Photo-Stimulated Luminescence Spectroscopy Stress Sensor for In-Situ Stress and Behind Casing Cement Integrity Measurement

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Presentation Outline

- Project background
- Technical approach
- Results to date
- Summary and potential path forward

Project Overview: Goals and Objectives

In Situ Stress Measurement

- Existing *in situ* stress measurement methods are either complex to implement or overly interpretive
  - Minifracs
  - Borehole imaging (breakouts)
  - Overcoring
  - Sleeve fracturing

Cement Stress Measurement

- No direct measurements of cement stress behind casing made in field today
  - Permanent state of health monitoring needed
  - Field research tool for better understanding of cement loading

Goal - Adapt previously demonstrated method for measuring stress in ceramic materials to develop:

1) Borehole in situ stress sensor <u>and</u>
2) Cement stress condition sensor

Benefit to the Program

Benefits –

1) Characterize in situ stress magnitude and direction
    - Simpler implementation
    - Better directional resolution
2) Directly measure cement stress
    - Utilize standard fiber behind casing methods
    - Does not depend on mechanical coupling of sensor to cement

Background - Issues with Borehole in situ Stress Measurements

- Hydrofrac methods
  - Conventional interpretation of test possible only if borehole axis aligned with one of major principal stress axes
  - Borehole axis must be in induced fracture plane (best for vertical wellbores)
  - Typically assumes linear elastic, homogeneous rock properties to determine in-plane principal stresses
  - Pre-existing fractures near wellbore can produce erroneous interpretation of test results

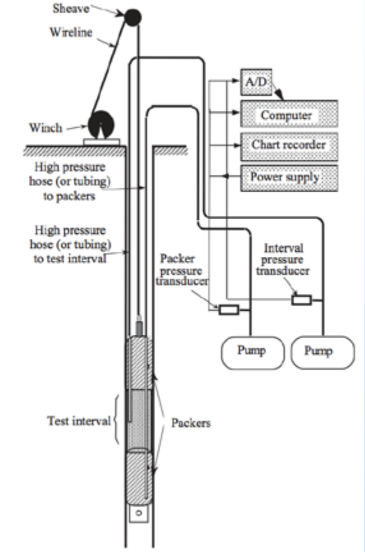
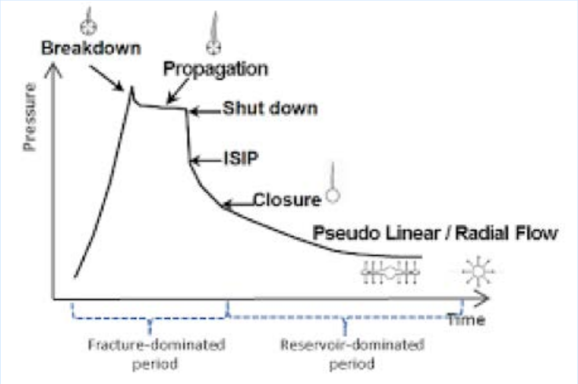


Fig. 1. Typical HF test equipment setup.

Haimson et al, 2003



Issue with Overcoring Stress Measurements

- Operation can be complex to implement and involves mechanically complex equipment
- Requires precise mechanical engagement with pilot hole wall
- Depth limited
  - Claims that can be done up to 2 km, but only done in field up to 1 km

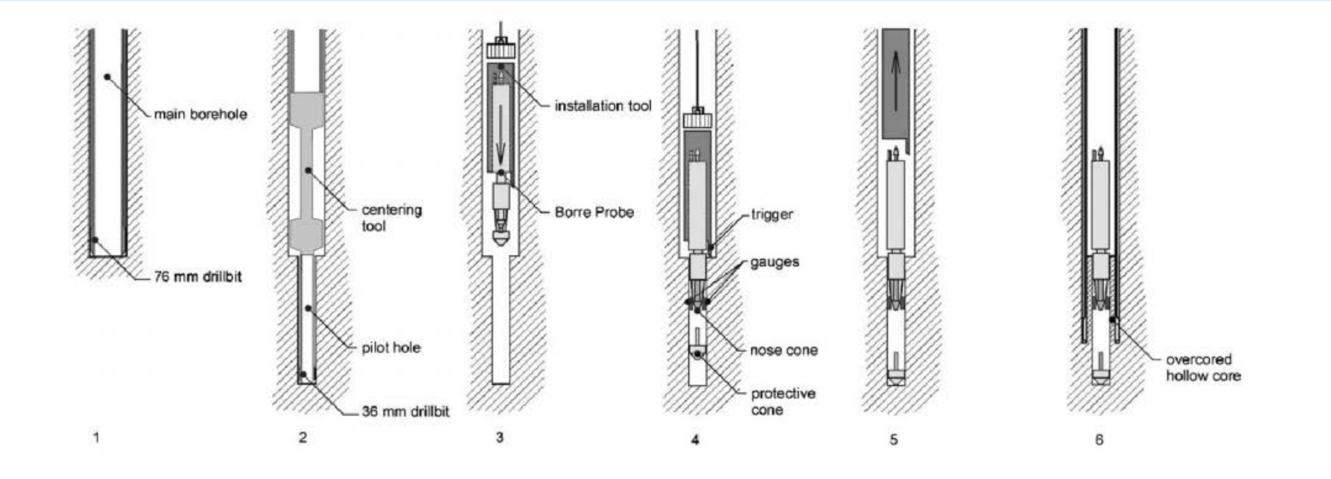
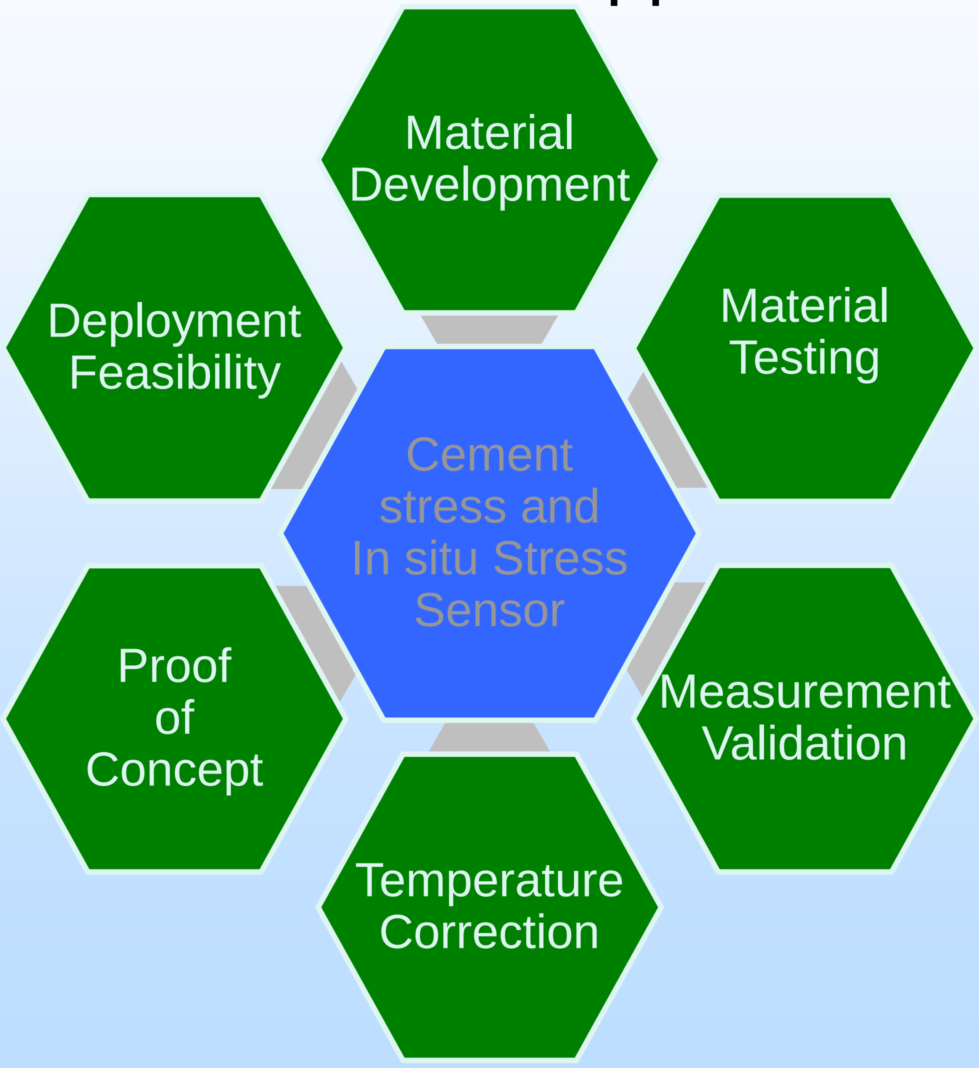


Figure 1: General steps in overcoring illustrated by the Borre probe (from Hakala et al., 2003).

Deformation Gauge

Technical Status

Technical Approach

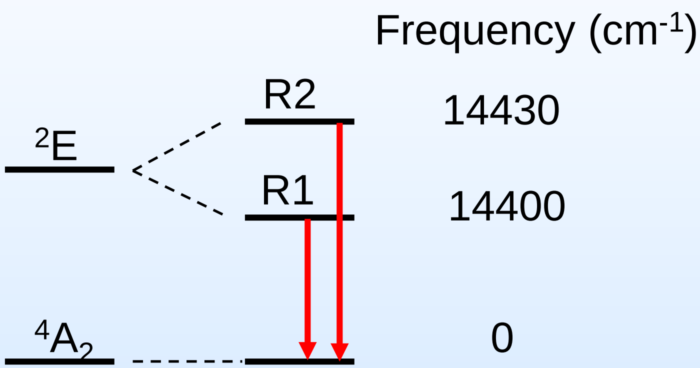


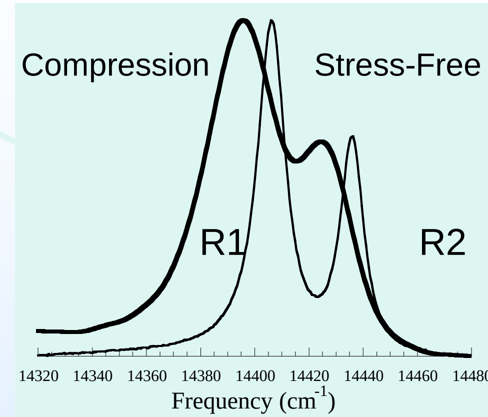
Project Organization

- ORNL - Lead
  - Develop and characterize stress sensing material
  - Develop temperature compensation approach
- NETL
  - Evaluate market and performance impacts of alumina doping of API Cements
- SNL
  - Evaluate feasibility of deploying stress sensing cement
- LBNL
  - Evaluate feasibility of measurement through fiber and deployment
  - Compare PS measurement to fiber interferometric measurement
- Reno Refractories – Industry Participant

Basis for PSLS Stress Sensing

Luminescence of Cr^{3+} in Al_2O_3





The peak shift gives the mean hydrostatic stress in randomly-oriented alumina.

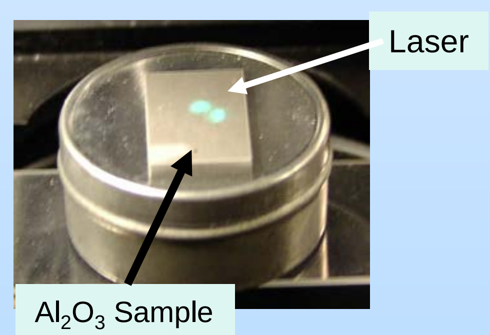
Stress changes the distance between the ion and the surrounding crystal which causes the energy levels to shift:

$$\Delta\nu = \Pi_{ij} a_{ik} a_{jl} \sigma_{kl}$$

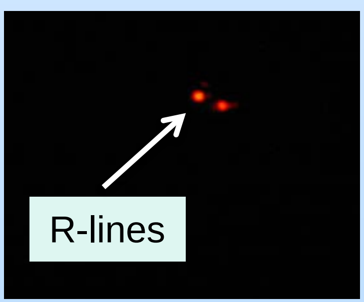
For isotropic polycrystalline α-Al_2O_3:

$$\Delta\nu = \tfrac{1}{3}(\Pi_{11}+\Pi_{22}+\Pi_{33})(\sigma_{11}+\sigma_{22}+\sigma_{33}) = \Pi_{ii}\sigma_h$$

Incident Laser Wavelength: 515 nm



With Filter: Emission at ~690 nm



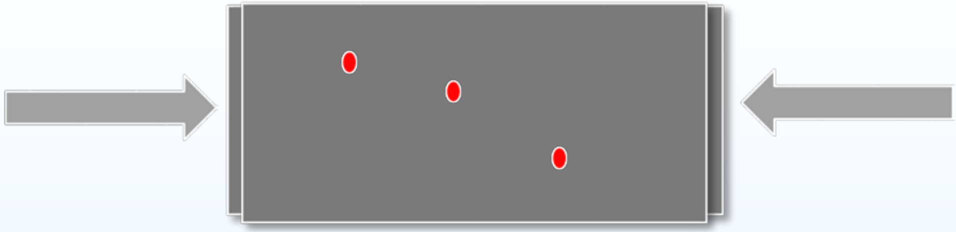
Material Development Overview

- Characterize alumina powders
- Develop cement mixing procedures
- Fabricate cement samples
- Characterize cement PS uniformity

Stress sensing material performance criteria

1. R1 and R2 peaks should be within 0.01 cm^{-1} for uniform stress state
2. Stress transfer between cement matrix and alumina must be adequate to capture minimum stress level
3. Grout must be slightly expanding to react displacement of borehole wall
4. Intensity of R-lines should be adequate to perform measurement in < 1 minute

Measurement Uniformity Criterion

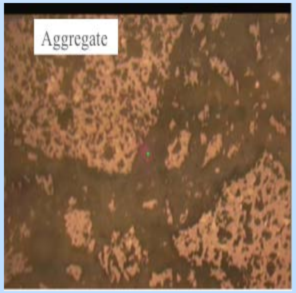


<u>Factors affecting measurement uniformity</u>

- Distribution of alumina in matrix
- Cementing of alumina to matrix
- Microscopic features
- Residual stresses in alumina

$$\Pi_{ii} = 7.62 \frac{cm^{-1}}{GPa}$$ for polycrystalline Alumina

Target stress resolution is 1 MPa



1st Powder Measurements – Small Spot Diameter

Standard deviation and intensities of commercially available alumina powders for 10 µm spot size

Powder Description	Particle Size (um)	Spot Size	STD (cm^-1)	Peak Width (cm^-1)	Intensity (counts/s)
Alcoa A2 Unfired	150	10 um	0.0416	9.7270	27212.90
Inframat 200 nm @ 1200°C	0.2	10 um	0.0528	9.4101	45291.20
Inframat 200 nm @ 1400°C	0.2	10 um	0.0574	9.4329	29933.80
Alcoa A2 fired @ 1400°C	150	10 um	0.0911	9.8466	39840.60
Inframat 35 um	35	10 um	0.0930	9.4645	744.30
Type DX 0.3 um	0.3	10 um	0.0965	9.0934	185.13
Inframat 20 um	20	10 um	0.0977	9.5480	4733.30
Inframat 200 nm @ 800°C	0.2	10 um	0.1008	10.1625	4046.38
Type N 0.3 um	0.3	10 um	0.1025	9.3237	122.29
Inframat 200 nm	0.2	10 um	0.1348	12.6365	8336.12
SigAld 10um	10	10 um	0.1434	10.3200	13770.60
Inframat 12 um	12	10 um	0.1501	11.4908	3073.11
Type DX 1 um	1	10 um	0.1543	9.5016	993.38
Inframat 150 nm	0.15	10 um	0.1547	12.9824	9759.59
Inframat 15 um	15	10 um	0.1600	10.4740	1052.95
US Research Nanomaterials 80 nm	0.08	10 um	0.2062		
Inframat 5 um	5	10 um	0.2072	12.6365	4707.27
Inframat 25 um	25	10 um	0.2654	9.9683	1508.66
Inframat 10 um	10	10 um	0.3162	11.7383	5864.28
Inframat 200 nm @ 600°C	0.2	10 um	0.3560	11.4219	6339.77
Inframat_1 to 1_4 mm		10 um	0.4203	12.8563	4452.89
Inframat 200 nm @ 1000°C	0.2	10 um	0.5726	10.2499	3069.41
Inframat 3 um	3	10 um	0.7222	12.9111	5015.05
Alfa Aesar 1um	1	10 um	0.8741	10.5240	2175.00

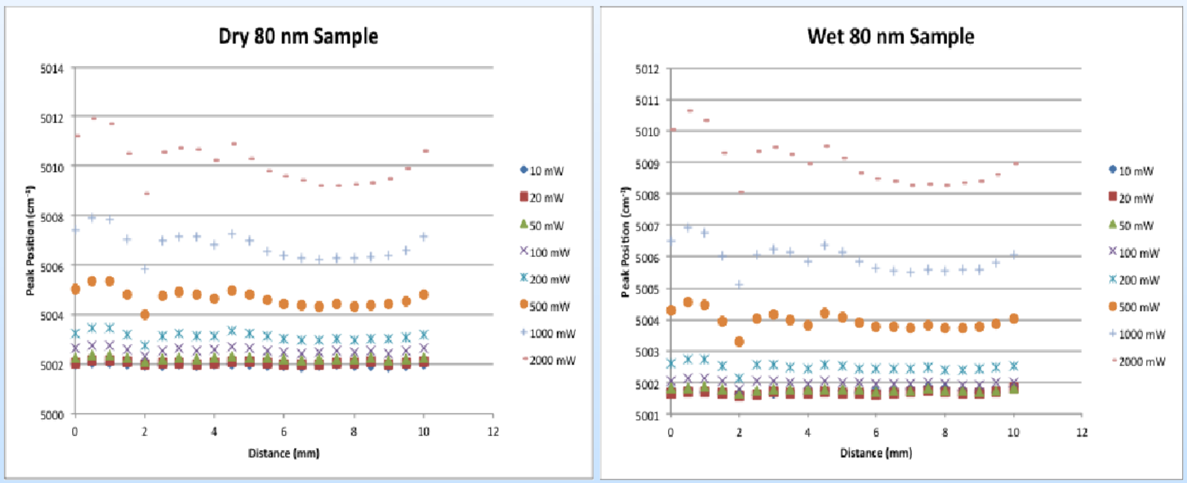
2nd Powder Measurements – 1 mm Spot Diameter

Standard deviation and intensities of commercially available alumina powders for 1 mm spot size

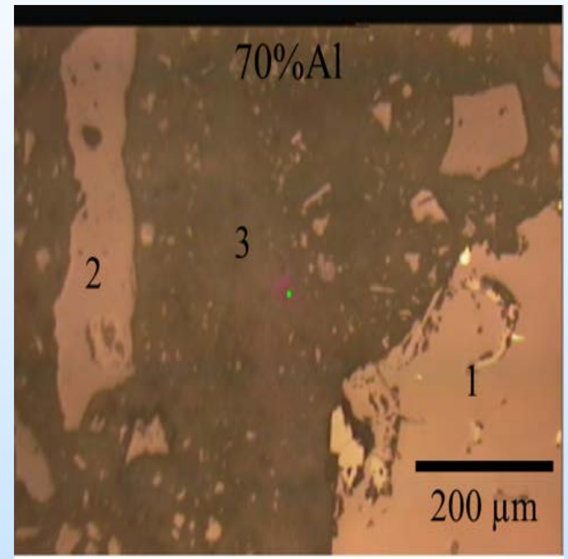
Powder Description	Particle Size (um)	Spot Diameter	STD (cm^-1)	Peak Width (cm^-1)	Intensity (counts/s)
Sigma Aldrich 10 um	10	1mm	0.0055	10.2788	2852.63
Inframat 200 nm @ 1000°C	0.2	1mm	0.0124	9.7918	1151.45
Type N 0.3 um	0.3	1mm	0.0127	9.4725	102.43
Inframat 35 um	35	1mm	0.0130	11.6449	263.16
Inframat 200 nm @ 1400°C	0.2	1mm	0.0173	9.2901	12329.90
Inframat 200 nm @ 600°C	0.2	1mm	0.0178	10.5327	1046.06
Inframat 25 um	25	1mm	0.0182	9.9849	654.75
Inframat 200 nm @ 800°C	0.2	1mm	0.0198	9.9146	1160.60
Inframat 15 um	15	1mm	0.0252	10.1887	185.54
Inframat 40 nm	0.04	1mm	0.0322	12.5234	1641.16
Alfa Aesar 1 um	1	1mm	0.0329	10.2526	672.90
Inframat 200 nm @ 1200°C	0.2	1mm	0.0370	10.2630	1353.84
Inframat 10 um	10	1mm	0.0410	12.0871	1538.6399
Inframat 12 um	12	1mm	0.0421	11.0832	624.99
Inframat 20 um	20	1mm	0.0524	10.1162	723.68
Research Nanomaterials 80nm	0.08	1mm	0.0530	11.1269	12146.36
Inframat 200 nm Control	0.2	1mm	0.0542	11.7894	758.22
Inframat 3 um	3	1mm	0.0664	12.0871	745.35
Type DX 0.3 um	0.3	1mm	0.1496	9.4013	110.12
Type DX 1 um	1	1mm	0.1601	9.5419	215.09
Inframat 5 um	5	1mm	0.1648	12.2630	874.08
Inframat 100 nm	0.1	1mm	0.1921	12.9499	653.57

Laser Power Effect on Piezospectroscopic Response

- Higher laser power levels have larger measurement standard deviations
- Likely due to material heterogeneity and thermal conductivity variation away from illumination point



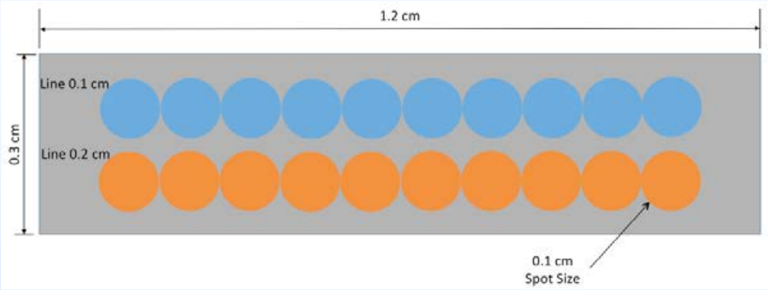
R2 peak position measured for 1 mm spot size at different locations along a 10 mm line segment on dry (left) and wet (right) API class H cement sample with 33.3% 80 nm alumina solid volume fraction for different laser power magnitudes



Mixing of material is important for producing uniform response!

Spatial Variation of Peak Position for Cast Samples

2D spatial scan locations

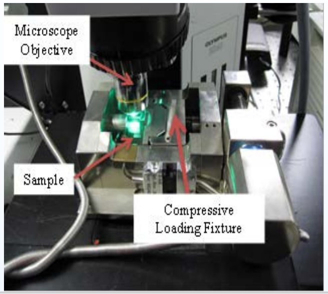


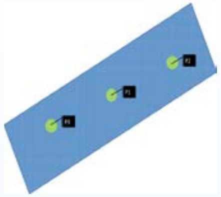
Average R2 Peak Position and Standard Deviation for Samples Cast with Different Alumina Powders

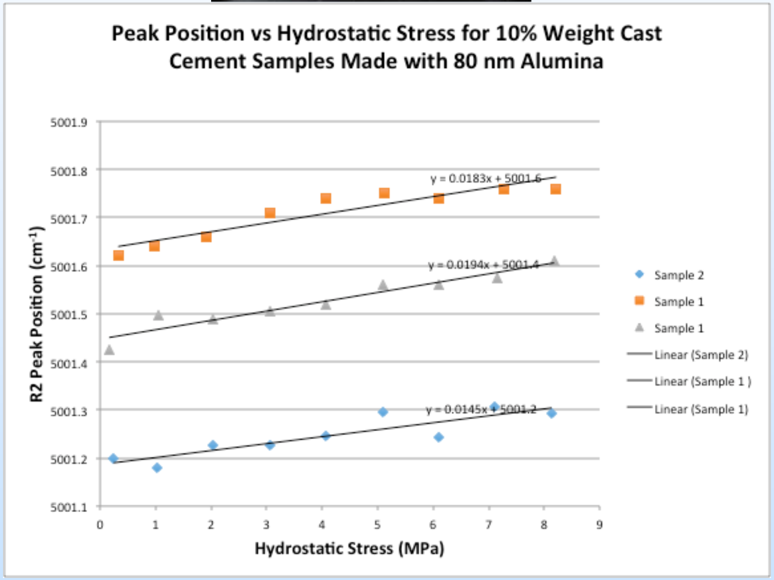
Composition	Avg. R2 PP (cm^{-1})	STD PP Position (cm^{-1})
300 nm @ 30 wt%	14434.7653	0.027286038
80 nm @ 30 wt%	14434.28727	0.03178992
Secar71	14434.701	0.037983206
80 nm @ 5 wt%	14434.23765	0.055967721
35000 nm @ 5 wt%	14433.84281	0.088187525
ThermaLock	14434.19393	0.241981507
5000 nm @ 5 wt%	14433.92162	0.272124763

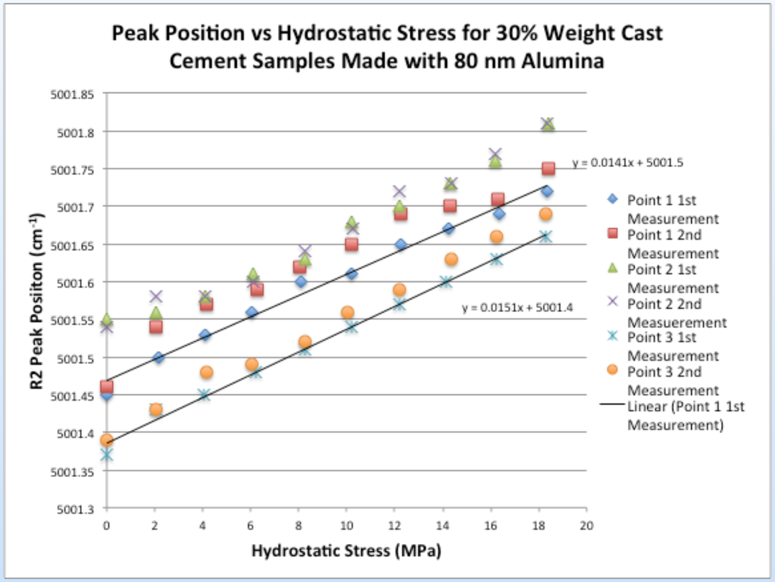
- Spatial variability of peak position for cast samples comparable to powder values for small mean particle size
- There appears to be larger variation for larger mean particle sizes

Uniaxial Compression Test Piezospectroscopic Response



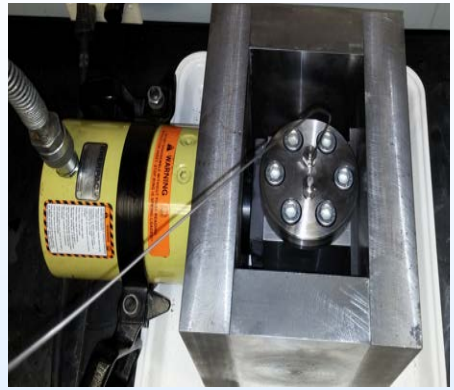


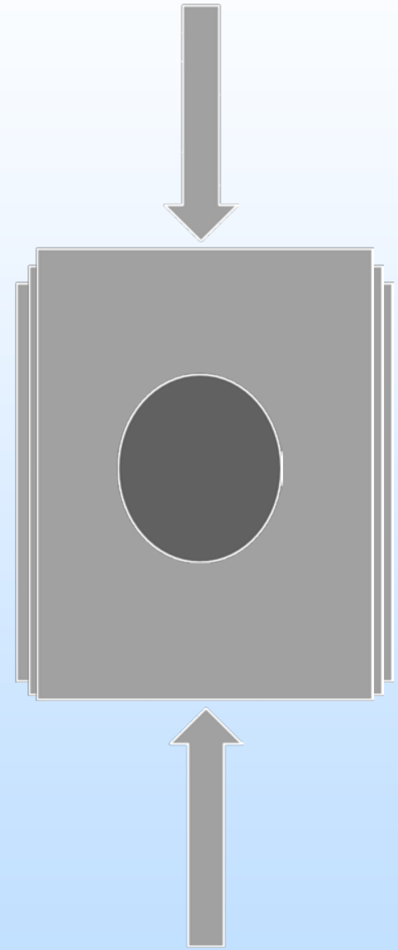




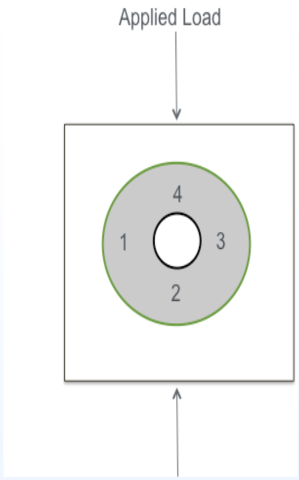
- Slopes of curves (PS coefficient) are reasonably consistent
- Good response even in lower alumina concentration cement
- PS coefficient indicates that there is a stress concentration effect with nanoparticles

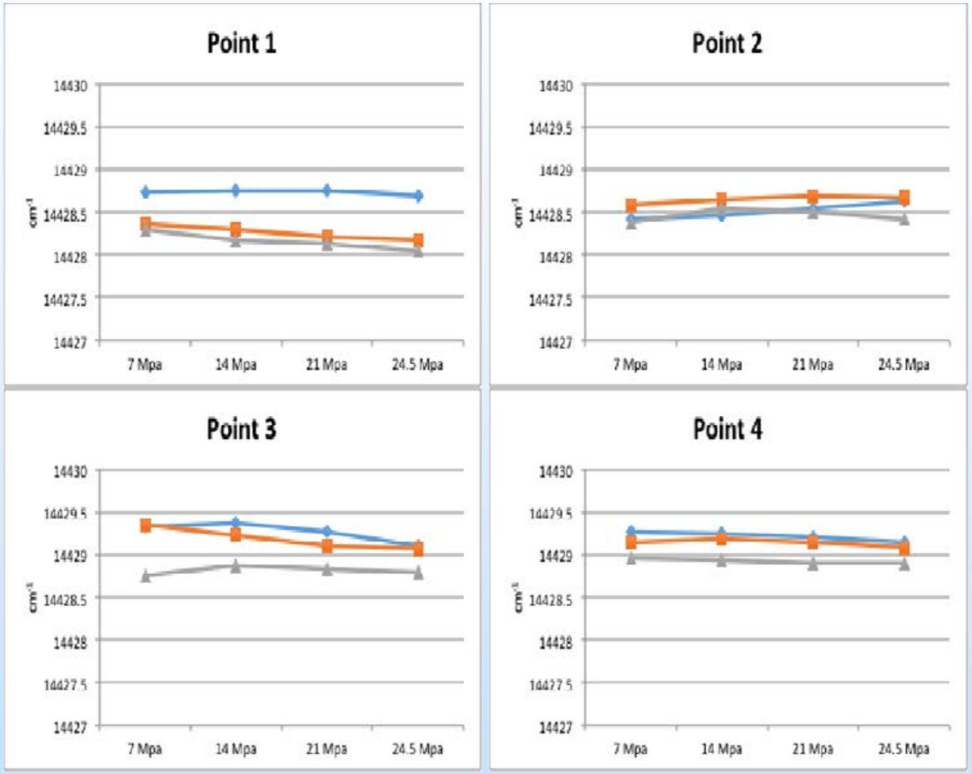
In Situ Stress Sensor Proof of Concept Laboratory Test Setup





Proof-of-concept experiment results





R2 peak position vs hydraulic press pressure at different measurement locations

- Decreasing peak position corresponds to increased compressive stress
- Expect compressive stress of points 1 and 3 to increase with increasing load and be 3x larger than change of points 2 and 4
- Trends not consistent
- Temperature effects not accounted for

Results inconclusive!

Accomplishments to Date

- Characterized suitability of large number of α-Alumina powders for use as dopants
- Identified numerous factors that affect piezospectroscopic behavior of doped cements
- Developed API Class H and Portland Cement formulations that exhibit reasonably consistent PS response
- Have evaluated deployment feasibility of ‘smart’ cement

Synergy Opportunities

– ‘Smart’ cement could help understand actual loads experienced by wells during operation
– Field application of stress measurements using developed material could be associated with a number of recently created field demonstration sites

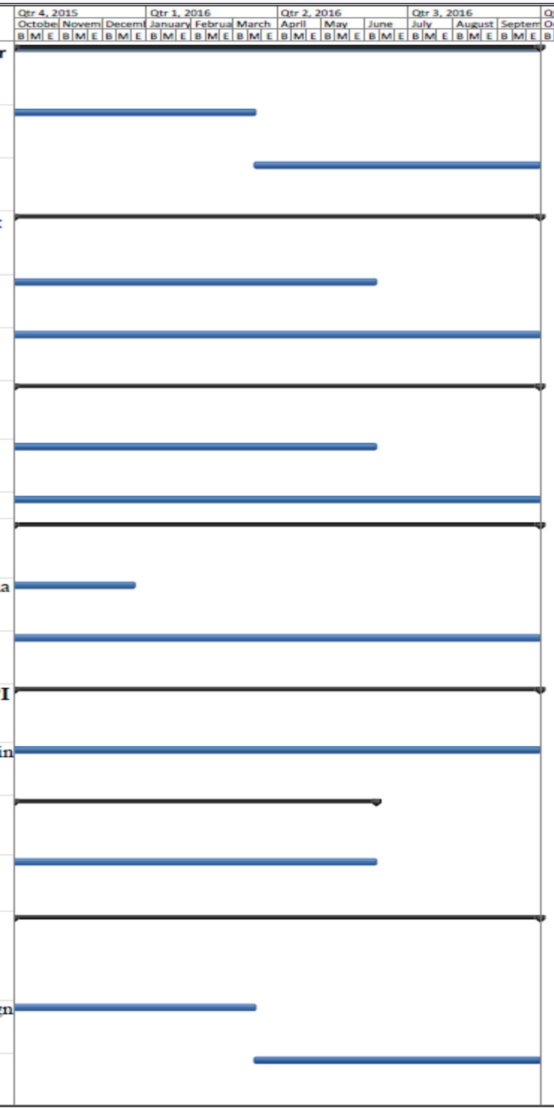
Summary

- Progress has been made developing a novel stress sensing material for borehole applications
- Alumina powder can exhibit PS variability that limits use as a sensor so powder selection and preparation is important
- Mixing of cement/alumina important for producing homogeneous composite
- Power level of laser stimulation can affect measurement
- Preliminary stress sensing cement samples exhibit initial load transfer issues but excellent linearity when stress transfer begins
- Results to date are encouraging and indicate that material can be used for stress measurement applications with further development

Appendix

Gantt Chart

ID	Task Name
1	**Task 1 Develop and test in situ stress sensor material suitable for downhole use**
2	Milestone 1 – Performance specification for field deployable material characteristics.
3	Milestone 2 – Performance characterization of stress sensor material.
4	**Task 2 Assess in situ stress sensor plug material field deployment feasibility**
5	Milestone 3 – Performance requirements for cementing and downhole casting.
6	Milestone 4 – Feasibility assessment of casting plug material downhole and plug drilling operation.
7	**Task 3 Conceptual engineering for deploying a luminescence spectroscopic stress sensor**
8	Milestone 5 – Performance requirements for fiber deployment system.
9	Milestone 6 – Conceptual design of fiber deployment tool.
10	**Task 4 Develop low Alumina cement formulation for wellbore integrity cement stress monitoring**
11	Milestone 7 – Define baseline cements that will be modified with Alumina doping.
12	Milestone 8 - Fabricate and test cement formulations that meet stress measurement requirements.
13	**Task 5 Evaluate market and performance impact of doping API class cements with Alumina**
14	Milestone 9 – Determine viability of using cements doped with Alumina in wellbore construction applications.
15	**Task 6 Develop temperature compensation method for stress measurement**
16	Milestone 10 – Develop temperature compensation approach for stress measurement.
17	**Task 7 Laboratory based comparison of photo-stimulated luminescence spectroscopic stress measurements with fiber-optic interferometric measurements.**
18	Milestone 11 – Specify fiber optic strain sensors to be deployed and design laboratory experiment.
19	Milestone 12 – Complete strain measurement of cement response using embedded fiber optic strain measurement system.



Bibliography

- Y. Polsky, R.J. Daniels, M. Lance, and C. Mattus, “Development of a Novel Stress Sensor for In Situ Stress Measurement”, *Proc. 41st Workshop on Geothermal Reservoir Engineering*, Stanford Univ., Stanford, CA, February 22-24, 2016.
- Other manuscripts currently in preparation