Geothermal Technologies Office 2013 Peer Review

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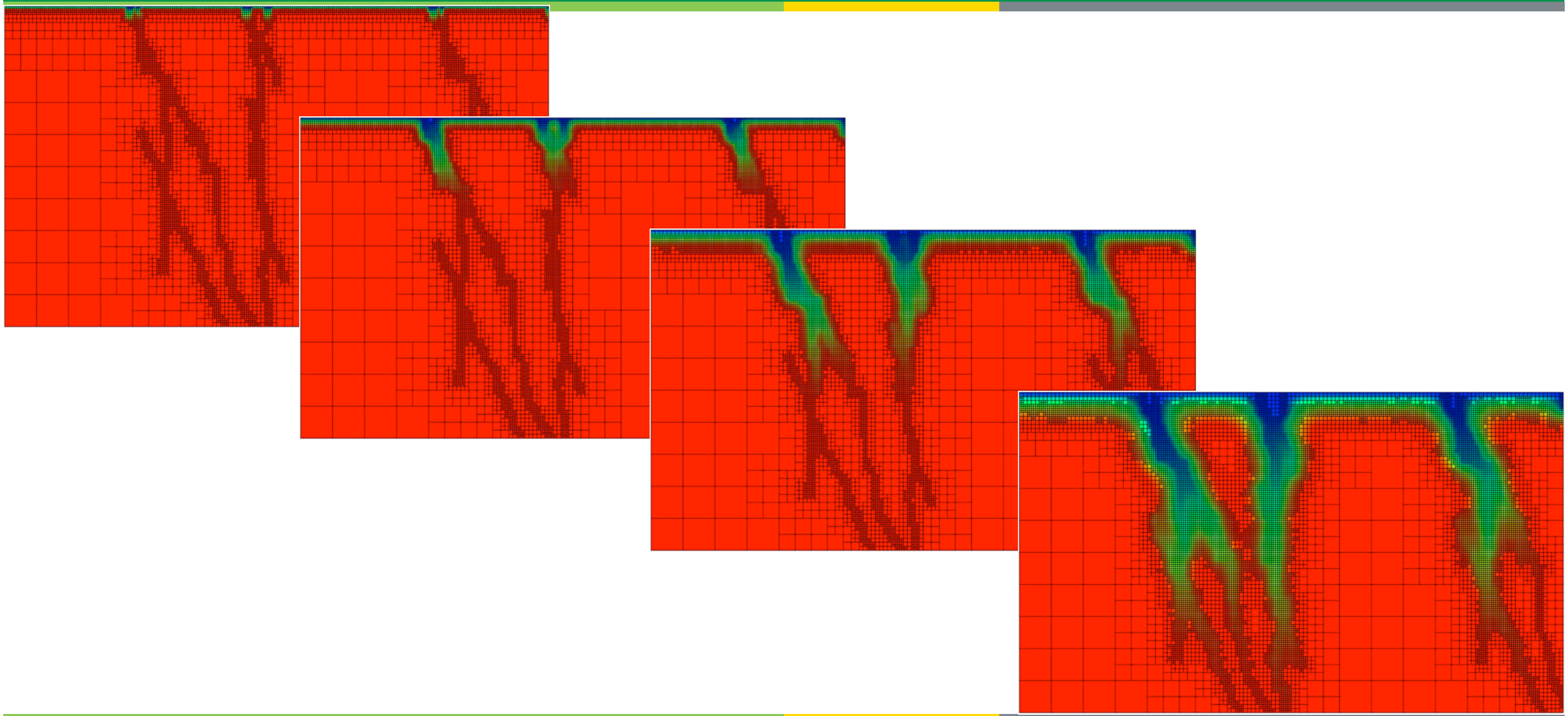

FRAC-STIM: A Physics-Based Fracture Stimulation, Reservoir Flow and Heat Transport Simulator (aka FALCON)

Project Officer: B. Segneri

Total Project Funding: $1,079 K

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R&D

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This presentation does not contain any proprietary confidential, or otherwise restricted information.

Relevance/Impact of Research

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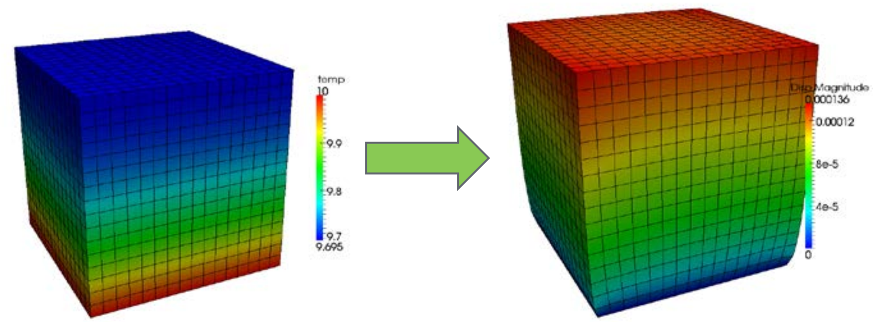
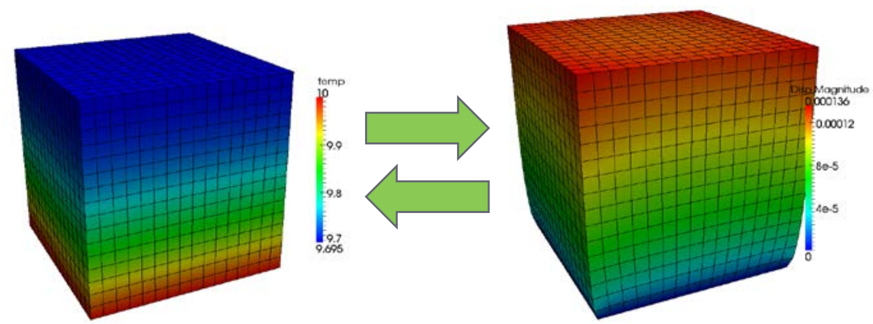
- Objective
  - Develop a true "fully coupled" simulation code that can be used for simulating coupled THMC process of EGS and hydrothermal reservoirs—at real world relevant scales
- Challenges, barriers, and knowledge gaps addressed
  - Current modeling of reservoir stimulation relies largely on linking (coupling) separate legacy simulation codes serially (via input decks) to solve separate parts of the system
    - Essentially "de-couples" the processes
    - Largely built upon legacy codes that don't take advantage of modern, high-performance computing
    - Effects of coupling method poorly understood
- Innovative aspects
  - Solve all governing equations simultaneously, using Fully Globally Implicit solvers (for fluid flow, heat transport, geomechanics, reactive transport)
    - Method identified as best approach for coupled problems since 1980's, but deemed impractical to implement
  - Built on massively parallel framework, can be used to examine real world spatial scale problems at relevant time scales
  - Takes advantage of recent advances in high performance computing, such as linear and nonlinear solvers, adaptive mesh refinement, physics-based preconditioning, etc.
- Impact to the Geothermal Technologies Office
  - Code can be used gain insight into EGS reservoir creation and long-term permeability evolution
  - Evaluate stimulation and reservoir management scenarios that minimize thermal drawdown
  - Code can be used for any THMC problem, exportable beyond GTO

Scientific/Technical Approach (1)

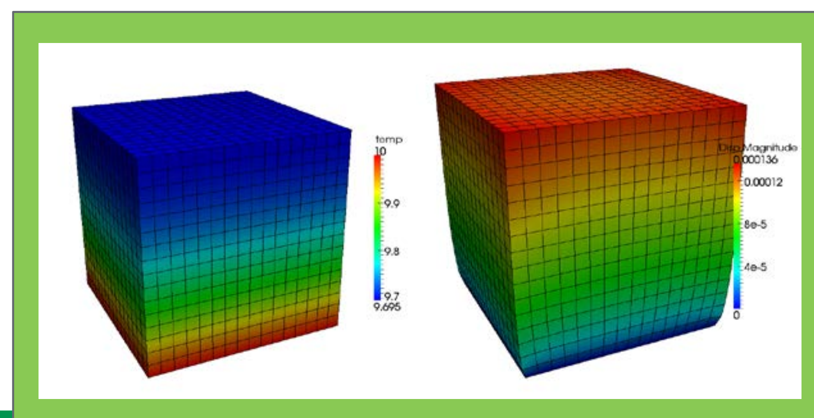
- Loose Coupling / Operator Split
  1. Solve PDE1
  2. Pass Data
  3. Solve PDE2
  4. Move To Next Timestep



- Sequential Coupling w/Iteration
  1. Solve PDE1
  2. Pass Data
  3. Solve PDE2
  4. Pass Data
  5. Return to 1 Until Convergence
  6. Move To Next Timestep



- Fully Coupled
  1. Solve PDE1 and PDE2 simultaneously in _one_ system
  2. Move To Next Timestep



Scientific/Technical Approach (2)

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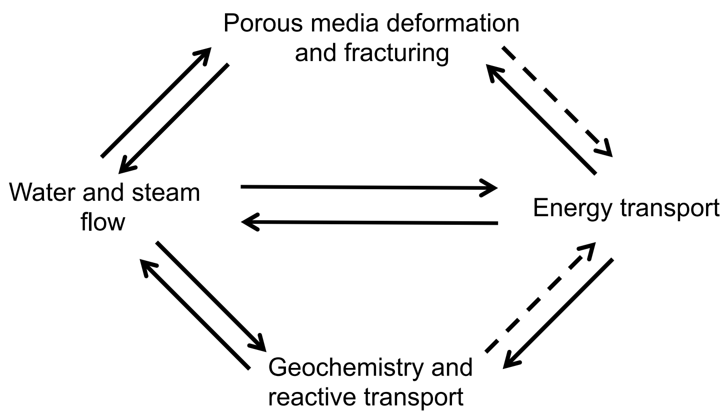
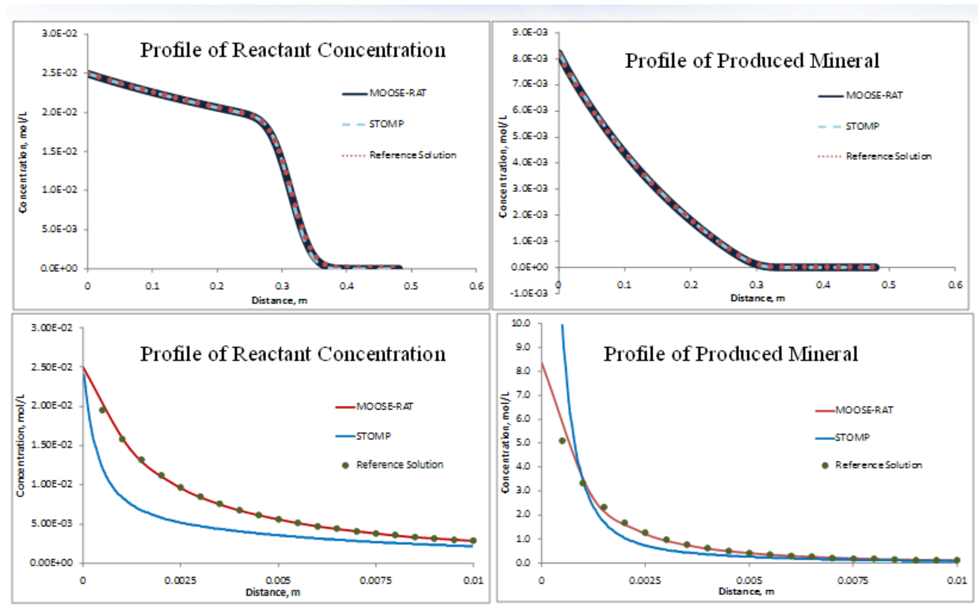
- Motivation for our approach



Slow Kinetics – Weak Coupling

Fast Kinetics – Strong Coupling



Weakly coupled processes — excellent agreement between fully-coupled and operator-split approaches
Strongly coupled processes — better agreement between fully-coupled and the reference solution

EGS reservoir creation involves a number of tightly coupled processes, and .....
solving these tightly coupled equations in a loosely coupled way carries the potential for error

Scientific/Technical Approach (3)

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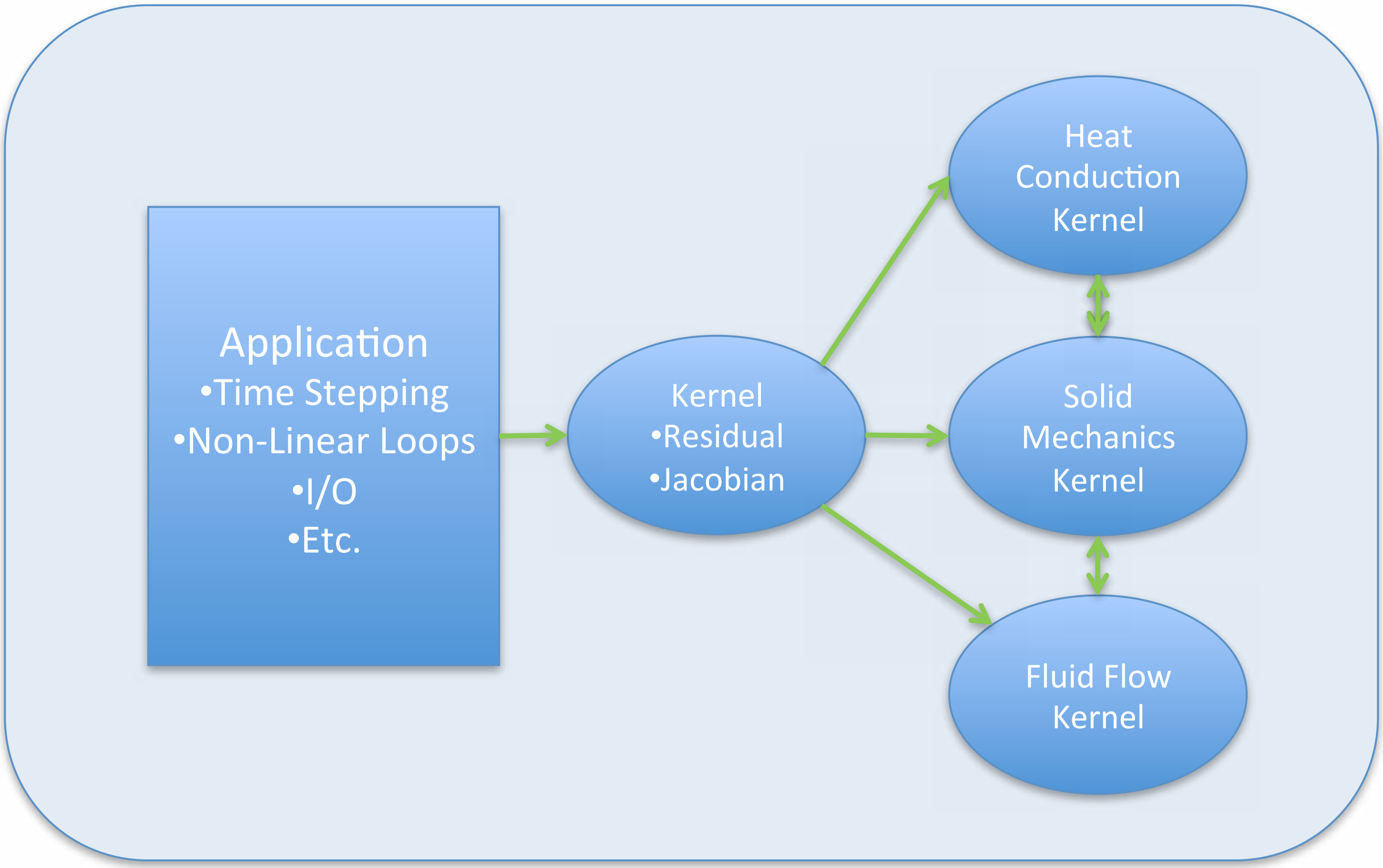
- Fully couple the model at the physics level of the problem
  - Develop ‘kernels’ for small, manageable parts of the problem (each term of the governing PDEs)
  - Couple the kernels at the PDE level
  - Solve all simultaneously, fully coupling the physics
- Developmental Framework
  - Finite element methods, coded in C++
  - Use INL framework library-Multiphysics Object Oriented Simulation Environment (MOOSE)
  - Apply state of the art nonlinear PDE solvers and tools/libraries
    - Jacobian Free Newton Krylov (JFNK) method
    - PETSc, Trilinos, hypre, NOX, libMesh
- Framework Interface conceals complexity
  - Provides core set of common services
  - Plug-and-play API
- Adaptable and easy to implement new physics

Scientific/Technical Approach (4)



Accomplishments, Results and Progress (1)

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- Code has been developed, milestones met. Code is released/available for use
  - Global Implicit Approach recognized as the 'State of the Art" as early as 1980's, but perceived to be impractical for use a relevant temporal/spatial scales
- Lead framework developer (Derek Gaston) received Presidential Early Career Scientist Award
- Receiving international attention and licensing
  - CSIRO, IESE
  - Program coordination, Iceland GEORG
- Received multiple GRC "Best Presentation" Awards, pubs in queue

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Prepare final report	Same	9/30/12
Share code/licensing	Same	9/30/12

Accomplishments, Results and Progress (2)

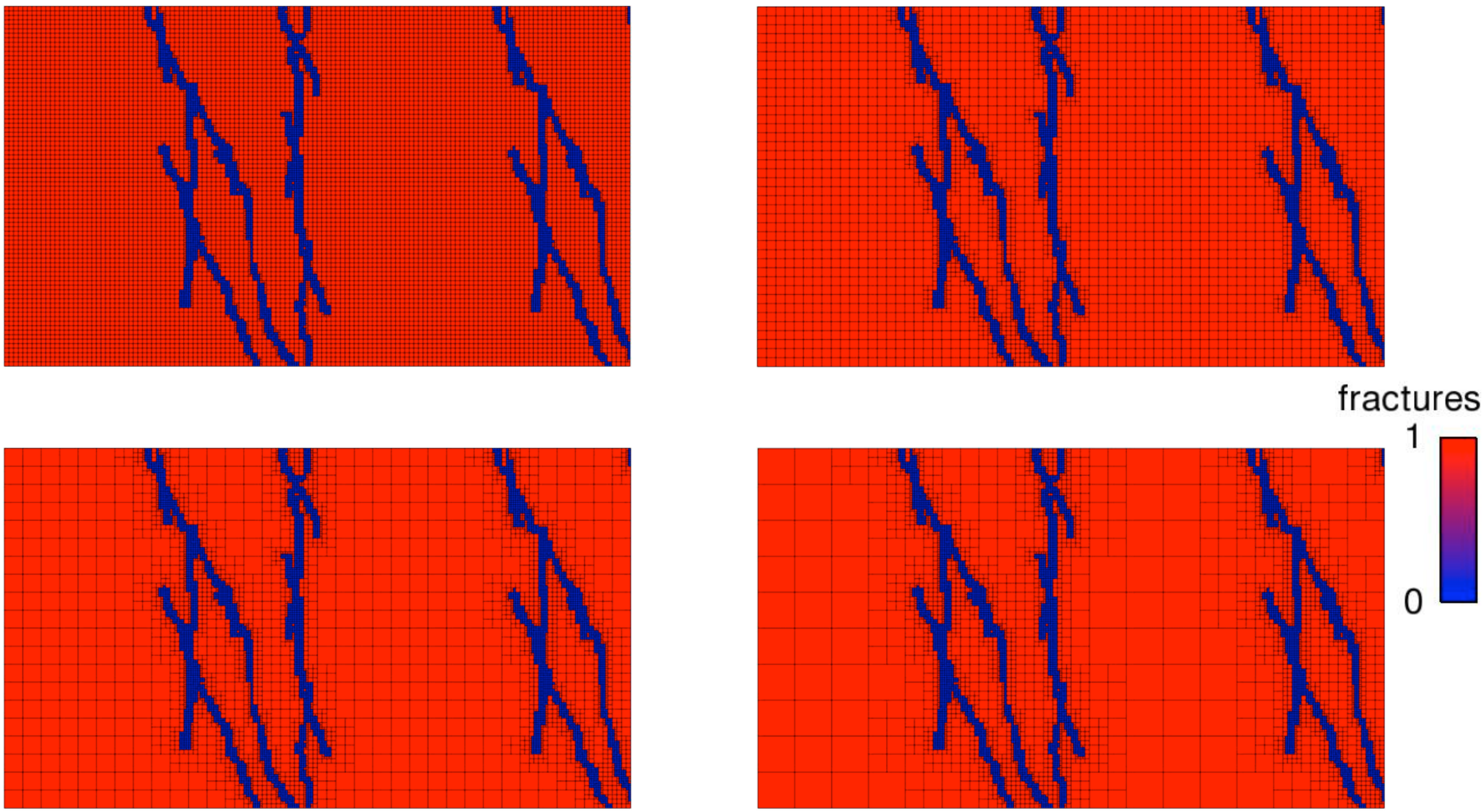
- Multiphase Fluid flow
  - Two phase requires pressure-enthalpy, single phase can use pressure-temperature
- Energy transport
  - Written in terms of temperature or enthalpy as primary variable
- Reactive Transport
  - Aqueous equilibrium speciation
  - Kinetic mineral precipitation/dissolution
  - Reaction induced porosity-permeability change
- Geomechanics
  - Solve in terms of displacement
  - Abaqus
  - Use stress as indication of near failure conditions, strain for changes in permeability
- Supporting kernels
  - EOS (IAPWS97/2008), material properties, constitutive relations, IO, adv. time stepping
  - GSLib inferface
  - FracMan interface

Two-Phase Darcy Flow
Thermal Conduction
Changes in Permeability
Water Convection
Reactive Transport
Steam Convection
Tracer Transport
Fracture Flow

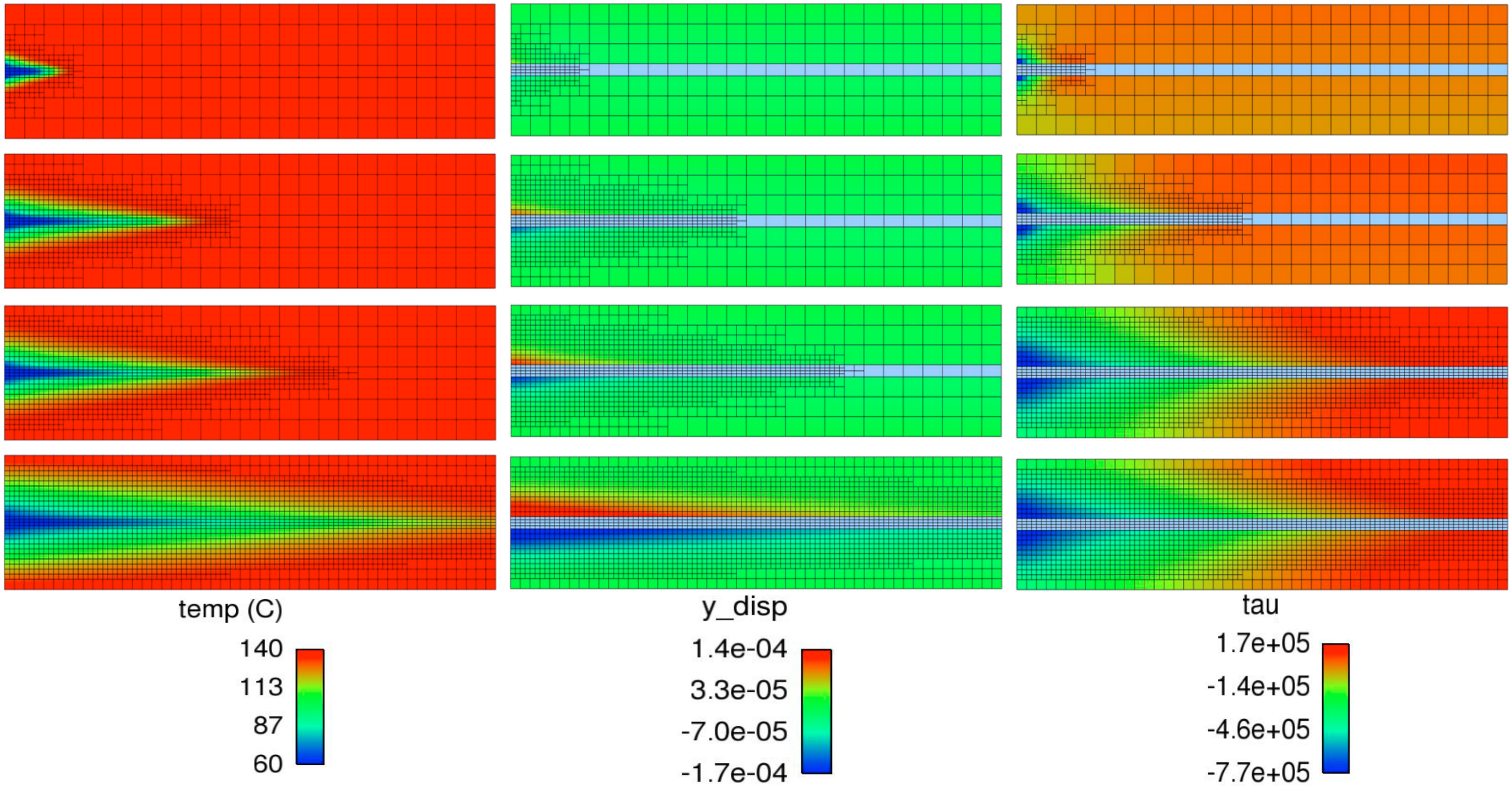
Physics in FALCON

Source/Sinks
Displacement
Water-Steam EOS
Stress-Strain
Dissolution/Precip
Damage Mechanics
Rel. Perm Functions
Perm Functions
1st & 2nd Order Time

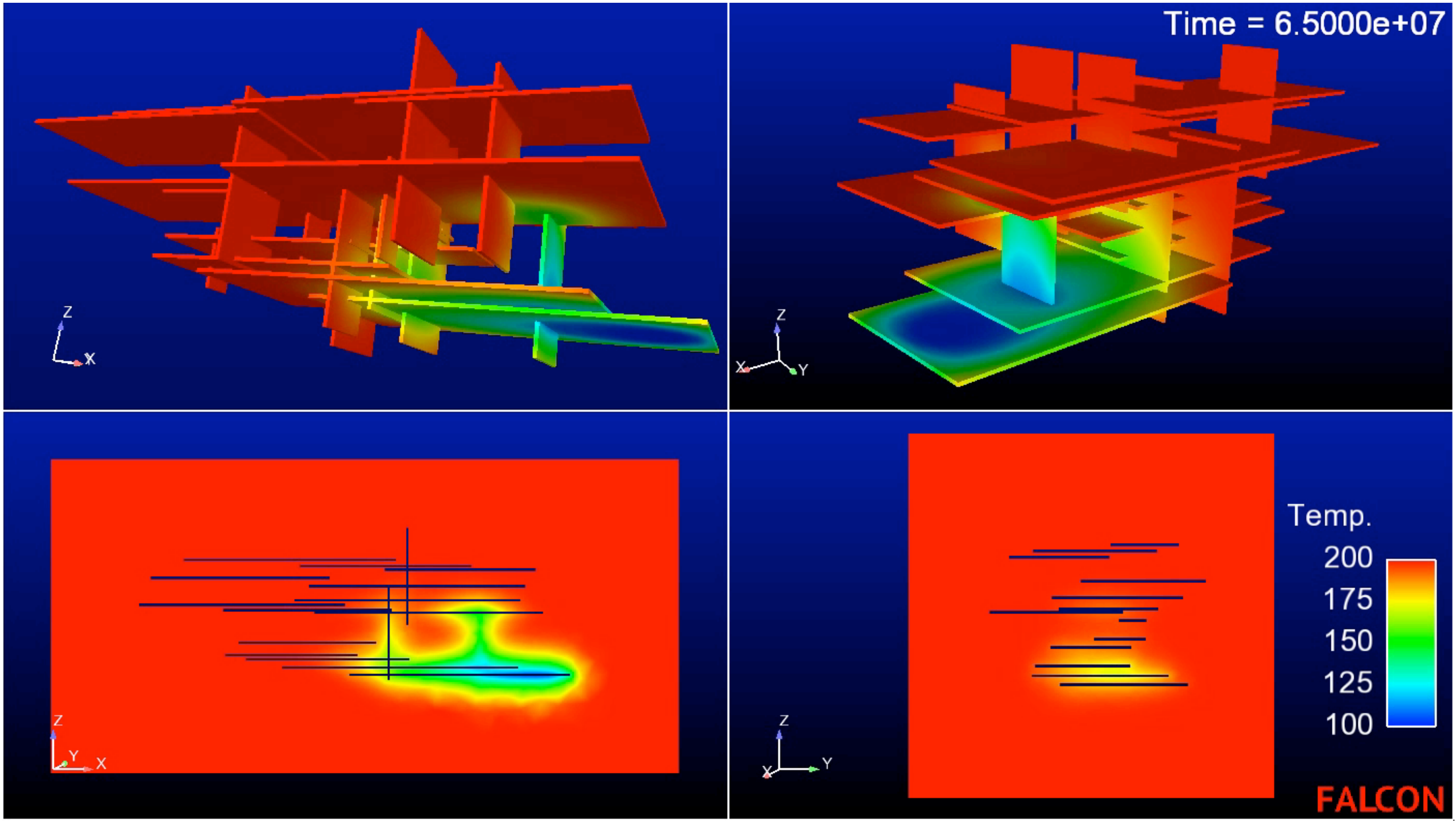
- Adaptive Mesh Refinement and Fracture Flow (animation)
  - Based on error estimation
  - Interface with FracMan© fracture distributions



- Thermal Stimulation of a Fault Zone (animation)
  - Reproduce injection behavior in HN-09, Hengill, Iceland
  - Evaluation of stimulation plan in RRG-09, Raft River, ID



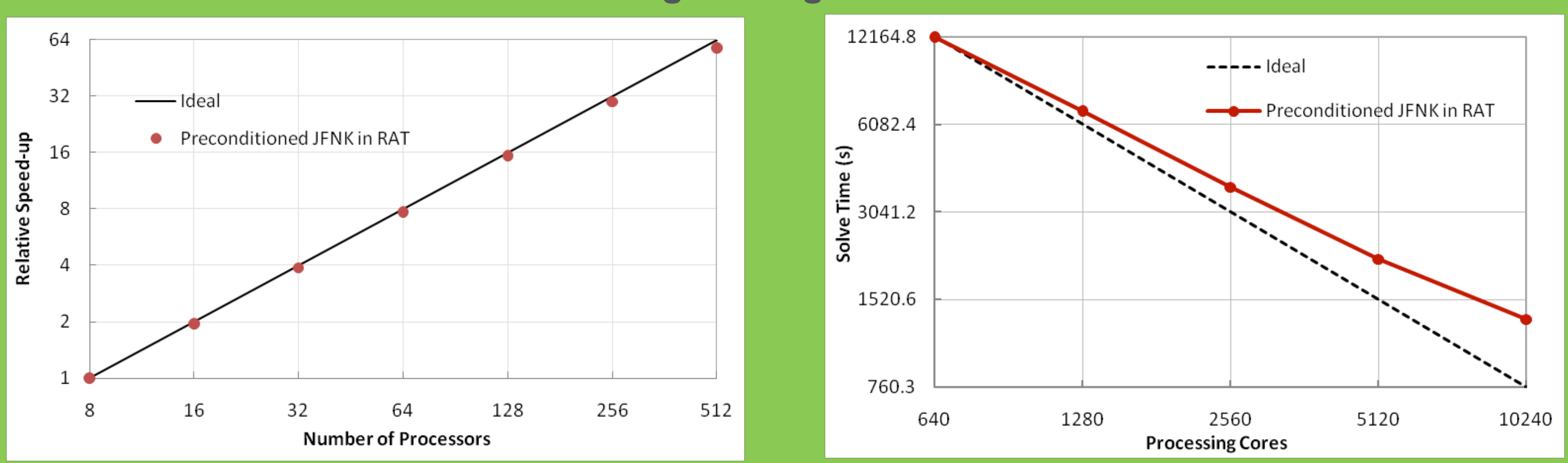
- Thermal Evolution of an Idealized Fractured System (animation)



Accomplishments, Results and Progress (6)

- EGS presents a unique challenge:
  - Fully-implicit, fully-coupled simulations with of lots of variables.
- High resolution domains are preferred to capture large variances in material properties, i.e., fractures
- Code scales very well on both the low and high end
  - High end is: 5 fully-coupled variables , 33 Million elements, 200+ Million DoFs

Strong Scaling Behavior



Future Directions

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- Project complete, code and capability development continues
- Planned improvements include
  - Implement control volume FEM: better mass and energy conservations while still take full advantage of FEM on geomechanics modeling
  - Better material property models for porosity/permeability changes induced by fracturing and post-failure hydraulic/mechanical behaviors
  - Incorporate simpler approaches to modeling fracture distribution (e.g. dual permeability model)
  - Provide link to inverse modeled parameter estimation tools
  - Extend to supercritical conditions
- Simulate EGS demonstration at Raft River
  - Start with basic system—fault zone
  - Examine entire reservoir later
- Deployment strategy = Collaborate, code currently licensed to
  - Institute for Earth Science and Engineering, Univ. of Auckland
  - CSIRO and University of Western Australia
  - EGI, University of Utah
  - Others in process
- Expected outcome is a numerical tool that can help elucidate system behavior under the most challenging computation circumstances, and be used in a predictive capacity at relevant spatial scales and resolution

Mandatory Summary Slide

- All "fully coupled" codes not created equally
- FALCON is built from the ground up as a geothermal reservoir analysis tool, suitable for
  - Testing hypotheses about reservoir evolution
  - Capturing detailed reservoir characteristics in large-scale models
  - Computationally intensive reservoir modeling problems (eg. inverse problems) via application of state-of-the-art numerical methods
  - Quickly incorporating "new" physics into reservoir simulation
- FALCON/MOOSE framework recognized internationally
  - After touring a number of US DOE and European labs, CSIRO chose our framework to build geothermal numerical capabilities
  - FALCON developers invited to coordinate model development activities for Iceland's GEORG

Project Management

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Timeline:

Planned Start Date	Planned End Date	Actual Start Date	Current End Date
April 2009	Sept 2011	October 2009	Sept 2012

Budget:

Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	Value of Work Completed to Date	Funding needed to Complete Work
$1,079K	$0	$1,079K	$1,078.8K	$2,500K	???

- Project leverages internal LDRD funds for Subsurface Science and Nuclear Fuels Modeling
- Collaborations bringing on additional coders and data at no cost
  - CSIRO in Australia
  - IESE in New Zealand
  - GEORG in Iceland
  - EGI, MIT, LSU, others
- Contributing the the Raft River EGS Demo
  - Stimulation plan evaluation
  - Reservoir modeling