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

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pm_05_lin

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OAK RIDGE National Laboratory

Overview

Timeline

- Start – Oct 2007
- Finish – Sept 2011
- ~ 25% Complete

Budget

- Total project funding
  - DOE – $1,200K
- Funding received in FY08
  - $300K
- Funding so far for FY09
  - $137K

Barriers*

- Design Data and Modeling Tools
  - Test method for reliability data
  - Probabilistic structural ceramic components design to ensure long-term durability and reliability of piezoactuator
- Manufacturability
  - Low temperature combustion (LTC) technologies require improved high precision manufacturing technology for fuel injector

Target

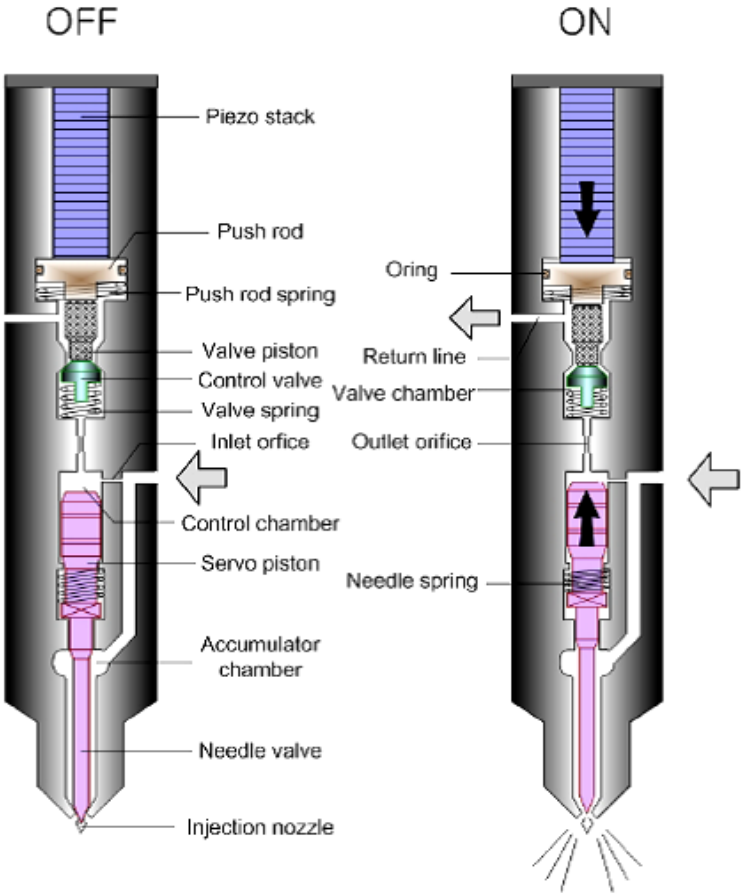
Enable heavy duty diesel engine efficiency of 55% by 2012

Partners

- Cummins Inc.

*FreedomCar and Vehicle Technologies Program, Multi-year Program Plan, 2006-2011, p. 2.4-5&7

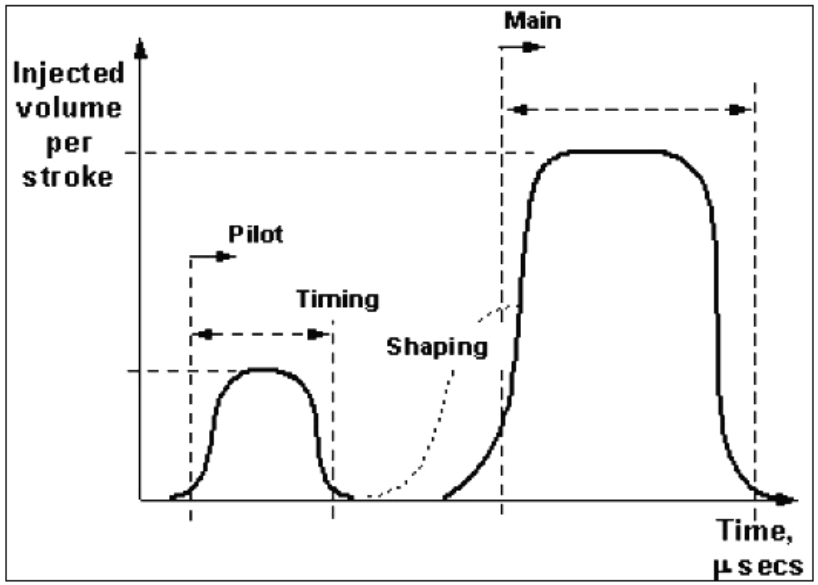
Piezoactuation Enables Precise Rate Shaping and Control of Fuel Injection Timing and Quantity



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 applied high electric field.
- Perform accelerated electric dynamic fatigue test on commercially available multilayer piezoacutator stacks.
- Identify degradation mechanisms of multilayer piezoacutator stacks after accelerated electric dynamic fatigue test.
- Establish a piezodilatometer to enable accelerated fatigue and dielectric breakdown testing for PZT piezoceramic.

Milestones

Sept 2008 – Milestone: Measure and compare reliability of commercially available multilayer piezoactuator stacks under consideration for use in diesel fuel injectors.

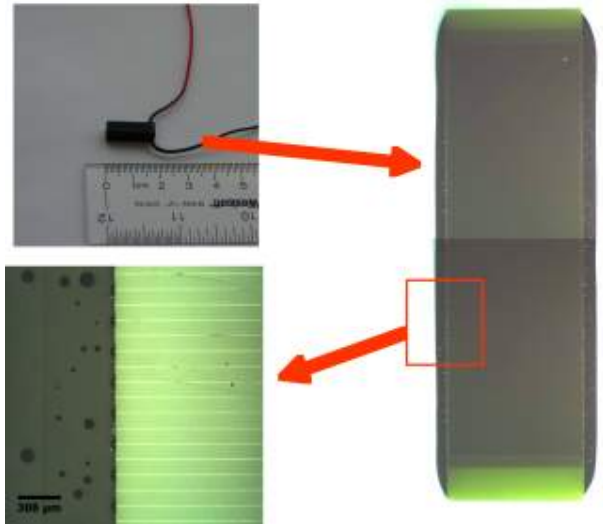
Sept 2009 – Milestone: Measure and compare piezoelectric and mechanical reliabilities of tape-cast and hot pressed PZT piezoceramics.

Sept 2010 – Milestone: 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 fuel injectors for Heavy Duty Diesel engines.

PMLAs have a macroscale and a microscale

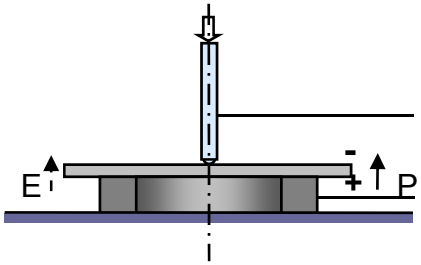


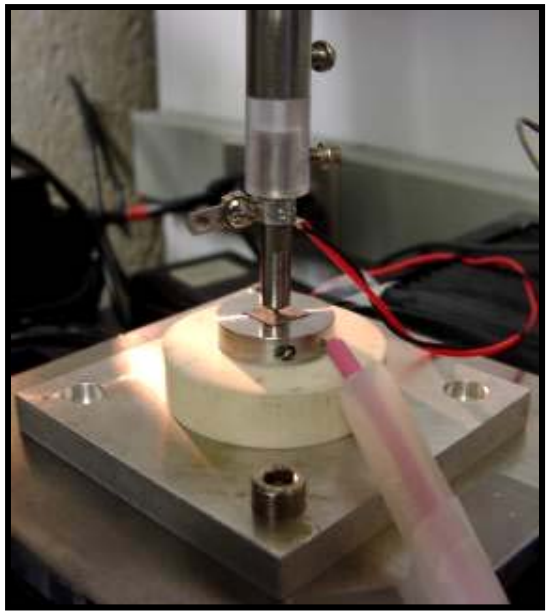
PMLAs would be used inside a fuel injector

Accomplishments

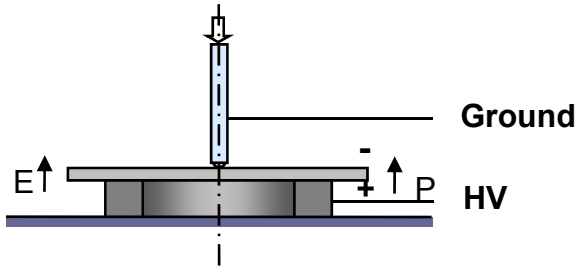
- **Mechanical strength of piezoceramics PZT-5A was measured using ball-on-ring setup under high electric field.**

OC – PoT,
positive electrode on tension

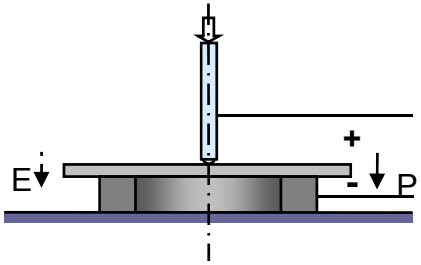




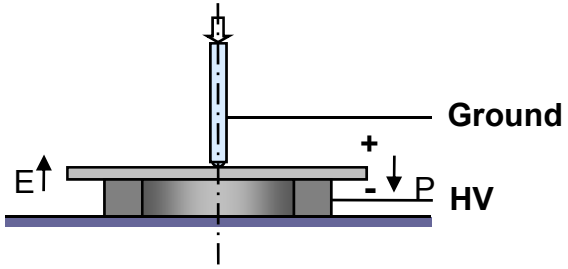
Ec – PoT,
positive electrode on tension



OC – NoT,
negative electrode on tension

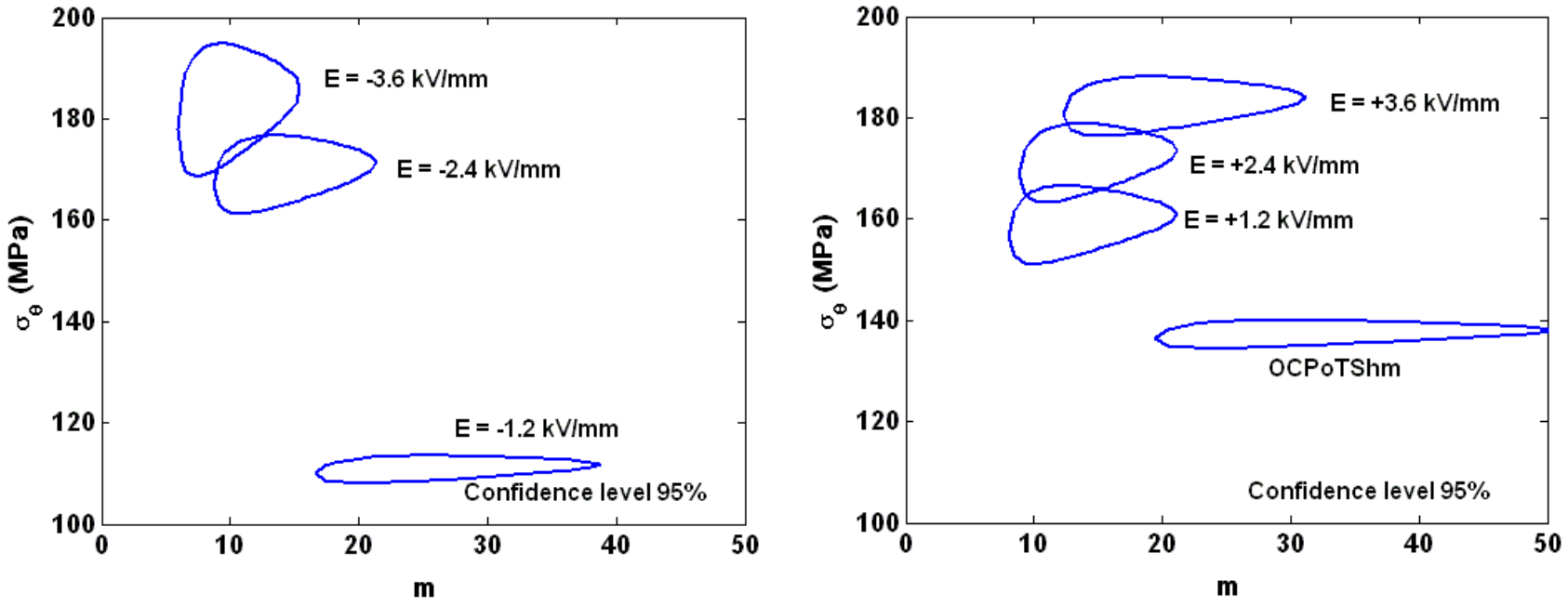


-Ec – NoT,
negative electrode on tension



Accomplishments (continued)

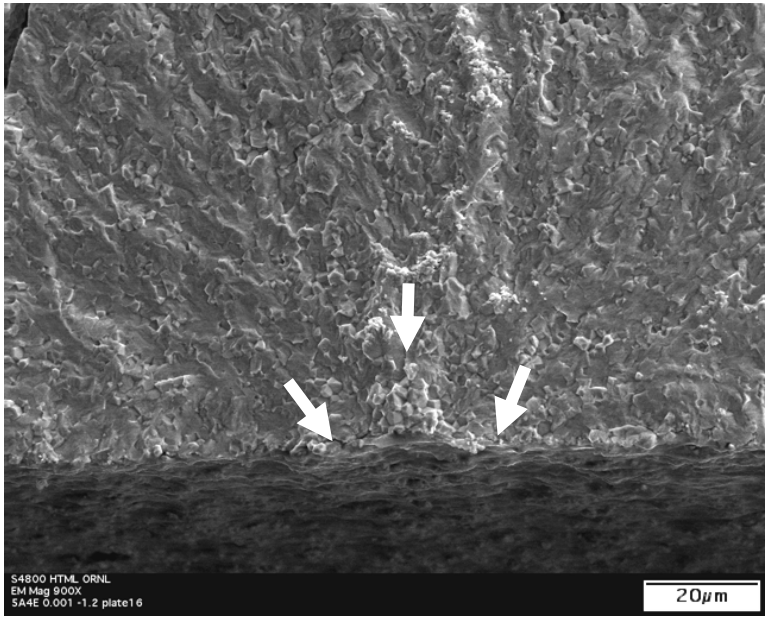
- Poled PZT-5A was observed to exhibit a strength decrease under an inverse coercive electric field.
- A strength increase was found under the electric field level greater than the coercive field independent of electric field direction.

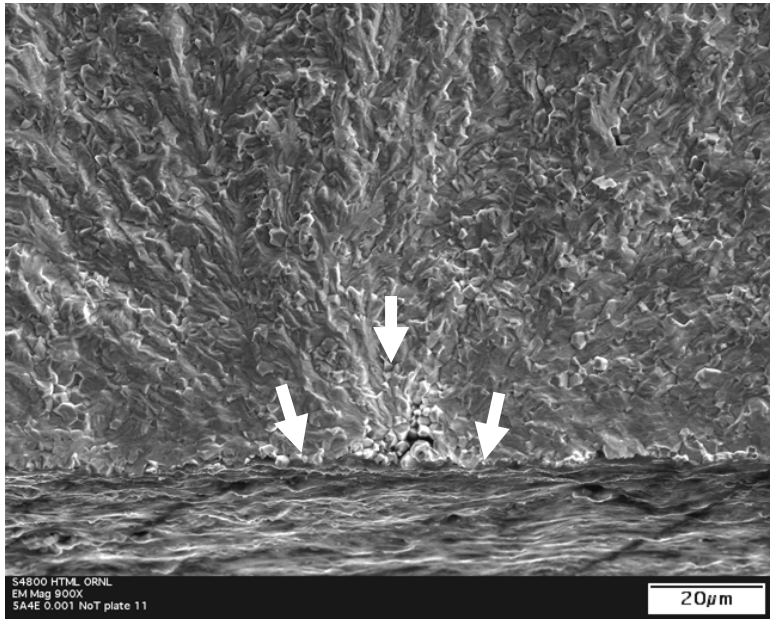


Confidence ratio rings (95% confidence level) under various electric loading conditions. The specimen size is 10.0 × 10.0 × 0.273 mm, the loading ball diameter is 2.00 mm and the supporting ring inner diameter is 7.444 mm.

Accomplishments (continued)

- **Fractography has been conducted on tested plates.**
- **Agglomerates and porous region were shown to be the strength limiting flaws.**



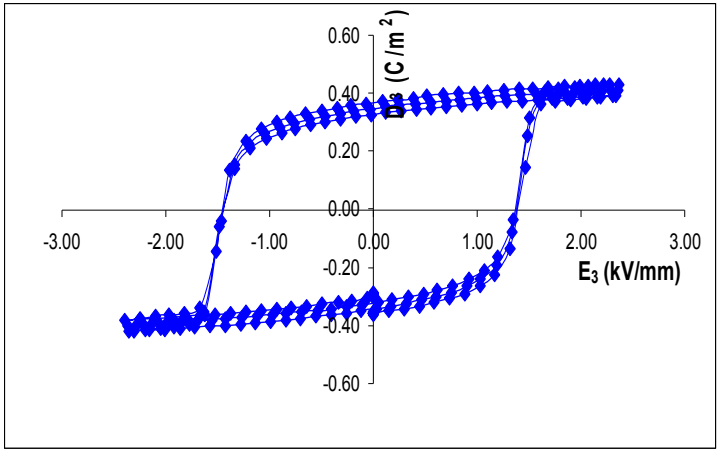


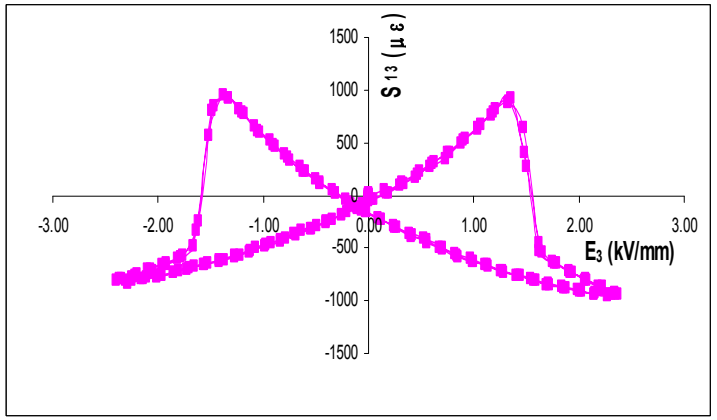
➢ **SEM images of fracture surface near the failure origin of a PZT disc with E = -1.2 kV/mm (σ_f = 113 MPa), and of that with E = 0 kV/mm (σ_f = 138 MPa)**

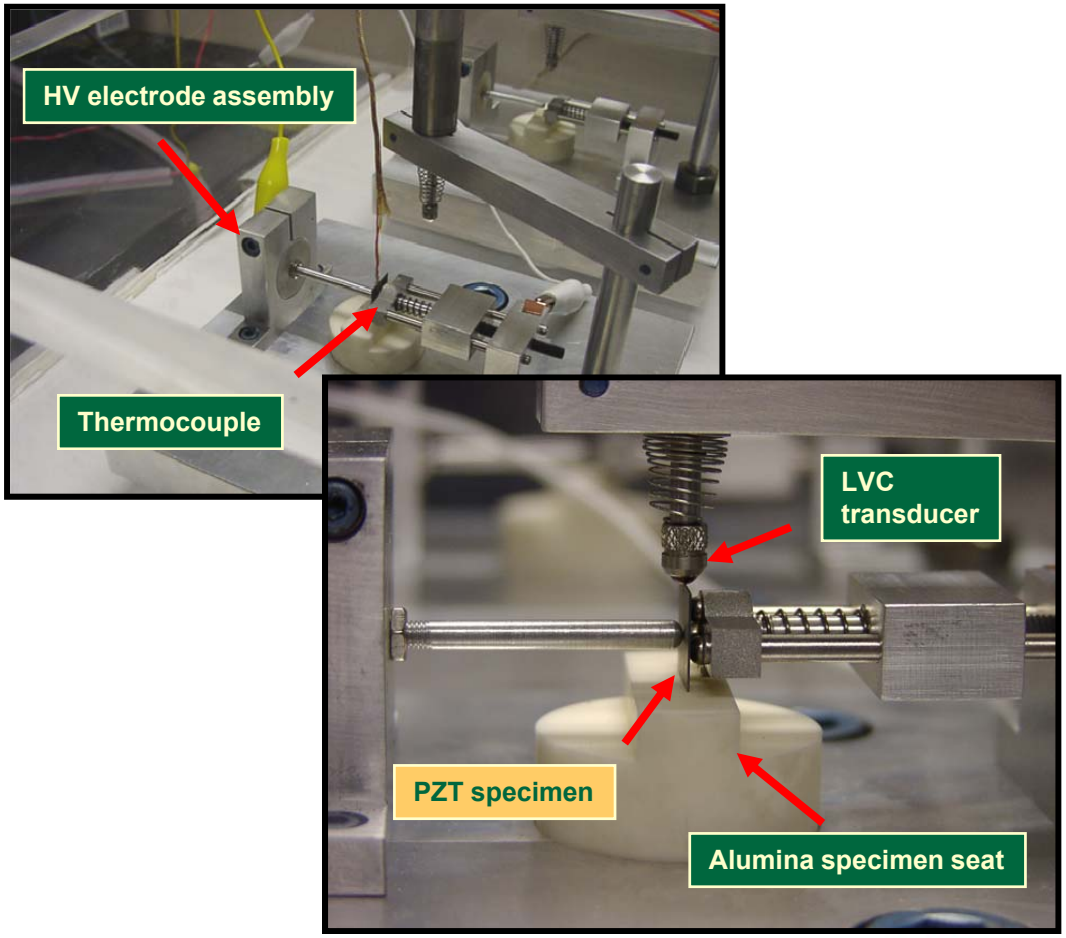
➢ **Strength limiting flaw is insensitive to the applied electric field**

Accomplishment (continued)

- A piezodilatometer enabling accelerated fatigue and dielectric breakdown testing for piezoceramic discs has been designed and assembled.
- The piezodilatometer was calibrated using a soft PZT piezoceramic.



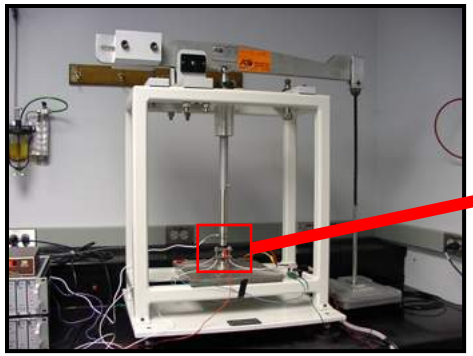


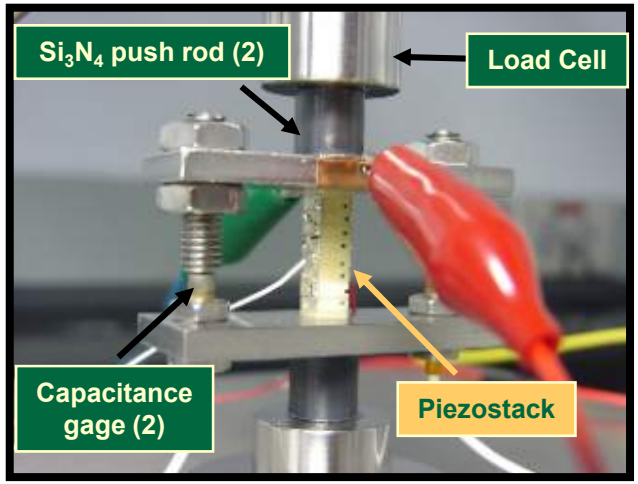


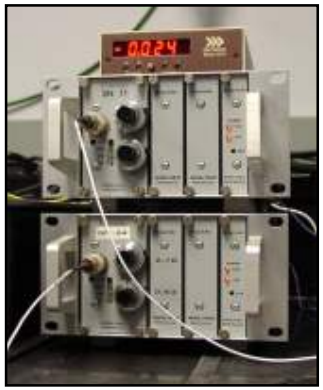
Charge density versus electric field and mechanical strain versus electric field loops for PSI-5A4E-03, 10mmx10mmx0.267mm, 0.1-Hz, ±640Vpk triangle wave.

Accomplishments (continued)

- **Accelerated electric fatigue facility was established for multilayer PZT stack reliability evaluation.**
- **Fatigue responses of PZT-5H and PZT-5A MLAs were studied under *uni-polar* and *semi-bipolar cycling* with an applied preload.**







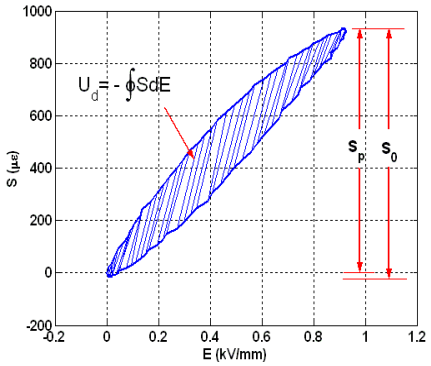
Load and displacement signal conditioners

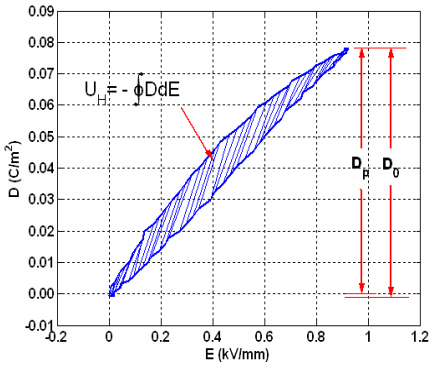
LabView test control & data acquisition

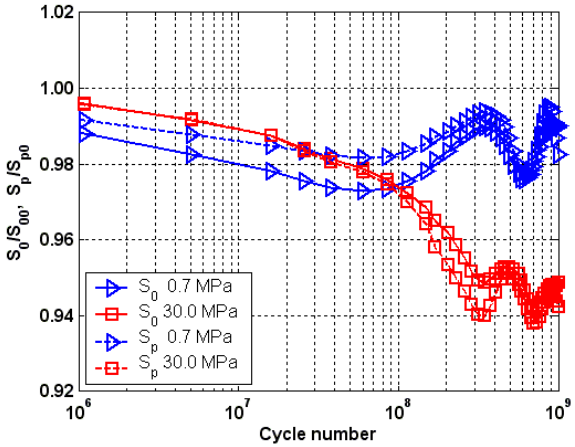
High voltage & high frequency amplifiers

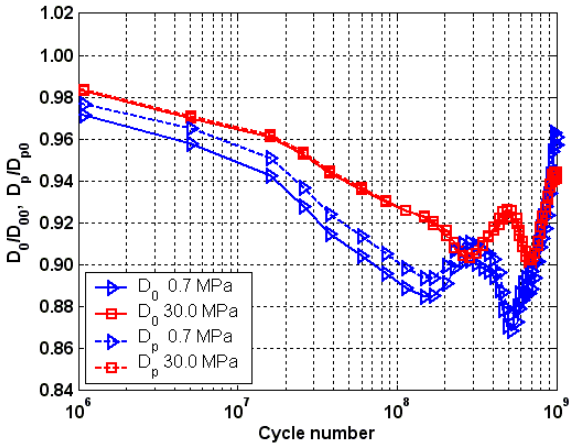
Accomplishments (continued)

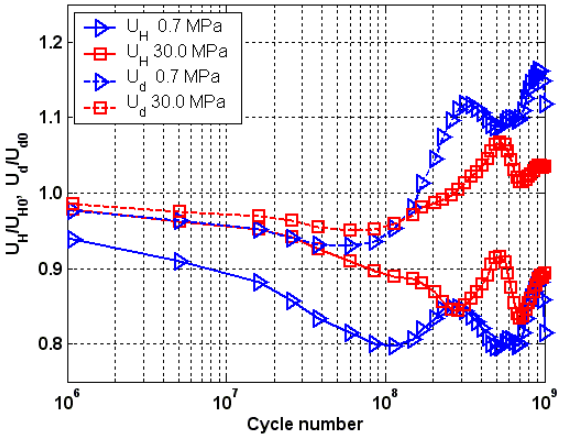
- **Fatigue responses of a PZT-5H multilayer piezoactuator under unipolar electric cycling with a preload were analyzed.**









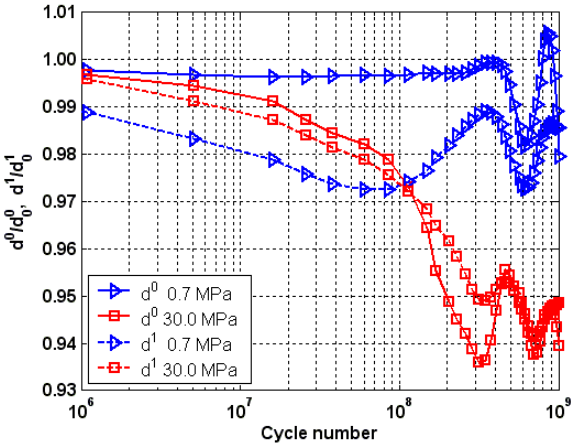


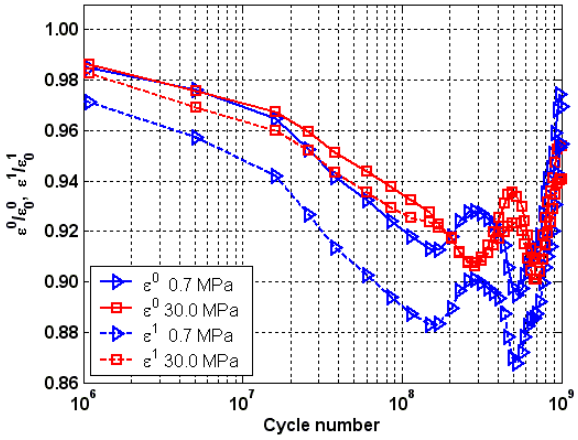
Accomplishments (continued)

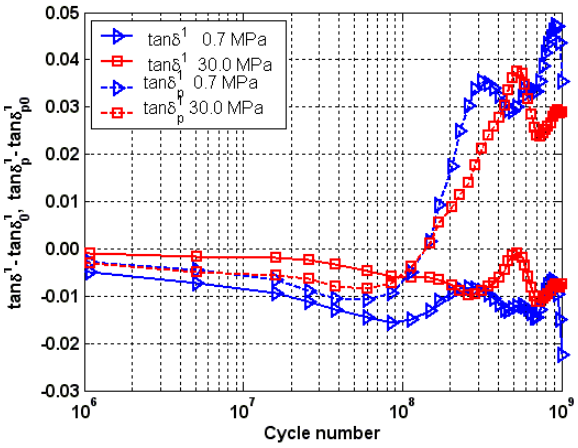
- **The fatigue responses of the PZT-5H multilayer piezoactuator under unipolar electric cycling were characterized using Fast Fourier Transformation (FFT).**

$$d^* = d' - jd'' = de^{-j\delta_p}$$

$$\varepsilon^* = \varepsilon' - j\varepsilon'' = \varepsilon e^{-j\delta}$$







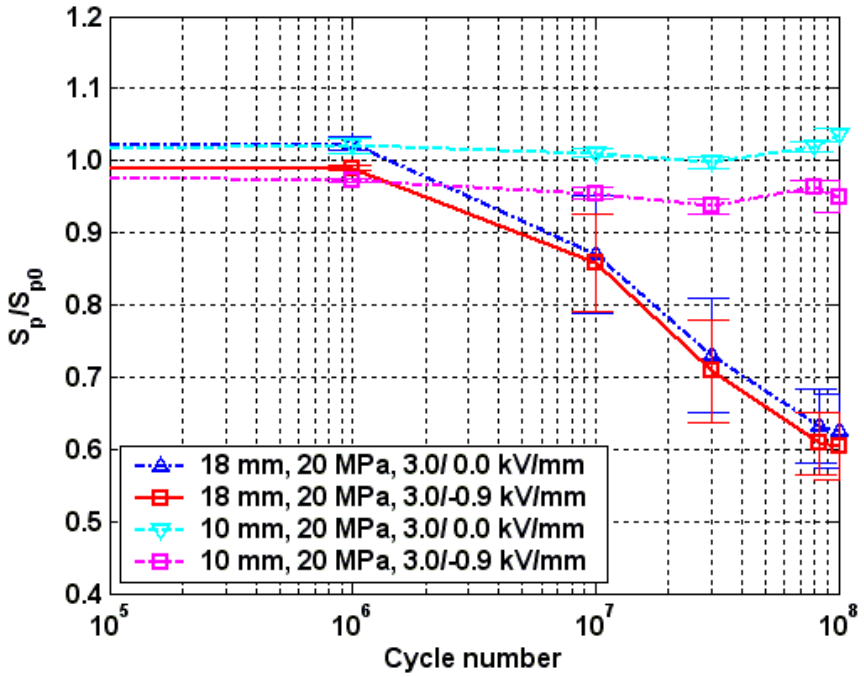
Accomplishments (continued)

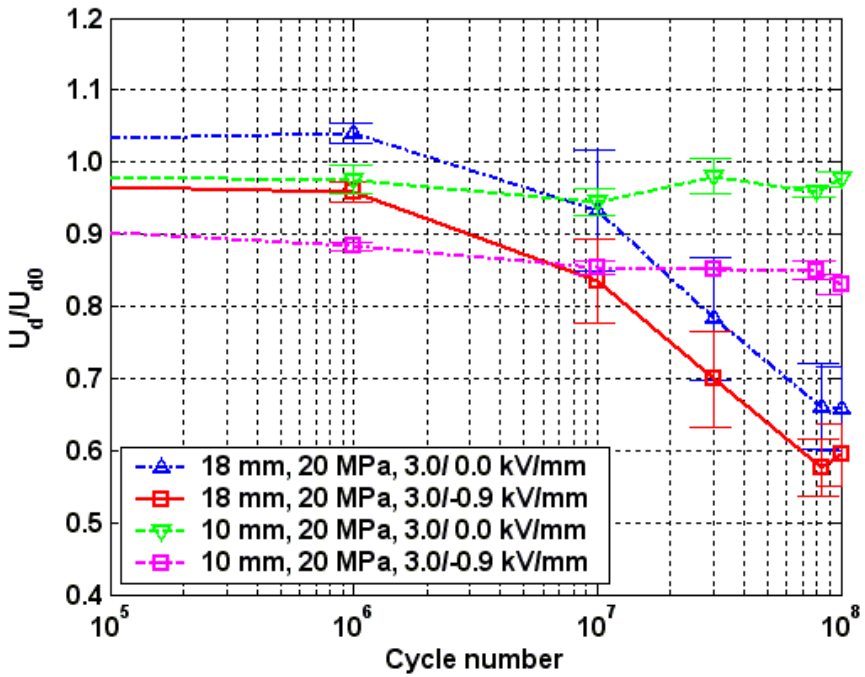
- **Two sizes of PZT-5A stacked multilayer piezoactuator were tested.**

No.	Size	Stack	Preload	Electric cycling load	Cycles	Condition	Test date
	mm^3		MPa	kV/mm, Hz	10^6		
01	5x5x18		20	+4.5/-0.9, 100	-	As-received	5/20-5/23/08
02	5x5x18		20	+4.5/-0.9, 100	100	As-received	5/27-6/17/08
03	5x5x10		20	+4.5/-0.9, 100	100	As-received	6/30-7/9/08; 8/3-8/15/08
04	5x5x10		20	+4.5/-0.9, 100	100	As-received	7/15-8/1/08
05	5x5x18		20	+4.5/-0.9, 100	185	As-received	8/18-9/24/08
06	5x5x18		20	+4.5/-0.9, 100	100	PMMA, 40μm	9/24-10/11/08
07	5x5x18		20	+4.5/-0.9, 100	100	As-received	10/21-11/5/08

Accomplishments (continued)

- **Variations of mechanical strain and piezoelectric hysteresis in cycling fatigue have been analyzed.**

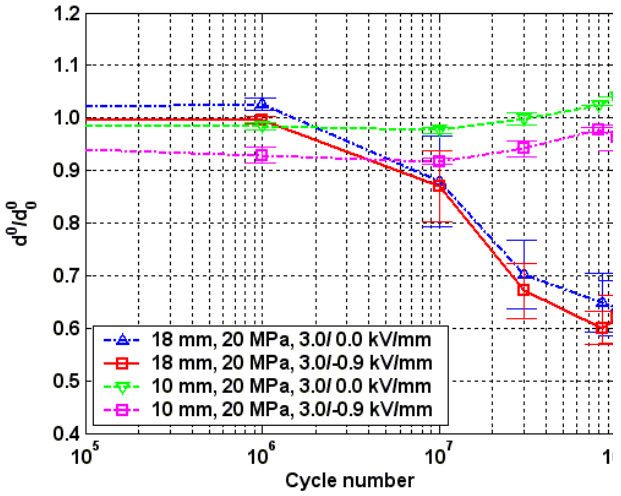


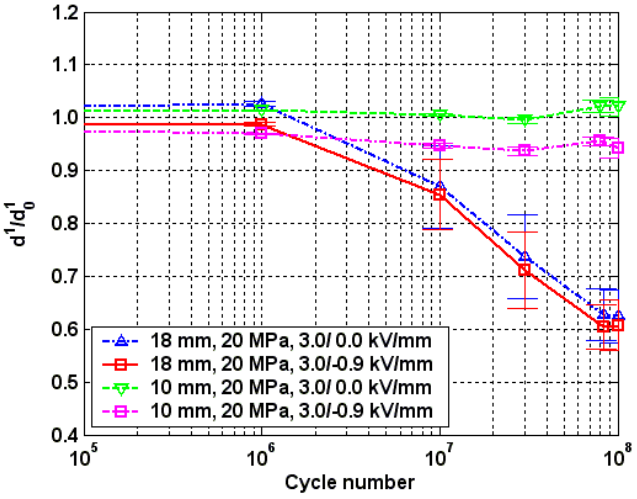


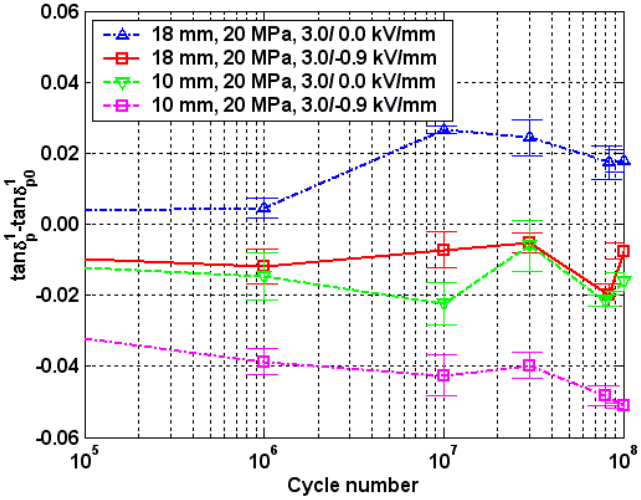
- **Normalized values are the averaged results of PZT stacks tested.**
- **Variations of mechanical strain and hysteresis were related to stack size.**

Accomplishments (continued)

- **The piezoelectric fatigue responses have been analyzed and characterized by using FFT.**





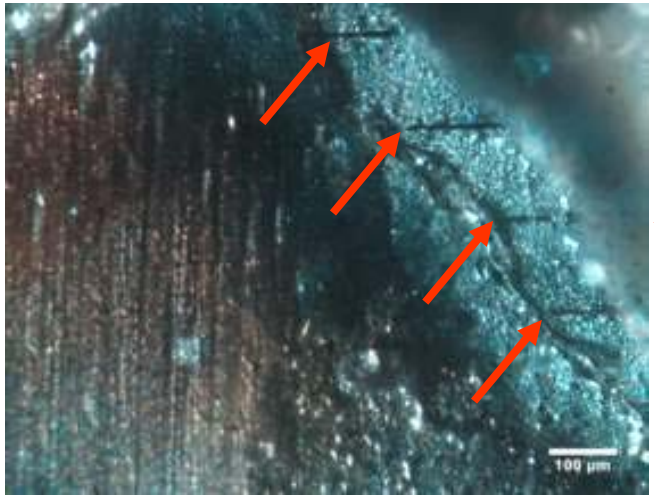


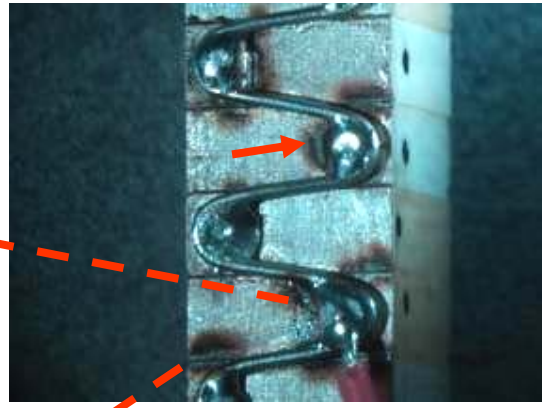
➢ **Variations of piezo coefficients and loss tangent were related to stack size.**

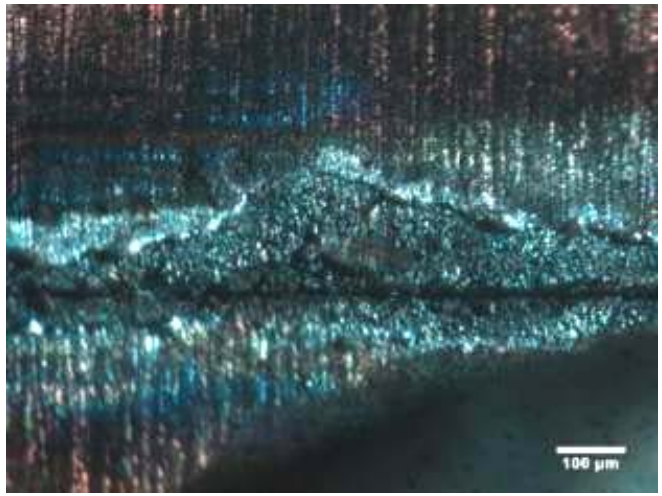
➢ **DC (d0) and 1st harmonic (d1) reduced ~ 40% for the larger stacks, but only ~ 5% for the smaller stacks.**

Accomplishments (continued)

- **Surface deterioration was observed and analyzed in tested PZT-5A multilayer piezoactuator .**



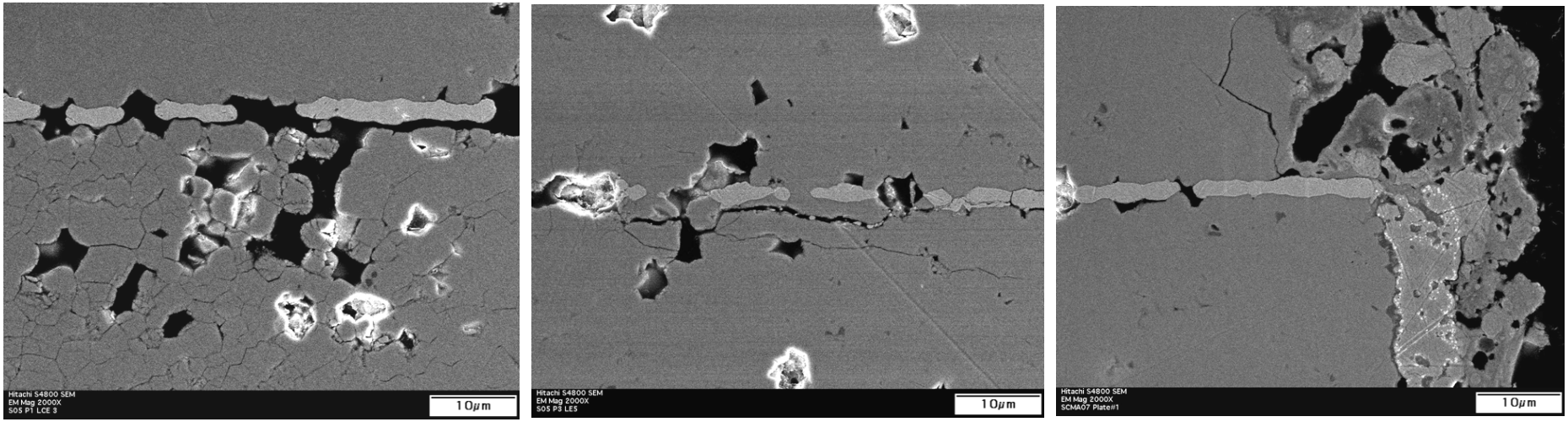




- **Optical images for the positive electrode side of multilayer piezoactuator after 185M cycles.**
- **Colored (significant arcing) areas occurred near bases of solder joint and interfaces between plates.**

Accomplishments (continued)

- Microstructure in fatigued multilayer piezoactuator was characterized using SEM.
- Interface delamination, electrode erosion, and secondary pores, and cracks were observed.



➢ Images of PZT-5A multilayer piezoactuator after 185 million cycles for plate 1 (left) and plate 3 (middle and right).

➢ The cross section is approximately along the solder joint axis near the positive electrode side.

Future Work

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

Summary

- A piezodilatometer has been designed, built, and calibrated.
  - ✓ The piezodilatometer equipped with an oil bath enables the accelerated fatigue test on piezoceramics and PZT multilayer piezoactuators
- Piezoceramic discs were tested under a variety of electro mechanical loading conditions:
  - ✓ Ball-on-ring testing was conducted under 3 to 4 times the coercive field levels in both electric direction with respect to poling direction.
  - ✓ Piezodilatometer testing was conducted under both quasistatic and dynamic loading conditions.
- Characterization method on fatigue responses of a tested PZT multilayer piezoactuator has been developed by using Fast Fourier Transformation.
- Fatigue tests on PZT multilayer piezoactuator have been extended to semi-bipolar electric loading mode.
  - ✓ This work will answer how much an electric driving can be pushed toward the negative direction.
  - ✓ Semi-bipolar driving was proved to be an effective approach to accelerating the electric fatigue process of a PZT multilayer piezoactuator .
- A 3-years Cummins-ORNL CRADA has been officially approved and the kick-off meeting was held at Cummins Inc.