

Design Optimization of Piezoceramic Multilayer Actuators for Heavy Duty Diesel Engine Fuel Injectors

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**Project ID:
PM001**

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Overview

Timeline

- **Start – Oct 2008**
- **Finish – Sept 2011**
- **~ 50% Complete**

Budget

- **Total project funding**
 - DOE – \$900K
- **Funding received in FY09**
 - \$300K
- **Funding so far for FY10**
 - \$239K



Barriers

- **Advanced Combustion Engine:**
 - ✓ Increasing efficiency while reducing pollutant formation
 - ✓ Controls for lean-burn combustion engines
- **Propulsion Materials**
 - ✓ Materials issues impacting high efficiency engines using conventional & alt. fuels

Target

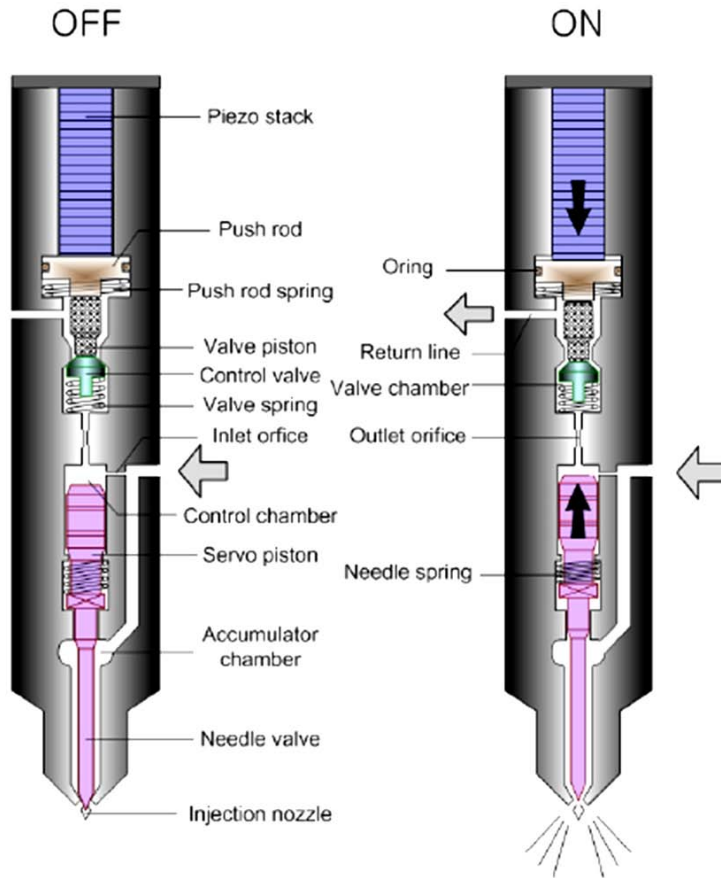
21CTP: Enable heavy duty diesel engine thermal efficiency of 55% by 2018
ACE: Improve commercial vehicle fuel economy at least 20%

Partners

- **Cummins Inc.**
- **Kinetic Ceramics, Inc.**
- **EPCOS**



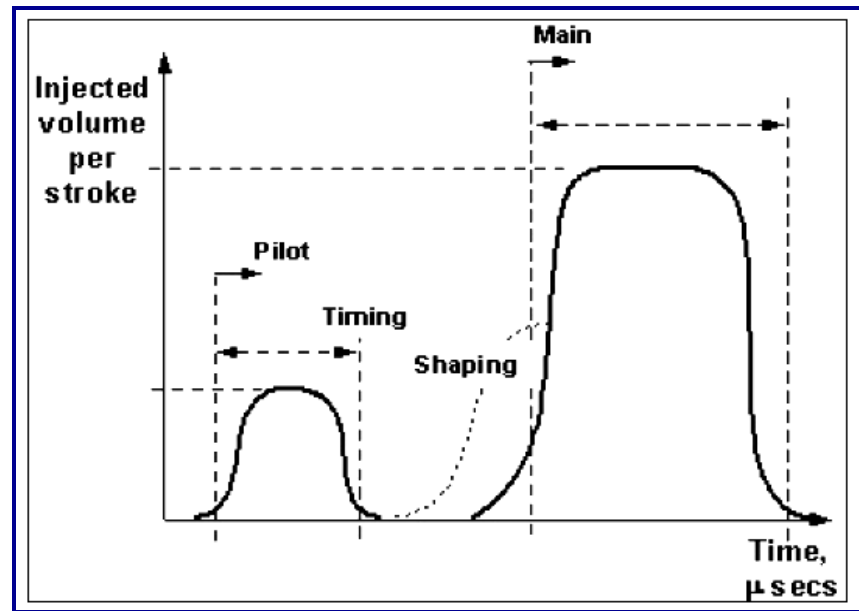
Piezoactuation Enables Precise Rate Shaping and Control of Fuel Injection Timing and Quantity



Piezostack used in a fuel injector

(Kim et al, SAE 2005-01-0911)

- Spray control of solenoid fuel injectors imprecise and limited
- Piezo fuel injector can improve fuel efficiency and reduce NOx emission and noise



**Applied voltage: <200V; Frequency: 200Hz;
Displacement: 80 μm ; Force: 3000N;
Temperature: <150°C; Lifetime: 1 million miles**

Objectives

- **Generate required mechanical data on PZT piezoceramics under high electric field and high temperature.**
- **Conduct accelerated fatigue and dielectric breakdown testing for PZT piezoceramics using piezodilatometer.**
- **Perform accelerated electric cyclic fatigue test on commercially available multilayer piezoactuator stacks.**
- **Identify degradation mechanisms of multilayer piezoactuator stacks after accelerated electric fatigue test.**

Milestones

Sept 2009: Measure and compare piezoelectric and mechanical reliabilities of tape-cast and pressed PZT piezoceramics (completed).

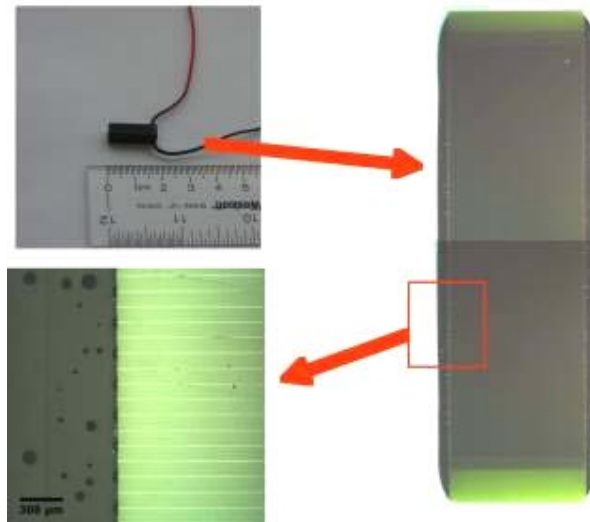
Sept 2010: Reliability study on identified PZT piezoceramics in controlled application environments.

Sept 2011: Life prediction and testing of optimized multilayer PZT piezoactuator stack.

Approach

- Measure and compare mechanical properties of PZT piezoceramics that are candidates for use in piezoactuators.
- Develop accelerated test methods that enable rapid and reliable qualification of piezoactuators.
- Measure response and reliability of piezoactuators and link to measured piezoceramic properties.
- Adapt to optimized fuel injectors for Heavy Duty Diesel engines.

PMLAs have a macroscale and a microscale

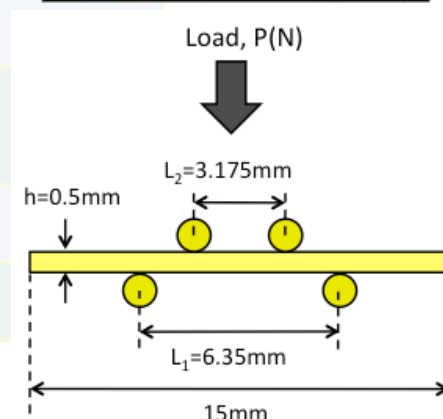
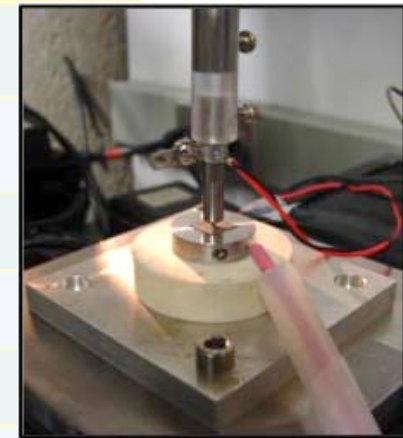


PMLAs would be used inside a fuel injector

Accomplishments

- Mechanical strength of piezoceramics PZT-5A type was measured and evaluated using ball-on-ring and semi-articulated four-point bending setups

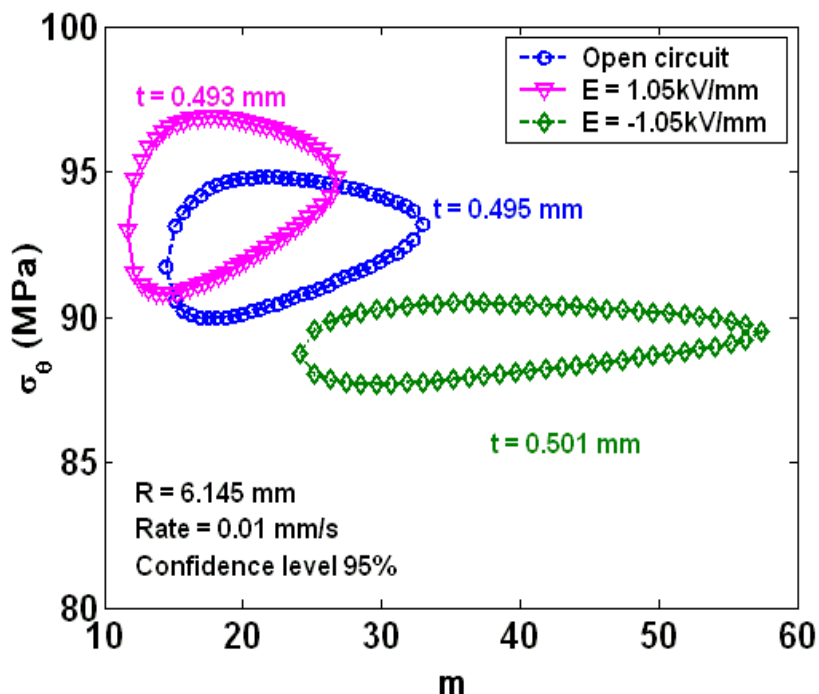
Studies	Testing conditions	KCI: As-extracted	KCI: As-received
Strength scaling	BoR: Polymer-ceramic	13	
	BoR: Steel-steel	18	14
	4-point bend	19	13
Electric effect: BoR	Open circuit		14
	E_c		14
	$-E_c$		14
Temperature effect: 4-point bend	RT	19	13
	100°C	12	
	200°C	12	14



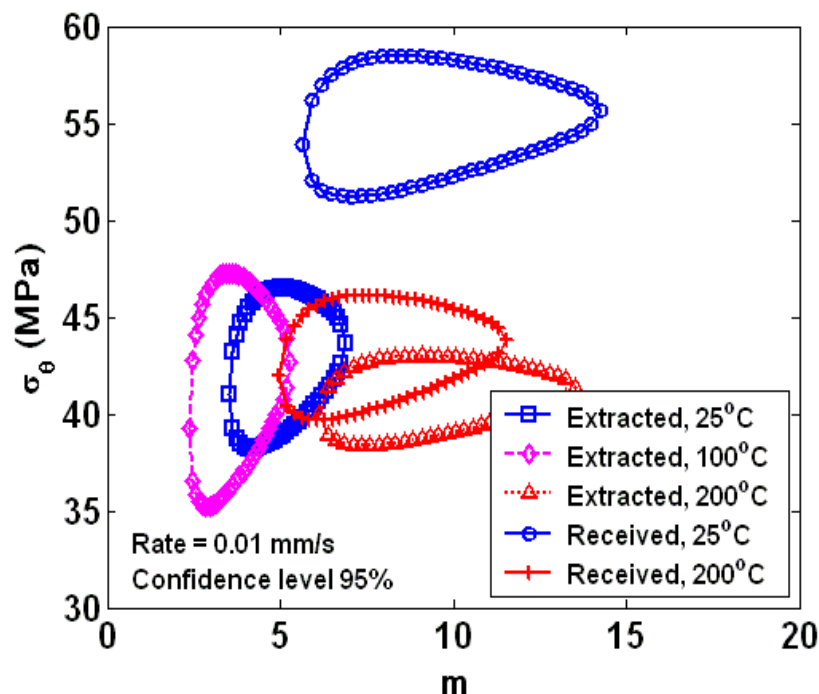
KCI pressed PZT ceramic was focused in FY09. As-extracted and as-received states of specimen were studied.

Accomplishments (continued)

- Mechanical strength depended on specimen states and testing configuration.
- Flexure strength exhibited variation upon electric loading, especially under negative field.
- Temperature effect was significant for as-received KCl PZT ceramic but not for as-extracted ones.



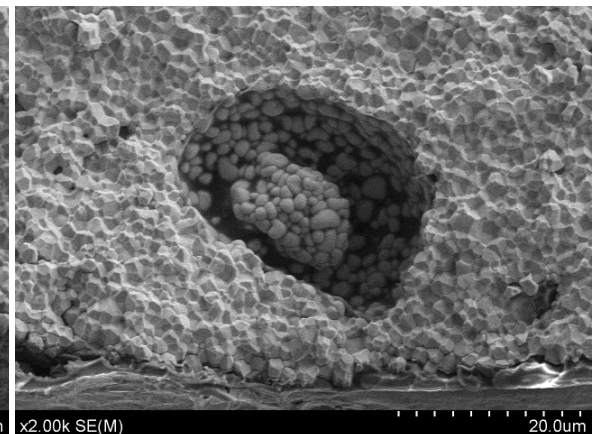
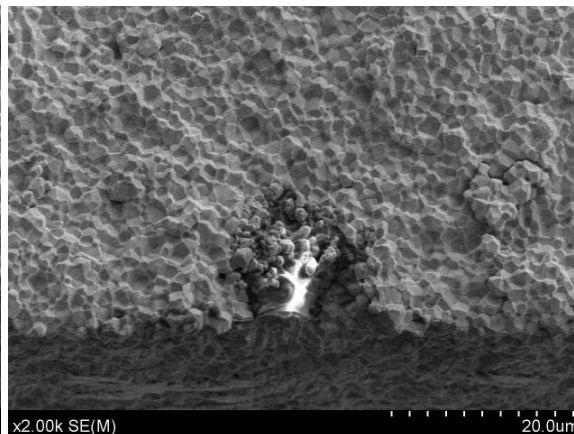
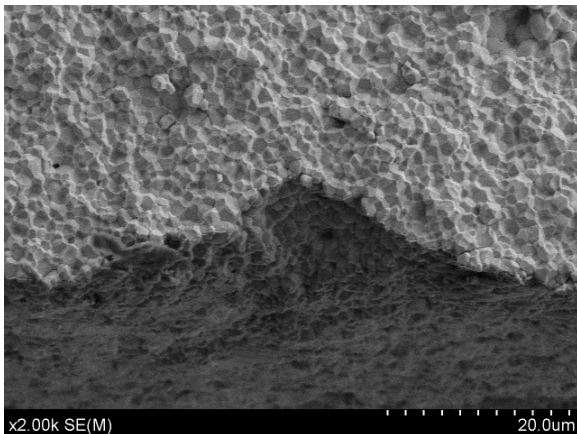
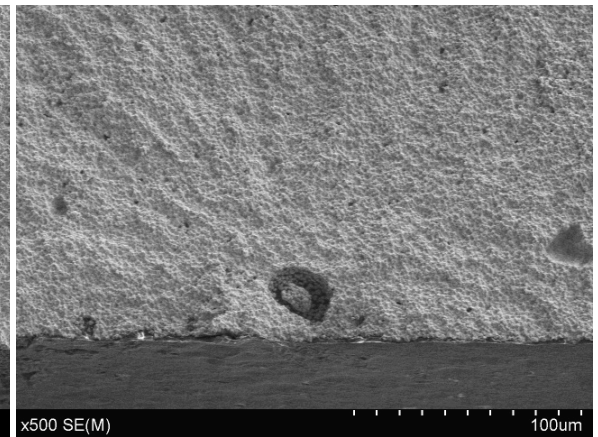
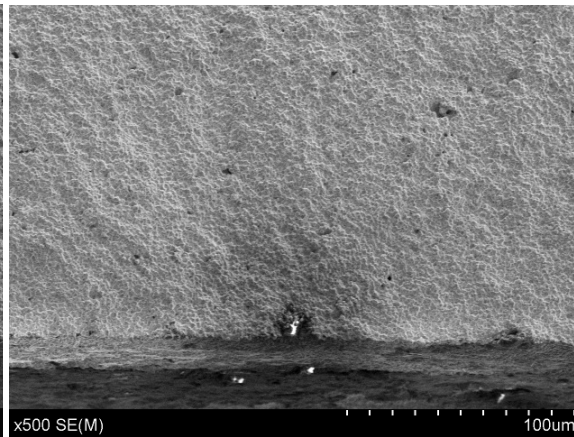
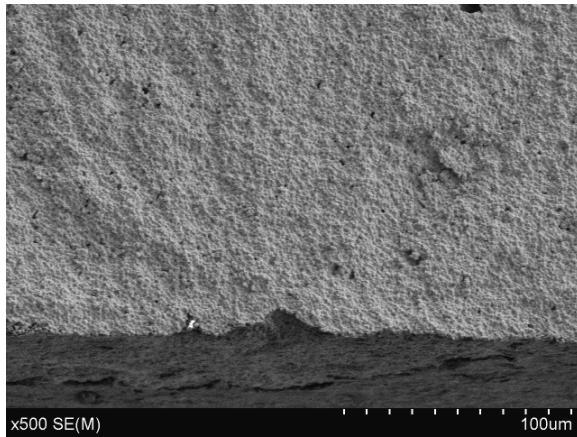
Electric field effect



Temperature effect

Accomplishments (continued)

- Volume and surface pores and agglomerates were observed to be the strength limiting flaws independent on test temperature and applied electric field state



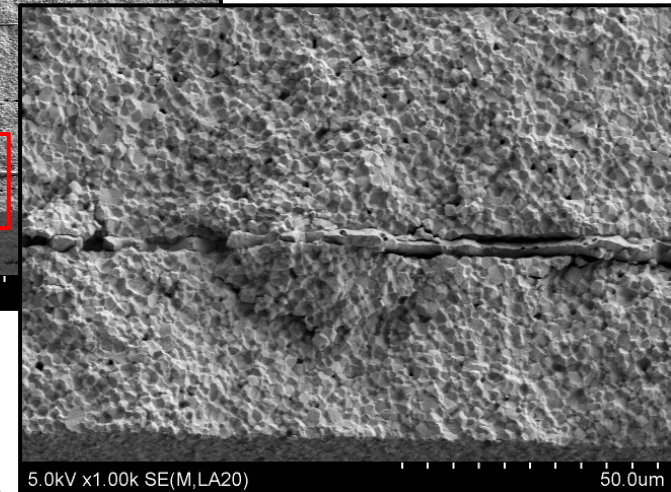
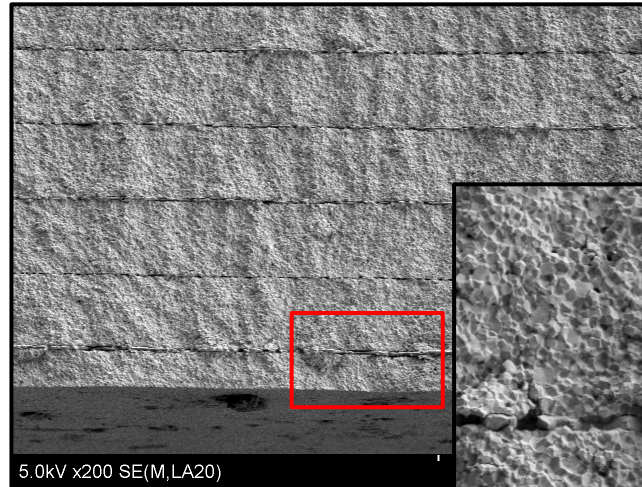
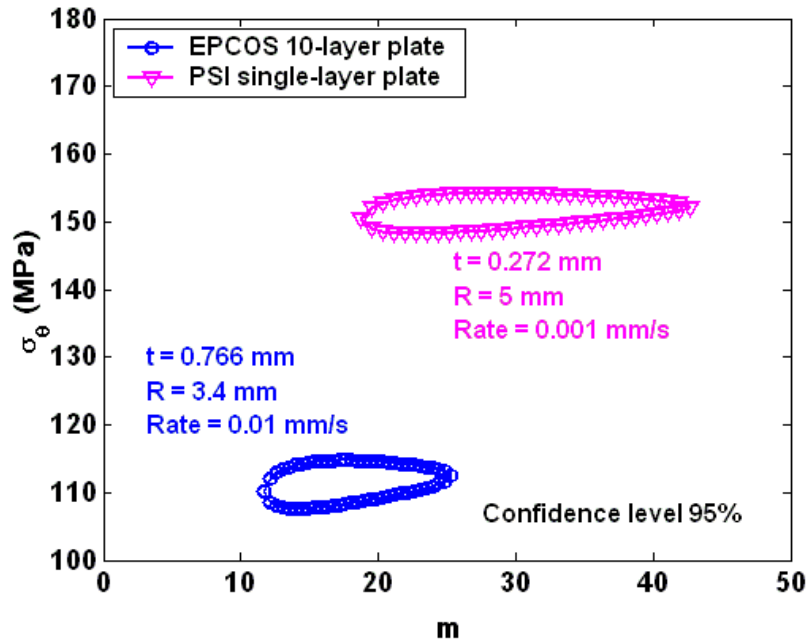
Surface pore

Surface agglomerate

Volume pore

Accomplishments (continued)

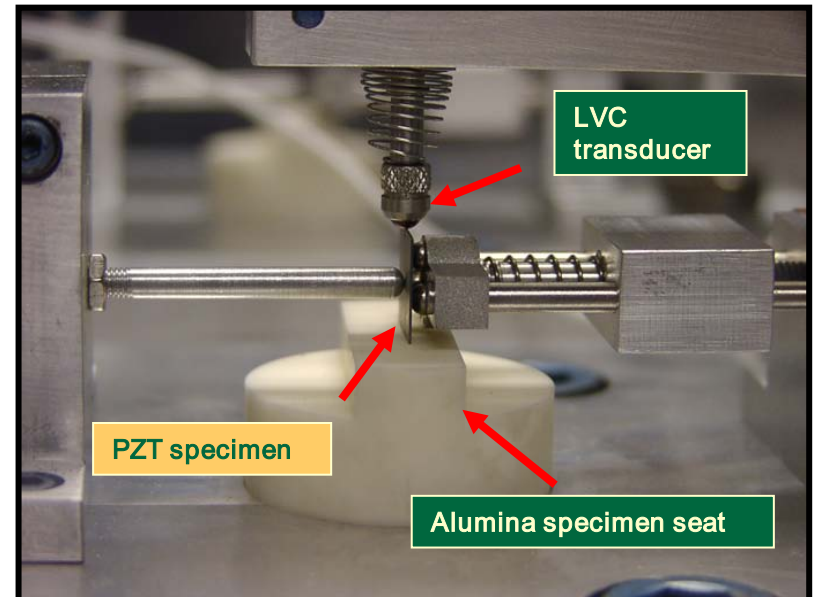
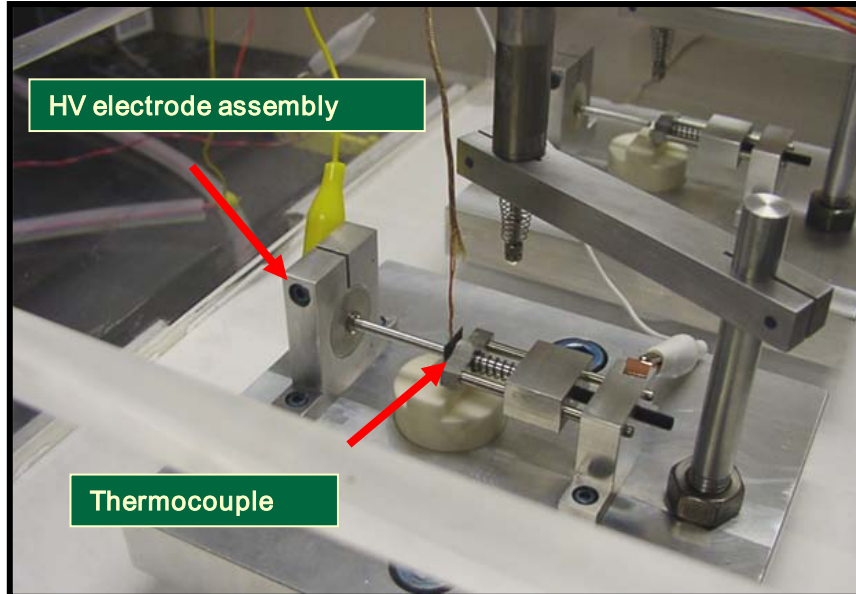
- Mechanical strength in Ball-on-Ring of EPCOS 10-layer PZT ceramic discs extracted from stacks was evaluated



- PZT plate specimens were based on the following sources:
 - ✓ Extracted from a EPCOS stack (AN0X8500b) also made from PZT5A type ceramic
 - ✓ Prepared on a PSI (Piezo Systems, Inc) PZT5A-4E sheet (tape-cast)
- Flexure strength depended on the specimen configuration and status of specimen tested.

Accomplishments (continued)

- A dual rod piezodilatometer enable evaluation of the accelerated electric fatigue of PZT ceramics under high driving field.
- Test procedures and data processing are being standardized using commercial software.
- Generated data will assist the root-cause failure analysis of PZT stacks after field tests.



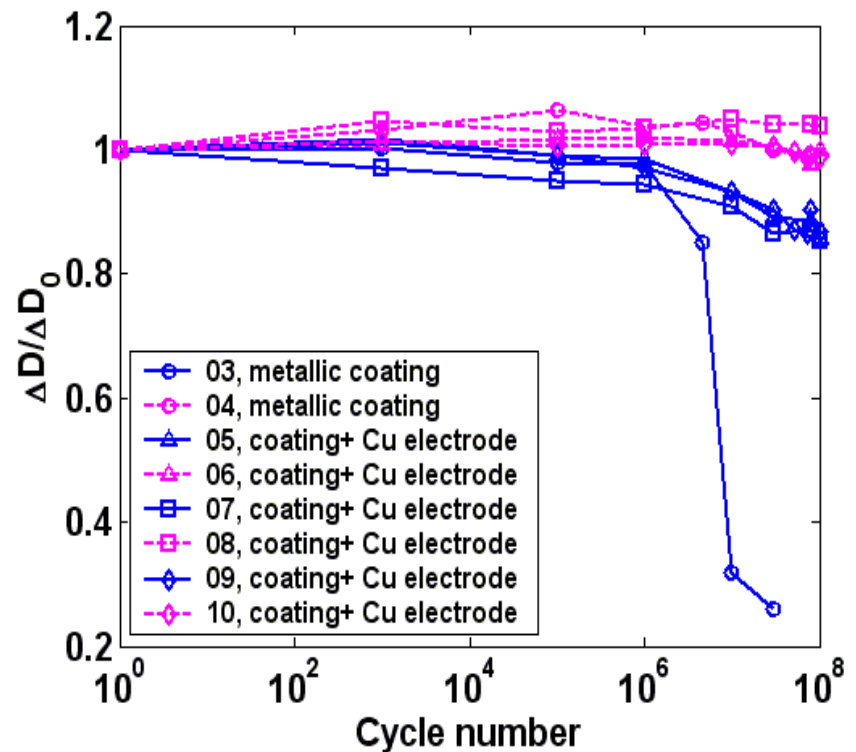
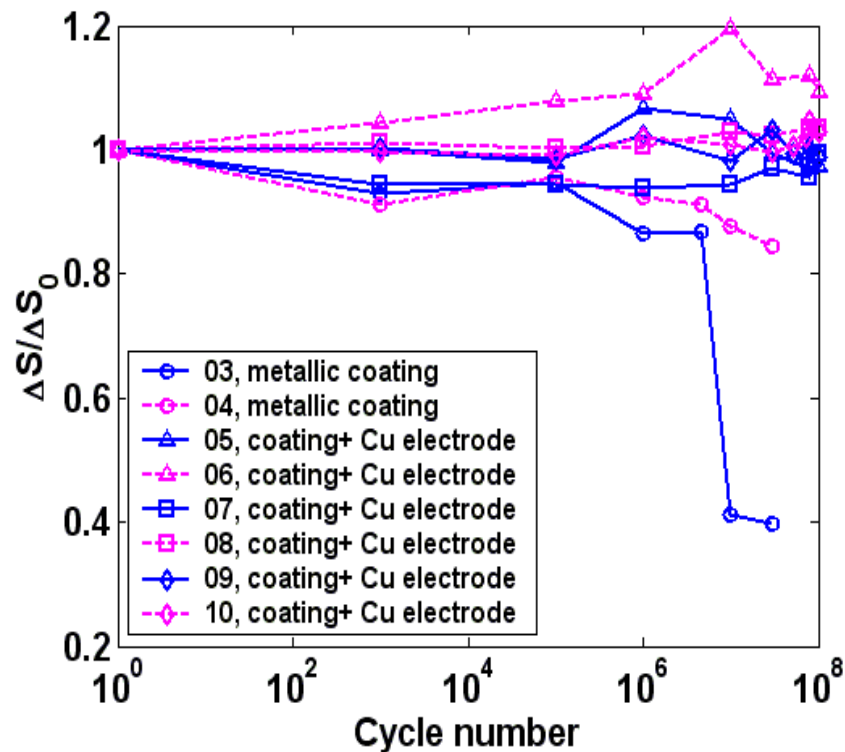
Accomplishments (continued)

- Electric fatigue responses of KCl PZT ceramic discs were studied.
- References (in magenta) were used during testing.

No	Thickness (μm)	Cu electrodes	Unipolar cycling: Vpk, Hz	Unipolar measurement: Vpk, Hz	Bipolar measurement: -/+Vpk, Hz
3	511	No	1,080; 200	1,080; 0.1	-/+1,080; 0.1
4	513	No	-	1,080; 0.1	-/+1,080; 0.1
5	486	Yes	1,020; 200	1,020; 0.1	-/+1,020; 0.1
6	480	Yes	-	1,020; 0.1	-/+1,020; 0.1
7	499	Yes	1,050; 200	1,050; 0.1	-/+1,050; 0.1
8	513	Yes	-	1,050; 0.1	-/+1,050; 0.1
9	513	Yes	1,080; 200	1,080; 0.1	-/+1,080; 0.1
10	476	Yes	-	1,080; 0.1	-/+1,080; 0.1

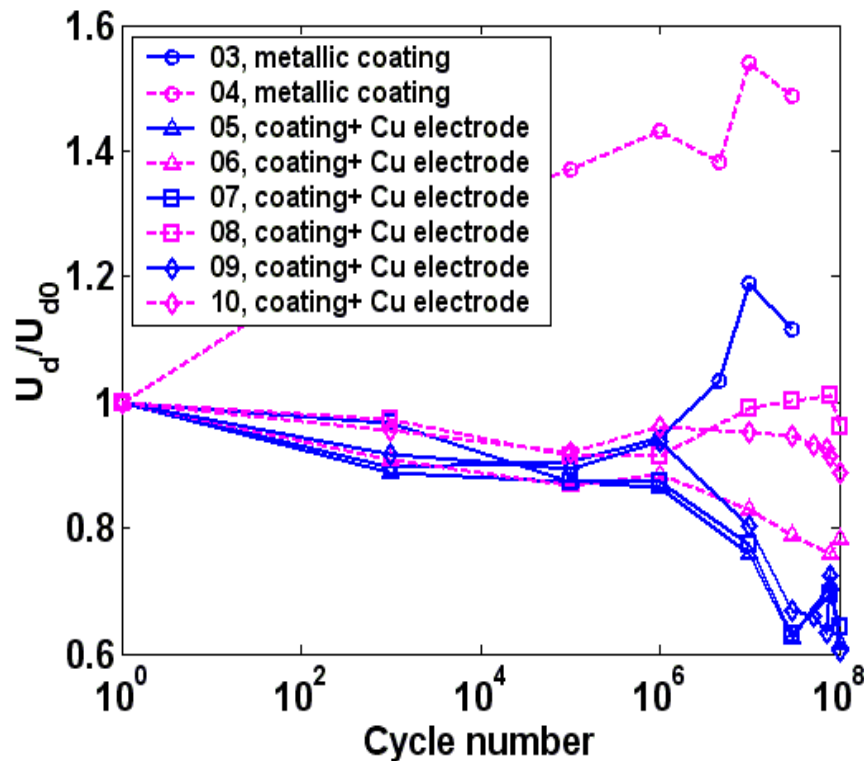
Accomplishments (continued)

- Quantities measured without Cu electrode decreased dramatically.
- Unipolar measurements for Cu electrode specimens revealed ~15% reduction in charge density, but no apparent trend observed for strain.

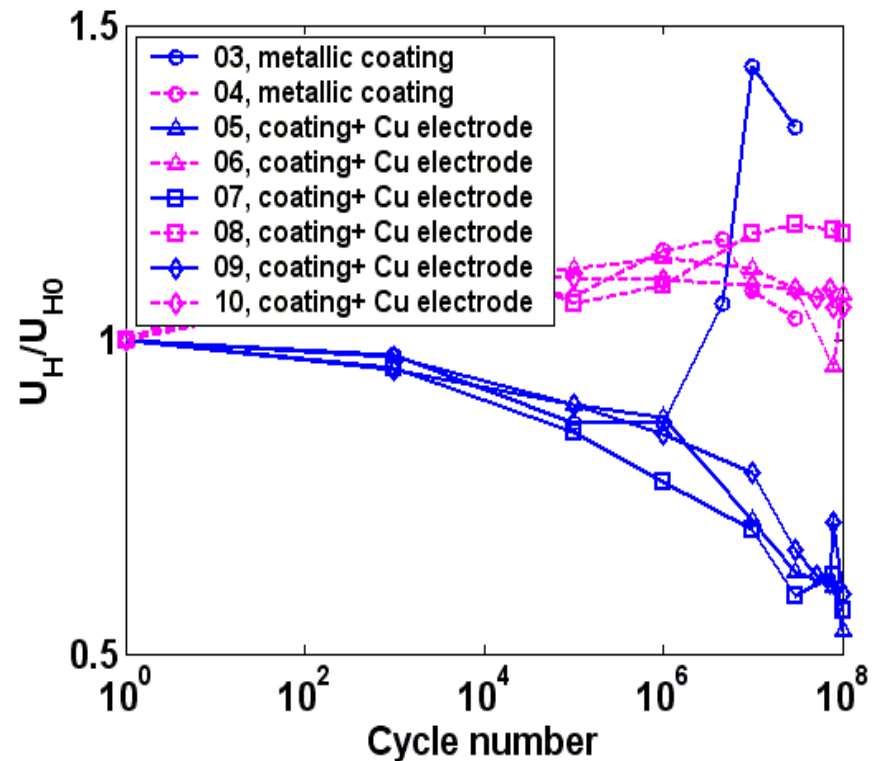


Accomplishments (continued)

- More than 30% reduction in piezoelectric and more than 40% in dielectric hysteresis were revealed by unipolar measurements for Cu electrode specimens.



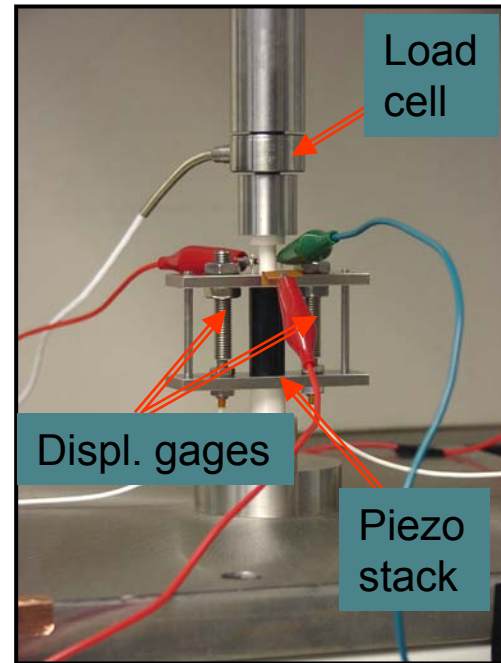
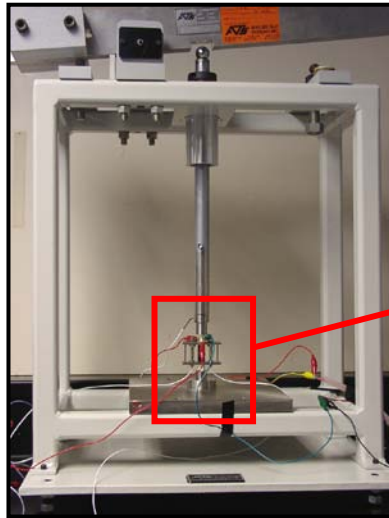
Piezoelectric hysteresis



Dielectric hysteresis

Accomplishments (continued)

- Accelerated electric fatigue facility was modified to accommodate special requirements of supplied PZT stacks from EPCOS and KCI.



Load and displacement
signal conditioners



LabView test control
& data acquisition



High voltage & high
frequency amplifiers

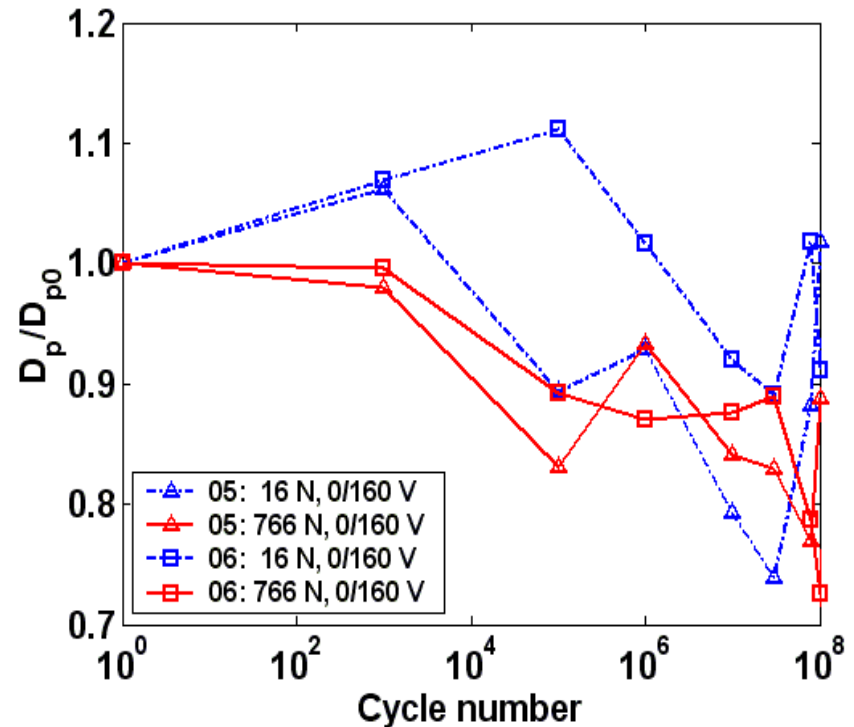
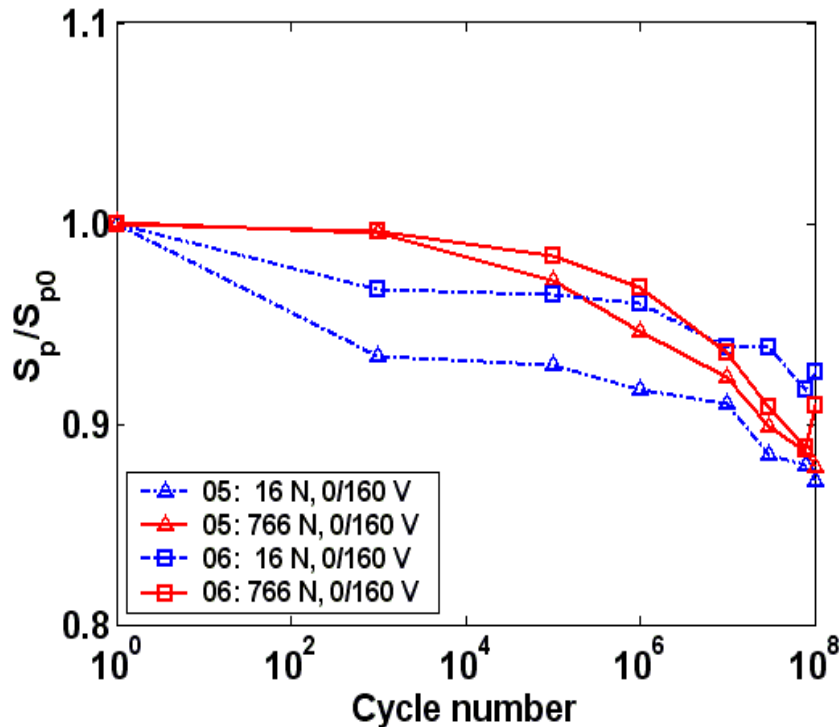
Accomplishments (continued)

- EPCOS PZT stacks were tested for loading parameter and fatigue response study.

No.	Studies	Size (mm ³)	C (μF)	Mech. preload (N)	Elec. Load (-/+V _{pk} , Hz)	Notes
01, 08' purchase	Prefatigue	6.8x6.8x30	2.9	16	0/480, 20	Breakdown
02, 08' purchase	Prefatigue	6.8x6.8x30	2.9	16	0/400, 40	Breakdown
03, 08' purchase	Prefatigue	6.8x6.8x30	2.9	766	0/400, 40	Breakdown
04, 06' purchase	Prefatigue	6.8x6.8x30	2.9	16	0/320, 40	Breakdown
05, 08' purchase	Fatigue	6.8x6.8x30	2.9	766	0/160, 50	10 ⁸ cycles
06, 08' purchase	Fatigue	6.8x6.8x30	2.9	766	0/160, 50	10 ⁸ cycles
07, by Cummins	Fatigue	6.8x6.8x30	2.9	766	-40/160, 50	10 ⁸ cycles

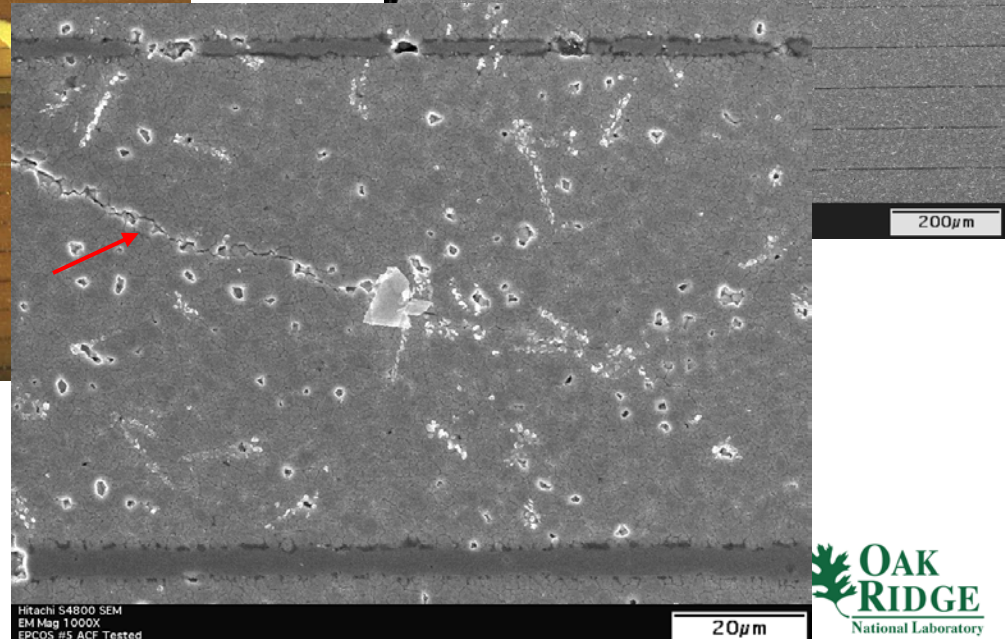
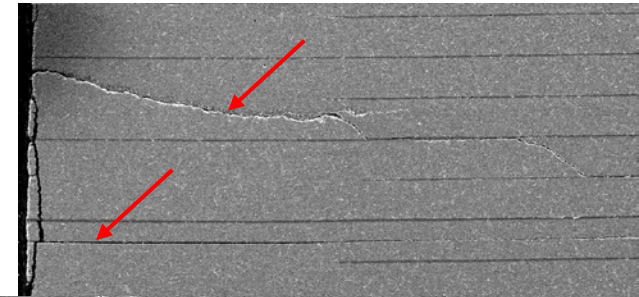
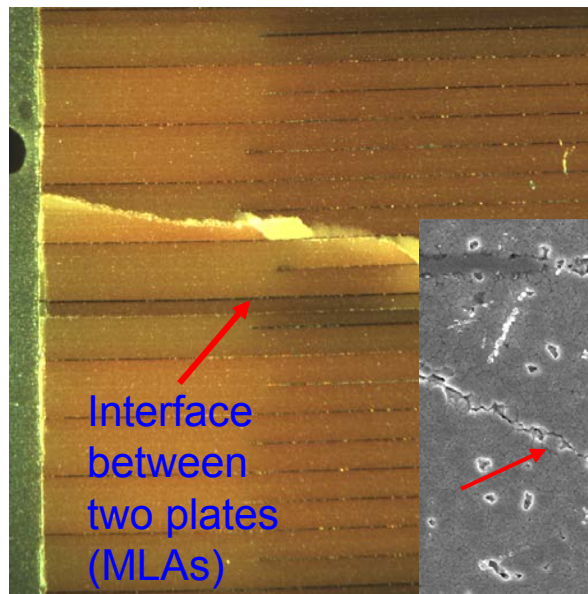
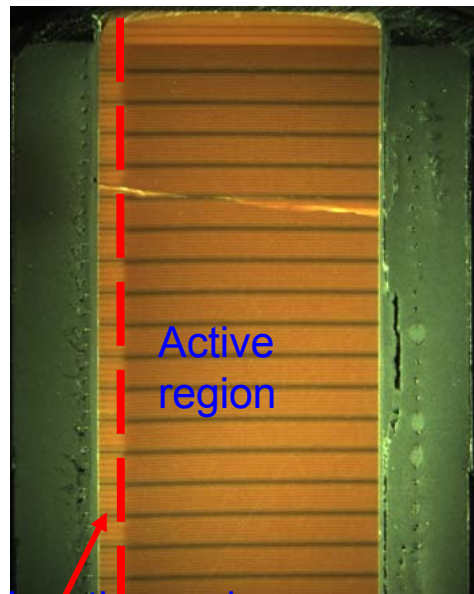
Accomplishments (continued)

- Mechanical strain recovery was observed for Cummins-supplied stack in semi-bipolar cycling.
- Electric unipolar cycling induced 10% and 20% reductions in strain and charge density, and ~ 30% reductions in hysteresis.



Accomplishments (continued)

- An extended fracture was developed near one end and across the width of stack on the section of fatigued stack 05.
- Cracking was more frequently observed between inactive and active regions near plate-to-plate interface.



Inactive region

PZT layer

Ag-Pd electrode

Collaborations

➤ Partners

- Cummins: A 3-years ORNL-Cummins CRADA on “Design Optimization of Piezoceramic Multilayer Actuators for Heavy Duty Diesel Engine Fuel Injectors” was officially established and executed since Oct. 2008.
- Kinetic Ceramics Inc. and EPCOS: collaborations to systematically manufacture and provide the PZT ceramic specimens and stacks critically needed to understand the effect of material processing and test conditions on the component degradation processes.

➤ Technology transfer

- CRADA with Cummins Inc. would facilitate the optimization of PZT stacks for HDD fuel injector to achieve 55% engine thermal efficiency by 2018.
- Collaborations with Kinetic Ceramics Inc. and EPCOS would provide key inputs to the PZT material suppliers to optimize the PZT process and stack component design to improve the long-term reliability of PZT actuators.

Future Work

- **Develop accelerated tests and database for candidate piezoceramics and PZT stacks of Cummins. A three-years Cummins-ORNL CRADA was officially approved by DOE on Sept. 29, 2008.**
- **Study piezoelectric and mechanical reliability of tape-casted and pressed PZT piezoceramics with emphasis on environmental effects.**
- **Evaluate accelerated electric fatigue response of PZT multilayer piezoactuator fabricated via tape-cast and cold-pressed approach.**
- **Employ probability design sensitivity analysis with FEA to identify optimum design of PZT multilayer piezoactuator .**
- **Fabricated additional PZT stack fatigue test frame with controlled environments.**

Summary

- **KCI PZT was focused and tested in as-extracted and as-received states:**
 - ✓ **Extraction process might affect measured strength as a result of heating.**
 - ✓ **Measured strength depended on experimental setups as related to the law of strength-size-scaling.**
 - ✓ **A negative electric loading induced the statistically-significant decrease in mechanical strength, but this was not true for a positive loading.**
 - ✓ **High temperature loading resulted in a significant decrease in strength.**
- **KCI PZT was also focused in electric cyclic fatigue study using piezodilatometer:**
 - ✓ **High field driving could result in the significant wear of electric contact.**
 - ✓ **Both unipolar and bipolar measurements can characterize the responses of fatigued PZT specimen effectively.**
 - ✓ **High field cyclic loading led to decreases in charge density and hysteresis in unipolar measurement.**
 - ✓ **High field cyclic loading also led to an asymmetry of strain loop and a shift of charge density loop in bipolar measurement.**
- **EPCOS PZT stacks was studied using modified stack test facility:**
 - ✓ **Unipolar electric loading with a mechanical preload induced significant reductions in both mechanical strain and charge density.**
 - ✓ **Appreciable decreases in piezoelectric and dielectric hysteresis also occurred.**