution	**ITASCA Consulting Group**
Code:	**3DEC**
Mathematical algorithm:	3D Distinct Element
Physical Processes:	Thermo-Hydro-Mechanical modelling of fractured rock masses Discontinuous medium modelled as an assemblage of convex or concave polyhedra. Discontinuities treated as boundary conditions between blocks.
Physical Interaction:	Motion along discontinuities governed by linear and non-linear force displacement relations for movements in both the normal and shear direction (friction, dilatancy, cohesion, rugosity, stiffnesses) Material models include: elastic, anisotropic, Mohr-Coulomb, Drucker-Prager, bilinear plasticity, strain softening, creep, and user-defined. Joint fluid flow (flow in fractures is laminar and obeys a cubic law ; blocks are impermeable) Heat conduction in blocks, thermal convection in fractures filled with moving fluid
Special features	Internal macro-language that allows building complex models, hooking 3DEC to any other software, performing parameter studies, etc. Joint fluid logic and thermal calculations implemented for BRGM needs. Specific hydro-mechanical coupling developed by BRGM, dedicated to simulate the behaviour of fractured rock masses during hydraulic tests.
One application example	Influence of the stress field on the hydromechanical behaviour of the rock mass during the stimulation of GPK4.  *Shear displacements contours in one of the main fracture during injection in GPK4 (for 18.3 MPa overpressure stage), for 2 given stress fields*
Future developments	New flow boundary logic for limiting the flow extension of a given fracture. Procedures for automatically coupling 3DEC and FRACAS (code developed by ARMINES – D. BRUEL) in order to solve coupled hydromechanical problems where the role of the mechanics on the hydromechanical behaviour is either “strong” (3DEC case) or “light” (FRACAS case).
Benefits for Soultz Project	Helps understanding the hydro-mechanical behaviour of the fractured rock mass during hydraulic tests.
References	Gentier, S., Rachez, X., Dezayes, C., Blaisonneau A. and Genter, A. (2005). How to understand the effect of the hydraulic stimulation in term of hydro-mechanical behaviour at Soultz-sous-Forêts (France) in Geothermal Energy – The World’s Buried Treasure (Proceedings of the GRC 2005 Annual meeting, Reno, USA, September 2005) Rachez, X., Gentier, S. and Blaisonneau, A (2006) “Hydro-mechanical behaviour of GPK3 and GPK4 during the hydraulic stimulation tests – Influence of the stress field” (Proceedings of the European Hot Dry rock Association Scientific conference, Soultz-sous-Forêts, France, 15&16 June 2006).

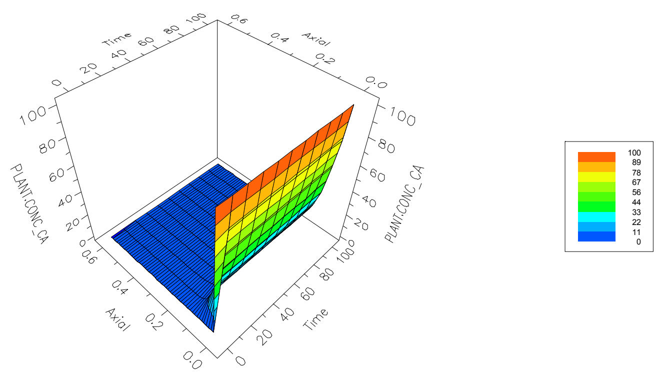
Author(s):	**Daniel Billaux, Caroline Darcel**
Institution	**ITASCA Consultants SAS**
Code:	**3FLO**
Mathematical algorithm:	Finite Element; 3D
Physical Processes:	Flow in fracture networks, represented by a 3D network of 1D channels. Flow in porous media using Galerkine or Mixed-Hybrid 3D finite elements Flow in interacting fractures and porous media Pollutant transport, simulated by the particle tracking method Geochemistry, coupled or not with solute transport, taking into account most types of reactions
Physical Interaction:	Conductivity (1D channel), permeability (3D element), porosity, aperture, storativity, dispersivity, diffusion, etc.
Special features	Internal macro-language that allows building complex models, hooking 3FLO to any other software, performing parameter studies, etc. Advanced fracture tool, adapted for BRGM needs, that allows mixing 1D channels and 3D finite elements.
One application example	A flow and transport model of the Soultz reservoir is under progress. Its aim is to reproduce the in-situ tracer test that has been performed during the fluid circulation test conducted between the injection well GPK3 and the production wells GPK2 and GPK4.  *Perspective view of the model exchanger*
Benefits for Soultz Project	Will help understanding the in-situ tracer tests
References	Billaux, D., J. P. Chilès, K. Hestir and J. Long (1989) - « Three-Dimensional Statistical Modelling of a Fractured Rock Mass — An Example From the Fanay-Augères Mine » Int. J. Rock Mech. & Min. Sci., 26 (3-4), 281-299. Billaux, D., and S. Gentier (1990) - « Numerical and Laboratory Studies of Flow in a Fracture » in Proceedings of the International Conference on Rock Joints (Loen, Norway, 1990), pp. 369-374. Rotterdam: A. A. Balkema.

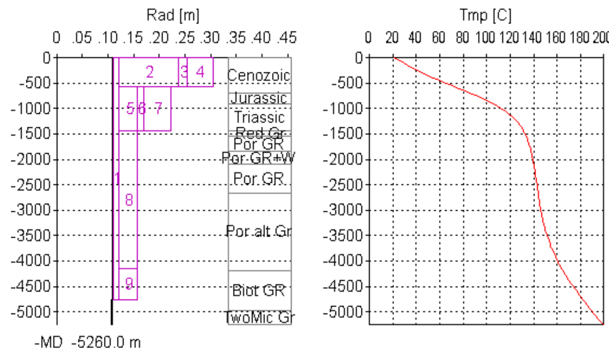
Author(s):	**S. Ollivella, J. Vaunat ; M. Rosener**
Institution	**ETC - UPC, Barcelone ; EOST, Strasbourg**
Code:	**Code_Bright**
Mathematical algorithm:	Finite element method is used for the spatial discretization while finite differences are used for the temporal discretization ; 1D to 3D
Physical Processes:	Hydraulic (linear, non-linear); Thermal (linear, non-linear); Mechanic (linear),
Physical Interaction:	diffusive/ dispersive flux, advective flux caused by fluid motion, advective flux caused by solid motion (depending on activated governing equations)
One application example	Different fault zone geometries were built and tested to look at the hydraulic and thermal behaviour of the structure. Special configurations like a sealed gauge zone were tested too.  *Geometry, grid, heat flux and Total Dissolved Matter distribution*
Future developments	Chemical evolution
Benefits for Soultz Project	Estimation of the damage zone impact on heat and mass transfer in a fault zone during geothermal exploitation
References	Rosener M., Géraud Y., Vaunat J. and Fritz B. 2007 Damage zone integration into fault models : implication on heat and mass transfer during geothermal exploitation, EHDRA Scientific Meeting, Soultz-sous-Forêts.

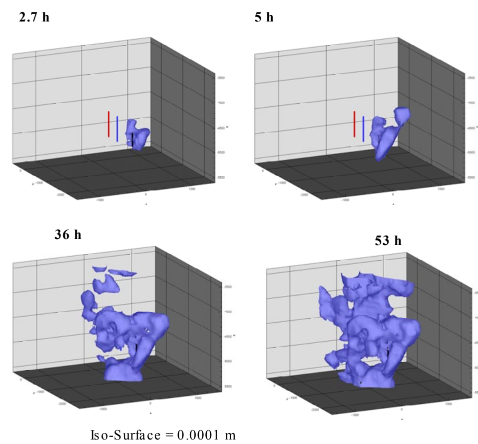
Author(s):	Michel Rabinowicz
Institution	Observatoire Midi-Pyrénées Toulouse
Code:	Convection
Mathematical algorithm:	Finite 3-D difference for the thermal equation, 2-D spectral for the flow equation
Physical Processes:	Darcy flow and convection in a porous media
Physical Interaction:	Variable permeability and viscosity
Special features	2-D flow-fields in vertical gouges coupled with the 3-D thermal field within the walls and gouges
One application example	 We inject cold water in a well and produce it warm in another one both being in hydraulic connection with a vertical stimulated gouge. The temperature and flow evolutions during 30 years of production are computed.
Benefits for Soultz Project	Prediction of production temperature of Soultz Plant
References	Bataillé A., P. Genthon, M. Rabinowicz, B. Fritz: Modeling coupled free and forced convection in a vertical permeable slot: implications for the heat recovery of a geothermal plant, Geothermics, 35, 654-682, 2006. Tournier, C.; P. Genthon, M. Rabinowicz: The onset of natural convection in vertical fault planes; consequences for the thermal regime in crystalline basements and for heat recovery experiments. Geophysical Journal International. 140; 3, 500-508, 2000. Rabinowicz, M., J. Boulegue, P. Genthon: Two- and three-dimensional modeling of hydrothermal convection in the sedimented Middle Valley segment, Juan de Fuca Ridge. Journal of Geophysical Research, B, 103, 10, 24,045-24,065, 1998.

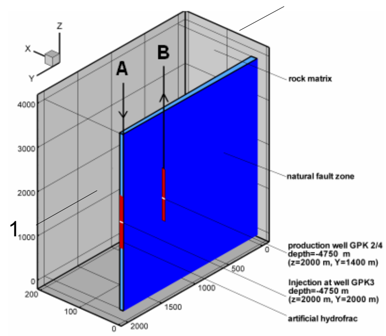
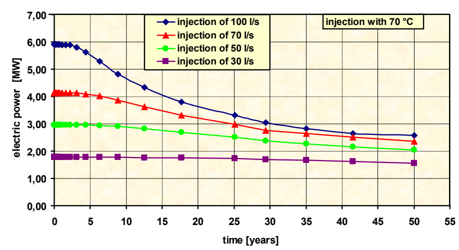
Author(s):	**D. Bruel, C. Baujard**
Institution	**Paris School of Mines - Geosciences**
Code:	**Fracas**
Mathematical algorithm:	Finite Volume, Stochastic Discrete Fracture Network
Physical Processes:	Hydraulic (linear, non-linear); Thermal coupling (*); Non-miscible fluid flow (*); Fracture mechanics (normal; shear and irreversible post rupture dilation) (*) Not both at the same time
Physical Interaction:	Advection; Buoyancy; Viscosity for thermal coupling Density-driven flows for biphasic flow. Permeability (function of pressure; stress; fracture parameters)
Special features	Stochastic Generation of a Discrete Fracture Network with Deterministic Faults segments and Fracture zones.
One application example	The hydraulic stimulation of GPK2, GPK3, and GPK4 were successfully reproduced (see figure below) in terms of well pressure response and hydraulic diffusivity of Soultz reservoir. Tracer tests were used to calibrate the reservoir volume and an estimation of reservoir volume invaded by injection fluid during long-term circulation test of summer 2005 was proposed.  *On top, recorded microseismic events; on bottom, computed shear events with Fracas*
Future developments	Seismic magnitude events, thermal coupling with Non-miscible fluid flow
Benefits for Soultz Project	Forecast of stimulation events and accessible gains in hydraulic properties Evaluation of fluid density impact during stimulation; Forecast of tracer breakthrough curves and thermal behaviour of the stimulated reservoir
References	Baujard, C. and Bruel, D., 2007. Numerical study of the impact of fluid density on the pressure distribution and stimulated volume in the Soultz HDR reservoir. Geothermics, 35: 607-621. Bruel, D., (2007) Using the migration of the induced seismicity as a constraint for fractured hot dry rock reservoir modelling. Int. J. Rock. Mech. Min. Sci. & Abstr., 2007, in press. Bruel D., (2002), Impact of induced thermal stresses during circulation tests in an engineered fractured geothermal reservoir. Example of the Soultz sous Forêts, European hot fractured rock geothermal project, Rhine Graben, France, Oil & Gas Science and Technology, Rev. IFP, vol. 57, n°5, p. 459-470.

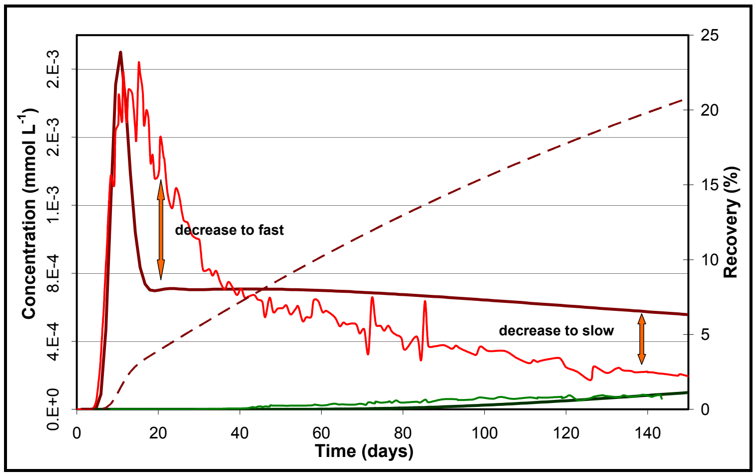
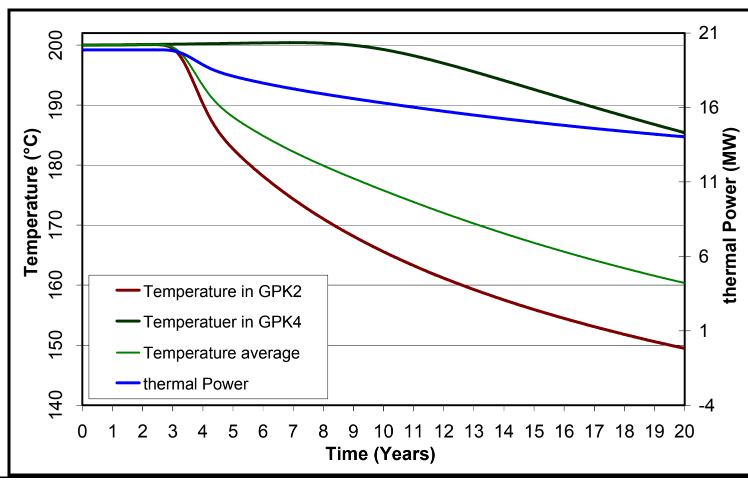
Author(s)	**S. Portier with the contributions of L. André; D. Bächler; P. Durst; T. Kohl; V. Rabemana; and F-D. Vuataz.**
Institution	**CREGE, Neuchâtel with the collaboration of GEOWATT AG, Zürich**
Code	**FRACHEM**
Mathematical algorithm	The 3D finite element code FRACTure (Kohl and Hopkirk, 1995) and the 3D finite volume code CHEMTOUGH (White, 1995) were coupled. The characteristics of the Soultz system, such as the high salinity of the fluids and the re-injection of the fluid after production, preclude the use of the original geochemical model implemented in CHEMTOUGH. Durst (2002) made several modifications: implementation of the new method to calculate activity coefficients (Pitzer model), the reaction kinetics subroutines for the minerals, modification of the calculation of the reaction surface areas and the permeability changes, as well as introduction of the possibility to simulate re-injection processes.
Physical Processes	Hydraulic processes; thermal processes; chemical reactions; advective transport of chemical species and variation of porosity and permeability.
Physical Interaction	Thermodynamic equilibrium; species concentration; precipitation/dissolution; brine-rock interactions; kinetic model; reaction rates; porosity changes; permeability changes, reaction mineral surface area changes.
Special features	1D or 2D deterministic fracture sets are mapped onto a finite element mesh.
One application example	The circulation of injected cold brine in the 5000-m deep Soultz reservoir was modelled. After a brine circulation of 1800 days, calcite appeared to be the most reactive mineral with about 1300 kg dissolved in the first 50 meters of the fractured zone and about 1500 kg precipitated in the second half of the fracture. Silicates and aluminosilicates tended to precipitate near the injection well but in small quantities. A consequence of these reactions was a change in reservoir porosity and permeability. In the vicinity of the injection well, porosity increased by about 30 %, mainly due to calcite dissolution, while porosity decreased by 5 % near the production well. Carbonate reactions seemed to control the porosity of the reservoir, at least during the first 1800 days of circulation. Carbonate behaviour in the deep Soultz reservoir seemed to be in coherence with the results observed for the shallow reservoir.  *Increase of porosity in the vicinity of the injection well due to carbonates dissolution during injection of supersaturated brine at 65 °C.*
Future developments	Sensitivity studies; fracture geometry; redox processes; chemical speciation.
Benefits for Soultz Project	Forecast of chemical and thermal evolution of produced fluid; forecast of minerals behaviour and resulting porosities evolution due to mineral reactions and forecast the effectiveness of the chemical stimulations to enhance the reservoir porosity/permeability. The code appears to be a good tool for investigating the impact of the geochemical processes on reservoir properties.
References	André L., Rabemanana V. and Vuataz F.-D., 2006, Influence of water-rock interactions on fracture permeability of the deep reservoir at Soultz-sous-Forêts, France. Geothermics 35, 507–531. André L., Spycher N., Xu T., Pruess K. and Vuataz F.-D., 2006, Modelling brine-rock interactions in an Enhanced Geothermal System deep fractured reservoir at Soultz-sous-Forêts (France): a joint approach from two geochemical codes: FRACHEM and TOUGHREACT. Lawrence Berkeley National Laboratory, Berkeley. LBNL-62357 Collaboration Report. Bächler D., 2003, Coupled Thermal-Hydraulic-Chemical Modelling at the Soultz-sous-Forêts HDR reservoir (France). PhD thesis, ETH-Zürich, Switzerland, 151 p. Durst P., 2002, Geochemical modelling of the Soultz-sous-Forêts Hot Dry Rock test site: coupling fluid-rock interactions to heat and fluid transport. PhD thesis, University of Neuchâtel, Switzerland, 128 p. Portier S., André L. and Vuataz F.-D., 2007, Modelling the impact of forced fluid-rock interactions on reservoir properties at Soultz-sous-Forêts EGS geothermal site. Proc. European Geothermal Congress, Unterhaching, Germany.

Author(s):	**E. Stamatakis[a,b], A. Stubos[a], C. Chatzichristos [b] and J. Muller [b]**
Institution	**[a]National Centre for Scientific Research Demokritos, Greece** **[b]Institute for Energy Technology, Norway**
Code:	**gPROMS**
Mathematical algorithm: (discretization)	Axial domain: 2nd order Centered finite difference method; Radial domain: 2nd order Orthogonal collocation on finite elements
Physical Processes:	heat transfer mass transfer chemical reactions
Physical Interaction:	fluid velocity, fluid composition, pressure and temperature
Special features	radial dependency of velocity, temperature and concentrations
One application example	Scale tube length:60 cm; scale tube radious:1.25 cm; inlet flowrate: 0.005 kg/s; Pressure: 20 bar; Initial fluid temp: 120°C; inlet Ca: 100 mols/m^3; inlet $CaCO_3$:0  *Consumption of Ca at the inlet of the scale tube*
Future developments	Parameter estimation; objective function; optimization
Benefits for Soultz Project	Forecast of precipitation events; optimal design and operation of the plant
References	Stamatakis E., Bjørnstad T., Muller J., Chatzichristos C., Stubos A., "Simulation of mineral precipitation in geothermal installations: The Soultz-sous-Forêts case", presented during the Workshop 3 ENGINE – ENhanced Geothermal Innovative Network for Europe, Kartause Ittingen, Zürich, Switzerland, June 29 – July 1, (2006). Stamatakis E., Bjørnstad T., Chatzichristos C., Muller J., Stubos A., "Scale Detection in Geothermal Systems: The Use of Nuclear Monitoring Techniques", *presented during the Launching Conference of the European Project: Enhanced Geothermal Innovative Network for Europe (ENGINE),* Orleans, France, 13-15, February (2006). Stamatakis E., Muller J., Chatzichristos C., Haugan A., "Real-time monitoring of calcium carbonate precipitation from geothermal brines", *presented during the European Hot Dry Rock Association (EHDRA) Scientific Meeting*, Soultz-Sous-Forêts, France, 17-18 March (2005).

Author(s):	**T. Mégel**
Institution	**GEOWATT AG, Zurich**
Code:	**HEX-B2, Version 1.1, Borehole simulator**
Mathematical algorithm:	Finite Difference; 1D / 2D cylindrical
Physical Processes:	Navier-Stokes equation, mass conservation and pipe friction in the borehole; radial thermal diffusion in the borehole completion and rock mass
Physical Interaction:	Advection of NaCl-molality and temperature; buoyancy; density, viscosity and heat capacity as a function of temperature, pressure and NaCl-molality;
Special features	Calculation of pressure and temperature profiles from wellhead measures. Exit-/Entry points with specific time histories of temperature/NaCl-molality in different depths can be defined. Arbitrary borehole diameters and well completion.
One application example	Borehole models have been built and calibrated for the three deep wells of Soultz GPK2 GPK3 and GPK4. These models were used to calculate pressure and temperature profiles during injection or production in boreholes.  *HEX-B2 Well model for well GPK4, right: initial temperature*
Future developments	Understand better transient processes, especially for shut-in phases which sometimes show gaps between measured and calculated values
Benefits for Soultz Project	- Prediction of production temperature dependence with flowrate of wells GPK2 and GPK4, effect of entry-points - Pressure values when fracture failure occurs - Making test data comparable - It may not be necessary to use downhole sensors for each injection/production experiment in Soultz, as calculated HEX-B2 values can be used for interpretation
References	Mégel, T., Kohl, T. and Hopkirk, R.J., 2007. The potential of the use of dense fluids for initiating hydraulic stimulation. Geothermics, 35: 589-599.

Author(s):	**T. Kohl; T. Mégel**
Institution	**GEOWATT AG, Zurich**
Code:	**HEX-S**
Mathematical algorithm:	Finite Element; 3D
Physical Processes:	Hydraulic (linear, non-linear); Thermal (linear, non-linear); Elastic (linear), Fracture mechanics (normal; shear)
Physical Interaction:	Advection; Buoyancy; viscosity Poroelasticity (*); Thermoelasiticity (*); Permeability (function of pressure; stress; fracture parameters) (*) not yet activated
Special features	Deterministic and stochastic fracture sets are mapped onto a finite element mesh
One application example	The hydraulic stimulation of GPK4 in September 2004 was simulated using the available information of stress field. The model includes 15 major deterministic fractures of GPK2-GPK4 and accounts for stochastic fracture distribution at larger distance.  *Increase of permeability due to normal compliance and shearing during injection in GPK4*
Future developments	Parameter studies; Poroelasticity; Thermoelasiticity
Benefits for Soultz Project	Forecast of stimulation events; Can be used for stimulation design
References	Kohl T., Mégel T., 2007, Predictive modeling of reservoir response to hydraulic stimulations at the European EGS site Soultz-Sous-Forêts, Int. J. of Rock Mechanics, In press Kohl T., Baujard C., Mégel T., 2006, Conditions for Mechanical Re-Stimulation of GPK4, Soultz Scientific Meeting, Synthetic 2nd year report Kohl T. Mégel T., 2005, Coupled Hydro-mechanical modelling of the GPK3 reservoir stimulation at the European EGS site Soultz-sous-Forêts, Proc. 31th Workshop on Geothermal Reservoir Engineering; Jan. 31-Feb. 2, 2005, Stanford University, CA, USA.

Author(s):	**H. Sulzbacher; R. Jung**
Institution	**Leibnitz Institute for Applied Geoscience, Hannover**
Code:	**Rockflow**
Mathematical algorithm:	Finite Element; 3D
Physical Processes:	thermal, hydraulic and mechanic coupled processes (THM $_{plus}$)
Physical Interaction:	Advection; Conduction; Viscosity
Special features	Stimulated fractures, connected to the boreholes and an interconnecting natural fault zone are mapped onto a finite element mesh.
One application example	 *Deep reservoir in Soultz. Numerical model of the heat exchanger. Due to symmetric reasons only a quarter of the model has to be considered. A: GPK3, B: GPK4 or GPK2. The Cartesian coordinate system is oriented parallel to the strike of the model. Z=2000 m corresponds to a depth of 4750 m.*  *Production of electric power with different injection rates. Injection temperature is 70°C.* The long term production temperature and electric power of the deep heat exchanger has been computed for different fracture lengths, injection temperatures and circulation flow rates. The results show that due to the presence of the stimulated fractures the thermal performance and the lifetime of the system are significantly improved and are of commercial interest even if fluid flow is restricted to the relatively narrow fault zone.
Future developments	Calibration of the model with data from tracer experiments
Benefits for Soultz Project	Forecast of production temperature and production power
References	Grecksch,G., H. Sulzbacher, R. Jung (2003b): Hydraulic Modeling of the Deep Geothermal Reservoir in Soultz– ZIP Vorhaben "*Hot-Dry-Rock-Project Soultz – Hydrogeothermische Modellierung des HDR-Wärmetauschers" (Förderkennzeichen: 0327109B), "Hot Dry Rock Energy" (EC contract ENK5-CT-2000-00301)* Jung, R, S. Röhling,N.Ochmann, S.Rogge, R.Schellschmidt, R.Schulz, T.Thielemann (2002): Abschätzung des technischen Potentials der geothermischen Stromerzeugung und der geothermischen Kraftwärmekopplung (KMW) in Deutschland. *Studie im Auftrag des Büros für Technikfolgeabschätzung beim deutschen Bundestag (TAB)*

Author(s):	**M. Blumenthal, M. Kühn, H. Pape, V. Rath, C. Clauser**
Institution	**Applied Geophysics and Geothermal Energy** **RWTH Aachen University**
Code:	**SHEMAT**
Mathematical algorithm:	Finite Difference; 2D
Physical Processes:	Flow, heat, transport
Physical Interaction:	Flow and heat coupled via density, viscosity, compressibility, thermal conductivity, and thermal capacity (function of temperature and pressure). Temperature dependence of thermal rock properties.
One application example	The tracer test performed in 2005 was used to calibrate a simplified 2D horizontal model of the deep reservoir in Soultz. The model is based on known structural units: (1) two fracture families in the host rock; (2) mechanically stimulated zones around the wells; (3) a direct hydraulic connection between the wells.  
Future developments	3D model, water-rock interaction, chemical stimulation test, multiple porosity/permeablity module
Benefits for Soultz Project	Interpretation of tracer tests. Evaluation of hydraulic concepts. Forecast of heat extraction process under varying constraints (e.g. pumping rates).
References	Blumenthal M., Kühn M., Pape H., Rath V., Clauser C. (2007) Numerical simulation of a tracer test from the EGS test site Soultz-sous-Forêts. Jahrestagung der Deutschen Geophysikalischen Gesellschaft. 26.-29. März 2007, Aachen Kühn M., Pape H., Rath V., Wolf A., Clauser C. (2007) Interaction of a multi-fractured rock system with fluid flow, mass and heat transport, and chemical reactions. Jahrestagung der Deutschen Geophysikalischen Gesellschaft. 26.-29. März 2007, Aachen Pape H., Rath H. (2006) Simulation of reactive transport in a stimulated “hot dry rock” system with mass exchange between fracture systems of various thermal gradient, In: Proc. EHDRA Scientific Conference. June 15-16, 2006, Soultz-sous-Forêts, France