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

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**Project ID #:**
**PM051**

*This presentation does not contain any proprietary, confidential, or otherwise restricted information*



OAK RIDGE National Laboratory

# Overview

## Timeline

- Start – Oct 2008
- Finish – Sept 2014

## Budget

- Total project funding
  - DOE – $1,540K
    - 2013 - $190K
    - 2014 - $150K
  - Cummins - $1,540K Cost Share (DOE CRADA)

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

## Barriers*

- Changing internal combustion engine combustion regimes
  - Peak cylinder pressure
  - Fuel injection pressure
  - Fuel formulations
- Long lead times for materials commercialization

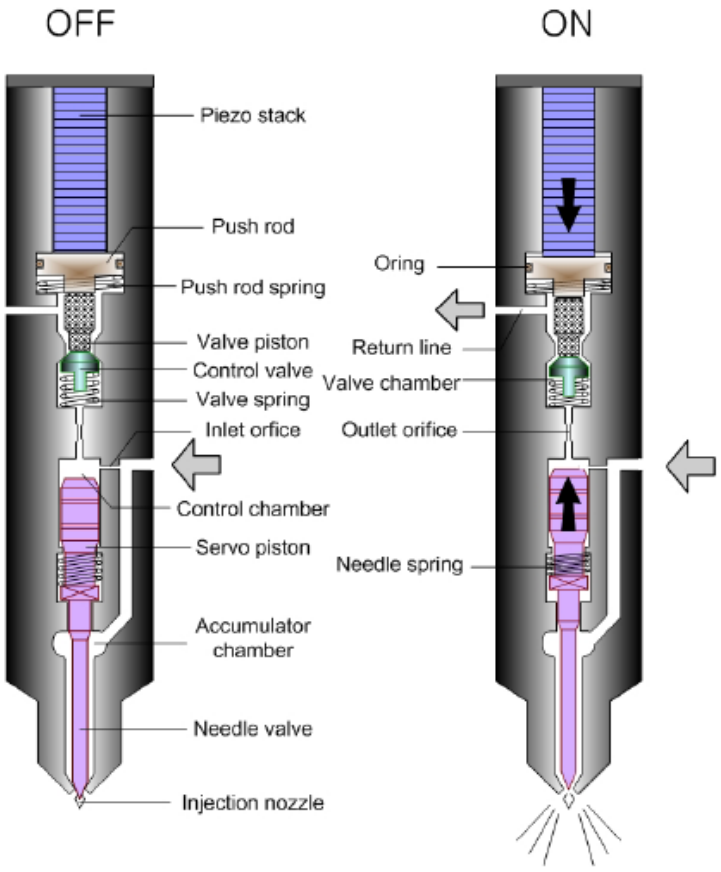
## Target

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

## Partners

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

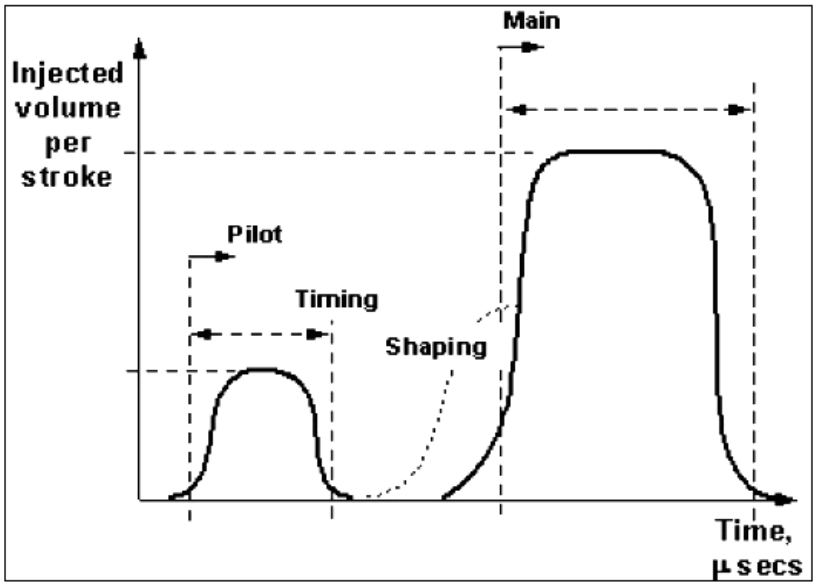
# Relevance - Piezoactuation Enables Precise Rate Shaping and Control of Timing and Quantity




**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 - Relevance

- Generate required mechanical data on PZT (lead zirconate titanate) piezoceramics under working conditions equivalent to piezo fuel injector.
- Conduct fatigue and dielectric breakdown testing on actuator components.
- 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 probabilistic design sensitivity analysis with FEA to identify optimum design of PZT multilayer piezoactuator.

# Milestones

- **Sept 2013: Effects of humidity and temperature (80% RH, 85ÁC) on the mechanical properties of PZT ceramics. *Completed*.**
- **FY14:**

✓ **Complete the preparation of setup for mechanical testing and finish the treatment of PZT specimens in controlled humidity and temperature (80% RH, 85°C). *Completed***

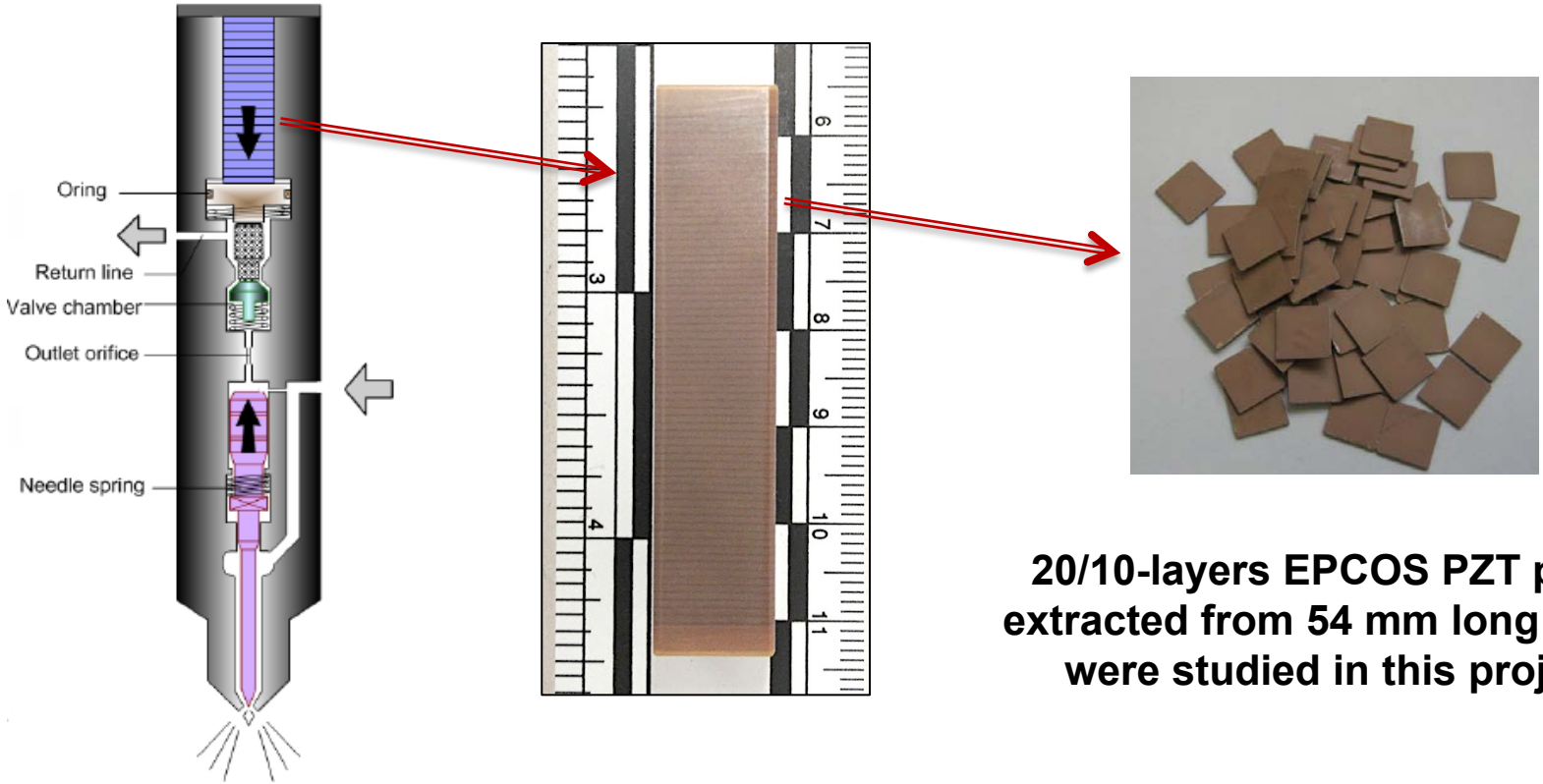
✓ **Complete study of the effects of humidity and temperature on the mechanical properties of supplied down-selected and equivalent PZT ceramics. *Completed***

✓ **Complete the preparation of setup and adaptation of testing facility for electric cycle fatigue test of PZT stacks at controlled temperature environment. *In progress and on schedule***

✓ **Complete study of cyclic fatigue of down-selected PZT stacks in temperature environment equivalent to that of fuel injection system in heavy-duty diesel engine (100 to 200°C). *In progress and on schedule***

# Approach

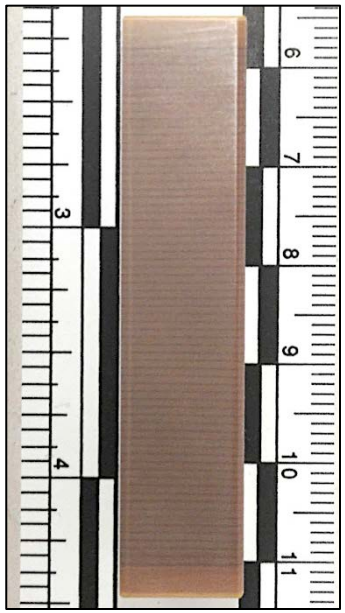
- Measure and compare mechanical properties of PZT piezoceramics that are candidates for use in piezoactuators.
- Measure response and reliability of piezoactuators and link to measured piezoceramic properties.
- Adapt to fuel injectors for Heavy Duty Diesel engines.

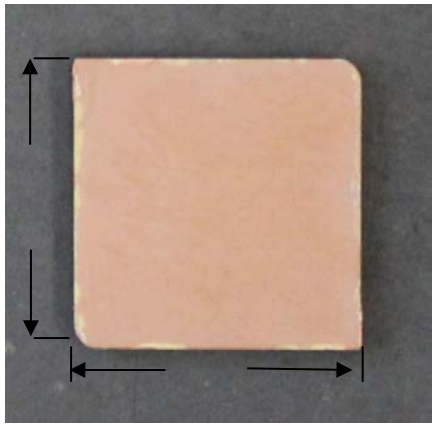


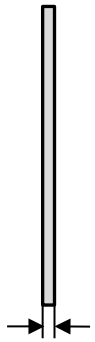

20/10-layers EPCOS PZT plates extracted from 54 mm long stacks were studied in this project.

# Accomplishments

## Temperature and Humidity Effects Were Investigated by Pretreating PZT in an Environmental Chamber





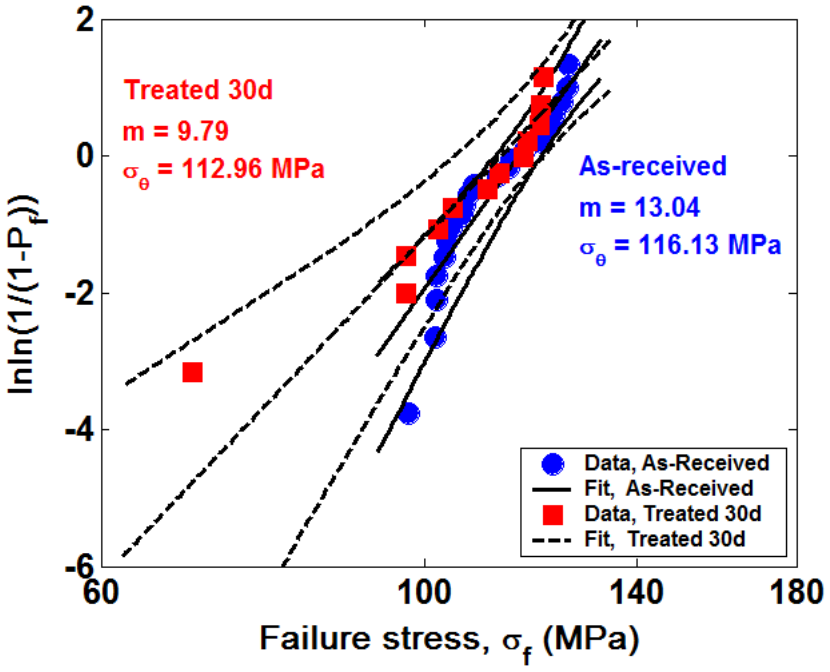



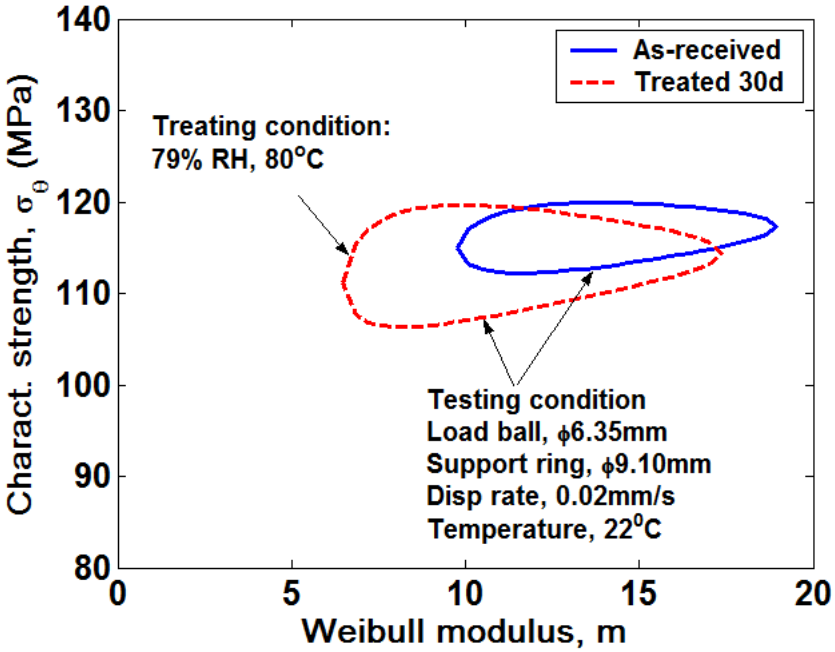

**10-layers EPCOS PZT plates extracted from 54 mm long stacks**

- **A vacuum oven (Fisher 281) was used along with KBr solution for environmental control: 79% R.H. at 80°C**
- **12 10-layer PZT specimens were treated 30 days.**

# Accomplishments (continued)

## No Significant Difference Was Found in Mechanical Strengths Between the As-Received and the Treated

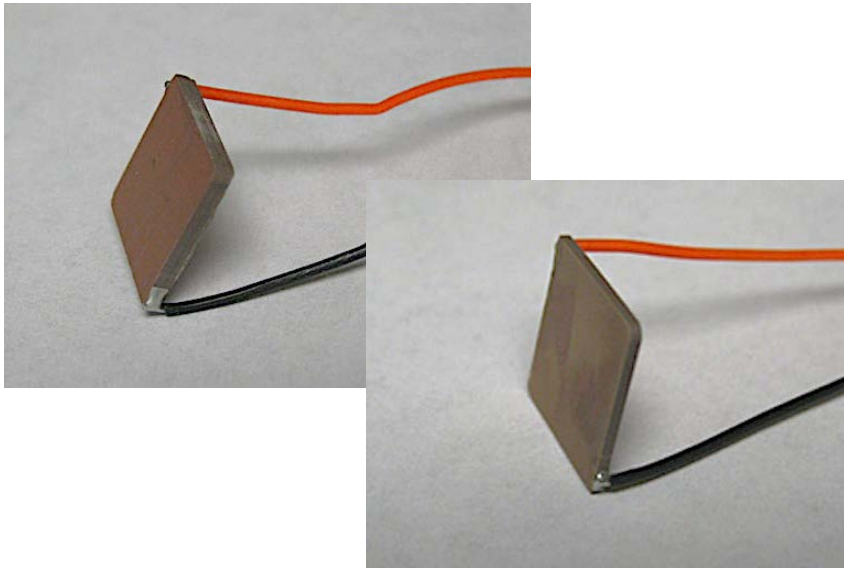



- Mechanical strength of PZT was studied using ball-on-ring testing.
- The two data sets overlap to a great extent. Performance of PZT subjected to long-term humidity and temperature exposure remains to be investigated.

# Accomplishments (continued)

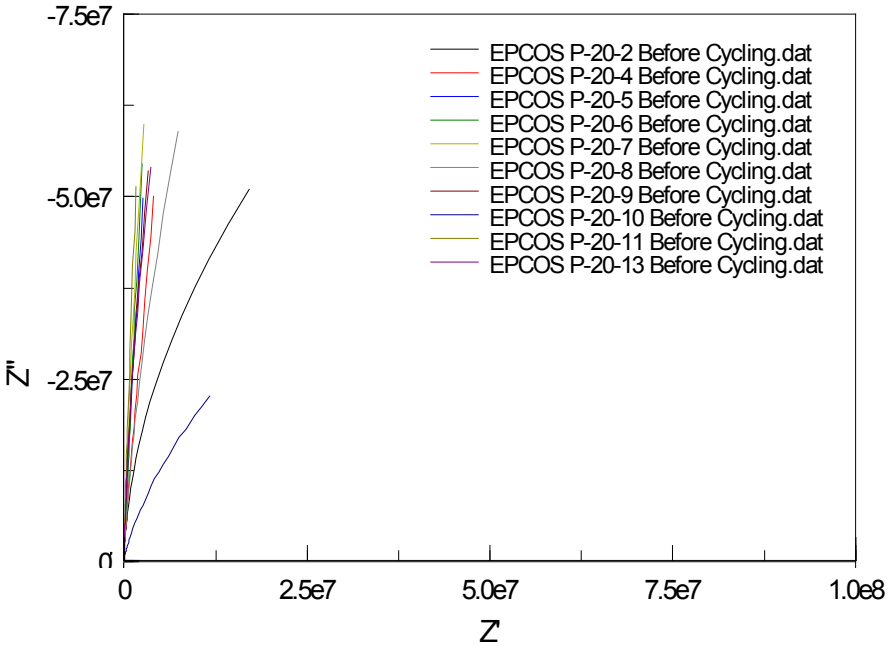
## Pre-Fatigue Condition of Extracted PZT Plates Was Examined by Impedance Analysis

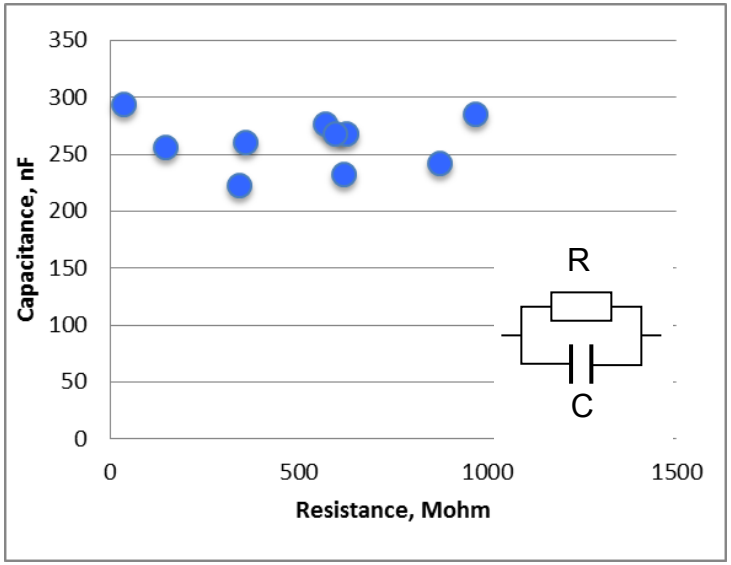


- 10- and 20-layer specimens were electrically wired at first.
- Impedance data were collected using an impedance analyzer (Solartron 1260): 50mV AC, 10 mHz - 100 KHz.

# Accomplishments (continued)

## Impedance Analysis-Based Capacitances Were Approximately 250 nF for 20-Layer PZT Specimens

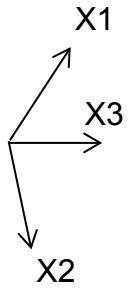


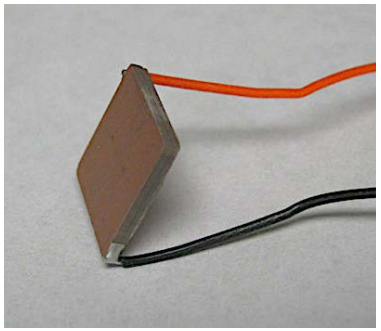




- Nyquist plots are given for a set of 20-layer specimens on the left.
- Parallel RC element was used in the analysis of impedance data.
- Large scattering in resistance (37 to 970 Mohm) was observed also.

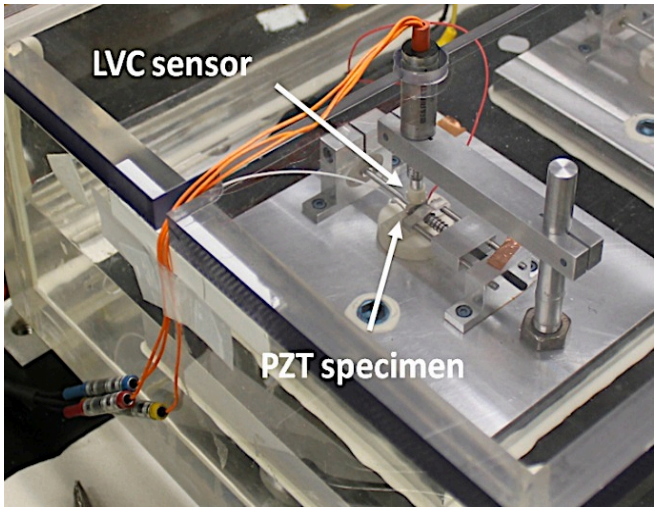
# Accomplishments (continued)

## ORNL Piezodilatometer Was Used to Characterize PZT Stack Electric Fatigue



**Electric field is applied in X3; piezoelectric response in X1 ($d_{31}$) and dielectric response in X3 ($\varepsilon_{33}$) are focused.**

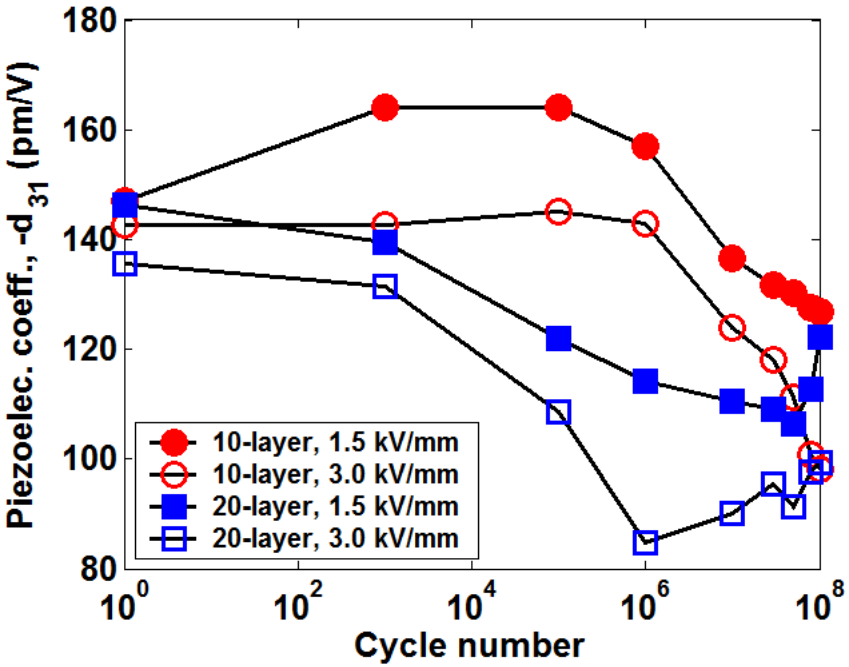


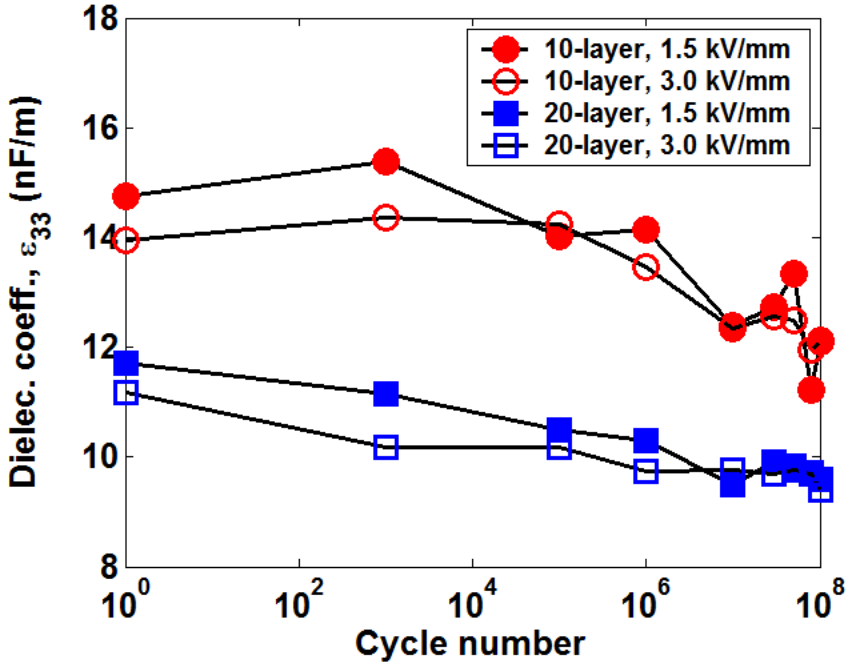

***Piezodilatomer developed by ORNL***

- **Cycling: 3.0/0.0 kV/mm, 100Hz; $10^8$ stop cycles.**
- **Measurement: 3.0/0.0 kV/mm, piezoelectric at 0.1Hz, dielectric at 50Hz.**
- **FC-40 dielectric fluid is used to suppress dielectric breakdown.**

# Accomplishments (continued)

## Substantial Degradation Occurred in Both Piezoelectric and Dielectric Coefficients

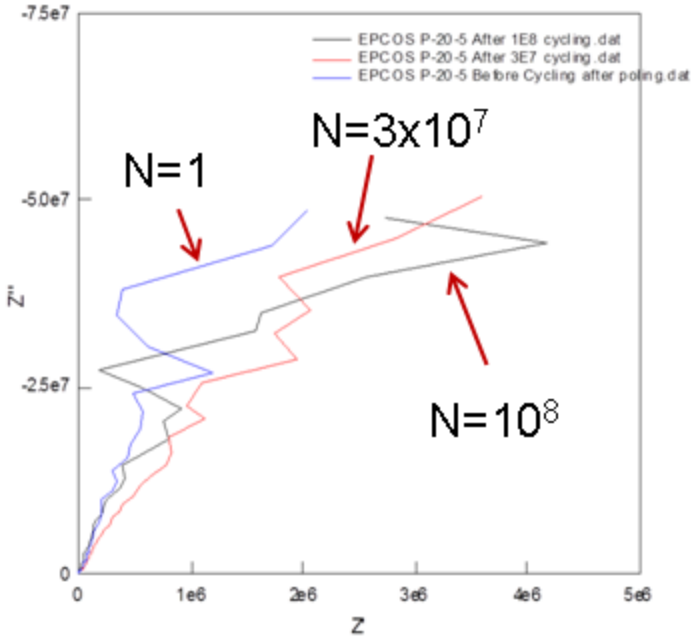


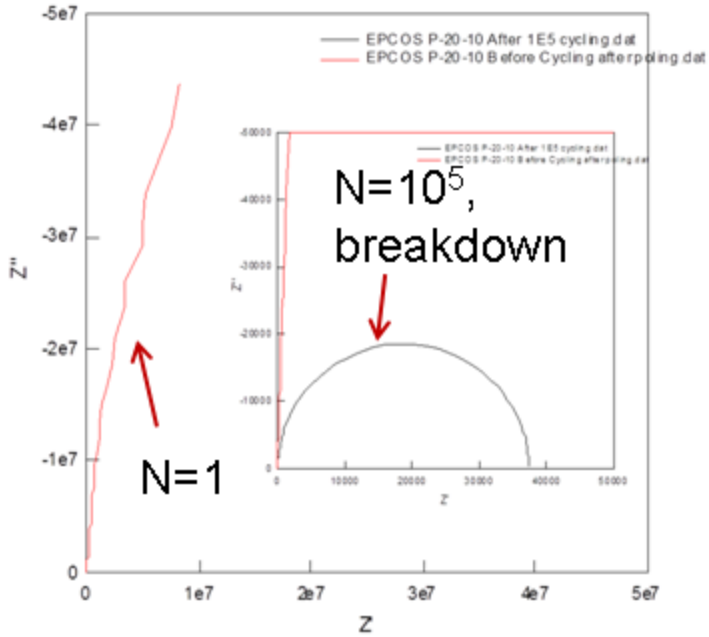




- The number of layers plays an important role in fatigue of piezoelectric coefficient, and the dielectric itself largely depends on the number of layers also.
- The results are critical input for further analysis of PZT stacks. No relevant data are available now.

# Accomplishments (continued)

## Significant Difference Was Seen in Impedance Responses Between Fatigued and Failed Specimens

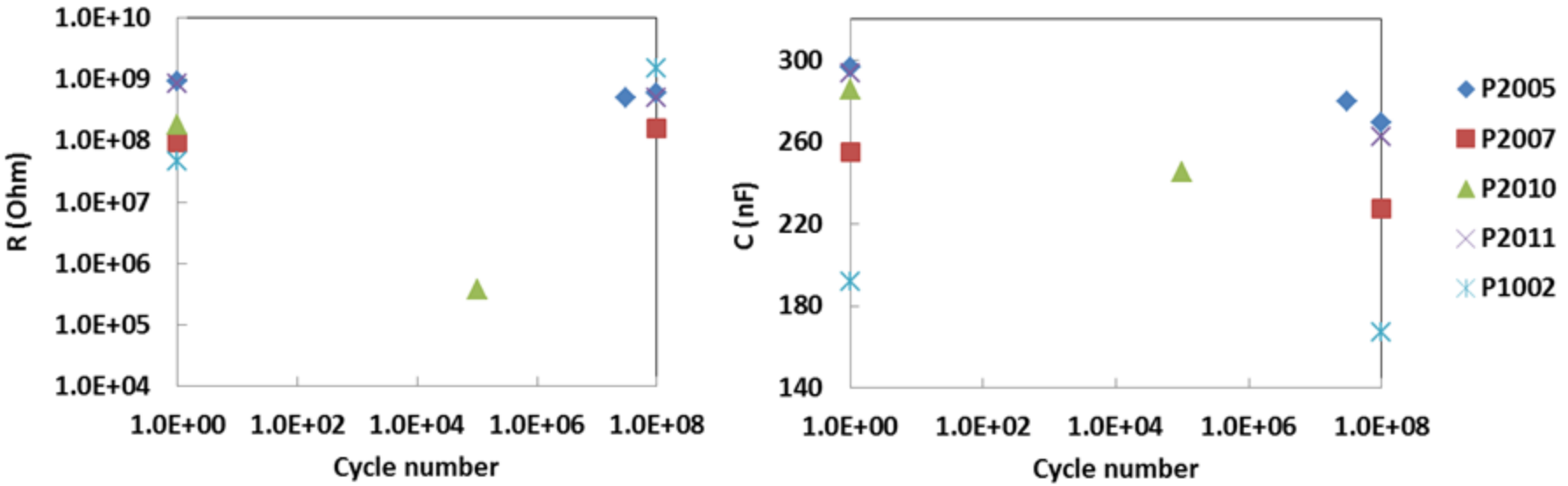



- **The Nyquist plot fluctuated in the cycle test of a 20-layer specimen (left side).**
- **The Nyquist plot changed into a well-defined semi-circle after breakdown in another 20-layer specimen (right side).**

# Accomplishments (continued)

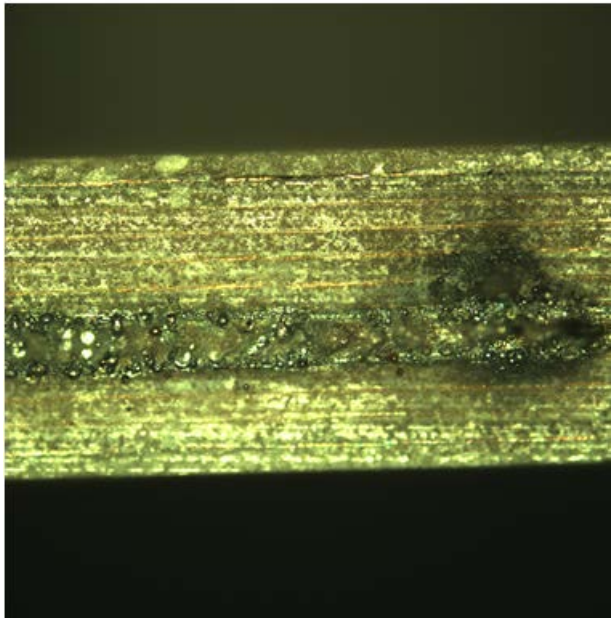
## Capacitance C Showed a Defined Decreasing Trend with Accumulated Cycles



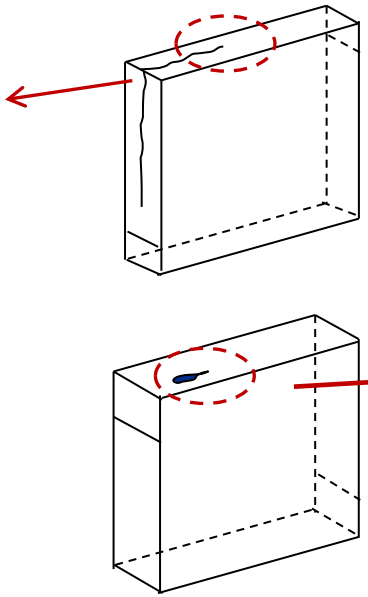

- Capacitance C decreased with the number of cycles. No defined trend can be seen in Resistance R.
- Impedance analysis can be a potential tool for structural health monitoring of PZT stacks in service.

# Accomplishments (continued)

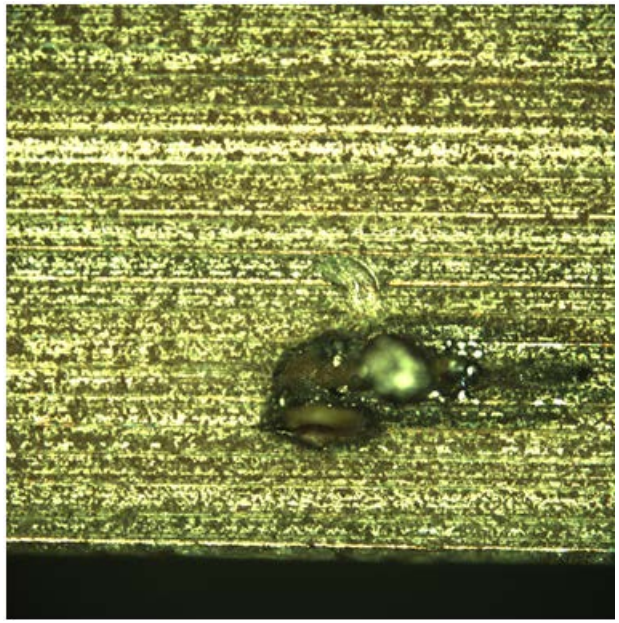
## Extensive Burnings due to Electrical Discharge Were Observed in Failed Stacks



Extended burning zone on termination and non-termination sides in a 10-layer specimen.

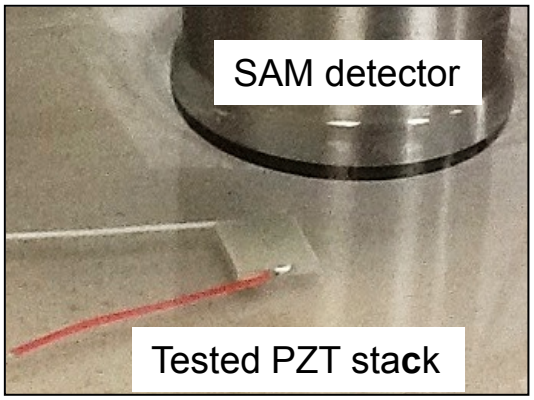


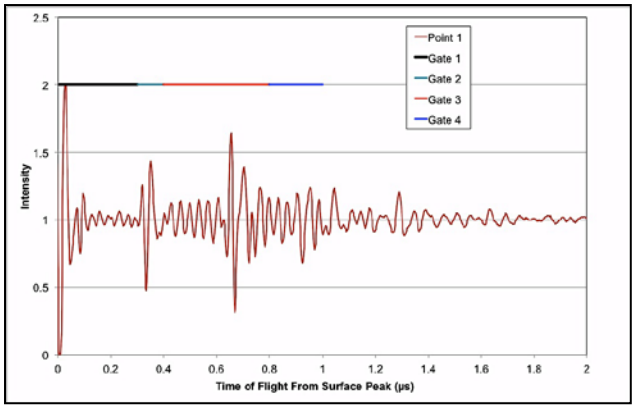
Localized burning on non-termination side in a 20-layer specimen.

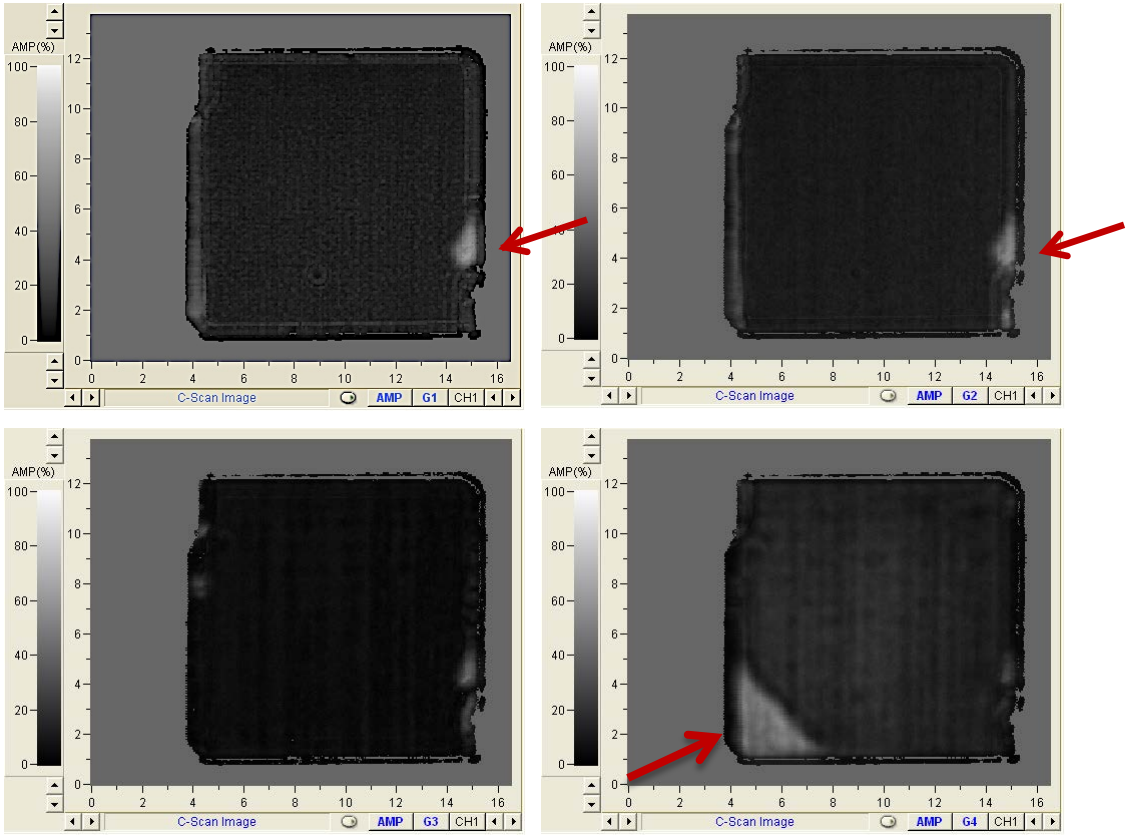


# Accomplishments (continued)

## Damages within Tested Stacks Were Revealed by Scanning Acoustic Microscopy (SAM)



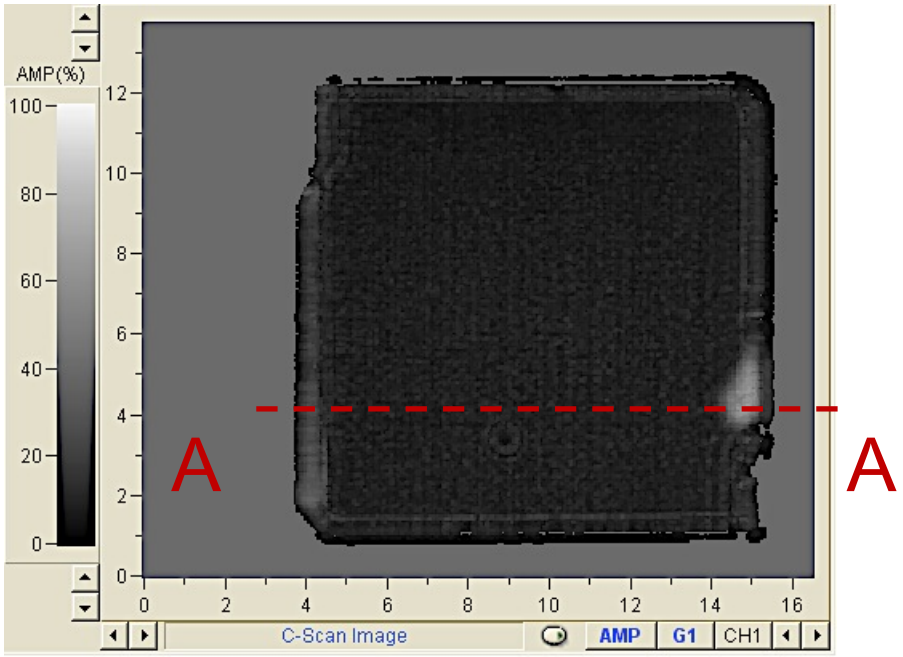



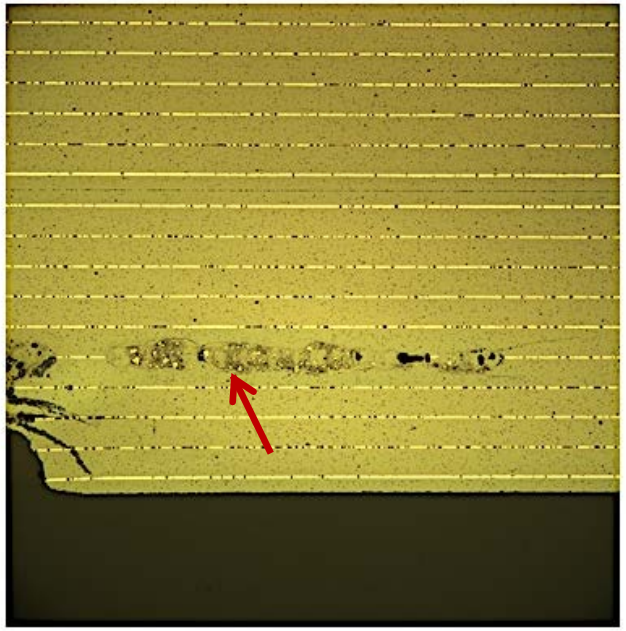




**Localized structural damages were shown in the gray areas of images on a tested 20-layer specimen.**

# Accomplishments (continued)

## Degradation of Internal Electrode Corresponded Well to the Damage Shown in SAM Images



**The 20-layer specimen imaged by SAM was sectioned and polished.**

**A melted internal electrode layer has been found to be related to the gray zone in SAM images.**

# Collaborations

- **Partners**
  - ✓ **Cummins: an ORNL-Cummins CRADA on "Design Optimization of Piezoceramic Multilayer Actuators for Heavy Duty Diesel Engine Fuel Injectors" was officially executed Oct. 2008. It will end Sept. 2014.**
  - ✓ **EPCOS: collaborations to systematically manufacture the PZT ceramic specimens and stacks needed to understand the effect of material processing and test conditions on the component degradation processes.**
- **Technology transfer**
  - ✓ **HDD fuel injector will be designed and commercialized by Cummins Inc.**
  - ✓ **CRADA with Cummins Inc. facilitates the optimization of PZT stacks for HDD fuel injector to achieve 55% engine thermal efficiency by 2018.**
  - ✓ **Collaborations with EPCOS provides 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

- Perform fatigue tests and update database for down-selected candidate EPCOS piezoceramics and PZT stacks of Cummins, Inc.
- Study piezoelectric and mechanical reliability of PZT with emphasis on humidity and temperature effects.
- Evaluate accelerated electric fatigue response of PZT stacks fabricated via tape-cast process.
- Use probabilistic design sensitivity analysis with FEA to identify optimum design of PZT multilayer actuator.

# Summary

- **Relevance: PZT ceramic actuator provides key technology to improve fuel efficiency and reduce emission of HDD engine**
- **Approach: measure and characterize PZT ceramics and stacks under electric fatigue and controlled environment**
- **Collaborations: Cummins (HDD engine) and EPCOS (PZT supplier)**
- **Technical Accomplishments:**
  - ✓ **Humidity and temperature effects on mechanical strength of PZT were studied by pretreating 10-layer specimens along with ball-on-ring testing.**
  - ✓ **Experimental study on down-selected piezo stacks has been successfully completed using 20/10-layer extracted specimens.**
  - ✓ **Substantial degradations were observed in both piezoelectric and dielectric coefficients during high-field cycle tests.**
- **Future work:**
  - ✓ **Evaluate mechanical performance of PZT ceramics under combined temperature, humility, and electric field**
  - ✓ **Electric cycle fatigue tests on PZT stacks under simulated application environments**
  - ✓ **Optimum design of PZT multilayer actuator using probabilistic component design**