Oil & Natural Gas Technology

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Quarterly Research Performance Progress Report
(Period ending 09/30/2015)

Borehole Tool for the Comprehensive Characterization of Hydrate-Bearing Sediments

Project Period (10/1/2013 to 9/30/2016)

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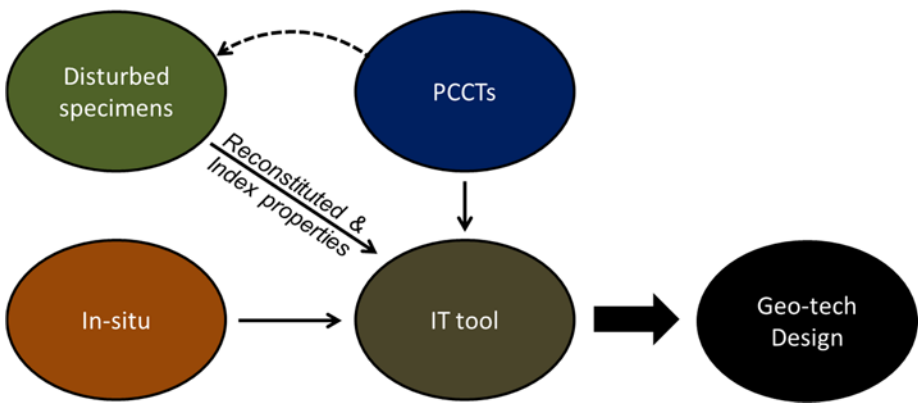
Office of Fossil Energy

DISCLAIMER:

Context – Goals.

The physical properties of hydrate bearing sediments are critical for gas production strategies, geo-hazard mitigation and its impact on gas recovery engineering. Typically, the determination of physical properties relies on correlations and experimental data recovered from conventional and pressure cores. Inherent sampling disturbance and testing difficulties add significant uncertainty. In this research, we develop a new comprehensive borehole tool for the characterization of hydrate bearing sediments, and an IT tool for the physics-bases selection of appropriate parameters.



Accomplishments

The main accomplishments for this period include:

- Borehole tool design: body (sub-task 3.4: Final design and construction)
  - First products from the workshop at KAUST
- Borehole tool (sub-task 4.3: Final design and construction)
  - Proof of concept: Arduino + Raspberry Pi + sensors
  - New generation
  - Development of packaging strategies for impact & pressure resistance
- Knowledge and IT (sub-task 2.1: Database)
  - Updated database and key factors analysis
  - Effect of hydrate formation method, hydrate habit and hydrate distribution

Plan - Next reporting period

(1) Final construction of the tool with new generation electronics and impact resistance packaging

(2) Field testing in shallow water (Red Sea)

(3) Coupling design for drilling operations

Research in Progress

After multiple delays following our relocation to KAUST, and difficulties with material and electronics import/customs, we are pleased to confirm that we are making steady progress again. We expect to have the body and modules ready and to conduct the first field test in the Red Sea in early December. Still, important conceptual developments, redesign of electronics, and new tool construction took place during this period and are reported herein.

In Situ Tool: Ahead of drilling

The new borehole tool comprises a train of modules made of stainless steel 316 for its corrosion and mechanical resistance. A new generation of sensors has been selected to measure physical properties of hydrate-bearing sediments at a given depth. Solids and fluid samplers will also be added.

A total of 3 in-situ tools are being constructed to avoid delays in field operations. Furthermore, these three tools will allow us to test different operation modes:

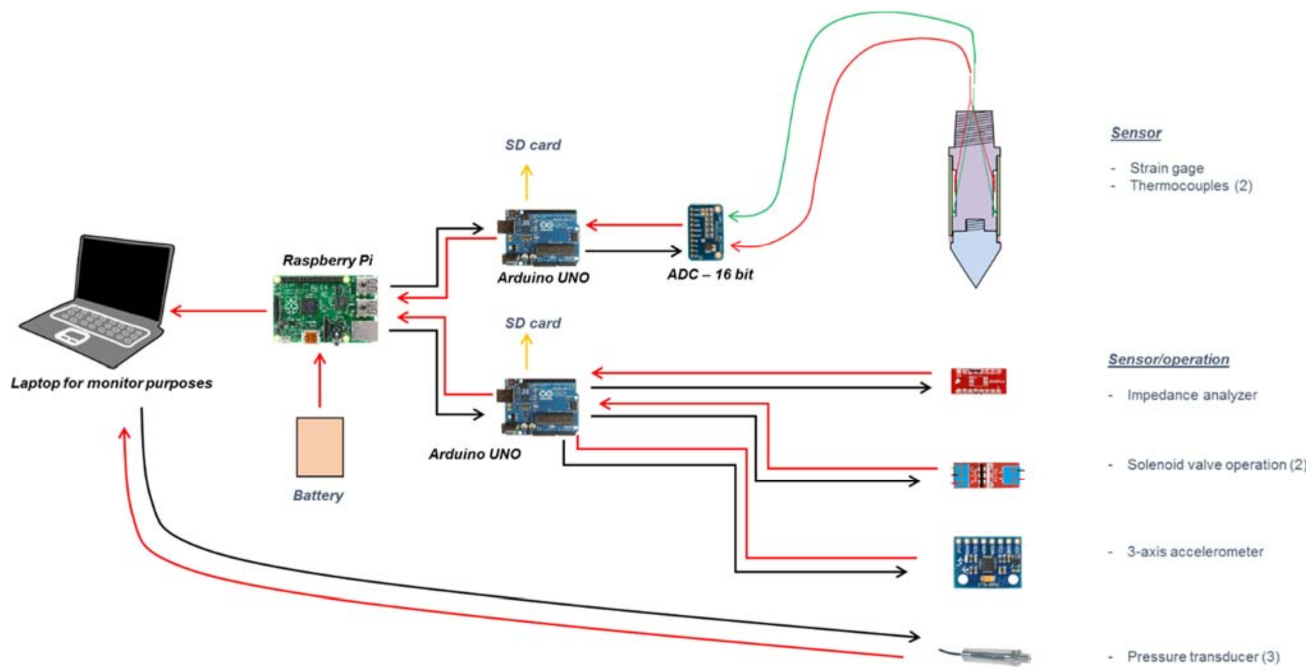
- full stand-alone (no communication with the surface),
- wired for real time data gathering and operation, and
- hybrid operation which can be customized according to the application.

New parts being machined are shown in Figure 1; these include soil samplers, body connections, and sensor modules

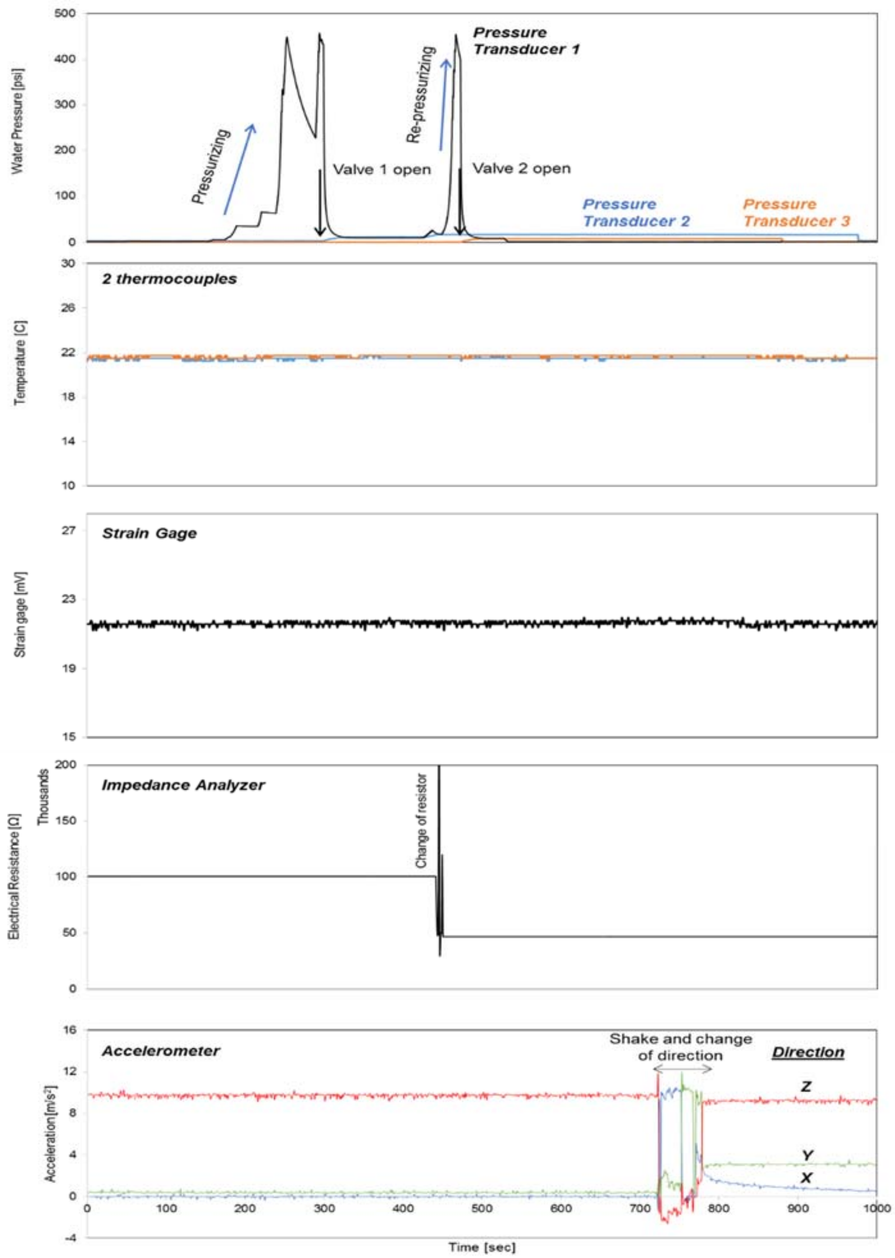
A major development was the redesign of electronics to improve the robustness of the operation (either stand-alone or wired).

Due to the amount of sensors and the limited space in the body to house the controllers, we decided to add a new component: a Raspberry Pi microcontroller. This controller can act as a master controller and two Arduino UNO will be the slaves. Therefore, the Arduino UNO will be the direct connection to the sensors and save the data in SD cards. The master will communicate with the Arduino when to operate and will keep the clock running (for sampling purposes).

The figure shows the proof of concept schematics for this new measuring system. In this case, the first Arduino will record the data from the strain gages and 2 thermocouples through an ADC (high resolution, 16 bit). The second Arduino will gather the data from the impedance analyzer, 3-axis accelerometer and will be able to operate 2 solenoid valves. Pressure transducers were also installed but commanded directly from the laptop.



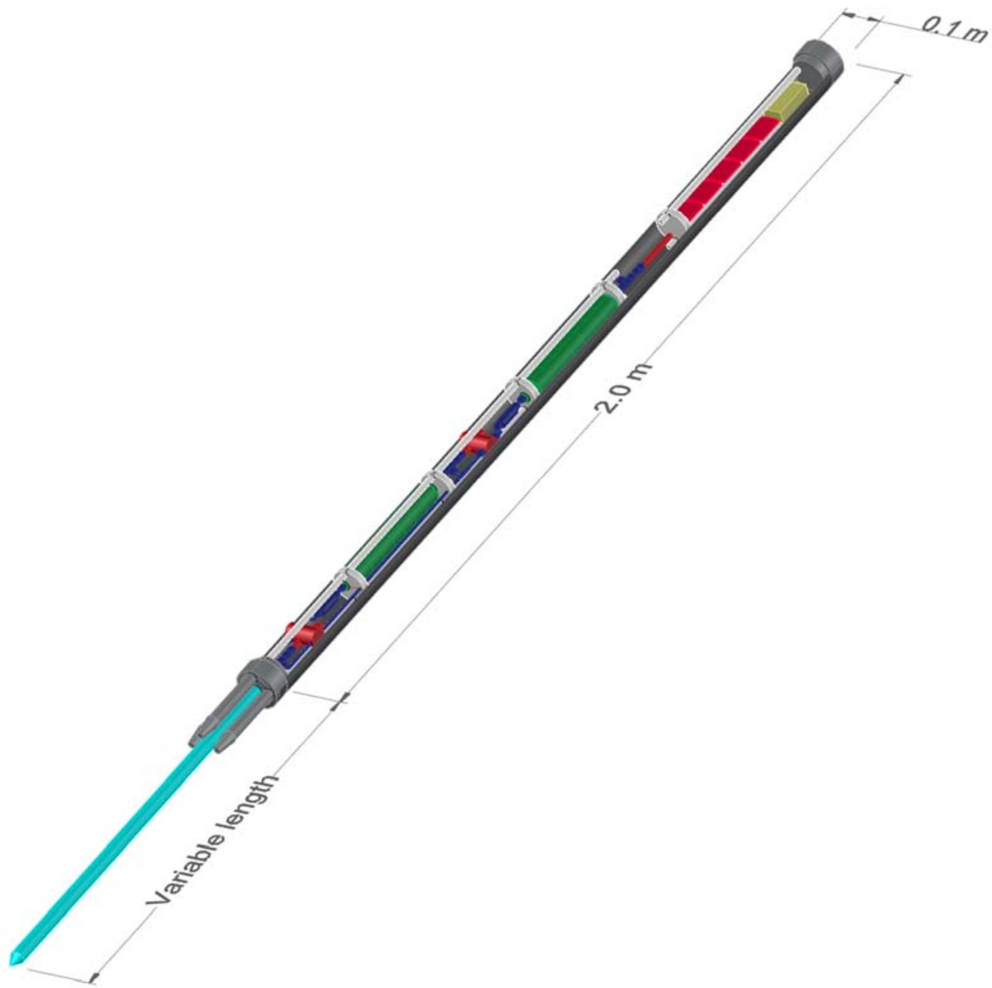
This new design was tested by connecting the hydraulic system to a water pressure source and the solenoid valves were operated to fill the two containers. The figure shows the results of this test: (a) water pressure recordings from 3 pressure transducers; pressure transducer 1 is the pressure on the external pressure vessel, and the other two are the internal pressure of the sampler containers; (b) temperature readings at the level of the strain gage; (c) strain gage readings; (d) impedance analyzer recordings with one change of resistor at 450 seconds of the test; (e) accelerometer readings, at 720 seconds of the test, the sensor was shaken and changed directions to determine reactions times.



Adaptation for shallow hydrate bearing sediments

Results from field, laboratory, and analytical/numerical studies conducted as part of this and other DOE projects in our group have shown the potential importance of near-surface hydrate bearing sediments.

We are developing a new method to deploy the tool for the characterization of shallow sediments. It will be complementary to borehole-based operations as shown in the figure.



Knowledge and IT-based tool

Data on stiffness, strength, electrical, hydraulic and thermal properties of hydrate bearing sediments were updated during this quarter.

Key factor analysis is based on an extensive collection of available laboratory data, correlations and the understanding of fundamental physics. Table 1 summarizes the governing factors for the physical properties of hydrate-bearing sediments.

Hydrate-bearing sediments properties are strongly influenced by pore habit and distribution. For the data we collected, we recognize the following hydrate formation methods:

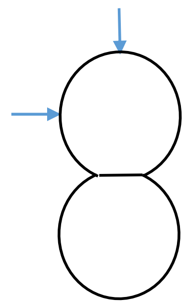
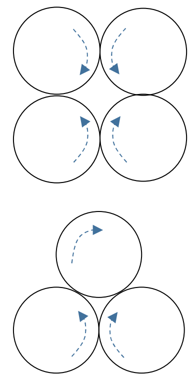
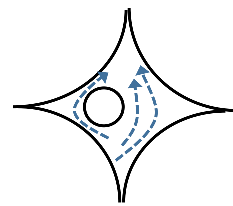
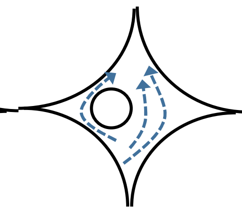
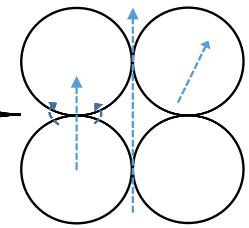
- Excess gas method: sediment is mixed with a certain amount of water and then packed. Hydrate-forming gas is injected and pressurized to form hydrate.
- Ice seed method: sand is mixed with water ice particles. Then the system is pressurized with hydrate-forming gas. Temperature increases to allow ice melt and form hydrate.
- Freeze/thaw/form: moist sand is frozen and thawed. Then the system is pressurized with hydrate-forming gas to form hydrate.
- Freeze/pressurize/thaw: moist sand is frozen. Then the system is pressurized with hydrate-forming gas. Temperature increases to allow ice melt and form hydrate.
- Dissolved in water: gas is dissolved in water. Hydrate forms from dissolved phase in water.
- Excess water method: A certain amount of gas is injected. Then the system is saturated with water and pressurized to form hydrate. Or circulate methane charged water through porous media.
- Saturate/displace/form: The system is saturated with water. Gas is injected to replace certain amount of water. Or gas may flow through the system to displace certain amount of water.

Hydrate formation affects the physical properties of sediments, according to formation history and pore habit. For example, cementation habit increases contact area (stiffness-related properties and thermal properties) while pore-filling habit decreases pore size (electrical and hydraulic properties). The effect of hydrate saturation and hydrate habit are conceptually summarized in Table 2.

By comparing different effects on various properties, we are able to evaluate the impact of hydrate pore habit on properties, with emphasis on conditions relevant to natural systems. Meso-scale uniformity (spatial variability) plays an additional effect.

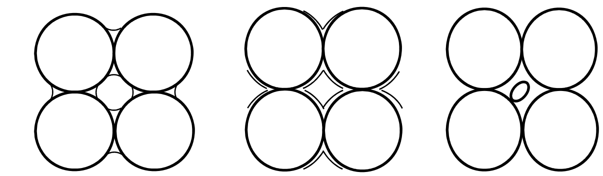
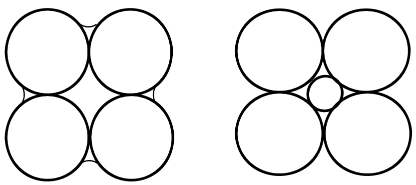
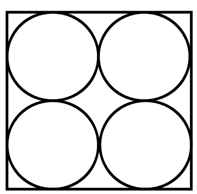
Physics-inspired models are being developed to provide robust predictions of the properties of hydrate-bearing sediments, taking into consideration pore habit. These models are guided by physical principles and are anchored to experimental observations and data.

Table 1. Key factor analysis for physical properties of hydrate-bearing sediments based on physics and observations.

		Seismic properties	Strength properties	Electrical properties	Hydraulic properties	Thermal properties
Physics						
	Properties of particle	Specific surface is a single index parameter that captures grain size, particle shape, mineralogy.	Determine friction angle and apparent cohesion.	Clay particles have high conductivity due to surface charges and high specific surface.	Pore size determines permeability. Permeability decreases as coefficient of variation in pore size increase.	Solid has the highest thermal conductivity. Higher quartz content ➔ higher thermal conductivity.
Host sediment	Packing	Dense packing has high small strain stiffness for same type of sediment.	High density, high strength and stiffness, high dilation tendency; hydrate becomes more significant for dense packing sediments.	Saturated sediments with high porosity have high electrical conductivity.	Dense packing has small permeability for same type of sediment.	High coordination number leads high thermal conductivity.
	Pore fluid	Water saturation affects P wave velocity of sediment.		Pore fluid dominates the bulk property. Volumetric water content determines		Thermal conductivity increases with degree of saturation.

				the electrical conductivity of unsaturated sediments.		
	Contact	Cementation increases small strain stiffness.	Cementation increases strength.			Large contact area → high thermal conductivity.
Hydrate	Hydrate saturation	S velocity and P velocity increases with hydrate saturation.	Hydrate increases strength and stiffness; sediments with higher hydrate saturation have higher dilation tendency and strain softening behavior.	As a non-conducting phase, hydrate decreases conductivity	Permeability decreases with increase of hydrate saturation.	Hydrate has similar thermal conductivity as water.
	Hydrate habit and distribution	Cementation habit has more effect on small strain stiffness of sediments.	Cementation tends to form sediments with higher stiffness and strength.	Hydrate pore habit and pore distribution affect the connectivity of fluid.	The reduction of permeability depends on how hydrates form in pores.	Hydrate increases conductive paths. It may also cement contacts.
Environment	Effective stress	Wave velocities increases with effective stress. When hydrate saturation is high, the effect of effective stress becomes irrelevant.	Sediments at high effective stress exhibit larger strength and greater stiffness, strain hardening and compressive tendency. Low effective stress → higher dilation tendency.	Effective stress increases and porosity decreases.		High effective stress increases packing density, coordination number and contact area.
	Temperature		Higher strength and larger stiffness was observed at lower temperature.	Electrical conductivity increases with increase of temperature (2% per 1 K).		Thermal conductivity increases slightly with temperature; thermal conductivity of gas increases with pressure.

Table 2. Conceptual models for the effects of hydrate saturation and habit on physical properties of hydrate-bearing sediments.

Hydrate saturation and hydrate habit	Properties	Features
 Contact cementing, Grain coating, Pore filling	Seismic properties	Only cementation habit has great effect on seismic properties.
	Strength properties	All pore habits has little effect on shear strength.
	Electrical properties	Electrical resistivity slightly increases.
	Hydraulic properties	Pore filling habit will have a greater effect on permeability.
Hydrate saturation < 0.2	Thermal properties	Pore habit has little effect on thermal conductivity of saturated sediments. For gas saturated sediments, thermal conductivity can increase significantly for cementation habit.
	Seismic properties	Hydrate builds the frame and seismic velocities increase significantly.
	Strength properties	Hydrate starts to have clear effect on shear strength.
	Electrical properties	Hydrate blocks pores and electrical resistivity increases.
Frame building	Hydraulic properties	Hydrate blocks pores and permeability drops dramatically.
Hydrate saturation 0.2-0.5	Thermal properties	Significant thermal conductivity increase should be observed for all habits.
	Seismic properties	Seismic velocities keep increasing.
	Strength properties	Shear strength increases significantly and hydrate saturation becomes a dominant factor affecting shear strength.
	Electrical properties	Electrical resistivity increases because of poor pore connectivity.
Hydrate saturated Hydrate saturation >0.5	Hydraulic properties	Permeability drops significantly and it may become impermeable.
	Thermal properties	Thermal conductivity keeps high without significant increase.

MILESTONE LOG

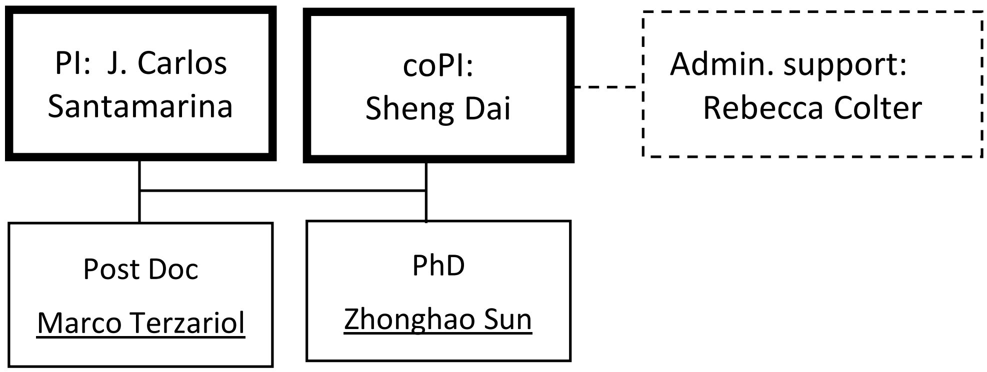
	Milestone	Completion Date	Comments
Title Planned Date Verification method	Completion PMP November 2013 Report	11/2013	
Title Planned Date Verification method	Insertion – Tool design September 2014 Report	9/2014	
Title Planned Date Verification method	Database and IT tool September 2014 Report	9/2014	Paper in preparation
Title Planned Date Verification method	Electronics in operation January 2015 Report	1/2015	New generation of electronics and packaging method in progress
Title Planned Date Verification method	Lab testing of prototype September 2015 Report	6/2015	Refer to previous reports
Title Planned Date Verification method	Tool deployment Before September 2016 Report	In progress	

PRODUCTS

- **Publications – Presentations:** None at this point
- **Website:** Publications and key presentations are included in http://egel.kaust.edu.sa/. (for academic purposes only)
- **Technologies or techniques:** None at this point.
- **Inventions, patent applications, and/or licenses:** None at this point.
- **Other products:** None at this point.

PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

Research Team: The current team is shown next. *Note: As agreed with DOE, Georgia Tech professor Sheng DAI has joined the project.*



IMPACT

None at this point.

CHANGES/PROBLEMS:

None at this point.

SPECIAL REPORTING REQUIREMENTS:

We are progressing towards all goals for this project.

BUDGETARY INFORMATION:

As of the end of this research period, expenditures are summarized in the following table. See specific comments in the footnote to the table

Baseline Reporting Quarter DE-FE009897	Budget Period 3							
	Q1		Q2		Q3		Q4	
	10/1/14 - 12/31/14		1/1/15 - 3/31/15		4/1/15 - 6/30/15		7/1/15 - 9/30/15	
	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total
Baseline Cost Plan								
Federal Share	40,059	341,026	40,059	381,086	40,059	421,145	40,059	461,204
Non-Federal Share	11,587	100,272	11,587	111,860	11,587	123,447	11,587	135,034
Total Planned	51,647	441,299	51,647	492,945	51,647	544,592	51,647	596,238
Actual Incurred Cost								
Federal Share	57,809	333,090	56,843	389,933	35,283	425,216	13,942	439,158
Non-Federal Share	25,961	100,696	36,582	137,278	0	137,278	0	137,278
Total Incurred Costs	83,770	433,786	93,425	527,211	35,283	562,494	13,942	576,436
Variance								
Federal Share	17,749	-7,936	16,784	8,848	-4,776	4,071	-26,117	-22,046
Non-Federal Share	14,374	424	24,995	25,419	-11,587	13,831	-11,587	2,244
Total Variance	32,123	-7,512	41,779	34,266	-16,364	17,903	-37,705	-19,802

Note: in our academic cycle, higher expenditures typically take place during the summer quarter; however, most of our charges this summer were minimal as Santamarina and one of the PhDs are not charged to this account any longer even though he remains fully involved in the project. This situation has now been regularized as the new Georgia Tech professor Sheng DAI has joined the project.

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