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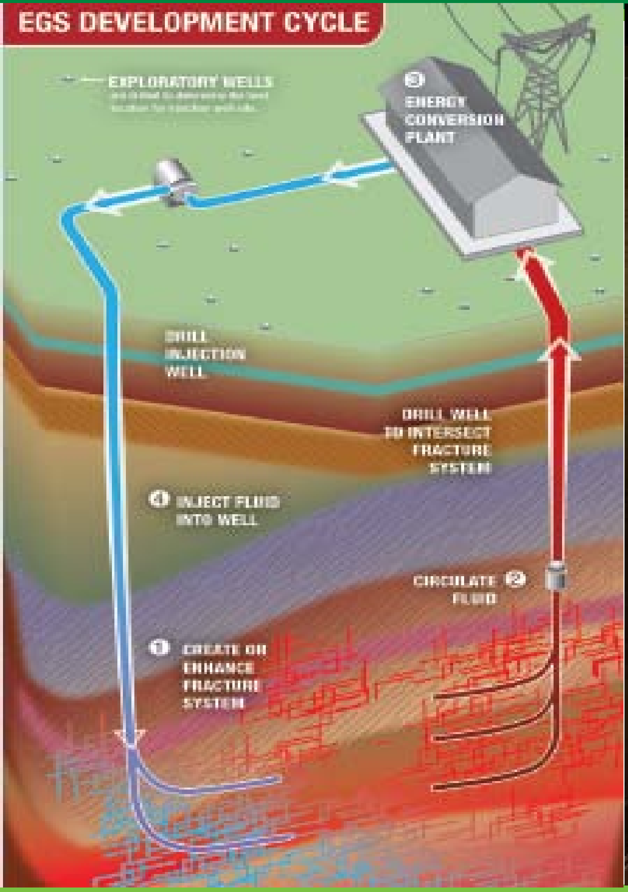

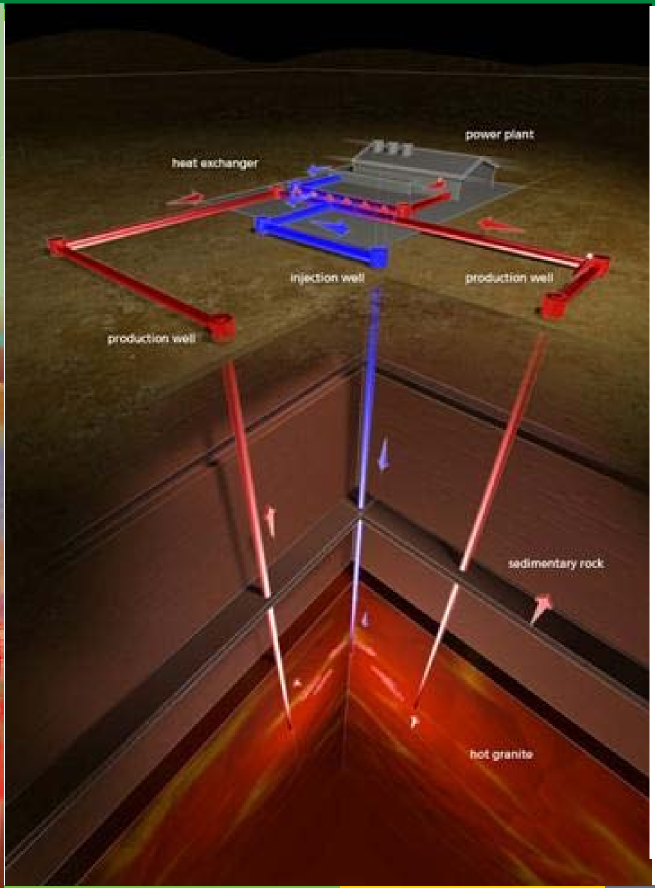

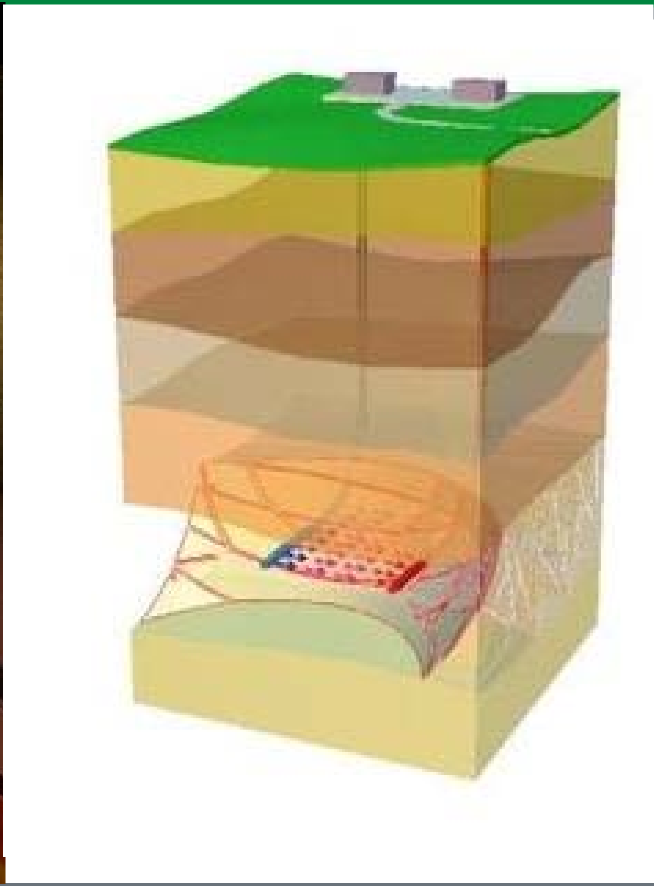

Development of Advanced Thermal-Hydrological-Mechanical-Chemical (THMC) Modeling Capabilities for Enhanced Geothermal Systems

May 19, 2010

Yu-Shu Wu
Colorado School of Mines

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Overview

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- Timeline

Start Date	End Date	Complete
01/01/10	12/31/2013	5%

- Budget

Contributor	Fund
Department of Energy (DOE)	$1,191,893
Computer Modeling Group Ltd. (CMG)	$441,600
Total	**$1,633,493**

- Barriers
  - few data or constitutive relations available for correlating flow/rock properties and rock deformation and fluid-rock interactions in non-isothermal fractured or porous media rock of geothermal reservoirs
- Partners
  - Colorado School of Mines
  - Lawrence Berkeley National Laboratory
  - Computer Modeling Group

Project Objectives

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- **Develop a general framework** for effective flow of water, steam and heat in in porous and fractured geothermal formations
- **Develop a computational module** for handling coupled effects of pressure, temperature, and induced rock deformations
- **Develop a reliable model** of heat transfer and fluid flow in fractured rocks
- **Develop a chemical reaction module** to include important chemical reactions in EGS
- **Develop an efficient parallel computing** methodology for simulation purposes
- **Apply the EGS simulator** to laboratory and field data of geothermal reservoirs

Expected Outcome & Impact of Research

- The reservoir simulator developed from this project will be among the first rigorous fully-coupled hydro-thermal-mechanical-chemical (THMC) reservoir simulator.
- This simulator will substantially enhance our ability to characterize EGS systems and provide practical approaches to assess the following:
  - Long-term performance
  - Optimum design
  - Operation strategies, and
  - Commercial feasibility

Project Team Members

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Member	Qualifications
Dr. Yu-Shu Wu	• **Colorado School of Mines** - CMG Reservoir Modeling Chair Professor in Petroleum Engineering Dept. - Professor of Petroleum Engineering Department (2008-Current) • **Lawrence Berkeley National Laboratory (LBNL)** - Staff Geological Scientist (1995-2008): One of the developers of the LBNL's reservoir simulator: "TOUGH2 family of codes," world-widely used in geothermal reservoir studies. • **Research Area of Interest** Multiphase flow and heat transfer in subsurface, CO_2 sequestration, reservoir simulation and geothermal energy
Dr. Hossein Kazemi	• **Colorado School of Mines** - Chesebro' Distinguished Chair Professor in Petroleum Engineering Dept. - Professor of Petroleum Engineering Department (1980-Current) • **Marathon Oil Company** (1969-2000) - Research Scientist, Senior Technical Consultant, Director of Production Research, Manager of Reservoir Technology, and Executive Technical Fellow at Marathon Petroleum Technology Center • **Research Area of Interest** - Reservoir Simulation (Naturally-Fractured Reservoirs, IOR/EOR), Geomechanics and Transient Well Testing • **Awards&Honors** - Member of the National Academy of Engineering - SPE Honorary and Distinguished Membership - SPE Improved Oil Recovery Pioneer Award (2006) - SPE Rocky Mountain North America Regional Reservoir Description and Dynamics Award (2008), etc.

Project Team Members

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Member	Qualifications
Dr. Tianfu Xu	• **Lawrence Berkeley National Laboratory (LBNL)** - Staff scientist: 16 years experience in development of numerical modeling of multiphase non-isothermal fluid flow and reactive transport in unsaturated and saturated porous media and fractured rock systems. - Chief developer of LBNL's multi-phase non-isothermal reactive flow and chemical transport simulator: "TOUGHREACT." • **Research Area of Interest** - *Geothermal energy development:* formation scaling due to water injection, optimization of injection water chemistry, chemical stimulation for enhanced geothermal system (EGS), use of CO_2 as working fluid for EGS (CO_2-EGS), controlling and mineral dissolution and precipitation in the reservoir. - *CO_2 sequestration:* fate and transport of injected CO_2 in storage reservoirs, mineral trapping, caprock and cement alterations due to CO_2 intrusion, and the impact of CO_2 leakage on groundwater quality.
Dr. Keni Zhang	• **Lawrence Berkeley National Laboratory (LBNL)** - Geological scientist (2000-current) - Primary developer of LBNL's parallel computing simulators: TOUGH2-MP, TMVOC-MP, and parallel TOUGH+HYDRATE. • **Research Area of Interest** - Large-scale, multi-component, multi-phase fluid and heat flow simulation for CO_2 geological sequestration, nuclear waste disposal, and gas hydrate studies.

Project Team Members

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Member	Qualifications
Computer Modeling Group (CMG)	• **The Largest Independent Developer of Reservoir Simulation Software** - Providing oil/gas reservoir simulation tools for EOR/IOR processes especially thermal reservoir modeling - Market leader: 300+ clients world wide - in 45 countries -Thousands of users world wide • **Products** - IMEX (Black oil modeling) - STARS (Advanced processes i.e. thermal modeling, naturally-fractured reservoir modeling, geomechanical modeling, compositional modeling, etc.) - GEM and WinProp (Compositional modeling) - Builder and Results (Visualization animation)

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General framework: Integral Finite Differences

$$\frac{d}{dt}\int_{V_n} \mathbf{M}\, dV_n = \int_{\Gamma_n} \mathbf{F} \bullet \mathbf{n}\, d\Gamma_n + \int_{V_n} q\, dV_n$$

Mass Balance for Component κ

$$M^{\kappa} = \sum \phi S_{\beta} \rho_{\beta} X_{\beta}^{\kappa}$$

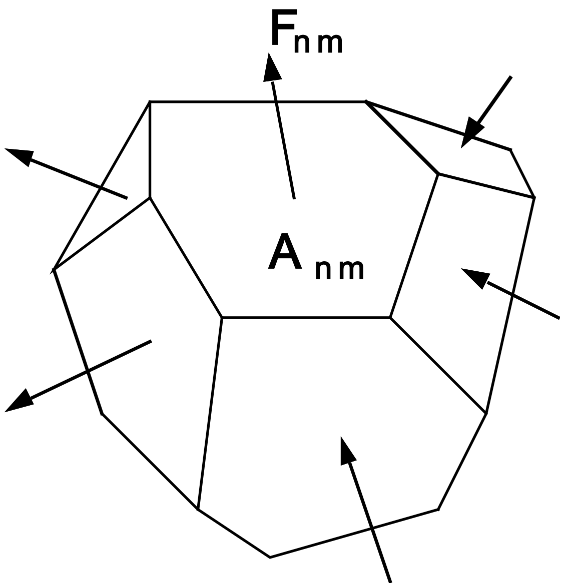
$$\mathrm{F}_{\beta} = -\mathrm{k}_0 \left(1 + \frac{\mathrm{b}}{\mathrm{P}_{\beta}}\right) \frac{\mathrm{k}_{r\beta} \rho_{\beta}}{\mu_{\beta}} \left(\nabla \mathrm{P}_{\beta} - \rho_{\beta} \boldsymbol{g}\right)$$

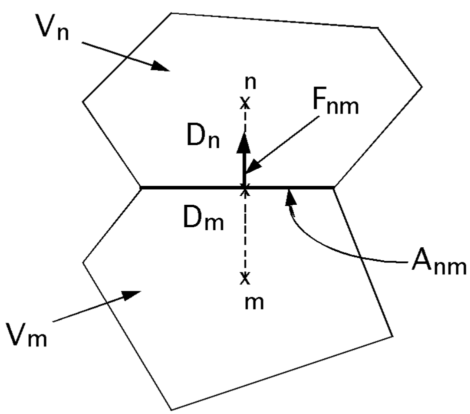
Heat Equation

$$M^{h} = (1-\phi)\rho_R C_R T + \phi \sum_{\beta} S_{\beta} \rho_{\beta} u_{\beta}$$

$$F^{h} = -[(1-\phi)K_R + \phi \sum_{\beta=1,2,3} S_{\beta} K_{\beta}]\nabla T$$
$$+ f_{\sigma}\sigma_0 \nabla T^4 + \sum_{\beta=1,2} h_{\beta} F_{\beta}$$

Technical Approach





$$\frac{d}{dt}\int_V M\,dV = \int_\Gamma \mathbf{F}\bullet\mathbf{n}\,d\Gamma + \int_V q\,dV$$

$$\int_{V_n} M\,dV = V_n M_n$$

$$\int_{\Gamma_n} \mathrm{F}\bullet\mathrm{n}\,\mathrm{d}\Gamma = \sum_m A_{nm}F_{nm}$$

$$\frac{dM_n}{dt} = \frac{1}{V_n}\sum_m A_{nm}F_{nm} + q_n$$

Stress Dependent Rock Properties

- Apply the continuum modeling approach to simulate multiphase fluid and heat flow, coupled with rock deformation in fractured and porous rock
- Develop or adopt constitutive correlations for describing how rock properties (intrinsic permeability, porosity, fracture aperture, capillary pressure, etc.) change with effective stress, fluid pressure, temperature, and other state variables
- Porosity and permeability of porous rock and fractures in an EGS system are assumed to correlate with the mean effective stress (σ'_m)

$$\phi = \phi(\sigma'_m, T) \qquad k = k(\sigma'_m, T) \qquad Pc = Pc_0\left(\frac{\sqrt{k_i/\phi_i}}{\sqrt{k/\phi}}\right)$$

Ref: Rutqvist et al. 2002; Wu et al. 2008

Chemical Reaction

- Aqueous-based reservoir stimulation is likely to promote dissolution of some rock minerals, while precipitating others, and lead to large impact on the permeability of the fracture network

- Mineral dissolution and precipitation are considered under kinetic conditions and The temperature dependence of the reaction rate constant can be expressed via an Arrhenius equation

- **Transport equations:** Mass balance (transport) equations for chemical components can be expressed as:

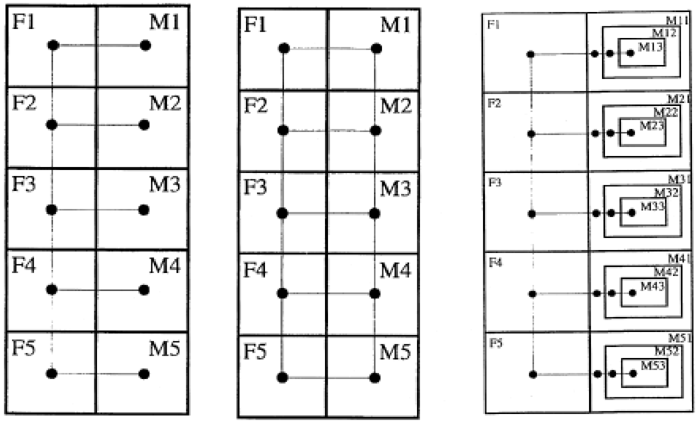
$$\frac{d}{dt}\int_{V_n}\mathbf{M}^{\kappa}dV_n = \int_{\Gamma_n}\mathbf{F}^{\kappa}\bullet\mathbf{n}d\Gamma_n + \int_{V_n}q^{\kappa}dV_n + \int_{V_n}R^{\kappa}dV_n$$

where κ is chemical component index, such as Ca^{2+}, $SiO_2(aq)$, and R is mass transfer from solid phases such as calcite and silica mineral dissolution and precipitation.

- Chemical reactions are considered as secondary equations

Fracture Models

- Generalized dual-continuum methodology: treats fracture and matrix flow and interactions using a multi-continuum numerical approach



Dual Porosity **Dual Permeability** **MINC**

- The Approach can be applied for
  - Discrete fracture i.e. hydraulic fracture (man made) and faults
  - Fracture network or naturally fractured reservoirs

Work Progress

Task 1: Development of framework model

- The work has started on the formulation for the framework model.

Task 2: Rock Deformation Module

- Literature survey of laboratory and field studies relating rock deformation to flow properties

Task 3: Chemical Reaction Module

- The work has started on the selection of chemical species and model incorporation coding.

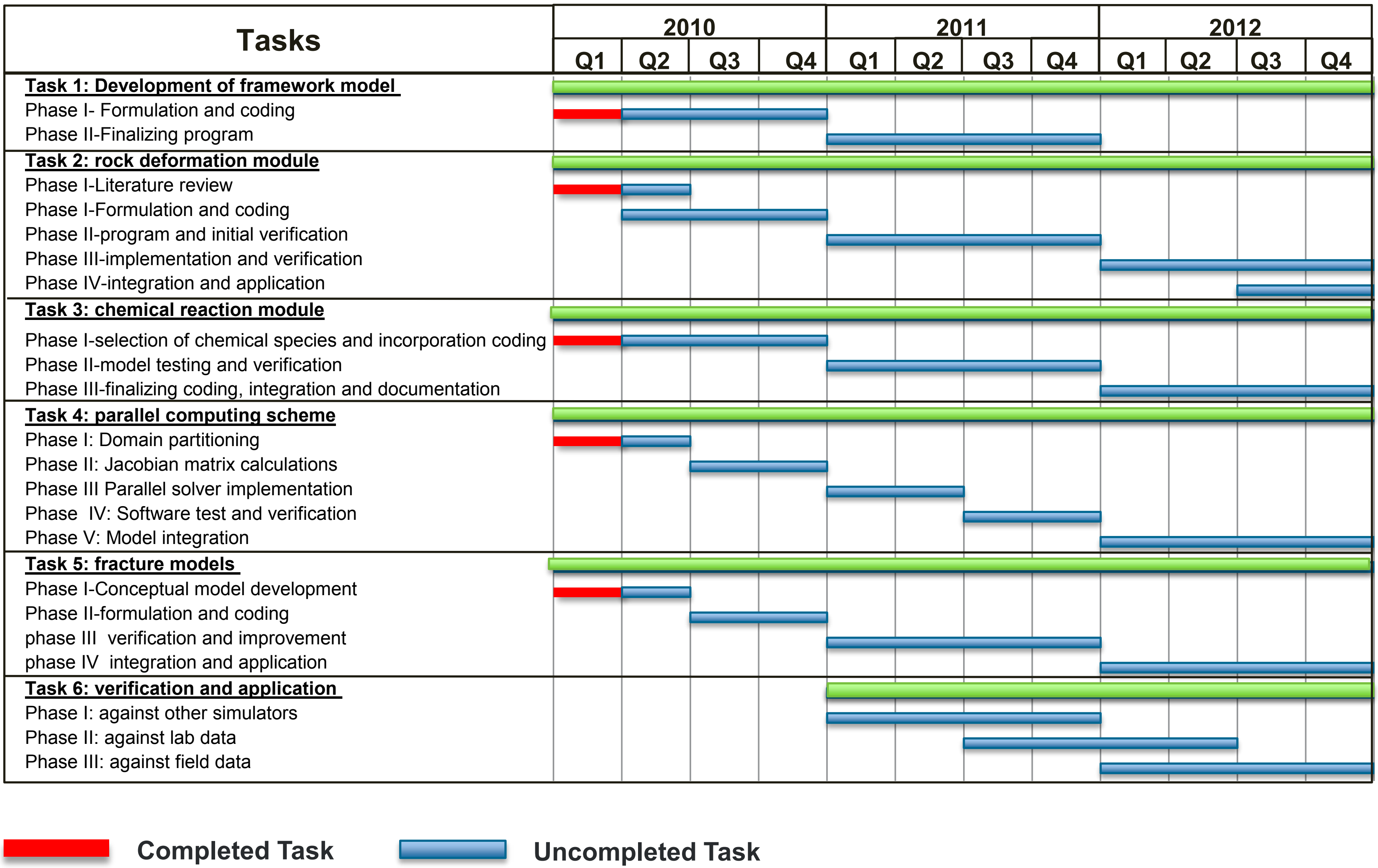
Task 4: Parallel Computation Scheme

- The work has started on the domain partitioning.

Task 5: Fracture Models

- The work has started on the conceptual modeling development of fractured reservoirs.

Project Schedule



Project Management

- The research will be carried at Colorado School of Mines (CSM) and at Lawrence Berkeley National Laboratory (LBNL)
- To ensure effective communication between CSM and LBNL and among the PI and CO-PI's, the Project PI: Dr. Yu-Shu Wu plans to work two days every month at LBNL over the three-year period of the project
- Monthly teleconferences will be held among the PI and CO-PI's to exchange information, update progress, discuss problems, and coordinate efforts

Project Management

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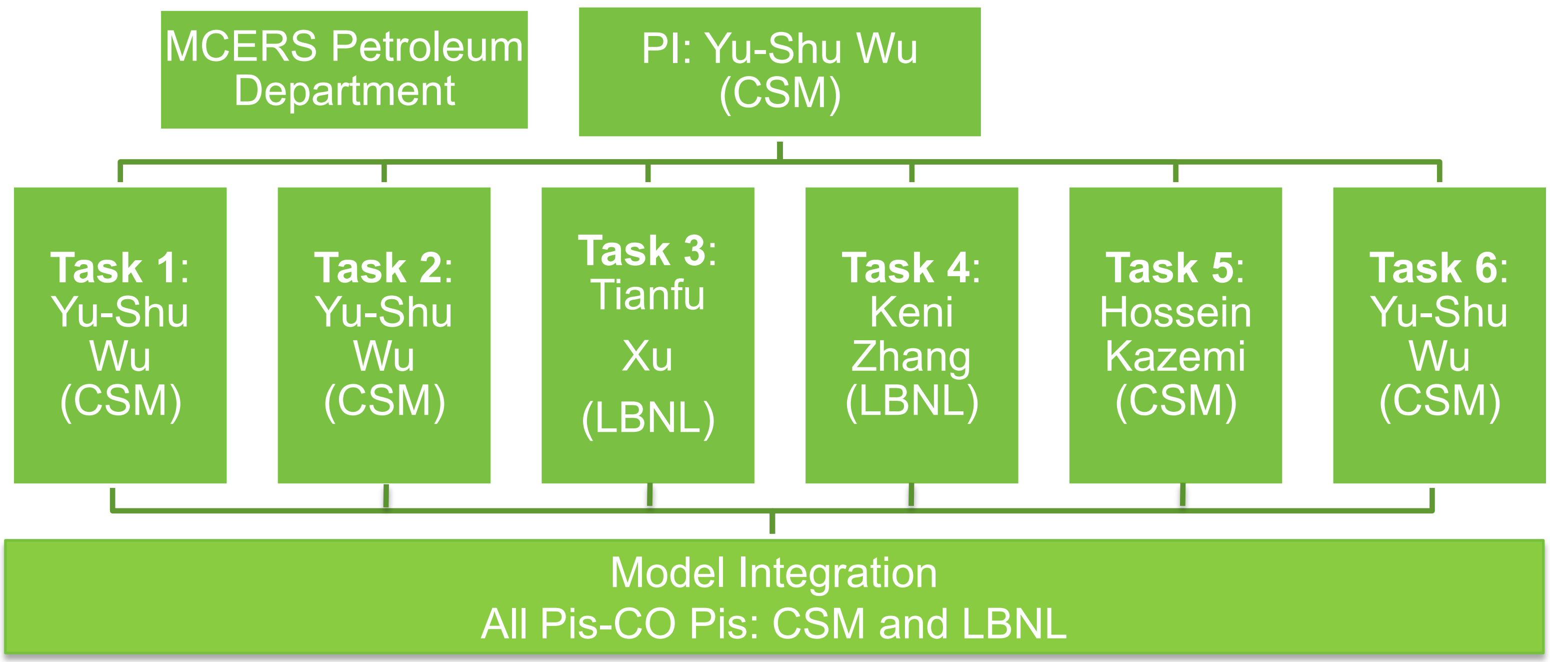
Project organization chart



Summary

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