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

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Overview

Timeline

- Start – Oct 2007
- Finish – Sept 2011
- ~ 75% Complete

Budget

- Total project funding
  - DOE – $1,200K
    - 2008 - $300K
    - 2009 - $300K
    - 2010 - $300K
    - 2011 - $300K
  - Cummins - $1,200K Cost Share

Barriers*

- Changing internal combustion engine combustion regimes
  - ✓ Peak Cylinder Pressure
  - ✓ Fuel Injection Pressure
  - ✓ Fuel Formulations
- Long lead times for materials commercialization

Target

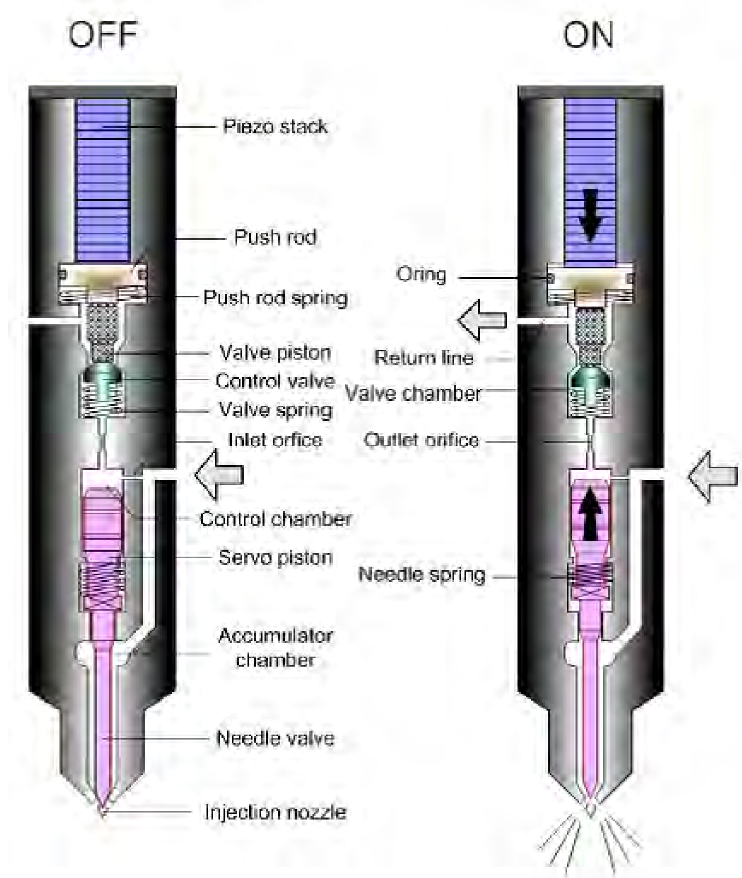
- Advanced fuel injection system with pressures > 2800 bar
- 50% improvement in freight hauling efficiency by 2015.

Partners

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

*Vehicle Technologies Program, Multi-Year Program Plan, 2011-2015

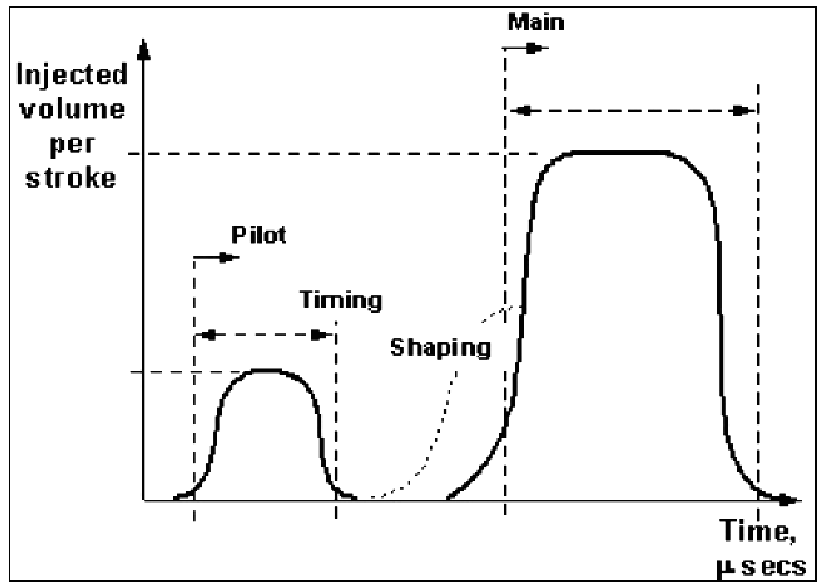
Piezoactuation Enables Precise Rate Shaping and Control of Fuel Injection Timing and Quantity



Piezostack used in a fuel injector

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

- **Spray control of solenoid fuel injectors is 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 fatigue and dielectric breakdown testing on actuator components using piezodilatometer
- Characterize fatigue responses of PZTs with respect to the application in fuel injection system
- Develop experimental approach to testing mechanical strength of PZT stacks
- Use probability design sensitivity analysis with FEA to identify optimum design of PZT multilayer piezoactuator

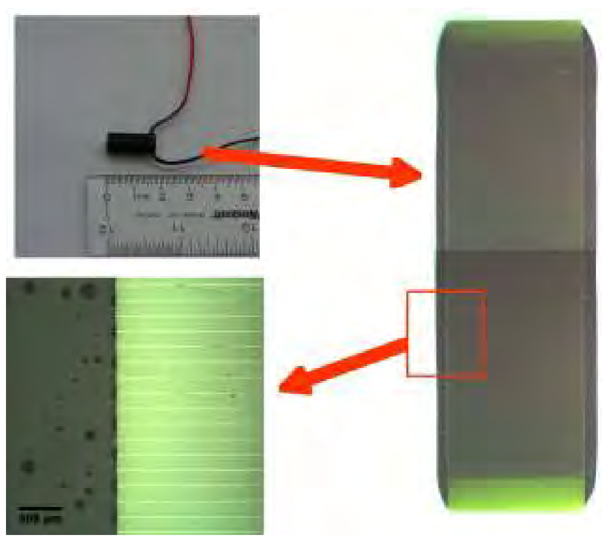
Milestones

- **Sept 2009: Measure and compare piezoelectric and mechanical reliabilities of tape-cast and pressed PZT piezoceramics.**
- **Sept 2010: Reliability study on identified PZT piezoceramics in various environments.**
- **Sept 2011: Testing and lifetime study of identified PZT piezoceramics and stacks.**

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 fuel injectors for Heavy Duty Diesel engines.

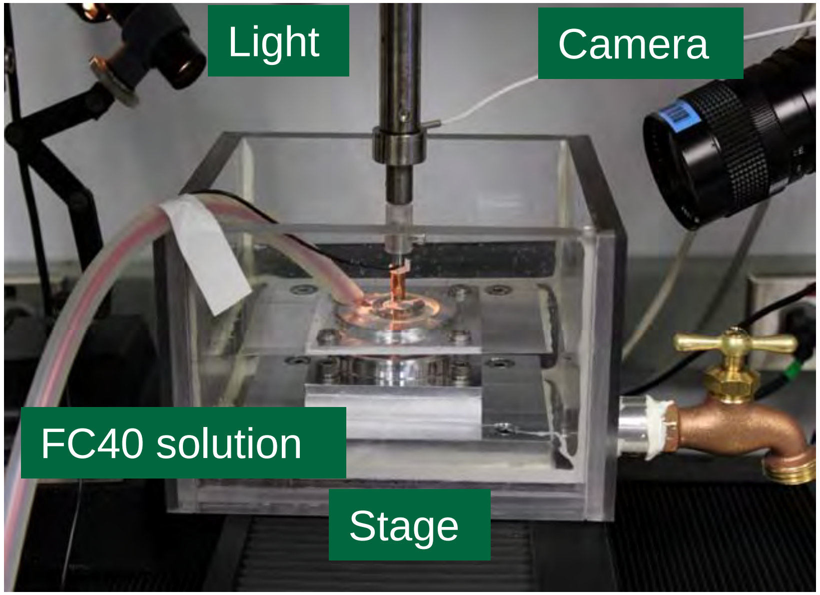
PMLAs have a macroscale and a microscale

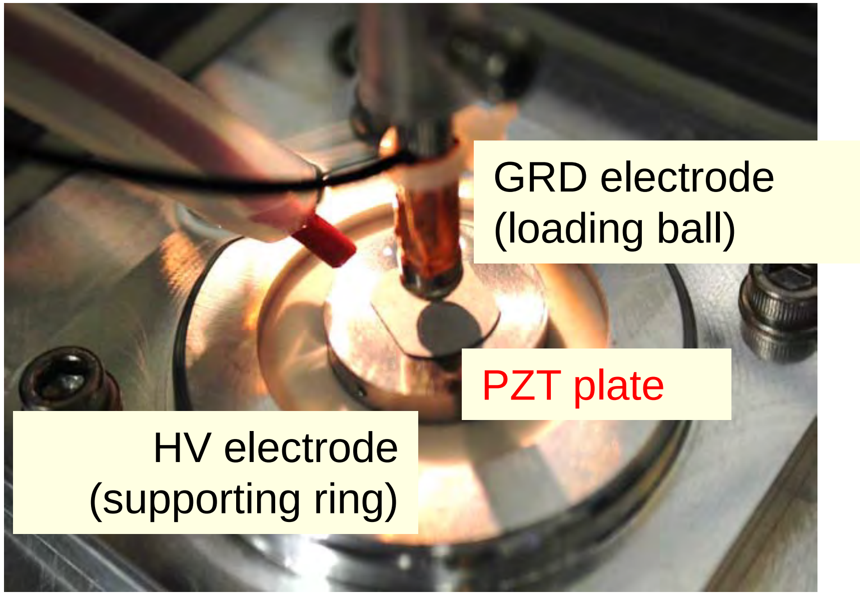


PMLAs would be used inside a fuel injector

Accomplishments

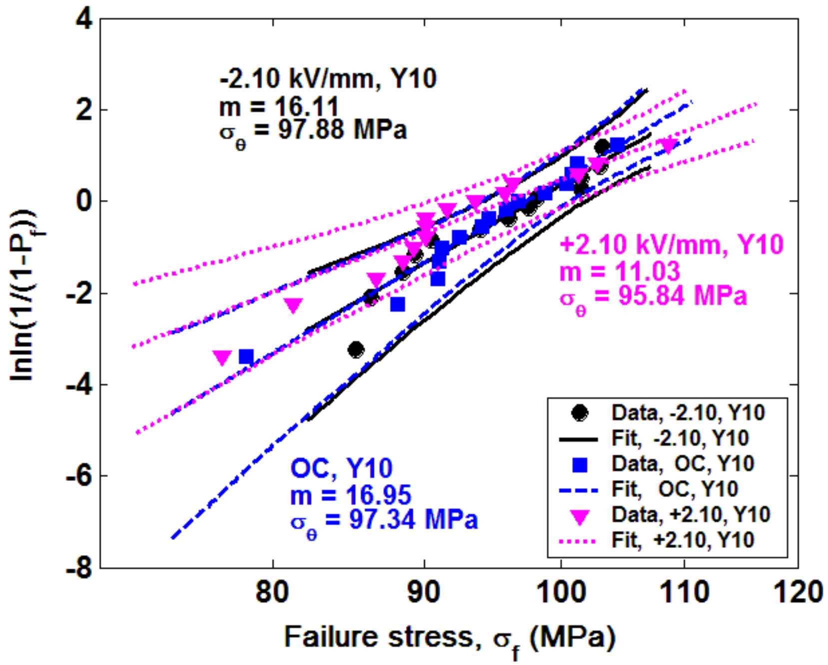
- ✓ **Ball-on-ring mechanical test facility with electronic liquid bath was developed.**
- ✓ **Electric loading capability has been upgraded to more than 1000 V.**
- ✓ **Mechanical reliability of PZT in electric field serves as input for stack design.**

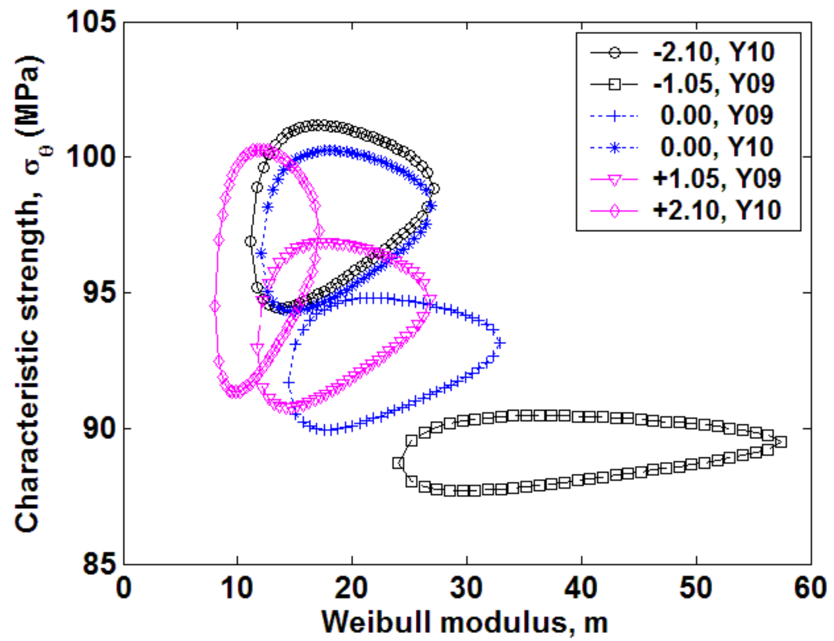




Accomplishments (continued)

- ✓ KCI PZT mechanical strength and field effect were evaluated in the range of $-2E_c$ to $+2E_c$.
- ✓ No significant effect of electric field was observed except that under $-E_c$.
- ✓ Electronic liquid did not affect the measured mechanical strength.

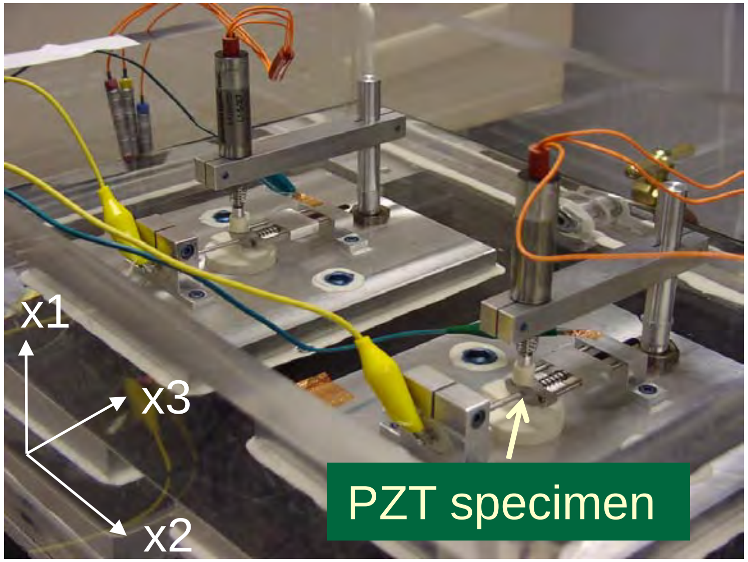




- ➢ Y09 – tests in air; Y10 – tests in electronic liquid FC-40.
- ➢ Ball-on-ring consisted of 6.35 mm loading ball and 9.5 mm supporting ring.
- ➢ Loading was controlled by displacement with a rate of 0.01 mm/s.

Accomplishments (continued)

- ✓ **Piezodilatometer was enabled to test and evaluate the fatigue of PZT in high field driving.**
- ✓ **Test procedures and data processing are being standardized.**
- ✓ **Fatigue data help failure analysis of PZT stack and screening candidate PZTs.**



- **Electric, mechanical, and thermal responses of PZT can be tested under electric loading.**
- **Electronic liquid bath is provided.**
- **Reference specimen is included to study the effect of environment.**
- **Unipolar & bipolar electric fatigue tests were for KCI PZT completed with 200Hz, 10^8 cycles; each 4-5 sets.**

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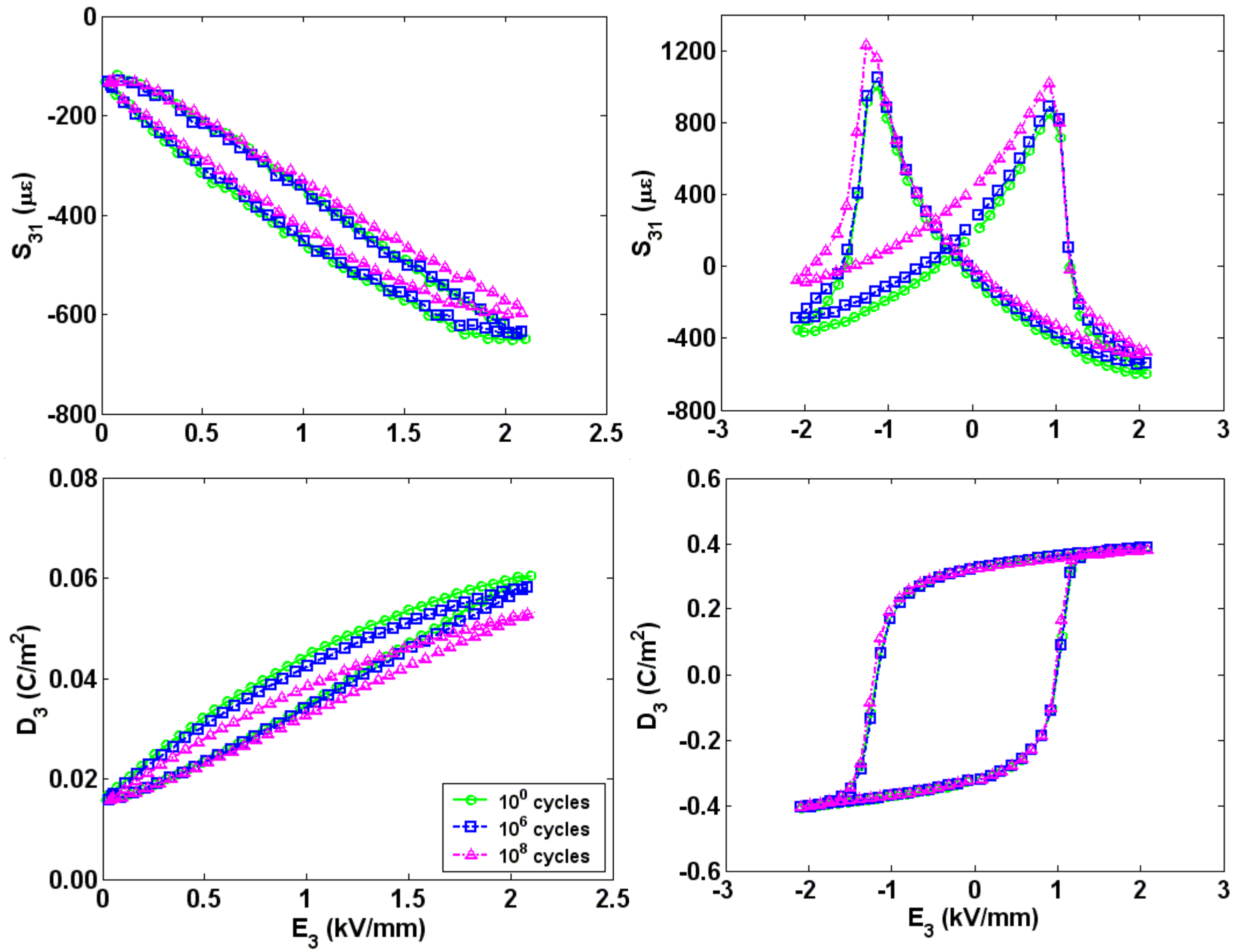
Accomplishments (continued)

- ✓ **Unipolar (left) and bipolar (right) measurements were developed.**
- ✓ **Loops of S(E) and D(E) exhibit various changes in electric fatigue.**

Mechanical strain

Charge density



Unipolar response

Bipolar response

- Cycling condition: 200 Hz sine, 2.1/0 kV/mm; FC-40 as medium.
- Unipolar measurement: 0.1 Hz triangle, 2.1/0 kV/mm;
- Bipolar measurement: 0.1 Hz triangle, 2.1/-2.1 kV/mm.
- Mechanical strain S_{31} was based on LVC transducer.
- Charge density D_3 was based on modified Sawyer-Tower circuit with 20μF capacitor.

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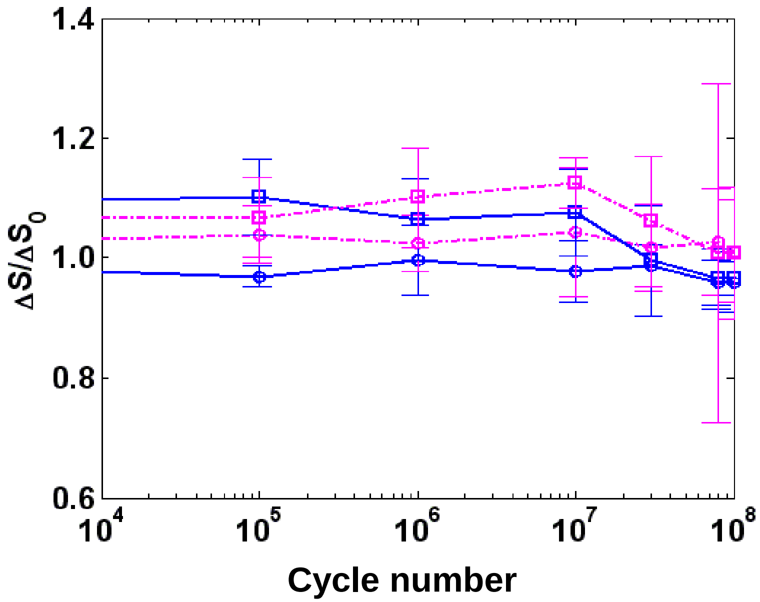
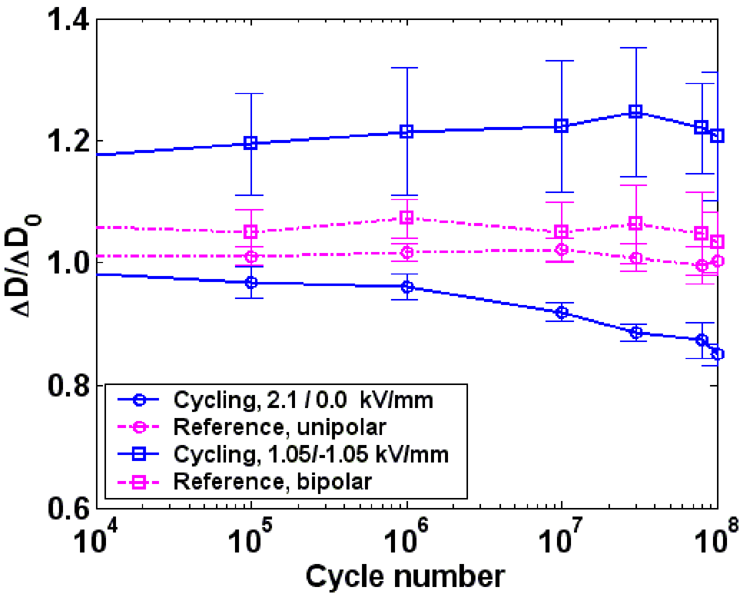
Accomplishments (continued)

- ✓ Unipolar measurement responses depend on cycling modes (unipolar or bipolar).
- ✓ Charge density (ΔD) exhibits a larger variation than mechanical strain (ΔS) .
- ✓ No trend exists in the variation of reference specimen’s responses.

Mechanical strain



Charge density



- ➢ Variations of amplitudes are used in screening PZTs. ΔS – amplitude of strain S(E); ΔD – amplitude of charge density D(E).
- ➢ Reduced domain contribution due to unipolar cycling was seen in decreased coefficients; renewed domain activity was seen in fluctuated coefficients in bipolar cycling.

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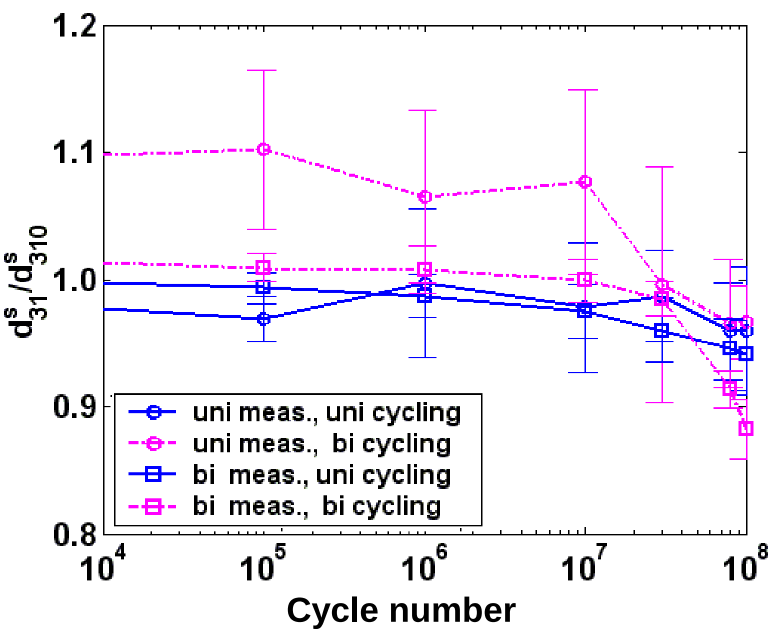
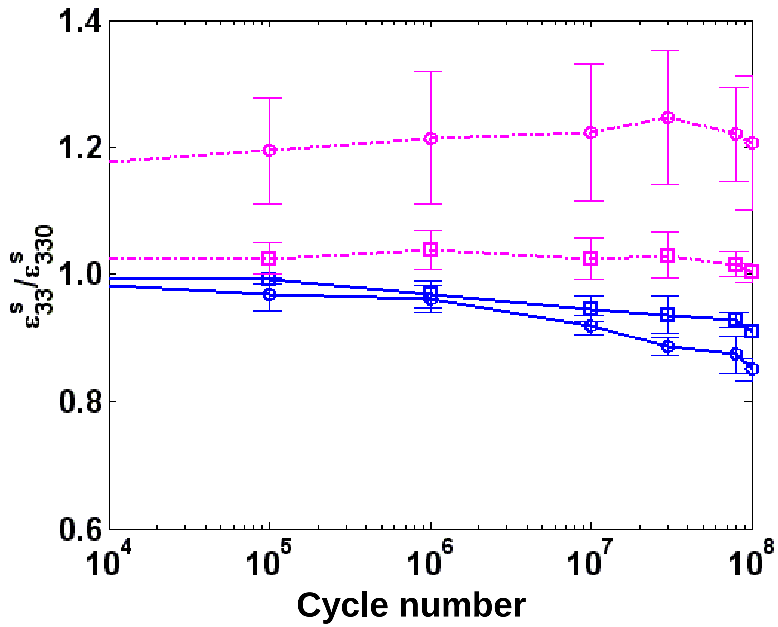
Accomplishments (continued)

- ✓ Piezoelectric and dielectric coefficients (d_{31} and ε_{33}) were extracted.
- ✓ Effect of bipolar cycling on the coefficients is quite appreciable due to the inverse field.
- ✓ Unipolar cycling led to decrease in coefficients with some fluctuation in the piezoelectric.

Piezoelectric coefficient



Dielectric coefficient

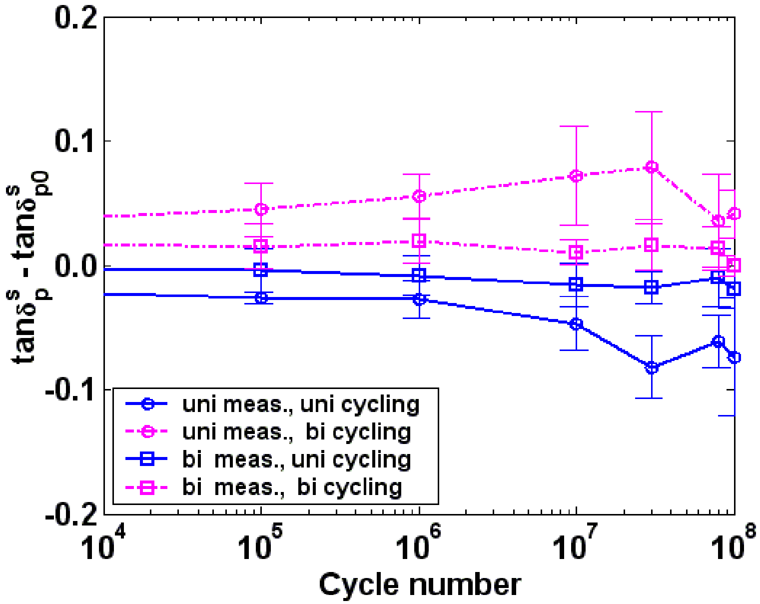


- ➢ Variation of d_{31} and ε_{31} is part of input to design and system control.
- ➢ Superscript s designates that coefficients are based on loop secants within defined field ranges.

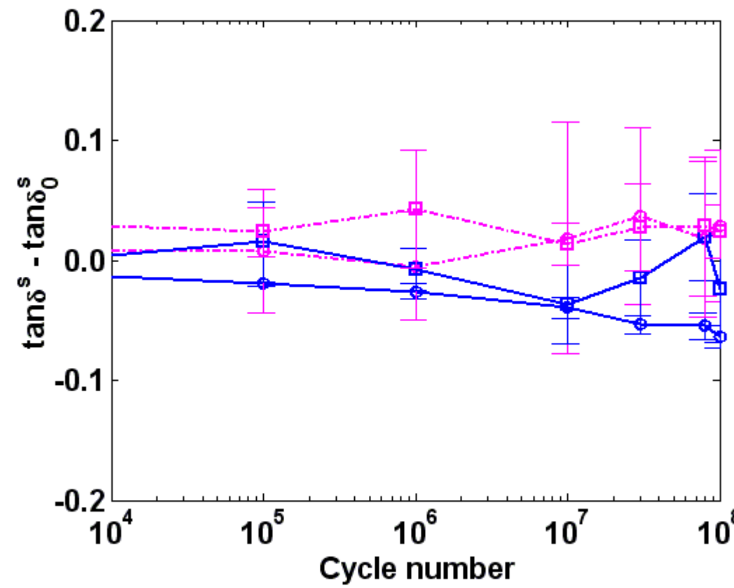
Accomplishments (continued)

- ✓ Loss tangents were estimated based on the S(E) and D(E) loops.
- ✓ Piezoelectric and dielectric loss tangents both are relatively stable within tested cycles.

Piezoelectric loss tangents



Dielectric loss tangents

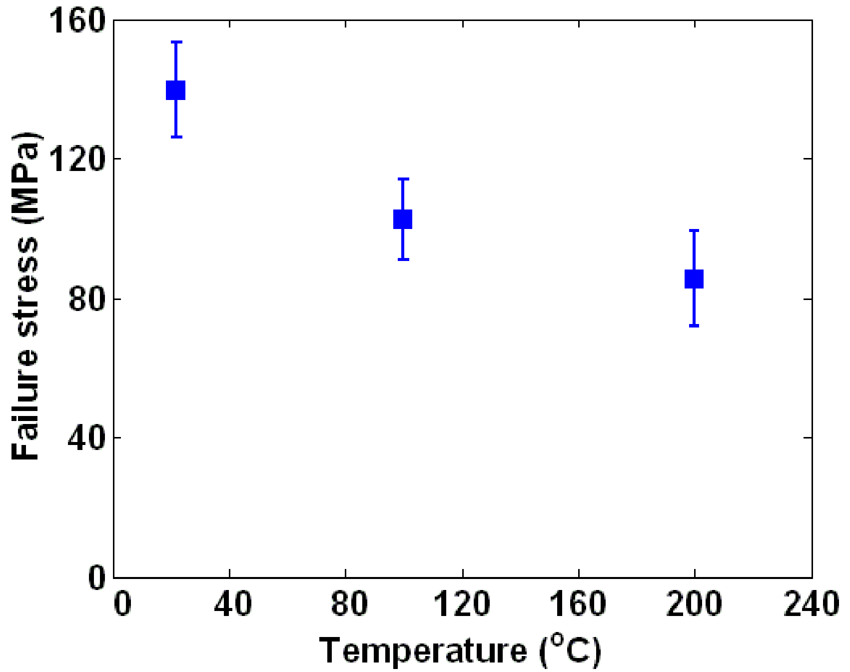


- ➢ Variation of piezoelectric and dielectric loss tangents is also part of input to design and system control.
- ➢ Loss tangents are defined in the field ranges same as those in piezoelectric and dielectric coefficients.

Accomplishments (continued)

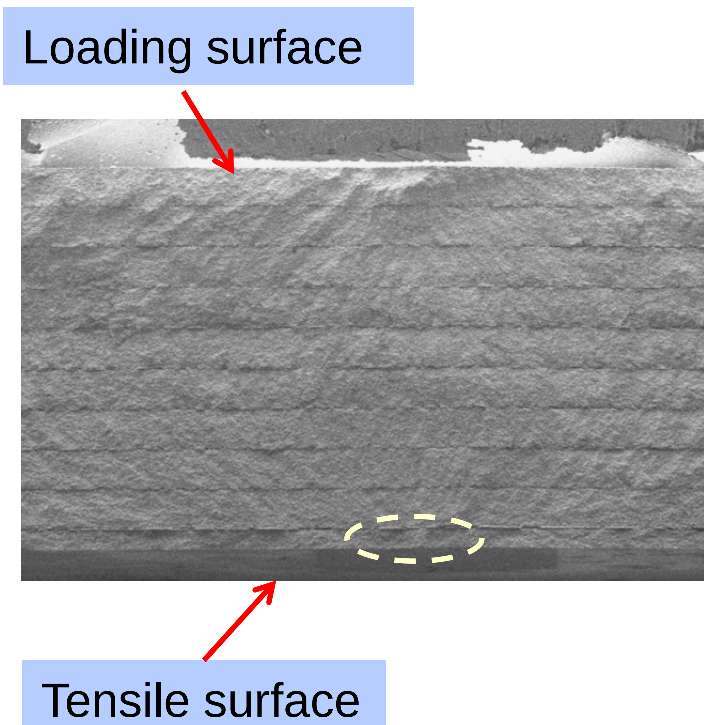
- ✓ Ball-on-ring mechanical tests were conducted on PZT stacks/plates at different temperatures.
- ✓ 10-layer PZT plates were extracted from EPCOS stacks using chemical procedure.
- ✓ Mechanical reliability of PZT plates in target temperature is basic input for stack design.

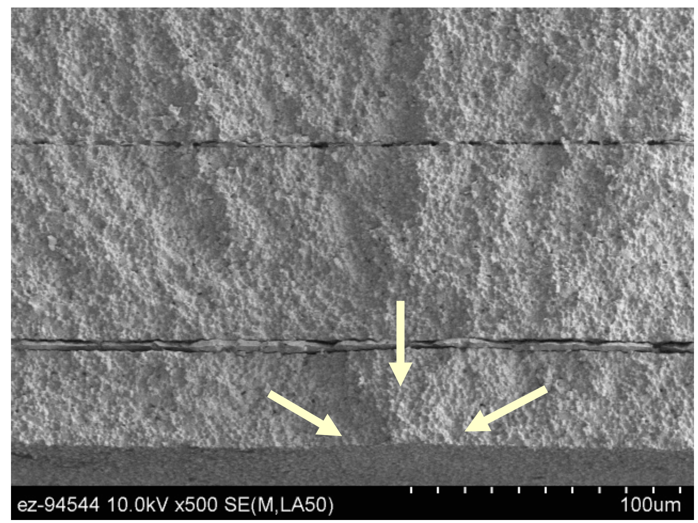
- PZT plates were extracted from EPCOS stacks using chemical procedure.
- Twenty two specimens were tested for each temperature condition.
- Double alumina tubular structure was constructed, inner tube edge serving as support ring.
- Ball-on-ring consisted of ϕ4.88 mm alumina support ring, and ϕ12.7mm alumina loading ball.
- Cross head was set at 0.01 mm/s.



Accomplishments (continued)

- **Fractography on failed 10-layer specimens was conducted using SEM.**
- **Failure origins are mostly located in the outer PZT layer.**
- **Failure was dominated by PZT, although failure origins sometimes contained inner electrode.**





Accomplishments (continued)

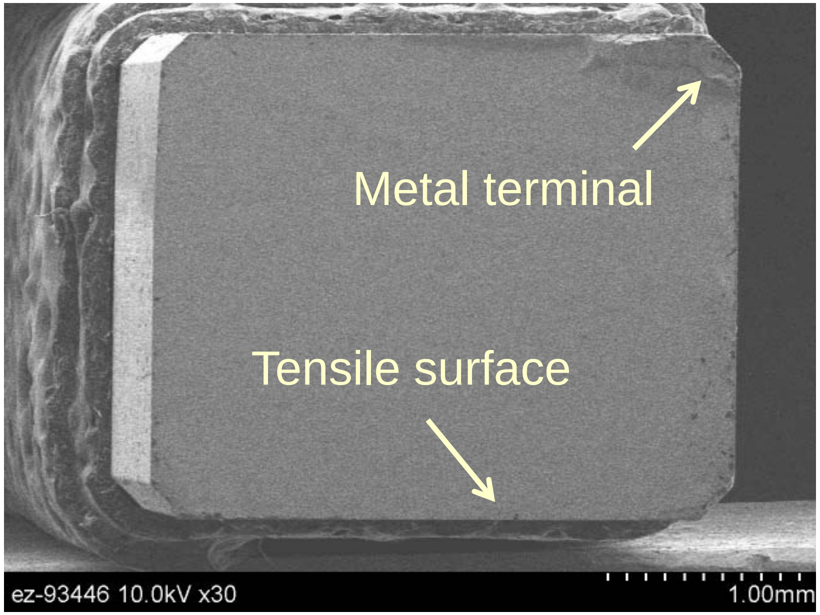
- Flexure strength of EPCOS stacks was evaluated using 4-point bend fixture.
- Longitudinal axis was aligned with tensile stress so plate-to-plate or layer-to-layer bonding is tested.
- Interface strength is essential to control delamination failure of PZT stacks.

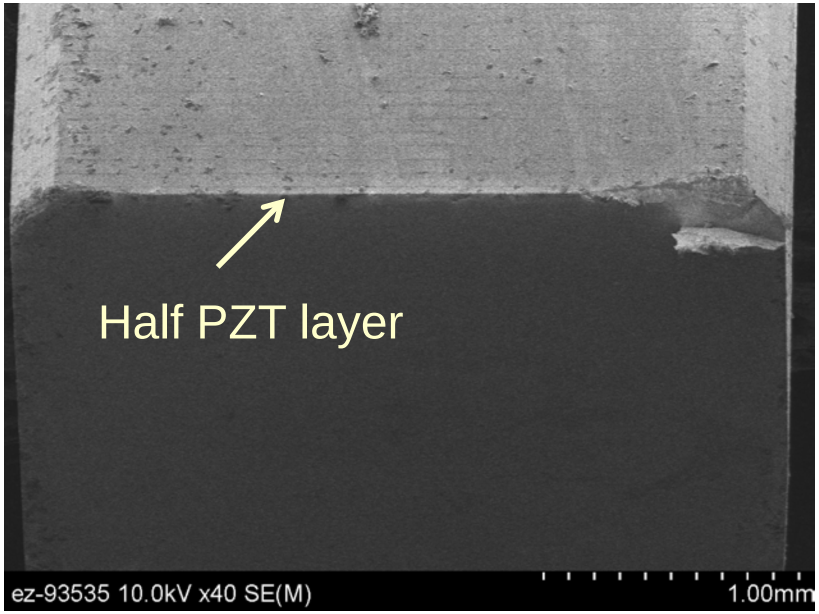
Purchase	Dimension mm^3	Quantity	Mean (MPa)	Std. Dev. (MPa)
2008	30x3x2.5	6	35.04	1.55
2006	30x7x3.2	2	22.10	-

- Bars were cut out of supplied stacks using thin diamond blades and ground.
- 4-point fixture had inner span 6.35mm and outer span 25.4mm.
- Cross head was set at 0.001 mm/s.

Accomplishments (continued)

- Plate-to-plate interfaces were obviously a favorite place to stack failure.
- PZT-to-internal electrode interfaces had a higher mechanical strength.
- No failure origin can be identified because no fracture ledge was seen on the failed surface.





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. Also, HDD fuel injector will be designed and mmercialized by Cummins Inc.
- ✓ Collaborations with EPCOS and Kinetic Ceramics Inc. 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.

Summary

- Mechanical strength of KCI PZT was evaluated in high electric field:
  - ✓ Electric did not influence the flexure strength within the range of $-2E_c$ to $2E_c$ except the case of $-E_c$.
  - ✓ No effect of electronic liquid on flexure strength was observed.
- Piezoelectric and dielectric properties of KCI PZT were tested:
  - ✓ Unipolar and bipolar measurements have unique feature in PZT characterization, each depending on cycling modes.
  - ✓ No trend exists in variation of reference specimen's responses.
  - ✓ Piezoelectric and dielectric coefficients and loss tangents were also extracted.
- Dielectric strength of EPCOS encapsulating material was studied:
  - ✓ Interface between polyester film and electrode played a critical role in local dielectric breakdown, even though the overall strength showed a quite high level.
- Mechanical property of EPCOS PZT stacks was studied:
  - ✓ For 10-layer PZT plates, ball-on-ring tests showed that mechanical strength decreased with increasing temperature.
  - ✓ 4-point bending tests revealed that PZT stack bars usually failed along the plate-to-plate interface.

Future Work

- Develop accelerated tests and database for down-selected candidate piezoceramics and PZT stacks of Cummins, Inc.
- Study piezoelectric and mechanical reliability of PZT piezoceramics with emphasis on environmental effects.
- Evaluate accelerated electric fatigue response of PZT multilayer piezoactuator fabricated via tape-cast process.
- Fabricated additional PZT stack fatigue test frame with controlled environment.
- Use probability design sensitivity analysis with FEA to identify optimum design of PZT multilayer piezoactuator .