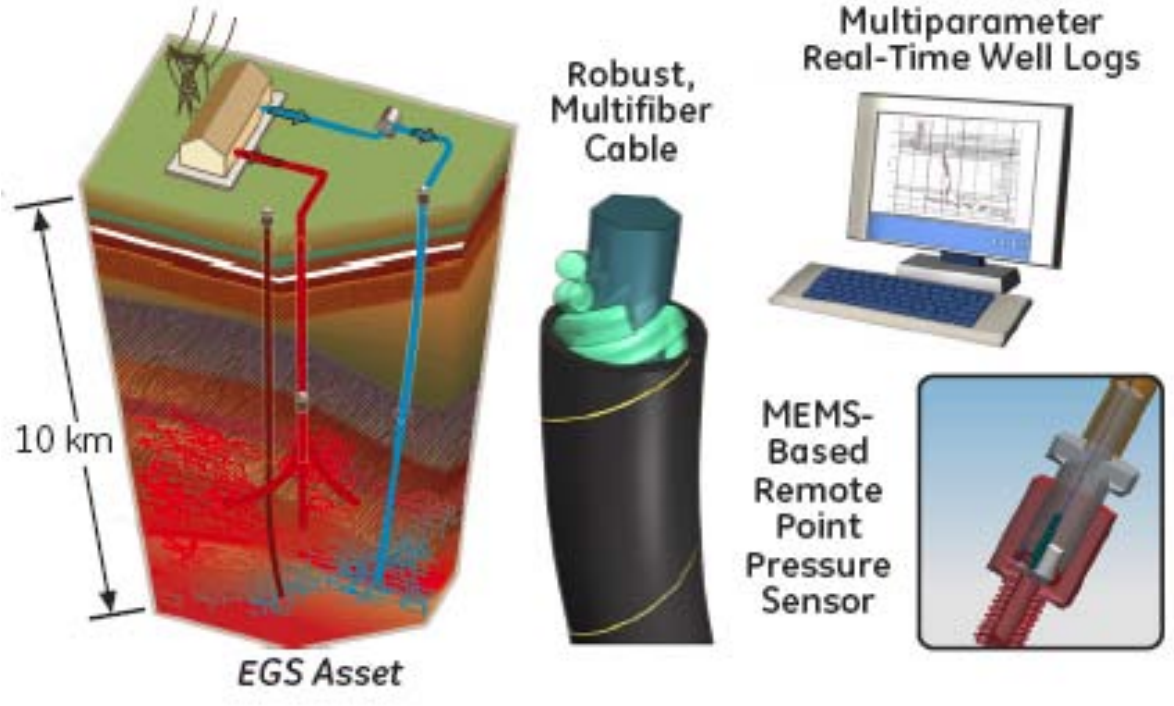


imagination at work

QOREX

AFL Telecommunications
A Fujikura Business

Sandia National Laboratories

Multiparameter Fiber Optic Sensing System for Monitoring Enhanced Geothermal Systems

May 19, 2010

Dr. Aaron J. Knobloch, PI
GE Global Research

High Temperature Tools and Sensors, Downhole Pumps and Drilling

Project Overview

- Timeline
  - Project Start: 3/30/2010 Project End: 3/30/2012
  - Progress: 5%
- Budget
  - Total DoE Share: $2,085,062 Total Cost Share: $567,689
  - Total Program Size: $2,652,751
  - FY10 $1.0M-1.2M
- Barriers – High Temperature Measurement Tools & Sensors
  - Well Construction (C)
  - Site/Well Characterization (D)
  - Reservoir Validation (I)
  - Reservoir Scale-up (L)
  - Reservoir Sustainability (M)
- Partners
  - GE Global Research (Lead)
  - Qorex LLC
  - GE Sensing
  - AFL Telecommunications
  - Sandia National Labs

Project Overview

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Project Team

GE Global Research
Point and Distributed Pressure Sensor Development

GE Sensing
Harsh Environment Sensor and System Supplier

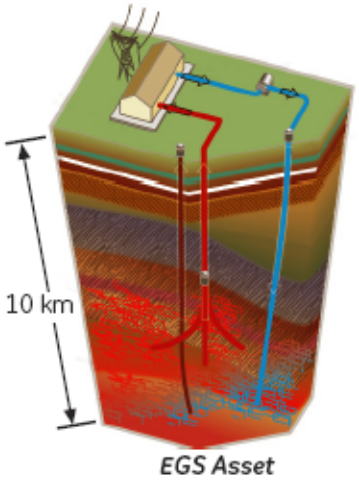
QOREX
Fiber Optics Sensing System Supplier

AFL Telecommunications
Fiber Optic Cable Supplier

Sandia National Laboratories
Geothermal Systems Evaluation

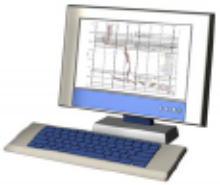
2-Year, $2.6M Program to Develop High Temperature Multiparameter Fiber Optic Sensing System for Enhanced Geothermal Systems

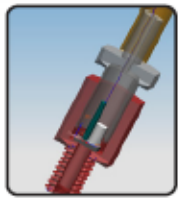
Program Objective: *Enable real-time, multiparameter, distributed, and spatially localized geothermal wellbore monitoring through the development and verification of fiber optic sensors capable of operation to 10 km depths at 374°C and 220 bar.*



EGS Asset


Robust, Multifiber Cable


Multiparameter Real-Time Well Logs


MEMS-Based Remote Point Pressure Sensor

Relevant Prior Work

- Distributed fiber optic sensors for coal gasifiers & gas turbines
- MEMS pressure sensors in avionics
- Harsh Environment Packaging
- Deployment of fiber systems in oil and gas

Technical Approach

- Evaluate fiber and sensor sub-systems at 374°C and 220 bar with hydrogen
- Raman, Brillouin and COTDR distributed sensors
- Develop and test a multi-fiber compatible cable
- Develop a MEMS point and FBG-based distributed pressure sensor

Technical Challenges

- Hydrogen-induced fiber darkening at temps >374°C
- Fiber mechanical reliability
- Cable design
- Accurately point pressure sensor

Program Deliverables

- Demonstrated reliability of fiber and sensing subsystems for EGS
- Distributed and point pressure fiber sensors for EGS
- A cable containing both distributed and discrete fiber optic sensor technologies
- A plan for field test of the technology

Anticipated Benefits of the Proposed Technology

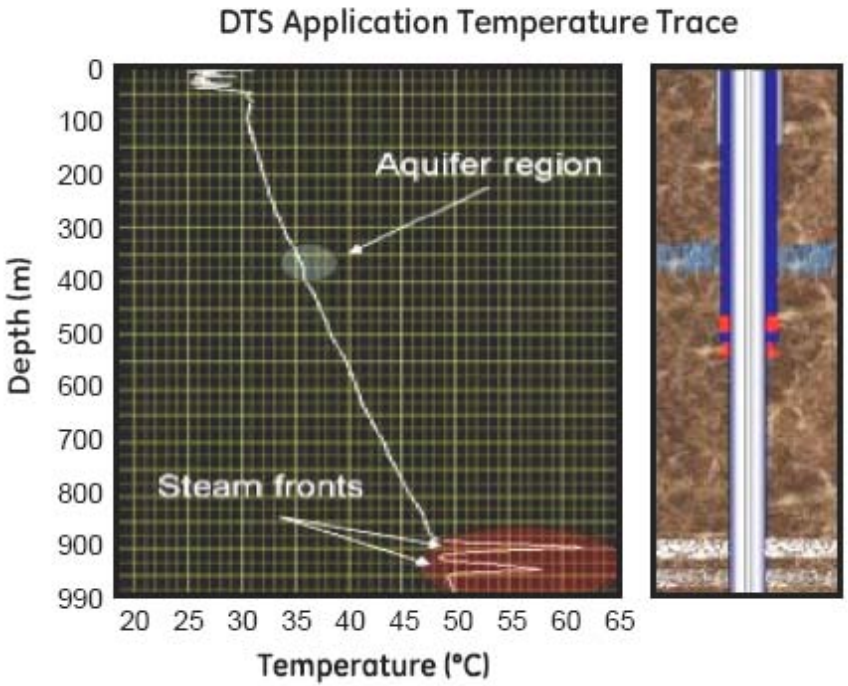
- Ability to log geothermal asset performance in real-time over the 10 km length of the wellbore
- A 374°C downhole tool, which is beyond the capability of current electronics
- Multiple parameters (pressure, temperature, strain, vibration) to develop and validate wellbore and reservoir models
- Real-time monitoring of thermal drawdown
- Identify inflow and breakthrough during stimulation
- Identify fractured volume in production

Project Relevance & Impact

Project Objectives

- Demonstrate reliability of fiber and distributed temperature, strain and vibration sensing sub-systems for EGS at 374ºC and 220 bar in the presence of hydrogen.
- Develop a high accuracy point pressure gauge and distributed pressure sensor to meet EGS requirements.
- Integrate multiple sensor sub-systems into a single field-ready cable and system.
- Plan for field deployment tests of this technology.

Project Relevance & Impact



The effects of injection into the stimulation well are clearly seen when using DTS to monitor the recovery well to 1km deep

Impact on Geothermal Energy Development

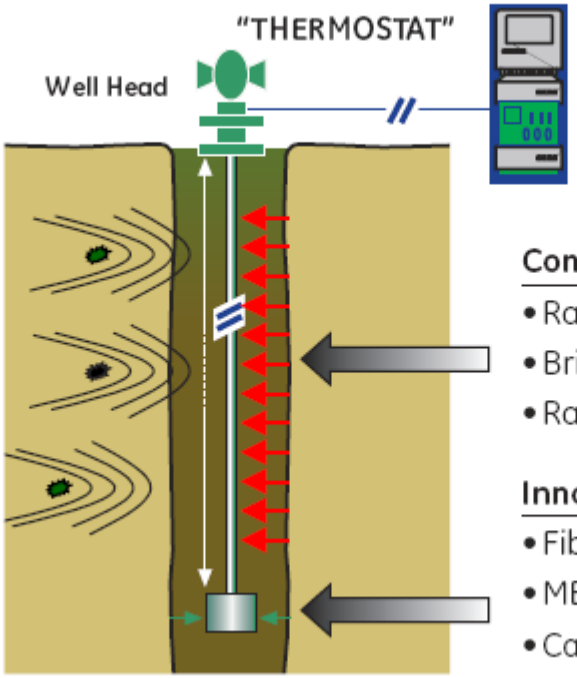
- Development of real-time, reliable sensors for distributed, multiparameter sensing of the geothermal asset
- Enable fracture system model development and validation during site characterization
- Measurements of thermal drawdown, water injection, and recovery during production

Technical Approach

Temperature Hardened (for EGS) Real-Time Multiparameter Optical Sensor System and Tool

Risks

- Hydrogen darkening
- Fiber mechanical reliability
- 374˚C temperature



Commercial state-of-the-art we will evaluate:

- Raman DTS – Distributed temperature
- Brillouin DTSS – Distributed strain
- Rayleigh COTDR – Distributed vibration

Innovations we will deliver:

- Fiber Bragg – Distributed pressure
- MEMS – Precision point pressure tool
- Cable design for multiparameter tool

Sensor Reliability

Two Key Risks are Being Mitigated:

- Hydrogen Darkening
  - Pure Silica Core Fibers
  - Reliability analysis examining mechanical and loss characteristics at high temperature

- Mechanical Reliability
  - Fiber coatings robustness to corrosion
  - Cable design – metal fatigue models of Armor

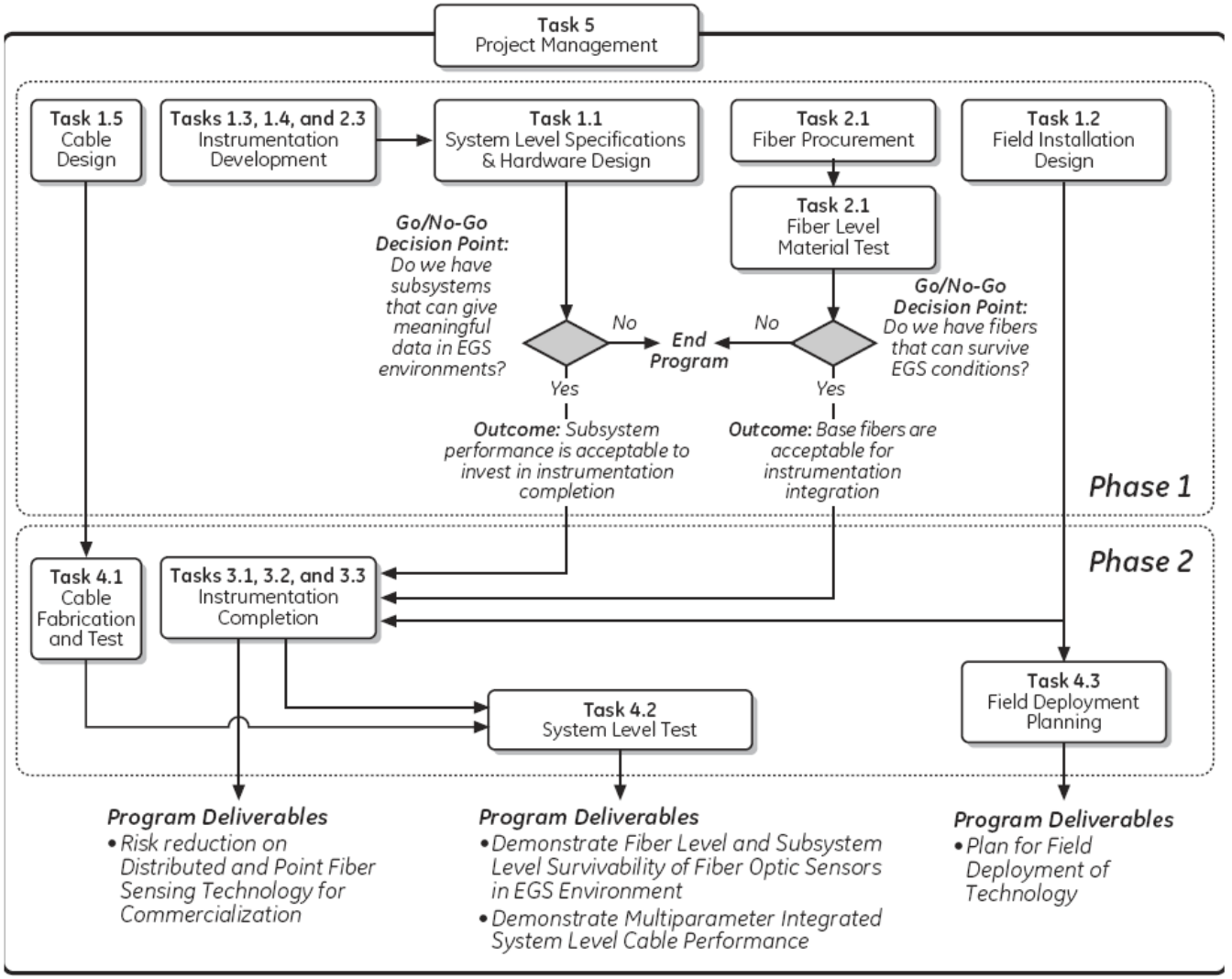
Analysis of Commercially Available Systems

- Raman DTS
  - Established, simple measurement system
  - Wavelength dependent differenital fiber attenuation
- Brillouin DTSS
  - Less mature, more complex approach to temperature & strain measurement
  - Single ended architecture that may be less sensitive to H2 ingress
- Coherent Rayleigh Backscatter
  - Acoustic method for measuring vibration of a fiber
  - Early stages of development and needs evaluation

Innovative Sensor & Cable Development

- Multiparameter Sensor
  - Brillouin DTSS – Adaptation to single core
  - Fiber Bragg Grating sensors & packaging
- High Accuracy Point Pressure
  - Based on GE product with accuracy of 0.001% and stability of 100ppm/year
  - Optical interrogation and die design for 375ºC and 220 bar application
- Cable Design
  - Leverage experience in SAGD applications
  - Ability to withstand thermal expansion without imparting strain to the fiber
  - Fiber splice & cable spooling processes development

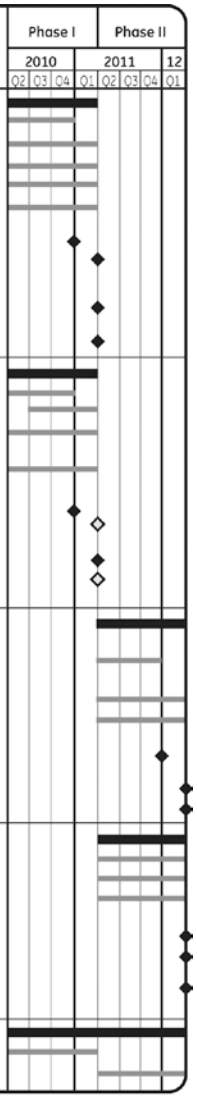
Project Plan



Project Timeline

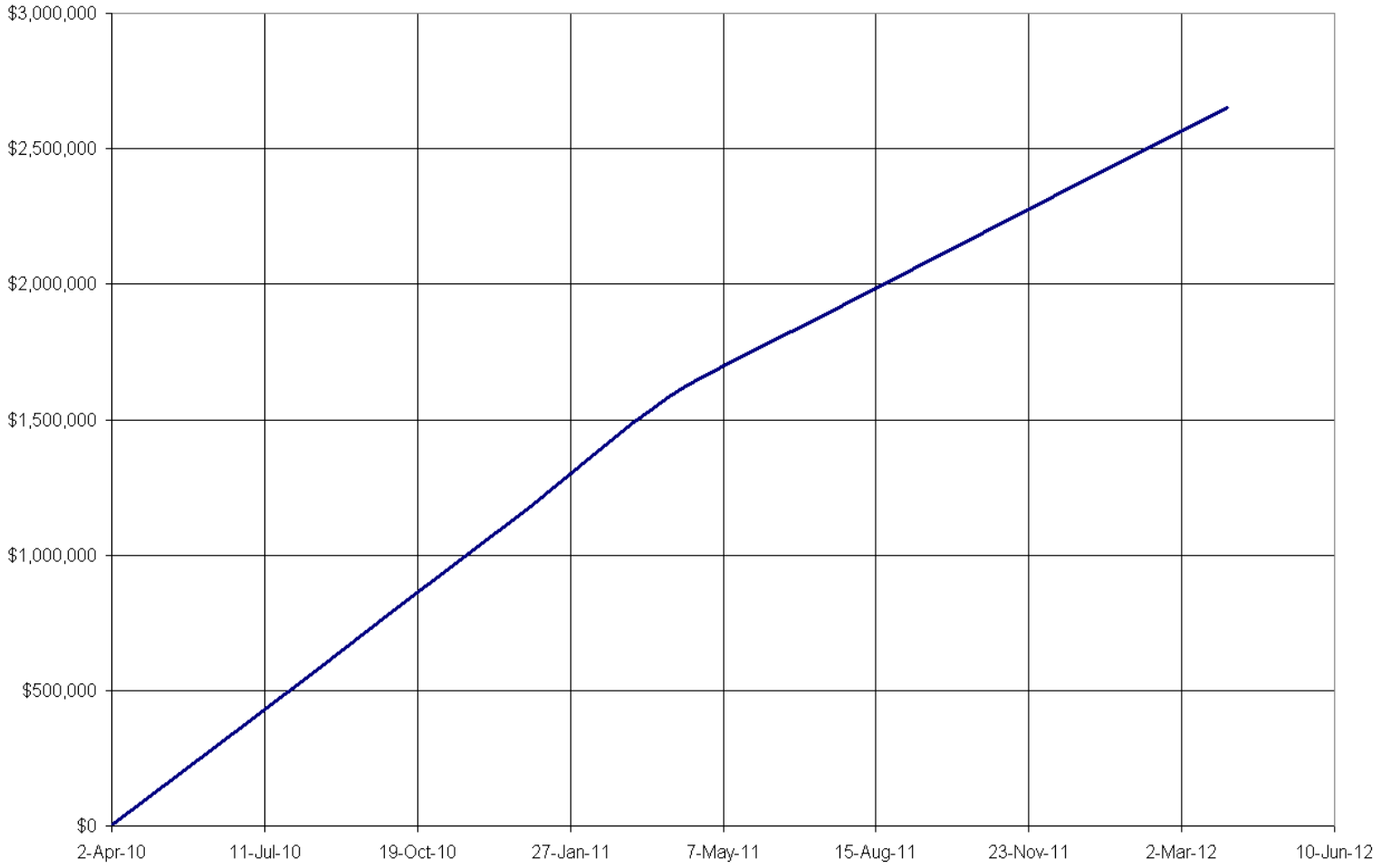
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Program Activities	GE	Qorex	AFL	Sandia	Start Date	End Date
Task 1 System Architecture & Component Development.	●	●			4/1/10	3/31/11
1.1 System Level Specification & Hardware Design.					4/1/10	12/31/10
1.2 Field Installation Design.					4/1/10	3/31/11
1.3 Point Optical Pressure Gauge Development.					4/1/10	3/31/11
1.4 Distributed Pressure Sensor Survivability and Modeling.					4/1/10	3/31/11
1.5 Cable Design.					4/1/10	3/31/11
Milestones:						
• *System Specification Complete*					12/31/10	12/31/10
• *First Spin of Point Pressure Gauge Demonstrates Base Performance With Demonstrable Path to Full Functionality on Second Spin*					3/31/11	3/31/11
• *Demonstration of Fiber-Level Performance on Distributed Pressure Sensor*					3/31/11	3/31/11
• *Cable Design Complete to Meet Specifications*					3/31/11	3/31/11
Task 2 Subsystem Procurement and Test.	●	●		●	4/1/10	3/31/11
2.1 Fiber Development & Procurement.					4/1/10	12/31/10
2.2 Fiber Material Testing.					7/1/10	3/31/11
2.3 Distributed Temperature, Strain and Vibration Vendor Evaluation.					4/1/10	3/31/11
2.4 Sub-System Test at Fiber Level.					4/1/10	3/31/11
Milestones:						
• *Confirm industrial fiber supply chain adequate for EGS*					12/31/10	12/31/10
• *Fiber testing validates acceptable performance for EGS (Go/No-Go)*					3/31/11	3/31/11
• *Fiber reliability model from material testing*					3/31/11	3/31/11
• *Confirm commercial DTS, DTSS, and COTDR subsystem performance (Go/No-Go)*					3/31/11	3/31/11
Task 3 Component and Subsystem Validation and Issue Resolution.	●	●			4/1/11	3/31/12
3.1 Distributed Temperature, Strain and Vibration Issue Resolution.					4/1/11	12/31/11
3.2 Point Optical Pressure Gauge Validation.					4/1/11	3/31/12
3.3 Distributed Pressure Cable Design Optimization.					4/1/11	3/31/12
Milestones:						
• *Vendor performance for DTS, DTSS and COTDR in EGS application validated*					12/31/11	12/31/11
• *Fully Functional Demonstration of Point Pressure Gauge*					3/31/12	3/31/12
• *Cable Integration of Distributed Pressure Sensor*					3/31/12	3/31/12
Task 4 System Integration and Test.	●	●	●	●	4/1/11	3/31/12
4.1 Cable Fabrication and Test.					4/1/11	3/31/12
4.2 System Level Hardware Integration and Test.					4/1/11	3/31/12
4.3 Field Deployment Planning.					4/1/11	3/31/12
Milestones:						
• *System Level Hardware Validated*					3/31/12	3/31/12
• *Concrete Field Deployment Plan in Place to Support an Actual Field Test*					3/31/12	3/31/12
• *Cable Fabrication Process demonstrated and Mechanical Properties Validated through Thermal and Mechanical Tests*					3/31/12	3/31/12
Task 5 Project Management and Reporting	●				4/1/10	3/31/12
5.1 Program Management, Phase 1					4/1/10	3/31/11
5.2 Program Management, Phase 2					4/1/11	3/31/12



Legend: ◆ *Milestone* ◇ *Go/No-Go Decision Point*

Project Spend Plan



Project Summary

- This effort brings together currently available technology with new sensors and packaging to develop key hardware necessary for well characterization, validation, and sustainability
- Key risks to the development of advanced optical sensors for geothermal systems will be mitigated
  - Hydrogen darkening of optical fiber
  - Mechanical design of package including armored cable
  - Integration of multiple measurands and measuring techniques into a single sensor system

Future Directions

- Key Outcomes
  - Ability to log real-time geothermal asset performance
  - Integration of multiple parameters in a single sensing systems
  - Understanding of the reliability and failure modes of current systems

- Specific Goals, milestones and decision points – See earlier planning and timeline slides

Supplemental Slides