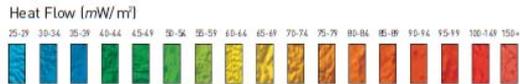
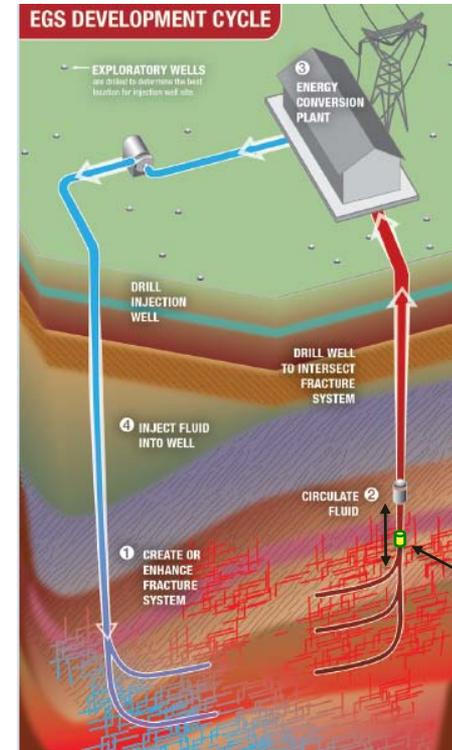


Geothermal Power Plants ♣
 Springs ♣ Hot ♣ Warm
 Pleistocene and Holocene Volcano ▲
 Geothermal Area Wells •
 Bottom Hole Temperatures (BHT) -

Land Heat Flow
 ♣ [data averaged .06°]
 Low Quality Land Heat Flow
 ♣ [data averaged .06°]



SMU Geothermal Lab, Geothermal Map of United States, 2004



Multipurpose
Acoustic
Sensor

Multipurpose Acoustic Sensor for Downhole Fluid Monitoring

May 19, 2010

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**Los Alamos National
Laboratory**

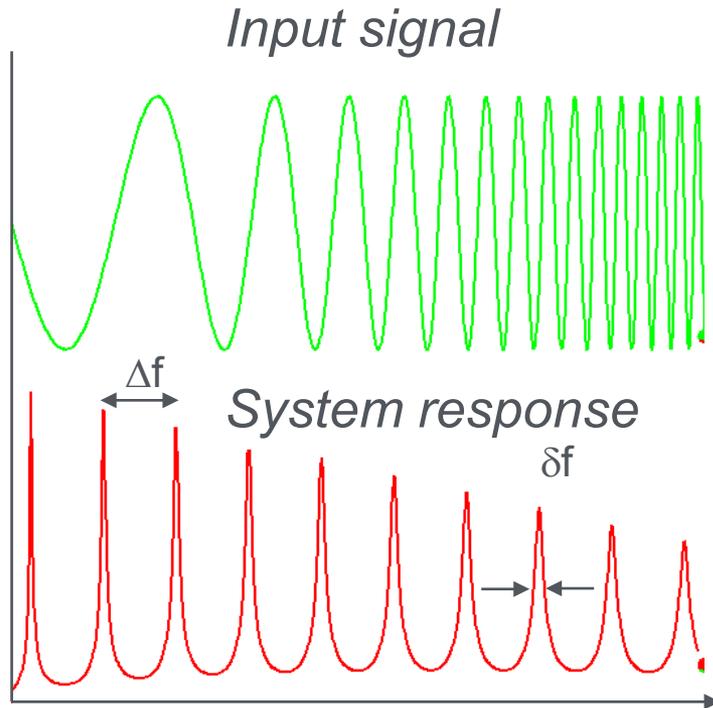
High Temperature Tools and Sensors, Down-hole
Pumps and Drilling

- Timeline
 - Project start date: Oct 2009
 - Project end date: Sep 2011
 - Percent complete: 18 %
- Budget
 - Total project funding: \$ 894,000
 - DOE share: \$ 894,000
 - Awardee share: \$ 0
 - Funding received in FY09: \$ 536,400
 - Funding for FY10: \$ 357,600
- Barriers
 - Site/Well Characterization Barrier D: Characterization – Subsurface environments in EGS regimes are inhospitable to existing downhole, in-situ characterization methods.
 - Demonstrate sensor capabilities that can be employed at a depth of 220 Bar and operation temperatures of 374°C.
- Partners: N/A

- Novel sensor design *based on acoustics*.
- Determine in real-time and in a single sensor package multiple parameters: temperature, pressure, fluid flow; and fluid properties, such as density, viscosity, fluid composition.
- Needed especially in Site/Well Characterization.
- All components, such as transducers, cables and electronics are commercially available.
- The unique design of the sensor allows its operation at very high temperature and pressure (22 MPa and 374°C). The active parts of the sensor are piezoelectric materials that can withstand adverse conditions of very high pressure and temperature.
- Advantages: (1) low power consumption, (2) all solid-state and rugged, (3) can withstand high temperature and pressure, (4) low cost, and (5) will replace 5-7 current instruments with a single one.

- Fluid composition including density and viscosity at various depths in a borehole provides geothermal reservoir properties.
- Borehole temperature at various depths provide diagnostic measurements for geothermal reservoir characterization:
 - determines thermal gradient along the borehole
 - provides location of borehole fracture intersections
 - allows estimation of thermal drawdown and recovery rates of the circulating systems
 - * The temperature provides diagnostic data during drilling, cementing, pressurization, and hydraulic-fracturing operations.
- Borehole pressure at various depths:
 - determines pressure gradient along the borehole
 - provides location of borehole fracture intersections
 - can provide information related to recovery rates of the circulating systems.
- Fluid flow determination provides fluid-flow patterns in a borehole. A typical borehole has fractures in several zones. The fluid flow can help characterize the man-made reservoir by:
 - determining the nature and location of the fractures,
 - determining the location and the amount of fluid that leaves and enters the borehole, and
 - determining the relative contribution of each fracture to the total reservoir.

- The underlying physical basis of the sensing technique proposed here is the Swept Frequency Acoustic Interferometry (SFAI) technique and resonance tracking.



Sound speed = $2d\Delta f$

Sound absorption $\sim \delta f$

Δf = frequency spacing

δf = peak width

There can be hundreds of such resonance peaks in a typical spectrum

- For every material in a sensor, there is an interdependent relationship between its fundamental resonance frequency and temperature, which can be used to measure *temperature* accurately.
- A cross-correlation analysis of the frequency spectrum on a dual electrode design on the piezoelectric cylinder provides *fluid flow measurement*.

	Y1Q4	Y2Q1	Y2Q2	Y2Q3	Y2Q4	Y3Q1	Y3Q2	Y3Q3	Y3Q4	Y4Q1	Y4Q2	Y4Q3
Stage 1: Preliminary Investigation and Analysis												
Task 1: Materials identification.		M1										
			Gate 1									
Task 2: Theoretical modeling and algorithm development.										M2		
Stage 2: Concept Definition												
Task 3: Sensor geometry.									M3			
Stage 3: Concept Development												
Task 4: Flow measurement and fluid composition									M4			
											Gate 3	
Task 5: Temperature and pressure calibration.									M5			
Stage 4: Technology Development and Verification												
Task 6: Adapt design to existent hot-rock project tool												
Task 7: Demonstration of proof of concept in laboratory												M6

- Task 1: Materials identification, completed.
- Task 2: (Started) Will run for the entire duration of the project. Good progress to-date. Investigated different approaches for signal processing.
- Task 3: Performed preliminary investigations related to sensor geometry.

- Identified materials and equipment needed for sensor development.

Common **transducers** have low Curie Temperature (T_C) → the transducer loses its piezoelectric property completely at temperatures close to T_C .

PZT: 195 – 350°C; **LiNbO₃**: 1150°C, **La₃Ga_{5.5}Ta_{0.5}O₁₄**: > 1200°C.

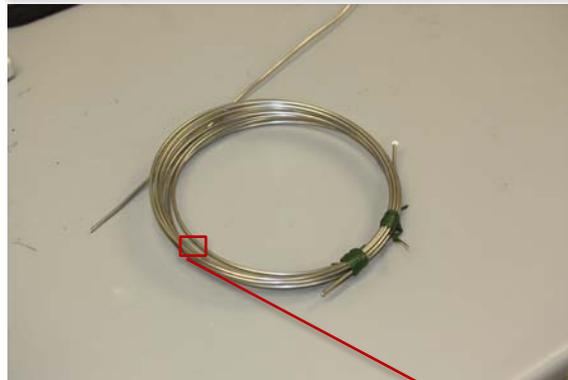
Pressure vessel



Max pressure:
41 MPa
Max temperature:
600 °C

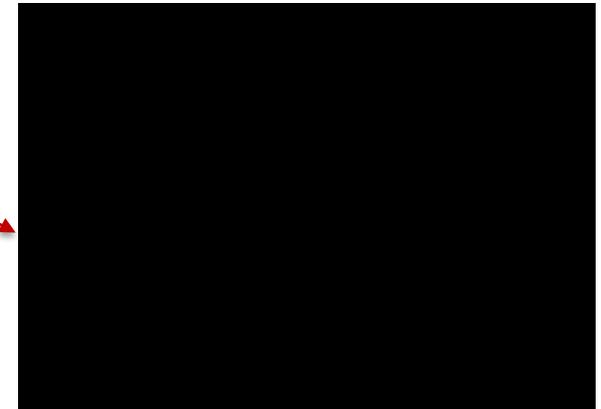
*The conditions from the call are:
22 MPa and
374 °C

High temperature coaxial cable



Sheath: Copper lined stainless steel
Core: Copper
Insulator: mineral powder

Can be used at very high temperature: **600°C**, and under **very aggressive media**.

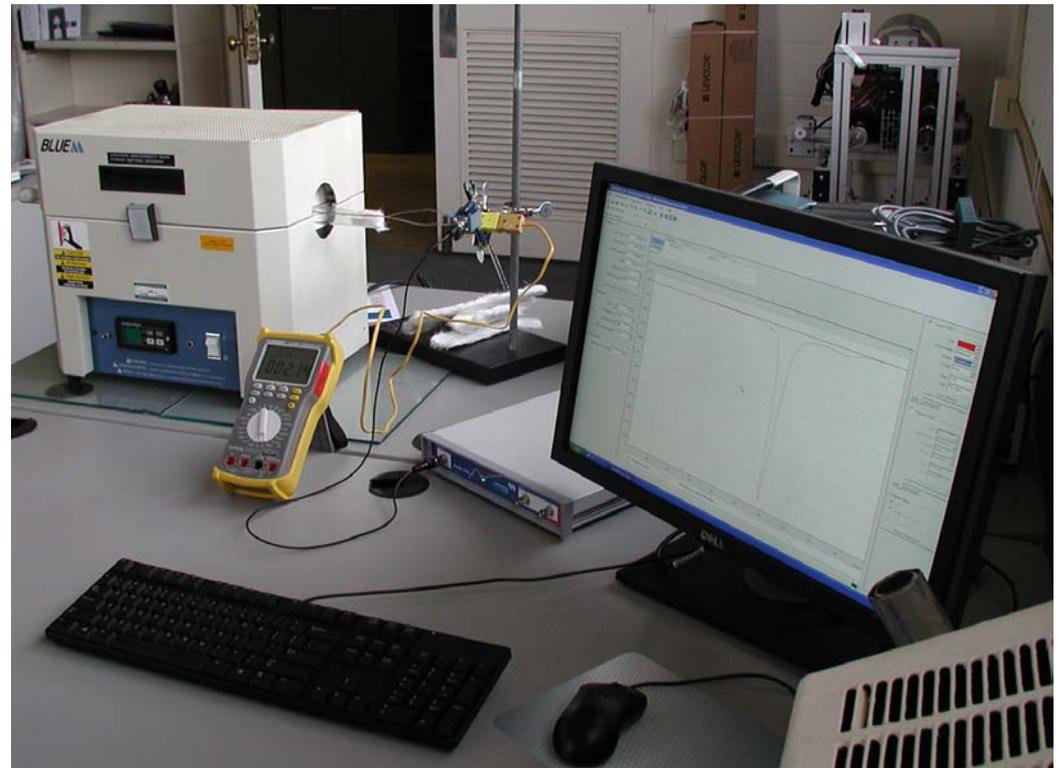


Temperature Determination Experiments

Temperature range: room temperature to 450°C.

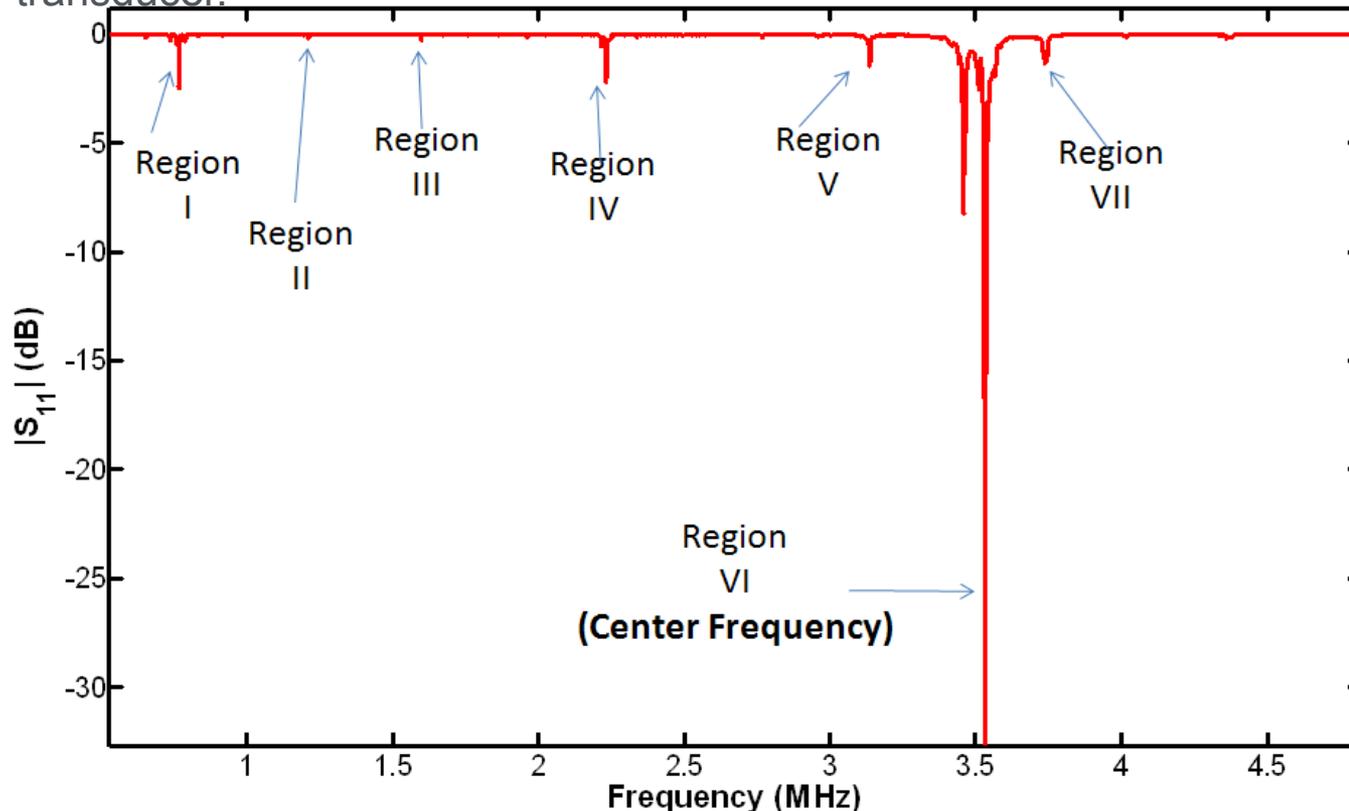
Natural resonances of the transducer are tracked using SFAI.

LiNbO₃ transducer



Lithium Niobate Transducer Reflectivity Spectrum: $300 \text{ kHz} < f < 5 \text{ MHz}$

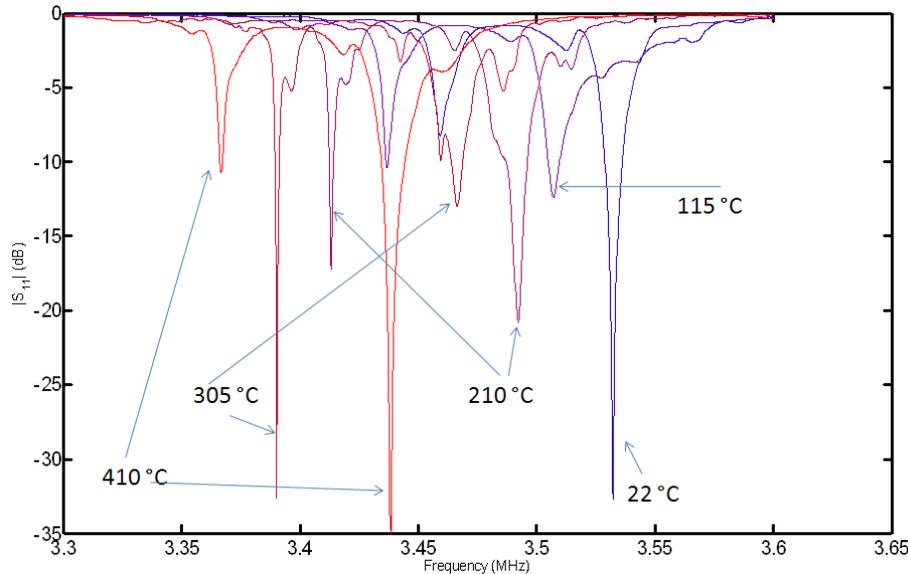
There are several natural resonances present in the frequency spectrum, each corresponding to different modes of vibration of the transducer.



Region VI – Center Frequency

“Split Peak” → Messy & Hard to Track

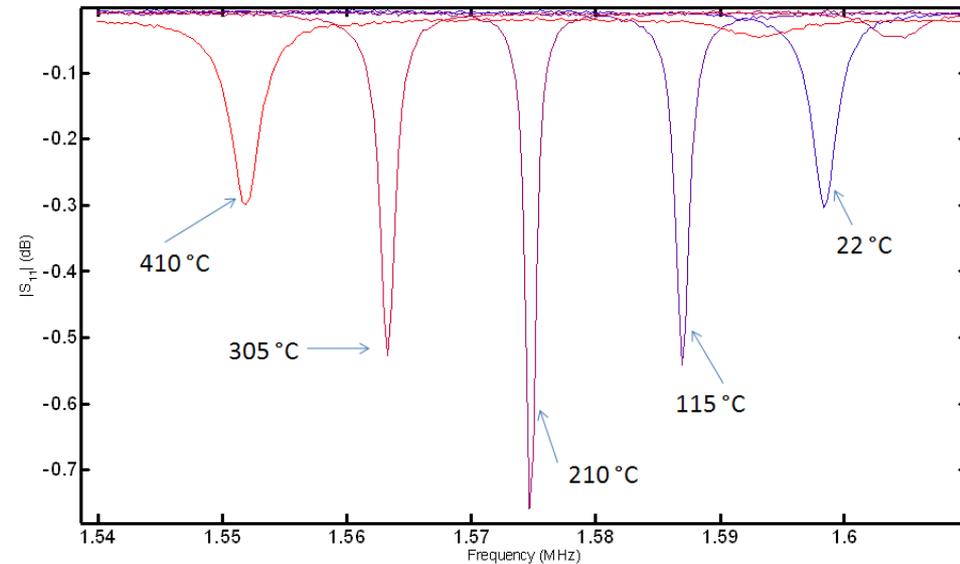
The center frequency of a transducer is the obvious choice for tracking temperature and/or pressure changes. However, in this case it turns out to be very difficult to track.



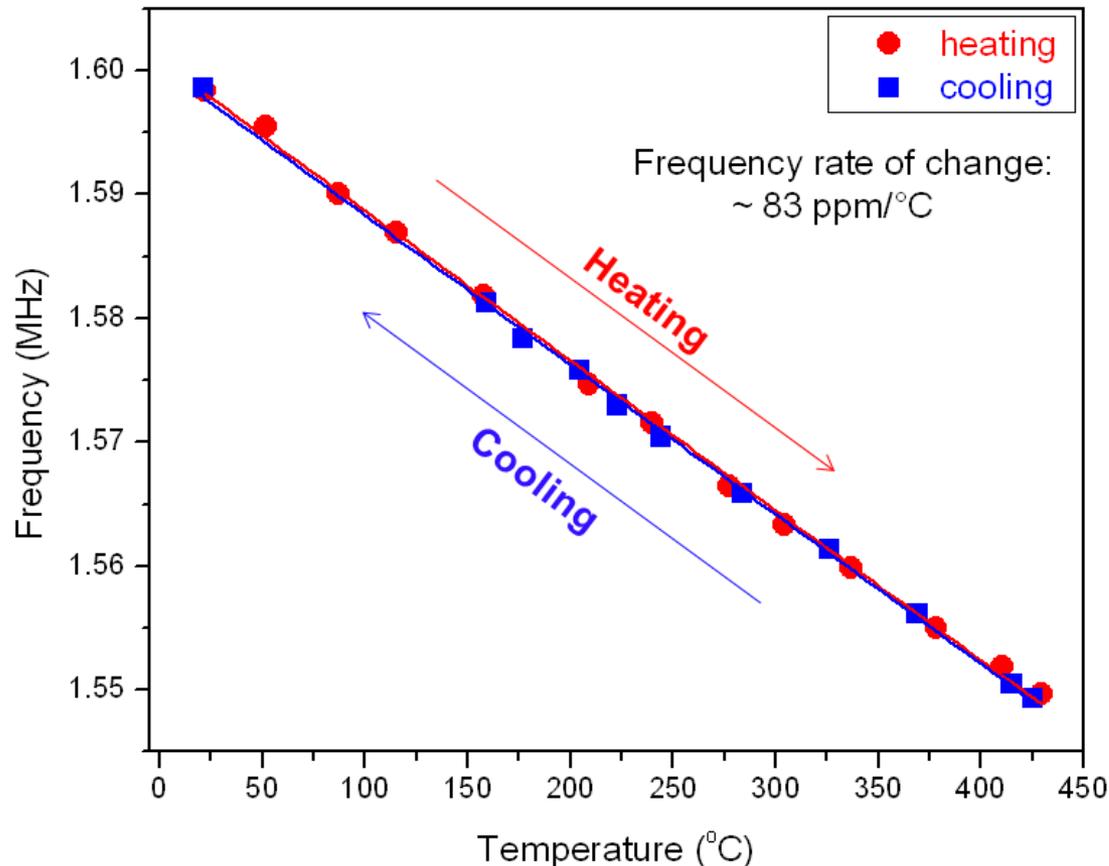
Region III – 1.58 MHz Resonance

Single Peak → Clean & Easy to Track

Tracking any of the other characteristic resonances of the transducer is a better choice, e.g. see the temperature dependence of Region III below.



Region III – 1.58 MHz Resonance

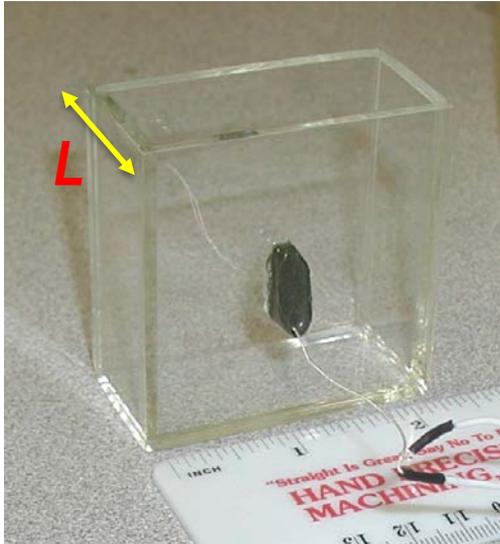


No Temperature Hysteresis!

The temperature tracking is independent of cooling or heating cycle.

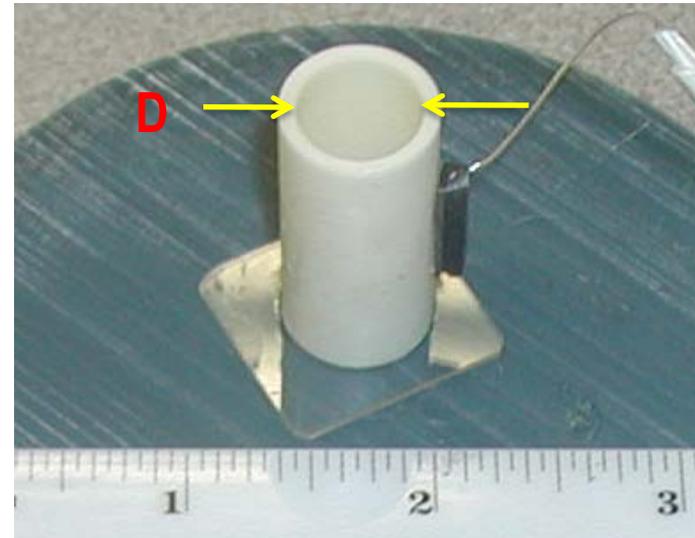
Sensor geometry

Rectangular geometry



- Standing waves: $\sin(kx)$
- Resonance: $f_n = \frac{cn}{2L}$
- Sound Speed: $c = 2L\Delta f$

Cylindrical geometry



- Standing waves: $J_b(kr)$ (Bessel Functions)
- Sound Speed: $c = 2D\Delta f$
- Good approximation when (for water and $D=3.0$ cm, $f_{low}=500$ kHz) $f_{low} > \frac{30c}{\pi D}$

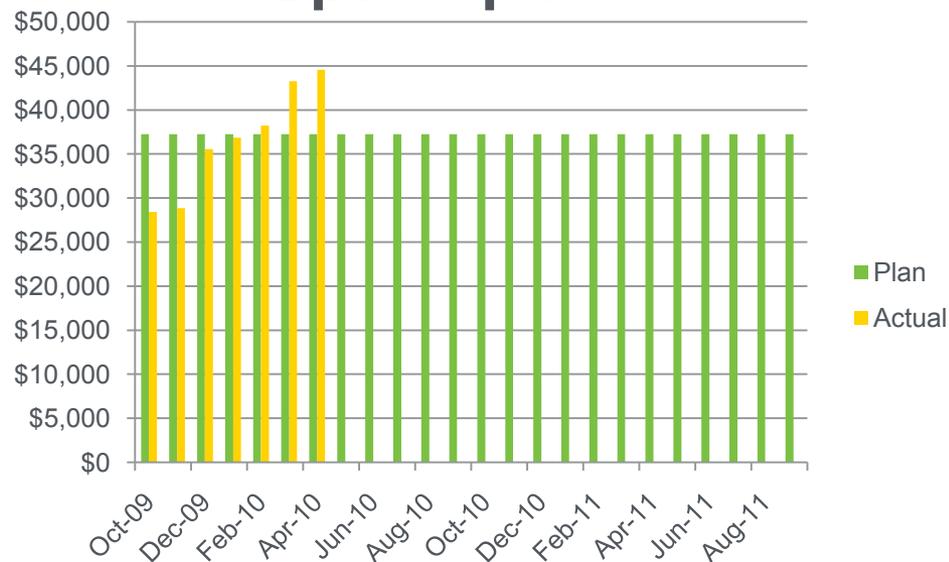
Preliminary theoretical investigation of both geometries was performed.

A good agreement between the experimental data and the theory was observed. Further refinement of the final design is under works.

- The work performed is on schedule. Materials for sensors were identified and procured. We are working toward theoretical modeling and sensor geometry. Good progress on both tasks.
- Acoustics team:
 - PI: Cristian Pantea, 7+ years experience in high pressure – high temperature condensed matter physics (typical ranges of up to 10 GPa and 2200°C), and 6+ years experience in acoustics.
 - Co-PI: Dipen Sinha, 25 years experience in sensor development in a wide range of fields from biomedical to geological. He is the inventor of the SFAI technique and has 20 patents and three R&D100 awards.
 - Hired postdoc at the beginning of this year: Blake Sturtevant, recently graduated PhD in Acoustics and Materials Science. His specialty is piezoelectric materials with high temperature stability.
- Selected for one of the two technical presentations for the New Mexico Office of Recovery and Reinvestment leaders visit at LANL, Mar 30, 2010, represented by former NM governor Toney Anaya.

- Coordinating the work performed by the team.
- Coordinating and mentoring the newly hired postdoc.
- Monthly checks on budget situation.
- Constant monitoring of work performed and future directions.
- Spending according to plan. Fluctuations are due to a slow start, and later on due to major equipment acquisition.

Spend plan



- Theoretical modeling and algorithm development (rest of FY 2010 and FY 2011)
- Sensor geometry (rest of FY 2010 and FY 2011)
 - Investigate the best sensor geometry able to withstand adverse conditions of pressure, temperature, and corrosive media.
 - Optimize sensor geometry
 - Develop sensor for pressure determination
- Flow measurements and fluid composition (FY 2011)
 - Develop sensor component for flow measurements
 - Develop sensor component for fluid composition determination
- Temperature and pressure calibration (FY 2011)
 - Build multipurpose acoustical sensor to incorporate all desired measurements
 - Test at *in-situ* conditions characteristic to geothermal reservoirs
 - Perform calibration of multipurpose acoustic sensor

- Identified and acquired sensor materials that can withstand adverse conditions characteristic of EGS.
- Identified and acquired equipment necessary for the multipurpose acoustic sensor development.
- Initiated work on theoretical modeling and algorithm development for data analysis.
- Initiated work on sensor geometry.
- Solved problems related to high uncertainty determination of temperature
 - The natural resonance of the ‘pure compressional’ mode of the transducer can’t be used in temperature determination
 - However, lower vibrational modes can be used reliably.