Oil & Natural Gas Technology

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Quarterly Research Performance Progress Report (Period ending 7/31/2013)

Hydrate-Bearing Clayey Sediments: Morphology, Physical Properties, Production and Engineering/Geological Implications

Project Period (10/1/2012 to 9/30/2016)

Submitted by:
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Office of Fossil Energy

ACCOMPLISHMENTS

Context – Goals. *Fine grained sediments host more than 90% of the global gas hydrate accumulations. Yet, hydrate formation in clayey sediments is least understood and characterized. This research focuses on* <u>*hydrate bearing clayey sediments*</u>*. The goals of this research are (1) to gain a fundamental understanding of hydrate formation and ensuing morphology, (2) to develop laboratory techniques to emulate "natural" formations, (3) to assess and develop analytical tools to predict physical properties, (4) to evaluate engineering and geological implications, and (5) to advance gas production alternatives to recover methane from these sediments.*

Accomplished

The main accomplishments for this period include:

- Continued training of the two first-year PhD students working in the project
    - hydrate bearing sediments, with emphasis on clayey sediments
- Advanced reviews and preliminary exercises on
    - representation of discrete feature networks (DFN) to represent lenses
    - COMSOL representation and simulations
- Advanced studies of hydrate formation in clayey sediments
- Imaging
    - Final decisions and purchases for our new X-ray micro-CT, with special capabilities to study hydrate bearing sediments specimens under high pressure
    - preliminary testing of components
    - completed adaptation of reconstruction and display software (additional developments will be required, such as stacking, image enhancement, automation)
- Lab: we are moving back to our original renewed facilities, and reassembling all testing systems (the move is 60% done as of 7/31)

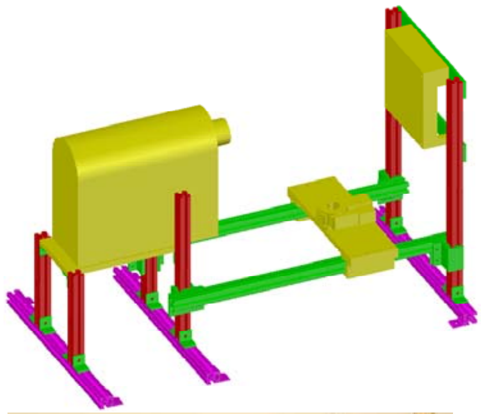
Plan - Next reporting period

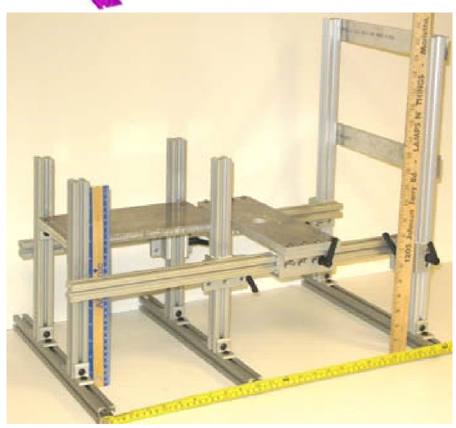
Complete reorganization of new lab facility, complete X-ray microCT deployment and calibration, perform a comprehensive imaging study of hydrate bearing sediments, advance the analysis of properties of sediments with segregated hydrate.

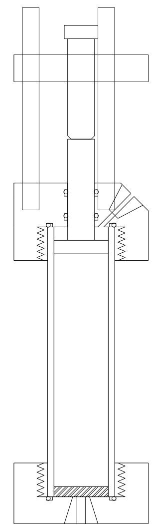
RESEARCH IN PROGRESS

Imaging System: MicroCT for high pressure specimens

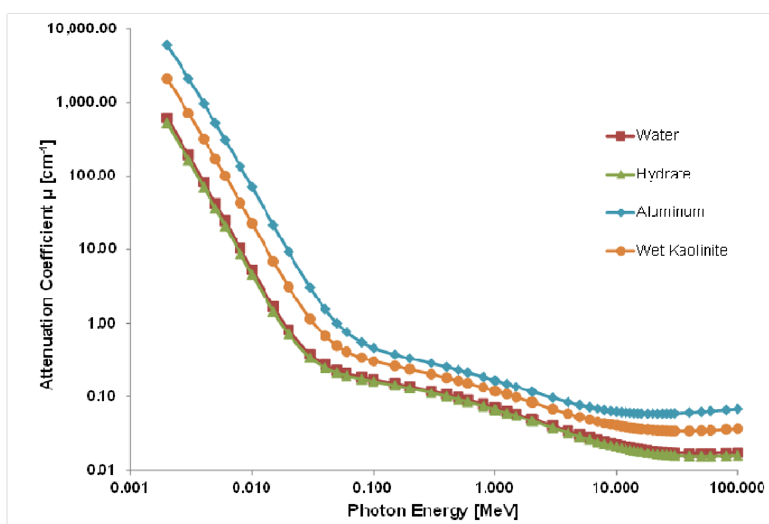
All parts have been designed, purchased and partially assembled (to be finalized in our new laboratory). Control, recording, inversion and rendering software are ready.







Phase discrimination in tomographic images reflects their relative absorption. Results on this figure show the attenuation of aluminum, water saturated kaolinite, water and hydrate. Clearly, attenuation is closely related to mass.

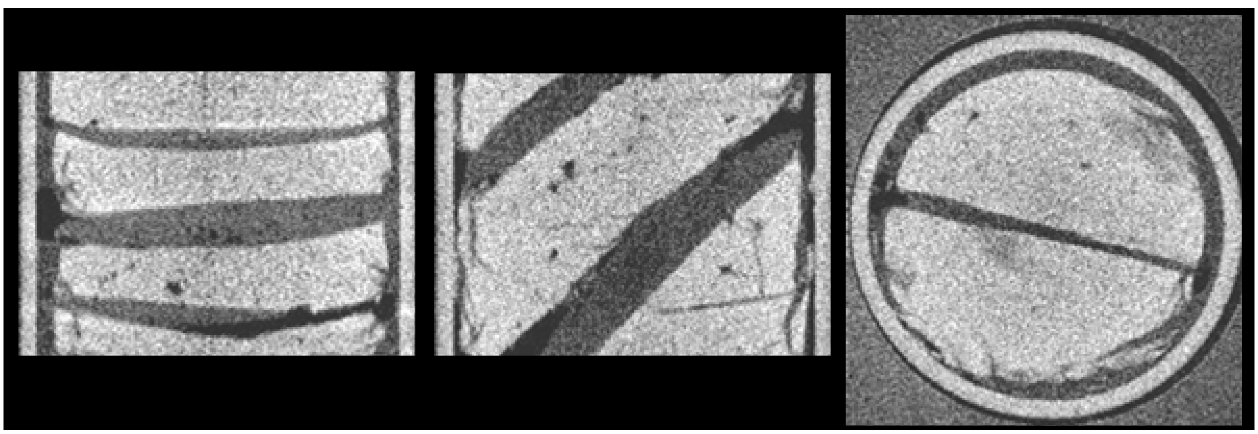


Clay sediments with preferential lenses orientation - Tomographic images

Specimens were prepared with preferential orientation of ice lenses. The purposes of this exercise were twofold:

- to control lenses topology and to attain simple geometries that lend themselves to close-form analyses and/or numerical representation
- to avoid complex lenses geometries that are typically obtained in small chambers under controlled boundary P&T conditions (reported in previous reports)

The figure shows tomographic images obtained with a simple system (similar to the one above) using all our software. The three cases shown correspond to horizontal, inclined and vertical lenses (cross section). While the geometry was pre-enforced by slicing, the peripheral lenses observed in the three cases formed naturally as a result of boundary conditions and cryogenic suction.



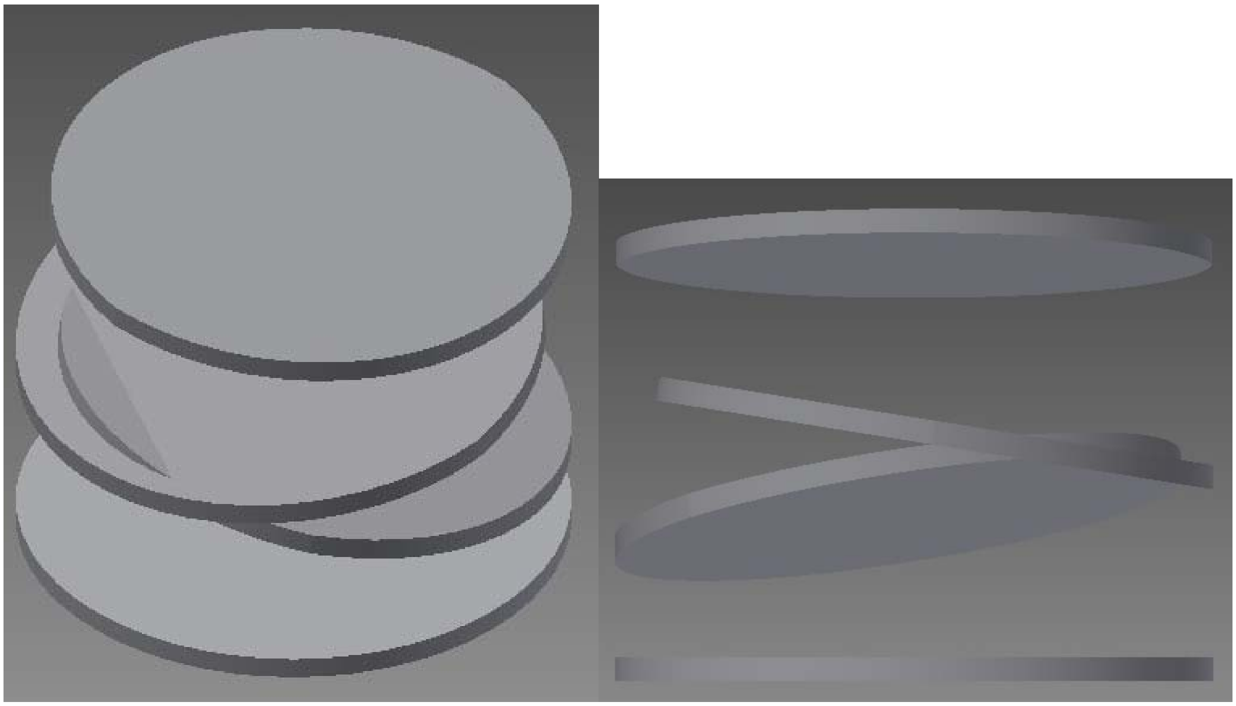
Hydrate lenses – Characteristics and representation

Constraining topology. We have not been able to develop robust criteria for the separation between lenses yet. Similarly, there is not conclusive evidence about the possible range of intersection angles between lenses. We anticipate a correlation between lenses aperture, d_{max} (i.e., the maximum opening) and length, L. In non-interacting opening mode discontinuities, the causal association can be explored using theory of elasticity.

$$d_{max} = \Delta\sigma \frac{2\left(1-\nu^2\right)}{E} L$$

where $\Delta\sigma$ is the opening mode driving stress, ν is Poisson's ratio and E is the medium Young's modulus.

Representation. Using Autodesk Inventor, ice lenses can be simply modeled using three known points on the circumference of a circle. A database of 3-points created in Excell was imported into Inventor to observe the lenses in 3D. Inventor images are readily transferred into COMSOL Multiphysics by exporting drawing files to STEP files.



Hydrate Bearing Fine Grained Sediments – Properties

The physical properties of hydrate-bearing fine-grained sediments depend on the spatial distribution of gas hydrate and the properties of hydrate and the surrounding sediment (typically water saturated and subjected to cryogenic suction). We are starting to explore the properties of hydrate bearing sediments and to reconsider previous experimental studies conducted by the PI and others during the last decade. We are advancing these studies while we are still attempting to delimit the possible topologies observable in hydrate bearing clayey sediments.

The properties of hydrate bearing fine-grained sediments will depend on the properties of the segregated hydrate mass and the host sediment.

Table. Properties selected for hydrate and fine-grained sediments

Property	Methane Hydrate	Fine-Grained Sediment
Hydraulic Conductivity, k_H [cm/s]	0	$1x10^{-7}$
	$k_H = C_F \frac{1}{S_S{}^2} \frac{g}{\mu} \frac{\rho_f}{\rho_m} \frac{e^n}{1+e}$	Taylor 1948
Thermal Conductivity, k_T [W/mK]	0.575[b], 0.51[j]	1.9-2.2[a], 2.1-2.8[c]
	$k_{T,parallel} = \alpha_L \cdot k_{hydrate} + (1-\alpha_L) \cdot k_{soil}$	Upper Bound
	$k_{T,series} = \left[\frac{\alpha_L}{k_{hydrate}} + \frac{(1-\alpha_L)}{k_{soil}} \right]^{-1}$	Lower Bound
Compressibility $C_c = \frac{\Delta e}{\Delta \log \sigma'}$		0.154-1.05[b], 0.21[j]
	$C_c = 1.15 \cdot (e_0 - 0.35)$	Nishida 1956
	$C_c = 0.256 \cdot e_L - 0.04$	Burland 1990
	$C_c = 2.203 \cdot \rho_c \cdot e_0 \left(1 - \left(\frac{0.35}{e_0} \right)^2 \right)$	Pestana 1994
Shear Stiffness	$G_{\max} = 1230 \frac{(2.973-e)^2}{1+e} \sigma_c{}^{0.5}$	Hardin and Black 1968
	$G = 1000 \cdot K_2 \cdot (\sigma_m')^{0.5}$	Seed and Idriss 1970

S_S: specific surface. μ: fluid viscoisuty. ρ_f: fluid density. ρ_m: mineral density. e: void ratio.
α_L: volume fraction of segregated hydrate

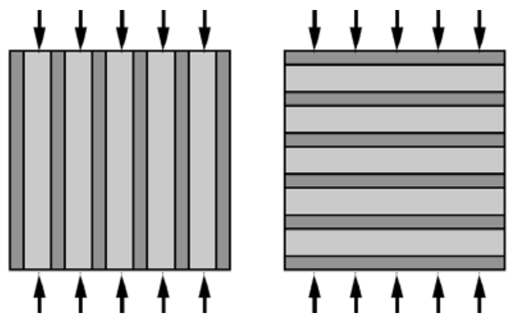
	Methane Hydrate	Fine-Grained Sediment
Heat Capacity, C_p [J/kgK]	2031-2080[l]	880-1145[k]
Density, ρ [kg/m^3]	0.925-0.94[demo]	2, 2.58[g]
Poisson's Ratio	0.314[f], 0.33[k]	
Bulk Modulus, K [GPa]	8.41[o], 8.762[h]	20.9[g]
Shear Modulus, G [GPa]	3.54[o],3.574[h]	6.85[g]
Compressional Velocity, V_p [m/s]	3770[o], 3778[h]	3.41[i]
Shear Velocity, V_s [m/s]	1960[ho], 1963.6[f]	1.63[i]

a) Becker (1992), b) Burland (1990), c) Cortes et al (2009), d) Dai et al (2012), e) Davidson (1983), f) Huang and Fan (2004), g) Helgerud (1999), h) Helgerud (2002), i) Lee (1996), j) Lee (2010), k) Robie and Hemingway (1991), l) Sloan and Koh (2008), m) Waite (2005), n) Waite (2007), o) Waite (2009)

Analytical Solutions

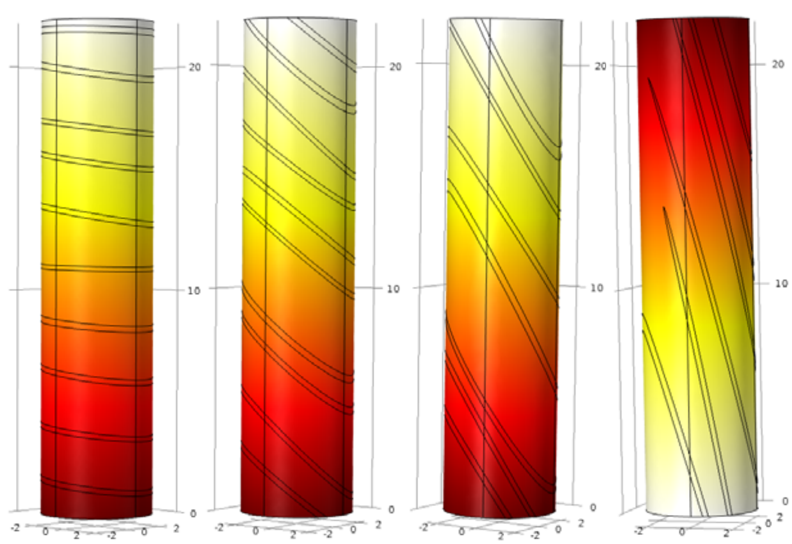
Effective medium models can be used to estimate physical properties of mixtures with known spatial configuration, such as hydrate bearing fine-grained sediments with disk-shaped hydrate lenses [Eshelby analyses; Kuster and Toksöz model; Berryman's solutions].

Upper and Lower Bounds. Upper and lower bounds can be computed for a given physical property by assuming end-member lenses topology. Segregated hydrate in fine-grained sediments could lead to material properties outside the Hashin-Shtrikman bounds, but properties will always be within Voigt and Reuss Bounds.

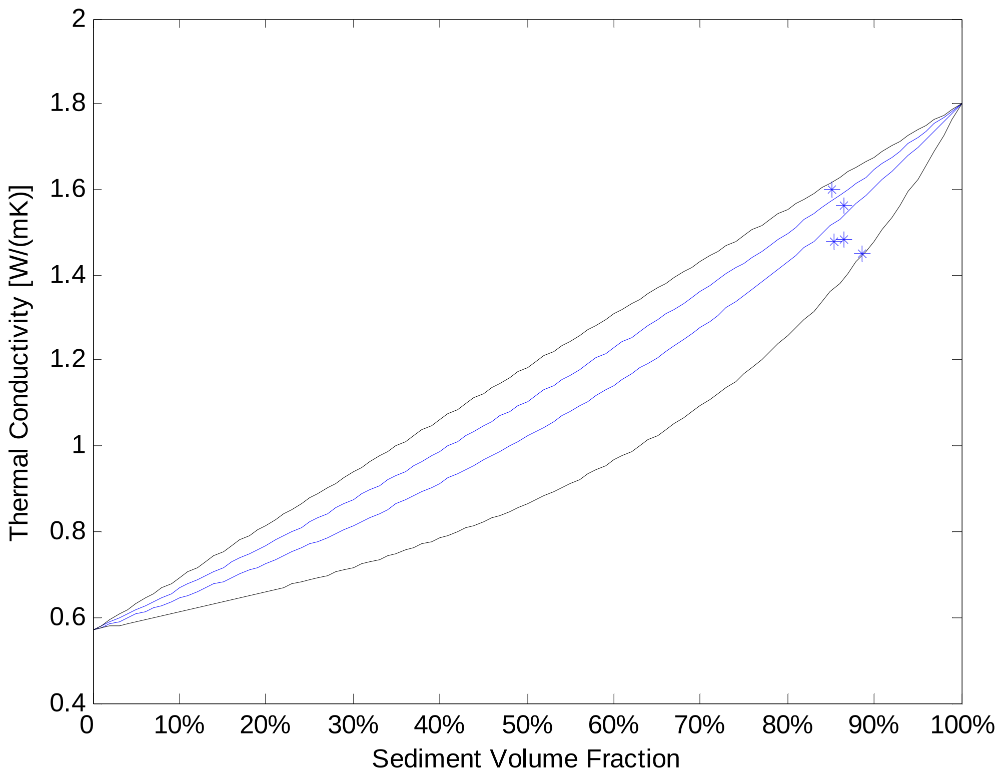


Numerical Simulations

These simulations are conducted using COMSOL (based on past experiences, we anticipate more complex studies using Abaqus FEA in future studies). Several realizations of randomly distributed lenses are generated for a given number of hydrate lenses. The 3D numerical models are meshed using tetrahedral element.



The figure shows numerical results HS bounds (blue) and the wider series and parallel bounds. as noted above, the properties of fine-grained sediments with segregated hydrate lenses can be outside the Hashin-Shtrikman bounds, are within Voigt and Reuss Bounds.



MILESTONE LOG

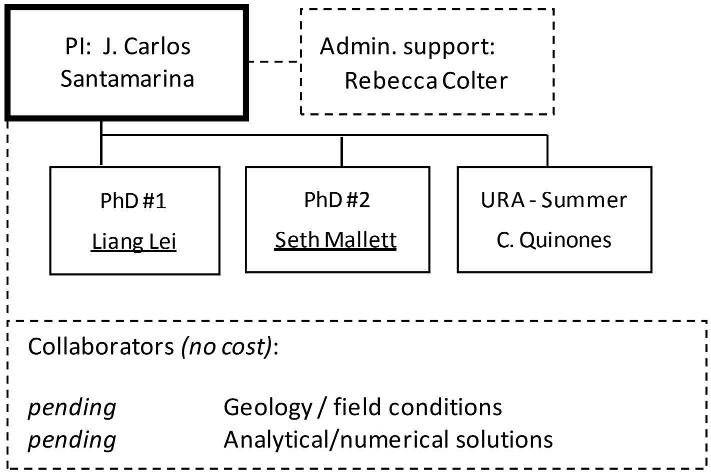
Milestone	Planed completion date	Actual completion date	Verification method	Comments
Literature review	5/2013	5/2013	Report	Completed first phase. Will continue throughout the project
Preliminary laboratory protocol	8/2013	8/2013	Report (with preliminary validation data)	this and previous reports
Cells for Micro-CT	8/2013	8/2013	Report (with first images)	this and previous reports
Compilation of CT images: segregated hydrate in clayey sediments	8/2014		Report (with images)	
Preliminary experimental studies on gas production	12/2014		Report (with images)	
Analytical/numerical study of 2-media physical properties	5/2015		Report (with analytical and numerical data)	
Experimental studies on gas production	12/2015		Report (with data)	
Early numerical results related to gas production	5/2016		Report	
Comprehensive results (includes Implications)	9/2016		Comprehensive Report	

PRODUCTS

- **Publications – Presentations:**
  Hydrate bearing clayey sediments: Formation and gas production concepts (Completed. To be submitted for publication 8/7/2013)
- **Website:** Publications (for academic purposes only) and key presentations are included in http://pmrl.ce.gatech.edu/.
- **Technologies or techniques:** The X-ray microCT system developed for this project will be documented in an upcoming manuscript.
- **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. We anticipate including external collaborators as the project advances



IMPACT: Hydrate lenses morphology, representation and emulation. Imaging in high resolution tomographer.

CHANGES/PROBLEMS: None.

SPECIAL REPORTING REQUIREMENTS: We will be operating our own microCT for high resolution imaging of hydrate bearing sediments in our own laboratory before the end of August.

BUDGETARY INFORMATION: As of the end of September, expenditures during BP1 are (Note: includes Fall 2013 tuition and PhDs' salaries):

Baseline Reporting Quarter	Budget Period 1									
	Q1		Q2		Q3		Q4 ***		Q1	
	10/1/12 - 12/31/12		1/1/13 - 3/31/13		4/1/13 - 6/30/13		7/1/13 - 9/30/13		10/1/13 - 12/31/13	
	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total	Q1	Cumulative Total
Baseline Cost Plan										
Federal Share	39,212.06	39,212.06	39,212.06	78,424.12	39,212.06	117,636.18	39,212.06	156,848.24	39,212.06	196,060.30
Non-Federal Share	11,423.38	11,423.38	11,423.38	22,846.76	11,423.38	34,270.14	11,423.38	45,693.52	11,423.38	57,116.90
Total Planned	50,635.44	50,635.44	50,635.44	101,270.88	50,635.44	151,906.32	50,635.44	202,541.76	50,635.44	253,177.20
Actual Incurred Cost										
Federal Share	-	-	16,173.48	16,173.48	20,190.94	36,364.42	89,478.84	125,843.26		
Non-Federal Share	-	-	52,426.43	52,426.43	13,105.68	65,532.11	-	65,532.11		
Total Incurred Costs			68,599.91	68,599.91	33,296.62	101,896.53	89,478.84	191,375.37		
Variance										
Federal Share	(39,212.06)	(39,212.06)	(23,038.58)	(62,250.64)	(19,021.12)	(81,271.76)	50,266.78	(31,004.98)		
Non-Federal Share	(11,423.38)	(11,423.38)	41,003.05	29,579.67	1,682.30	31,261.97	(11,423.38)	19,838.59		
Total Variance	(50,635.44)	(50,635.44)	17,964.47	(32,670.97)	(17,338.82)	(50,009.79)	38,843.40	(11,166.39)		

*** Federal Share figure for Budget Period 1; Q4 (7/1/13 - 9/30/13) represents actual expenses and encumbrances through 12/31/13

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