International Partnership for Geothermal Technology

Geothermal Reservoir Modeling

Recommendations for Research and Development

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Table of Contents

EXECUTIVE SUMMARY

The International Partnership for Geothermal Technology (IPGT) provides a forum for geothermal leaders from government, industry and academia to coordinate their efforts and collaborate on projects. The IPGT has defined a number of areas of technology focus, establishing working groups to summarize the current state of the art and provide recommendations on ways to advance the technology in that area. To date, four nations have signed the IPGT charter: Australia, Iceland, Switzerland, and the United States.

The Reservoir Modeling Working Group has held several workshops in member nations. The goal of the workshops were to gather information from host nation leaders in geothermal reservoir engineering and modeling regarding the simulation capabilities needed to address technical challenges facing engineered geothermal systems (EGS) and supercritical hydrothermal systems. At the workshops, input was actively solicited from geothermal industry representatives in the hope that the final list of technical challenges would also reflect the needs of professionals working in private industry. Reviewing the needs identified at the workshops, and from follow-on discussions between the Working Group members, a vision of the next generation of geothermal reservoir simulators has been prepared.

The vision centers on the development of a fully coupled thermo-hydro-mechanical-chemical (THMC) reservoir simulation code by the year 2020. The key strategy is a hierarchical approach, consisting of the development of laboratory and field datasets, which in turn support a series of model-component development exercises. These will focus on subsets of the full coupling that were identified as most relevant to geothermal reservoir creation and operation. The best possible conceptual and numerical approaches will be identified and implemented in order to improve the reliability and, hence, practical applicability of quantitative numerical modeling. The final code will integrate these components into a coherent simulation framework with the capabilities to describe the complex non-linear interactions and feedbacks associated with multiphase fluid flow, energy transport, regional- and local-scale geomechanical deformation (and fracturing), and geochemical interactions between the working fluid and host reservoir rock—all at highly variable timescales.

INTRODUCTION

The purpose of the International Partnership for Geothermal Technology (IPGT) is to accelerate the development of geothermal technology through international cooperation by providing a forum for government and industry leaders to coordinate their efforts and collaborate on projects. From an original seventeen potential topical areas, in 2008 the IPGT steering committee defined six areas of technology focus; *Lower Cost Drilling*, *Zonal Isolation/Packers*, *High Temperature Tools*, *Stimulation Procedures*, *Reservoir Modeling*, and *Exploration Technologies*. In 2010, the steering committee added at seventh topical area, *Induced Seismicity*. For each of these topical areas, whitepapers are being prepared to summarize the current state of the art and provide recommendations on ways to advance the technology in that area. The white papers will ultimately contribute to the development of a geothermal technology roadmap.

This document is the whitepaper on *Reservoir Modeling*. It has been jointly developed by Reservoir Modeling Working Groups formed in Iceland and the United States by holding workshops in the respective countries. The goal of the individual nation reservoir modeling workshops were to gather information from national leaders in geothermal reservoir engineering and modeling regarding the next generation of reservoir simulators needed to address technical challenges facing engineered geothermal systems (EGS) and supercritical geothermal systems. The Icelandic workshop was held in Orkugardur on March 4th 2010 with the members of the *Geothermal Research Group* (GEORG) in Iceland with over 50 participants from all the major power companies, universities and research institutions. The US held an online workshop on March 18th 2010 with over 20 participants, including representatives from non-IPGT member nations. The majority of the US invitees had a background in numerical modeling, as the goal of the US working group meeting was to gather information regarding the next generation of reservoir simulators. At both workshops, input was actively solicited from geothermal industry representatives in the hope that the final list of technical challenges would also reflect the needs of professionals working in private industry.

Reviewing the results of the two workshops, the conveners believe that there are great opportunities for international collaboration through IPGT in reservoir modeling that could enhance geothermal development. From the needs identified at the workshops, and follow-on discussions among the working group, this report presents a technology development vision and roadmap outlining the research needs and opportunities needed to develop and apply the next generation of geothermal reservoir simulators.

Background

Numerical simulation has played a pivotal role in elucidating the dynamic behavior of hydrothermal systems and for testing competing hypotheses in these complex, typically data-poor environments. Though our ability to rigorously describe key hydrothermal processes is still imperfect, there have been substantial advances over the past several decades. These advances owe mainly to the steady growth of computational power and the concomitant development of numerical models that have gradually minimized various simplifying assumptions. They include incorporation of more accurate equations of state for the fluid system, an increased ability to represent geometric complexity and heterogeneity, and faster and more accurate computational schemes. In some instances, these advances have revealed dynamic behaviors that were entirely obscured in previous generations of models.

The emerging technology of EGS poses additional computational challenges. For instance, the EGS concept is based on dynamic changes in fracture permeability that the current generation of continuum or dual-continuum hydrothermal models is ill equipped to describe. The success of EGS requires increasing the permeability of a large volume (~1 km^3) of rock – typically by a factor of 10^2 or so – without generating an unacceptable level of seismicity, and then maintaining the enhanced level of permeability in a geochemically reactive environment. In order for numerical modeling to be useful for understanding the mechanics of reservoir stimulation and managing the production capacity of EGS systems, the current generation of models must be substantially improved, or perhaps replaced by a new generation of more-sophisticated models. A recent increase in the level of geothermal investment in several countries affords an opportunity for rapid progress, particularly if there is multinational cooperation to resolve key issues.

There is clear field and laboratory evidence for extreme heterogeneity and dynamic variation in permeability in hydrothermal systems in general, and similar (or even stronger) dynamic variations are anticipated in EGS where there is a particular need for more realistic treatment of material heterogeneity in space and time. Attempts to represent this variability in numerical models are limited. More sophisticated representations of heterogeneity at the fault-zone [*Lopez and Smith*, 1995] or system-wide [*Matthäi et al*., 2004, 2007] scales generally do not involve high-temperature, multi-phase, multi-component flow. Attempts to represent dynamic variations in permeability in a hydrothermal context have been *ad hoc* rather than physically rigorous [*see e.g. Rojstaczer et al*., 2008]. Some newer geothermal simulators are proprietary and not available for review and use by the community at large [*e.g. Kohl and Megel*, 2007].

Whereas permeability enhancement for EGS is mainly a hydro-mechanical issue, permeability maintenance for a ~30-year reservoir lifespan may be largely a geochemical issue. Laboratory experiments involving hydrothermal flow under pressure, temperature, and chemistry gradients in crystalline rocks result in order-of-magnitude permeability decreases over daily to sub-annual timescales [*e.g. Summers et al*., 1978; *Morrow et al*., 1981, 2001; *Moore et al*., 1983, 1994; *Vaughan et al*., 1986; *Cox et al*., 2001; *Polak et al*., 2003; *Yasuhara et al*., 2006]. Field observations of continuous, cyclic and episodic hydrothermal-flow transients at various timescales also suggest transient variations in permeability [*e.g. Baker et al*., 1987, 1989; *Titley*, 1990; *Hill et al*., 1993; *Urabe et al*., 1995; *Haymon*, 1996; *Fornari et al*., 1998; *Sohn et al*., 1998; *Gillis and Roberts*, 1999; *Johnson et al*., 2000; *Golden et al*., 2003; *Husen et al*., 2004; *Sohn*, 2007]. Despite these empirical observations, only a few numerical-modeling studies have invoked temperature-, pressure- or time-dependent permeability, or the effects of reactive transport on permeability.

Realistic representations of heterogeneity could also benefit from the calculation of effective permeabilities. So-called "upscaling" is a standard procedure in reservoir engineering, helping to capture the essential heterogeneity of a geological model while reducing the number of grid-points in the numerical model, ultimately reducing computing time [*e.g. Christie*, 2001]. A closely linked issue is the need to relate actual observables (such as seismic activity) to the distribution of hydraulic parameters (such as permeability).

The very high temperatures in high enthalpy and supercritical geothermal systems cause additional challenges. The nature of fluid flow near the temperature-dependent brittle to ductile transition and heat transfer from hot source rock to geothermal fluids is poorly understood. Two-phase (steam+liquid) flow is abundant and very little is known about relative permeability functions under reservoir conditions [*Ingebritsen et al.*, 2010]. Dissolved components such as salts and CO_2 alter the temperature-pressure (depth) conditions at which liquid and steam coexist. Very high temperature systems that would nominally be in the one-phase "supercritical" field of pure water experience boiling and condensation due to impurities leading to complex patterns of vapor-dominated and two-phase zones in the subsurface [*Coumou et al.,* 2009]. In spite of recent advances for water-salt systems [*Driesner & Heinrich*, 2007, *Driesner*, 2007, *Coumou et al*., 2009], developing accurate equation of state models for these high temperature systems, combining them with reliable relative permeability models, and incorporating them into simulators remains a major challenge and will be key to meaningful predictive simulations of these systems.

Even with the current generation of multi-phase, multi-component simulators (see Table 1 for summary of selected current simulators) it is impossible to fully test against analytical solutions or empirical results. Analytical solutions are limited, and experimental data have to be developed for each specific application [*e.g. Woods*, 1999; *Bergins et al*., 2005; *Benard et al*., 2005].

Table 1 – Relative capabilities of selected multi-phase numerical codes commonly applied in simulations of geothermal systems. Numerical methods are: DEM - Discrete Element; FD - Finite Difference; IFD – Integrated Finite Difference; FE-Finite Element; FE-FV - Finite Element-Finite Volume. The columns labeled CO_2 and X_{NaCl} indicate whether the EOS formulations include those components, modified after *Ingebritsen et al.* [2010].

Name [Reference]	T_{max} (°C)	P_{max} (MPa)	Numerical method	Reactive transport	Deformation	CO_2	X_{NaCl}
CSMP++ [*Matthäi et al*., 2007; *Coumou*, 2008]	1,000	500	FE-FV				X
FALCON [*Podgorney et al.*, 2010]	350	100	FE-DEM		X		
FEHM [*Zyvoloski et al*., 1988, 1997; *Bower and Zyvoloski*, 1997 ; *Dutrow et al*., 2001; *Keating et al*., 2002]	1,500		FE	X	X	X	
FISHES[1] [*Lewis*, 2007; *Lewis and Lowell*, 2009]	800	1,000	FV				X

HYDROTHERM [*Hayba and Ingebritsen*, 1994; *Kipp et al*., 2008]	1,200	1,000	FD				
NaCl-TOUGH2 [*Kissling*, 2005b]	620	100	IFD				X
TOUGH2 [*Pruess*, 1991; *Pruess et al*., 1999]	350	100	IFD			X	X
TOUGH2-BIOT [*Hurwitz et al*., 2007]	350	100	IFD-FE		X	X	
TOUGH-FLAC [*Rutqvist et al*., 2002]	350	100	IFD-FE		X	X	
TOUGHREACT [*Xu et al*., 2004b]	350	100	IFD	X		X	
TOUGHREACT-FLAC [*Taron et al*., 2009; *Taron and Elsworth*, 2009]	350	100	IFD-FE	X	X	X	

[1] Successor model to GTHM [*Lowell and Xu*, 2000; *Bai et al*., 2003]

TECHNOLOGY DEVELOPMENT ROADMAP VISION

The vision of the Reservoir Modeling Working Group centers on the development of a fully coupled thermo-hydro-mechanical-chemical (THMC) reservoir simulation code by the year 2020. The code will require the capabilities to describe the complex non-linear interactions and feedbacks associated with multiphase fluid flow, energy transport, regional- and local-scale geomechanical deformation (and fracturing), and geochemical interactions between the working fluid and host reservoir rock—all at highly variable timescales.

The key to the proposed strategy is in the hierarchical building of key components, consisting of the development or collection of laboratory and field datasets, which in turn support a series of model-component development exercises (both conceptual and numerical), all of which go to support the final goal of a physically realistic THMC model. The vision is shown graphically as a four-tiered *Technology Development Pyramid* in Figure 1.

It should be emphasized that the components to be developed in the lower tiers are expected to meet real needs in hydrothermal and EGS systems. In particular, the simulators contribute to:

1. Reliable reservoir engineering and management strategies of both hydrothermal and EGS by improving our ability to predict the results of permeability enhancement (reservoir stimulation) and evolution (fluid-rock interaction, thermal stresses and strains, etc.)

2. Improved predictions of reservoir performance to support estimations of production capacity,
3. Providing the means to confidently manage reinjection

Addressing these subsets of the fully coupled problem with due consideration at the third tier (and perhaps lower) level will provide the base for the success of the ultimate vision. The third and fourth tier simulators must be benchmarked against the challenge problems and datasets developed in the first tier. The work accomplished in any given tier of studies is not to be performed in isolation, or with consideration solely to the results of lower tier studies, but must be informed by the needs of future tiers and designed to support the overall goal of developing a fully integrated numerical simulator capable of answering the needs of industry.

In the sub-sections that follow, each tier of the pyramid is described in more detail.

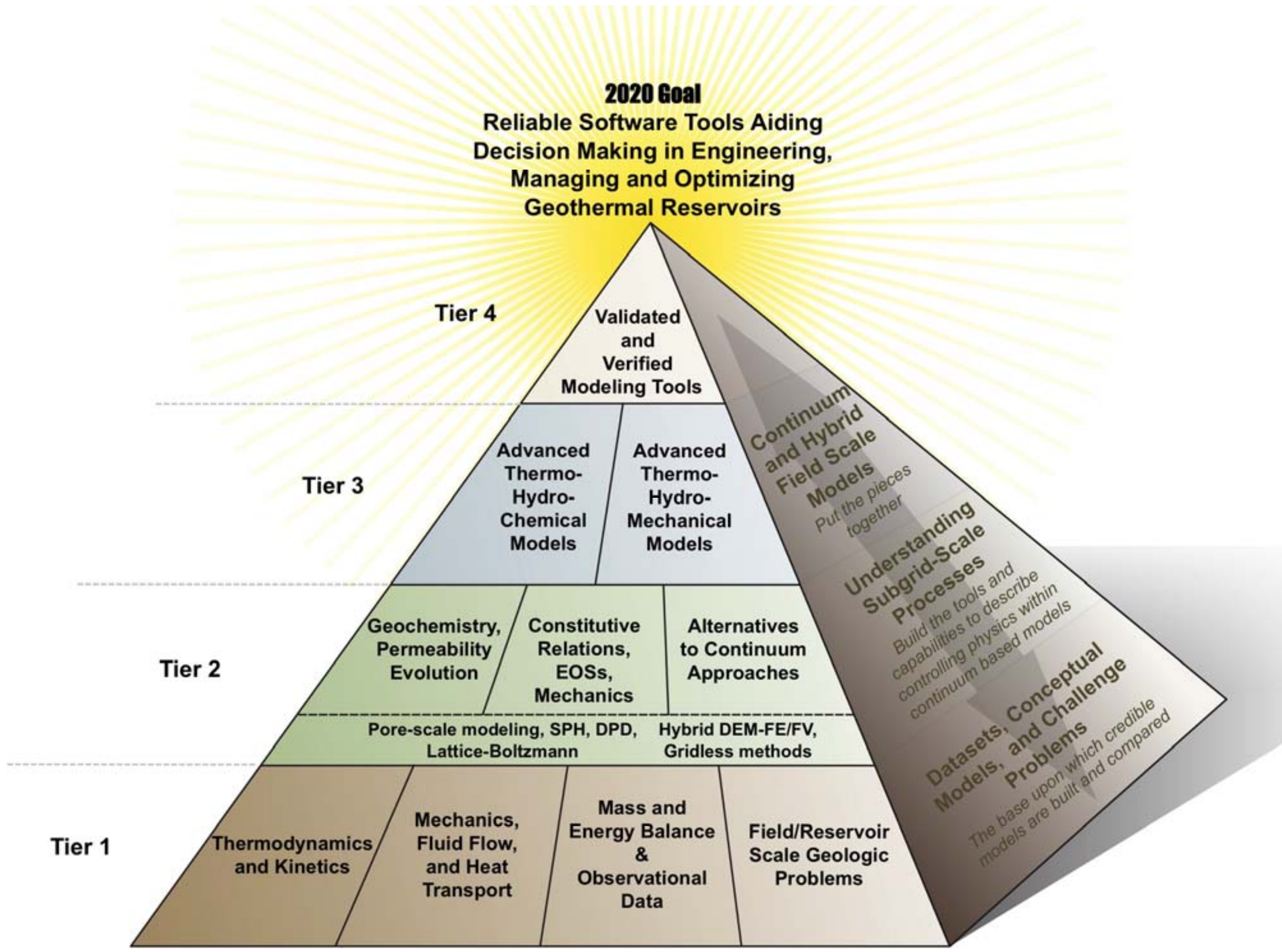

Figure 1. Technology Development Pyramid for reaching a 2020 goal of fully coupled thermo-hydro-mechanical-chemical simulators for predicting short- and long-term production capacity in hydrothermal and enhanced geothermal reservoirs. Acronym definitions are SPH (Smooth Particle Hydrodynamics), DPD (Dissipative Particle Dynamics), DEM (Discrete Element Model), FE (Finite Element), FV (Finite Volume), THMC (Thermo-Hydro-Mechanical-Chemical).

Tier 1: Datasets, conceptual models, and challenge problems

The basis of all physically realistic numerical simulation is the ability of models to reproduce observations and accurately predict system behavior within the bounds of uncertainty. The first items in the timeline ("Tier 1 Tasks") are tasks to develop or assemble laboratory and field data that may be used to support conceptual understanding of processes that are at present poorly constrained.

Laboratory datasets are needed in this endeavor because the development of a conceptual understanding of sub-grid scale processes requires an understanding of individual phenomena in isolation one from another The ability to model more complex groupings of these phenomena in a field setting is tested by the field datasets, the simulation of which is designed to exercise both the numerical simulators and the conceptual models they embody. Because these datasets are required to support model development, the products from the Tier 1 studies should be couched in terms of a series of challenge problems for numerical and conceptual models, thus allowing a systematic inter-comparison of independently developed simulators and providing a way of building confidence in their performance.

Inter-code comparison projects have been conducted in many other subsurface-modeling areas and have led to significant improvements. Previous efforts include the USDOE/Stanford code-comparison project [*Kruger*, 1980], which exercised the first generation of multi-phase geothermal simulators; the Hydrologic Code Intercomparison (HYDROCOIN) [*Larsson*, 1992], DECOVALEX (http://www.decovalex.com), and BENCHPAR [*Stephansson and Min*, 2004] projects, which focused on modeling coupled flow and transport processes; and, most recently, comparisons of subsurface CO_2-storage simulators [*Pruess et al*., 2004; *Ebigbo et al*., 2007]. An example of a continually evolving code verification effort, focusing on earthquake mechanics, can be found at http://scecdata.usc.edu/cvws/. In this code verification project, the scientific community can simply "check-out" datasets to test their code, and compare their results with other code developers [*Harris et al.*, 2009].

Appendices A-D document potential cooperative projects that can serve as a start for building the base of the pyramid. Some of these projects can be accomplished in collaboration with other working groups (such as Exploration, Stimulation, High Temperature Tools, and Induced Seismicity). Additional projects that can help support technology development in this area will continually be evaluated and added.

Tier 2: Subgrid-scale processes

The two aspects of model development the Tier 1 studies are intended to support—process conceptualization and numerical simulation of sub-grid scale properties—are shown on the Tier 2 of Figure 1. This tier focuses on building the numerical tools and capabilities to describe controlling physics within continuum-based models. . The methods developed in Tier 2 should consider innovative approaches to modeling processes, or use innovative processes to develop justifiable upscaling methods. These may be continuum-based approaches employing novel means of representing sub-grid scale processes, gridded or gridless methods, including (but not limited to) Discrete Element Models (DEM), Discrete Fracture (DF), Lattice-Boltzmann (LB), or Smooth Particle Hydrodynamics (SPH), or other creative numerical schemes for representing the processes of interest.

Appendices E-G document potential cooperative projects that demonstrate the tight coupling between Tiers 1 and 2. These suggested projects focus on expanding our understanding of processes that control the evolution of permeability in geothermal reservoirs, either in relation to fluid saturation conditions or the physical stress state of the system. Of course, these two suggested projects are in no way a definitive compilation of necessary work, but are provided as a demonstration of the types of research envisioned for this Tier.

Tier 3: Continuum and hybrid field scale models

The construction of numerical simulators from the process conceptual models and the numerical methods is presented in the third row of Figure 1. The simulators required as the product of these Tier 3 tasks are thermal-hydro-mechanical (THM, mostly addressing problems of the stimulation phase as well as thermoelastic problems during production) and thermal-hydro-chemical (THC, mostly relevant for the production phase) models; i.e., simulators that describe thermal-hydraulic processes coupled with either reactive transport chemistry or mechanical stress/strain modeling, but not both. The actual form of these models is not known at the present time, because simulator development will arise from the conceptual understanding and numerical simulation methods developed in the prerequisite studies (i.e., the Tier 2 studies). What is important however, is that both the Tier 2 and Tier 3 studies should both consider innovative approaches to modeling processes in thermal systems. As outlined above, these may include novel continuum-based approaches or methods or other creative numerical schemes for representing the processes of interest (such as DEM, DF, LB, SPH).

Tier 4: Fully coupled thermo-hydro-mechanical-chemical models

The final technical goal of the program is the development of a fully coupled THMC model, presented in Figure 1 as the Tier 4 activity at the top of the pyramid. The goal of merging the Tier 3 THM and THC models into a fully coupled THMC model is not a trivial undertaking; the primary reason for this is that the component processes, most notably the mechanical and chemical interactions, operate on vastly different timescales, posing difficult numerical questions in terms of time step size, numerical stability, efficient solution methods, etc. Representation of chemical and mechanical processes may also require different discretization schemes (in the case of gridded methods) or may be handled most efficiently by entirely different computational approaches. In addition, the usefulness of operator splitting vs. fully coupled approaches (or a hybrid of the two) will need to be evaluated.

PUTTING IT ALL TOGETHER

Tiers 1-4 formulate a vision for a rigorous roadmap of the theoretical and numerical developments needed for THMC forward simulation of geothermal reservoirs. This forward modeling framework is proposed to be quality tested by the best of practice computational methods, such as unit test, subversion control, formulation of semi-analytical benchmarks, inter-code comparison workshops and other verification procedures. An additional challenge is posed by the multi-scale assimilation of field, laboratory and engineering data. This inverse problem of assimilating input data such as seismic, rock properties, gravity, E&M, well logs, magnetics, chemistry and geologic into forward models of seismic gravity, magnetic, material failure, reactive flow, E&M, chemical reaction and geologic process is described on the right side of the pyramid.

The scope of this part of the pyramid is to provide a framework and data services for data visualization, forward modeling, model construction, data analysis, and data assimilation (inversion). The goal of the right side is meant to provide the general background and link to the reference implementations for the global set of THMC problems.

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APPENDIX A: MEASUREMENTS AND DATA GATHERING

Description: Measurements of data related to geothermal fields plays a fundamental part in reservoir modeling and predictions of reservoir behavior related to utilization. The measurements can in general be classified into two parts:

- Laboratory measurements in controlled conditions. This involves various flow parameters as well as behavior of fluids in porous and fractured media One important aspect of this is two-phase flow of steam and water, both in homogeneous porous media as well as in fractures, where the two phases interact and affect in turn each other's behavior. One such experiment is planned in Iceland, with the purpose of generating better relations for relative permeabilities in two-phase flow.

- Measurements conducted in estimating reservoir potential as well as measurements in wells during testing and production. Both types can be considered as in-situ investigations, and are thus not as well controlled as laboratory test. This involves parameters such as flow, pressure and temperature, and is available at different locations in wellbores.

Need: In most cases, theoretical mathematical models of physical processes are idealized representations of more complex real phenomena and can hence only be accurate results to some degree. Therefore model results should always be compared to real measurements to guide improvements to the mathematical methods and material property parameterizations. Also, fundamental behavior of models should be validated by real data to make sure that the physical processes are correctly interpreted, regardless of smaller errors in calculations or measurements.

A good dataset is therefore needed for all modeling work, preferably in a form that different modeling people can access and understand. This is very important both in smaller scales where localized models are compared to laboratory tests, as well as in larger scales where well related data is compared to large models involving whole-scale reservoirs. Related data, such as earthquake movements and surface investigations could also prove valuable.

Approach: Currently, there is a vast amount of data available at different places, under different ownership. The project will involve gathering of information about the available data, and in continuation gathering of available data. The data will be stored in a well-documented standard form for ease of use.

Laboratory measurements will be promoted where they are needed, but the intention here is to gather data from already performed tests, or tests that are currently being planned or performed. The project will also identify which experiments are currently the ones most needed.

APPENDIX B: DATABASE ON PRODUCTION CAPACITY OF EXISTING FIELDS AND WELLS FOR ESTIMATING GREENFIELD CAPACITY

Description: Dynamic reservoir models of geothermal areas are generally based on data obtained from boreholes. These data come at a considerable economic and environmental cost and therefore a necessity arises for a reliable assessment of the capacity of a field prior to drilling to weigh against these costs. This has commonly been done by a volumetric assessment, but the main parameters for the volumetric method have been only moderately constrained and the predictability of the volumetric model has not been studied in great detail. By comparing volumetric assessments made with various subsets of green field measurements for fields with a well-established capacity, the predictability of volumetric assessments based on green field data can be studied and modeled.

Need: In order to be able to effectively predict production capacity of geothermal systems by using models it is necessary to acquire a database on existing production capacity of fields and wells. The uncertainty in the volumetric assessment is very high. The estimation of the recovery factor can vary greatly between research groups. Data gathered with resistivity measurements may give the wrong impression on the size of the reservoir because current conditions are different from formation conditions. An estimation of how much energy can be harnessed sustainably from the reservoir needs to be established. Increase group work and cooperation with other groups to coordinate methods. Educated guesses need to be defined from facts since information based on educated guesses are often over interpreted and considered as facts by policy makers.

Approach: IPGT collaboration could be in the form of data sharing of well-known geothermal fields. A list could be constructed of fields with well-established capacities. Gather surface measurements from these fields. Catalogue the measurements for each field in a comparable way. Standardize the green field volumetric assessments for these fields and establish an error-estimation scheme that can predict the order of magnitude of the difference between the volumetric assessments and the established capacities. This database can as well be used for model validation in other tasks.

APPENDIX C: DEVELOPMENT OF CODE COMPARISON AND VALIDATION FRAMEWORK

Description: A significant code comparison study for geothermal reservoir simulators hasn't been undertaken for decades. Since the last study was undertaken, significant advances have been made in both our conceptual understanding of geologic phenomenon associated with geothermal reservoir behavior and computational capabilities and methods available to the modeling and model development community. Coupled thermo-hydro-mechanical-chemical processes can exhibit significant control on the performance of geothermal reservoirs. Methods to simulate the coupled processes vary, but several are receiving considerable attention, 1) Operator splitting approaches where sub-processes are solved sequentially, in the extreme case by independent codes that are linked via input files, and 2) Implicit coupling methods where all processes are solved simultaneously.

Need: Data to test and verify models simulating coupled behavior and numerical coupling methods are lacking.

Approach: The modeling working group should form a committee for this task. The duties for the committee would be to develop a set of standards for the data, develop a database and select where it should reside, develop the legal and scientific frameworks for putting what could be confidential data into the public domain, and issue a call (with modest funds) for people to provide the data.

Potential Collaborators:

This project should be carried out by the Reservoir Modeling Working Group.

APPENDIX D: PERMEABILITY ENHANCEMENT AND DEVELOPMENT IN RESPONSE TO STRESS AND FLUID PRESSURE EVOLUTION

Description: Enhancement of reservoir permeability through stimulation is a pre-requisite for production from EGS and often required in hydrothermal systems, but routine strategies that avoid unwanted levels of induced seismicity are not yet available. During production, changes in reservoir temperature are known to affect the permeability of geothermal reservoirs due to shrinking or contraction of the rock matrix. Coupled modeling suggests that the thermoelastic effects of cold-water injection into hot reservoir rocks are significantly greater than poroelastic effects. Injection of cold water at high pressure can also potentially lead to reactivation of natural existing fractures. While basic knowledge for simple geometries was derived as early as 20 years ago, a systematic and general understanding of these effects in fracture networks and fractured porous media is still in its infancy. Upscaling techniques for reservoir-scale simulations require developing constituitive relations for mechanical effects on permeability in fractured media.

Need: Physics-based simulations of the mechanics of fracture networks in response to high fluid injection rates, local variations of the stress field, and thermal evolution due to production. In order to be able to effectively model thermoporoelastic effects on the permeability evolution of geothermal reservoirs with continuum-based methods, effective and accurate constitutive relations will be required.

Approach: Understand permeability of fracture networks and fractured media as a function of:

- Far-field Stresses
- Evolving fluid pressure fields
- Stress evolution as a function of temperature during production
- Fracture aperture evolution with temperature and fluid pressure changes

These data can be then used to develop and validate pore- and meso-scale coupled THM models and extrapolate conditions beyond those tested in the laboratory and build a generalized description of the relationship. To meet the research needs, meso-scale THM models must be able to explicitly discretize fracture networks and model displacement and/or growth of fractures and tightly coupled with flow and heat transport models that also explicitly model flow and transport in fractures, not using the conventional equivalent porous media and dual-porosity (or permeability) approaches. The mechanical models that satisfy such needs at this scale include DEM, SPH, extended finite element method, boundary element etc. The flow and transport models include lattice Boltzmann, dissipative particle dynamics (DPD), smoothed particle hydrodynamics (SPH), pore network type flow models and multiphase Navier-Stokes solvers (CFD) coupled with interface tracking techniques.

APPENDIX E: UNDERSTANDING THE ROOTS OF MAGMATIC GEOTHERMAL SYSTEMS

Description: Understanding the driving force of geothermal activity is the main challenge of geothermal modeling. The power sources of geothermal systems in volcanic areas are cooling and even solidifying intrusions located relatively shallow in the earth's crust and a magma chamber at the depth of few km. The temperatures of mentioned bodies can be well over 1000°C. The critical temperature of water (T_c) is ~374°C and it is difficult to simulate water using numerical code at those conditions. Moreover, the knowledge on the state of the system at greater depths is limited. Deepest wells in high temperature areas are ~3km deep and the permeability below that depth is not known nor the interaction of water and the heat sources.

Due to inability of numerical codes to treat superheated ground water systems properly and the lack of knowledge on the deep roots of geothermal systems the interaction of the roots of the geothermal systems to the upper parts is normally simulated using the bottom boundary conditions. This is done without making any detailed assumptions on the system at greater depths.

Need: The understanding of the roots, along with the ability to simulate supercritical conditions, is essential for overall simulation of a geothermal system. Understanding the roots of geothermal systems and being able to model them will enhance the accuracy of the model prediction and the overall understanding of the thermodynamics of the geothermal activity.

Approach: The project of including the interaction of the heat sources, i.e. magma and intrusions, and the groundwater into the models, can be split into the three parts:

- Building a conceptual model of the roots. Sampling available geological, geophysical and geochemical data on geothermal systems. The question is, at what depths do the interactions between the heat sources and ground water take place and how does it work. One has to take into account sporadic or random intrusions along with constant heat sources.

- Developing methods (codes etc.) for calculating the conditions at the greater depths. Codes have to be able to handle supercritical conditions, the chemistry and the mechanics at those greater depths. The codes do also have to be able to handle random events such as faulting and formation of dykes.

- Merging the new conceptual model and the new numerical method. Simulate a real system.

APPENDIX F: DEVELOPMENT OF RELATIVE PERMEABILITY FUNCTIONS

Description: Understanding two phase flow of steam and water in geothermal reservoirs is of great importance as it influences how well high temperature geothermal areas can be utilized for heat and power production. The pressure gradient dependence on the flow is a function of density and viscosity of the fluid as well as the permeability and porosity of the rock. For the geothermal reservoir these properties must be known for two-phase geothermal fluid at different qualities. In spite of extensive use of reservoir models for flow of this type, the underlying equations include the pressure gradient, gravity, and flow velocity, but phase interaction is not taken into account. The effects of buoyancy and surface tension may be important when two phases flow with different velocities, and this is a potential weakness in existing reservoir models. Relative permeability functions commonly used for simulating multiphase flow of fluids in numerical models. Many of the methods used were developed for immiscible fluids and air-water systems.

Need: In order to more effectively model multiphase fluid flow in geothermal reservoirs with continuum-based methods, computationally effective and numerically accurate constitutive relations are required.

Approach: In order to develop relative permeability functions, laboratory experiments must be conducted in conjunction with detailed numerical modeling. Experiments must combine the collection of pressure and phase saturation data for two phase flow of water and steam through porous media over a wide range of temperatures and pressures. Direct observation of flow processes and phase behavior should also be considered, perhaps along with other visualization methods such as CT scanning. Chemical signatures should be considered to indicate separation of steam and water.

The laboratory data can be then used to develop and validate pore-scale models and extrapolate conditions beyond those tested in the laboratory and build a generalized description of the relationship. Models that satisfies such needs at this scale include Lattice-Boltzmann, dissipative particle dynamics (DPD), smoothed particle hydrodynamics (SPH), pore network type flow models and multiphase Navier-Stokes solvers (CFD) coupled with interface tracking techniques. The laboratory and modeling results should form the basis of relations that describe the characteristics of the flow, and could then be used in geologic-scale reservoir modeling.

APPENDIX G: FLUID-ROCK INTERACTION FROM EGS TO SUPERCRITICAL CONDITIONS

Description: At the high temperatures and pressures in geothermal systems, chemical reactions between the circulation fluid and rock become important as they may lead to hydraulic shortcuts in response to mineral dissolution, or to clogging of reservoir permeability and wells due to mineral precipitation and scale formation. Chemical treatment of such issues should be minimized to reduce environmental concerns.

In the context of EGS, current standard simulators are unable to simulate the progression of geochemical reaction fronts and their effect on production in complex fracture networks where geometric effects are expected to play an important role. Precipitation of clay minerals may act as "lubricant" on fracture surfaces affecting reservoir seismicity.

For supercritical systems, currently no reliable thermodynamic models for fluid-rock interaction are available because the large effects of the high water compressibility on the chemical thermodynamic of hydrothermal fluids have not been taken into account (and, hence, available codes and databases can make reliable predictions only at pressure substantially higher than those expected for supercritical geothermal systems).

In both environments, thermodynamic and kinetic databases need extension to cover broader ranges of temperature, pressure and fluid composition.

Need: To understand where and how in a reservoir will fluid-rock reaction fronts affect EGS productivity, thermal-hydro-chemical simulation codes that operate on realistic geometries of fracture media are required. To predict fluid-rock interaction in supercritical systems, thermodynamic models specifically designed for near- and super-critical fluids need to be incorporated into thermodynamic databases and equilibration codes.

Approach: Two lines of development are proposed

- Coupling of advanced chemical equilibration codes (that can generically handle chemistry in multiphase systems of fluids, gases and solids and are open to incorporation of new thermodynamic approaches to supercritical fluid chemistry) to transport codes that can handle complex geometries including fractured media.

- Extend thermodynamic databases by (a) incorporating recent formulations for supercritical fluid chemistry, (b) deriving improved formulations for thermodynamic functions (e.g. aqueous activity models) that allow for extending the validity over broader ranger of temperature, pressure and composition.