Actuator Components and Technology (ACT)

Final Program Review
DARPA Technology Interchange Meeting
Baltimore, MD; June 26, 2000

Presented by
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TRS Ceramics, Inc.

Outline

I. Program Goals

II. Consortium Accomplishments
- A. TRS
- B. Georgia Tech.
- C. Matsys
- D. PSU
- E. ACX
- F. Boeing

III. Overview of the AXIS Consortium

IV. Summary

ACT Program Goals

Develop High Strain Energy Density, High Reliability Piezoelectric Actuators Using Advanced Materials:

1) **High Strain (> 1%) Single Crystal Piezoelectric Actuators**

2) **High Stiffness Actuators from Cofiring, Diffusion Bonding, High Stiffness Alternatives to Epoxy**

3) **Increased Strength from Fine Grain Ceramic for Higher Strain (High Drive) and Improved Reliability**

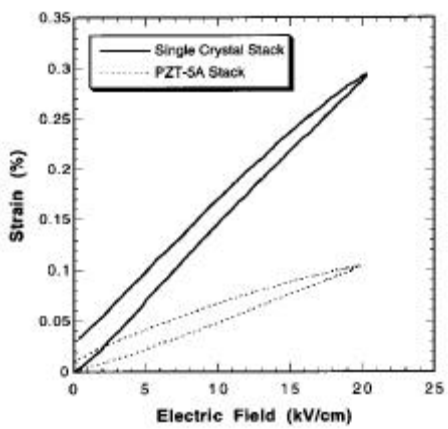
4) **Intelligent Process Controls for Improved Ceramic Quality and Reliability**

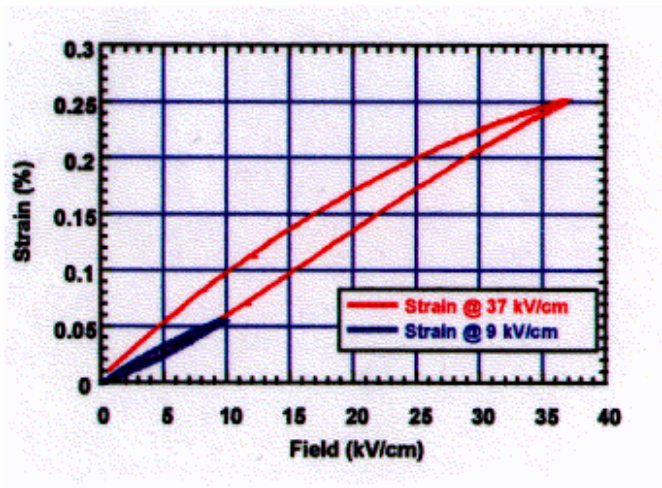
5) **Strain vs. Field, Stress, Frequency & Temperature of New Materials Reliability of New Materials**

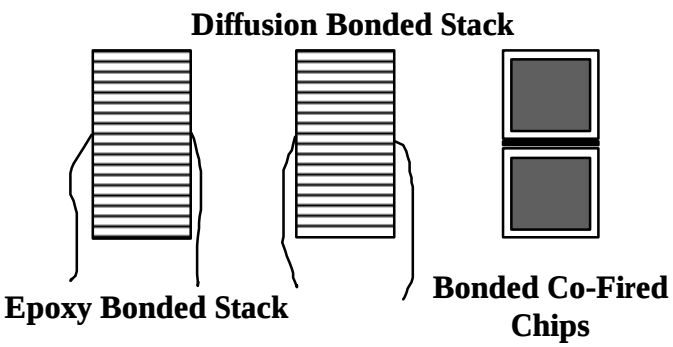
6) **Performance Evaluations in Smart Structures**

Strain Energy Density Improvements

$$e = \frac{1}{r4}\left(\frac{1}{2}\left(Ee^2\right)\right)$$







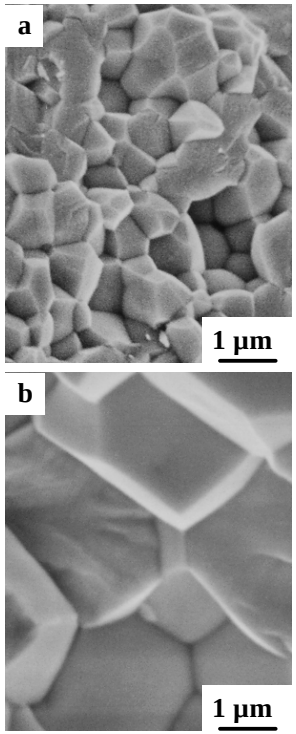
Single Crystal Stack > 3X Strain
Strain Energy Density > 5X

High Drive of Fine Grain Actuators
Strains ~ 0.25%

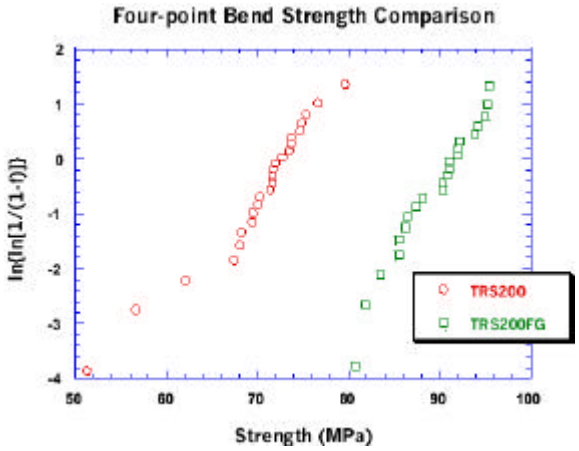
High Stiffness Bonding Materials
Epoxy Modulus ~ 4-5 GPa
Ni (Diffusion Bond) = 200GPa
Proprietary Stiff Bond Material ~ 60GPa
PZT ~ 50 - 60 GPa

Reliability Improvements

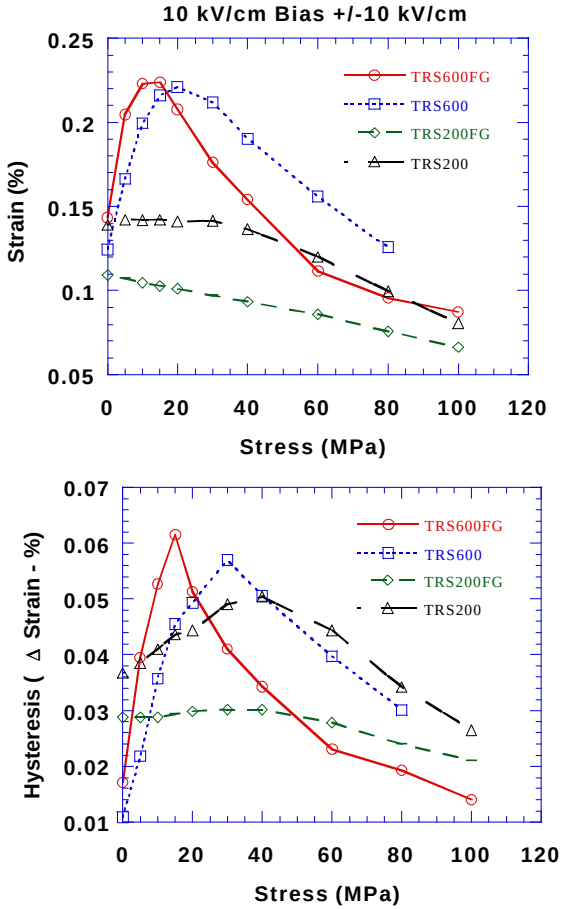
Fine Grain Ceramics



Increased Strength



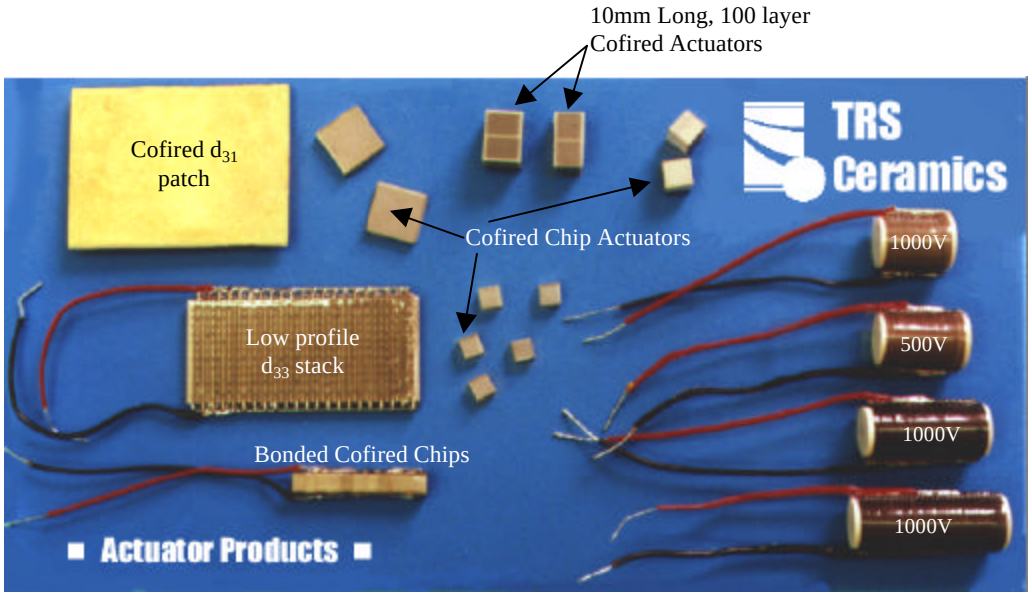
Greater Domain Stability Reduced Hysteresis



Program Achievements

- Fine Grain PZT and Single Crystal Actuator Properties Characterized
- TRS Fine Grain Actuators Demonstrated to Have Very High Strain Energy Compared to Other Manufacturers -- M. Mitrovic, G. Carmen, & F. Straub
- 10^9 Cycles Demonstrated @ 20 kV/cm, 30 Mpa, & 300 Hz
- High Stiffness Bonding Material Developed for Long Co-fired Actuators
- Diffusion Bonded Actuators Demonstrated with Cu & Ni Electrodes
- Single Crystal Stack Constructed > 2x Higher Strain than Ceramic
- Improved Passive Damping with Low Profile d_{33} Stacks
- Fine Grain Cofired Actuators Developed 7mm x 7mm x 10mm, 100 Layers; Ag/Pd Cofiring Demonstrated

TRS Accomplishments: Actuator Development



Fine Grain Stacks

1) **Fine Grain Stacks (500 - 1000V)**

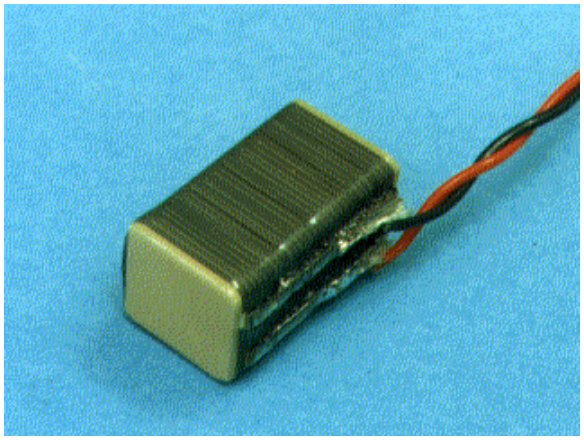
2) **Low Profile d_{33} Stacks**

3) **Cofired Multilayers (7x7x10mm)**

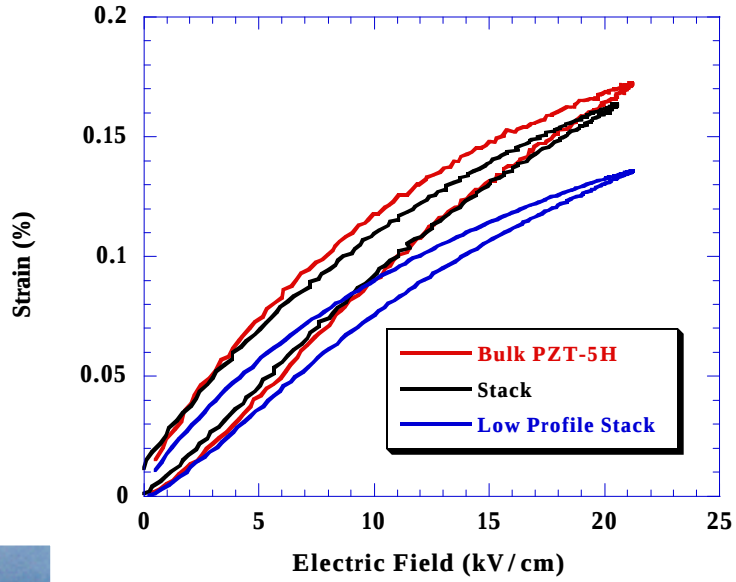
4) **d_{31} Cofired Multilayer Patches**

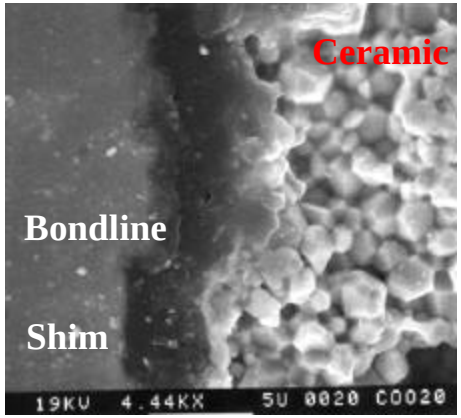
5) **Glass Bonded Stacks (Cofired Segments)**

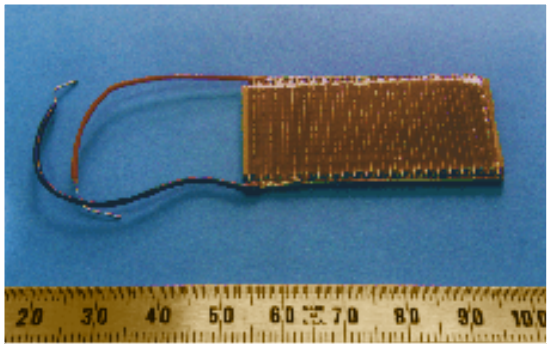
Epoxy Bonded Stacks



Fine Grain Stack

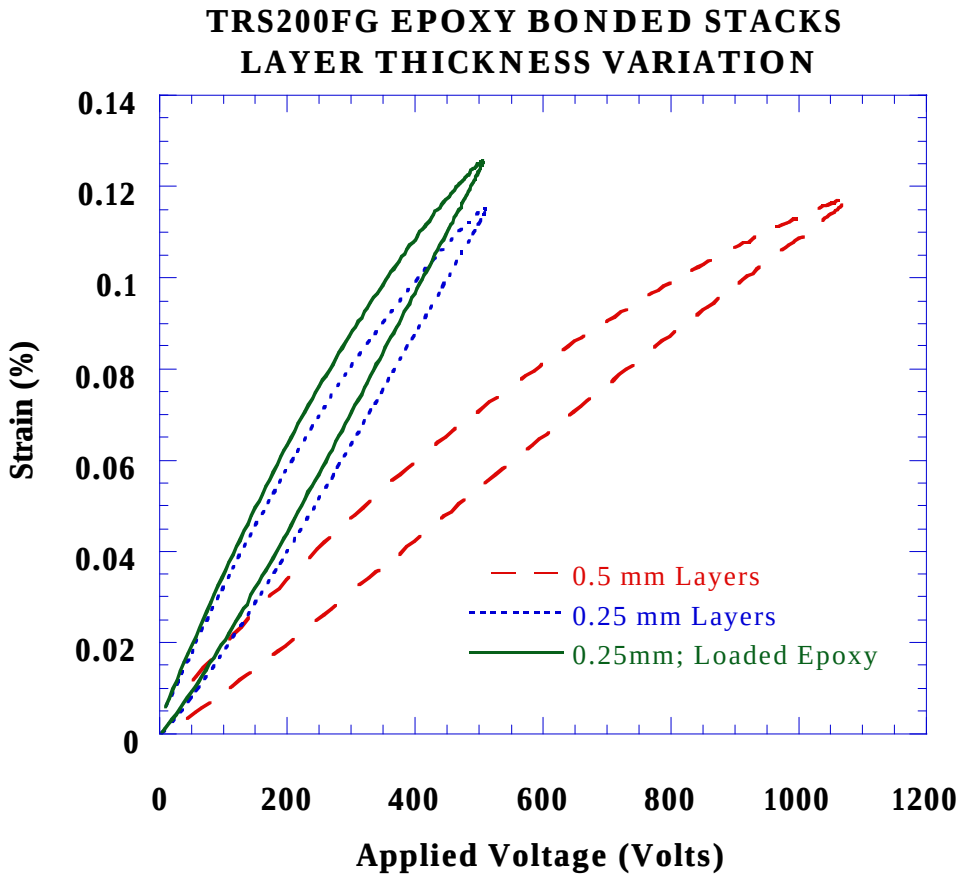






Low Profile Stack

Reduced Layer Thickness: 500V Stacks



Issues:

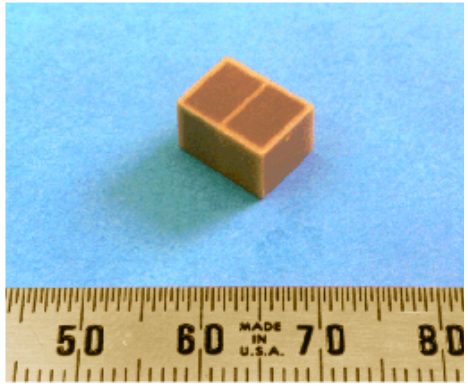
- Reduced Stiffness from Increased # of Epoxy Bonds
- Reduced Strain due to Clamping from Shim

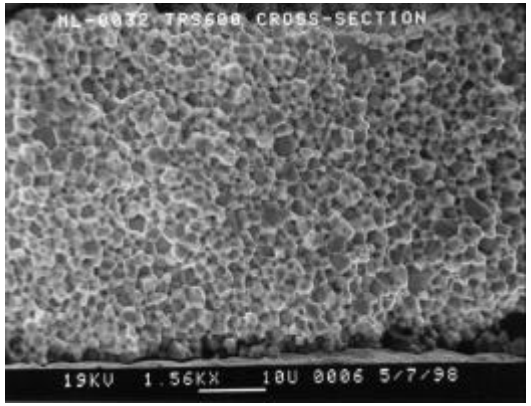
Solutions:

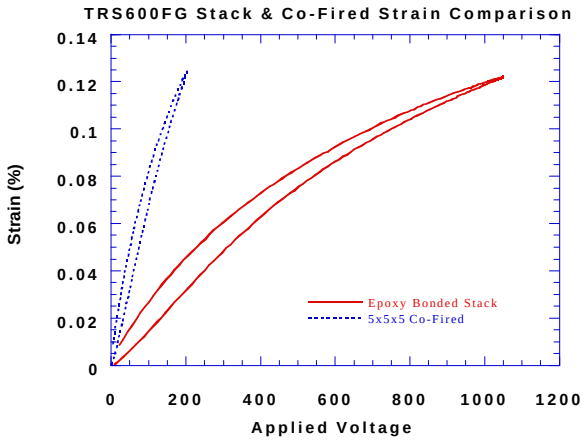
- Ceramic Loaded Epoxy Electric Contact Still Maintained
- Thinner Shims; 0.5 mils Possible

Cofired Actuators

Maximum Size:
7mm x 7mm x
10mm
100 Layers



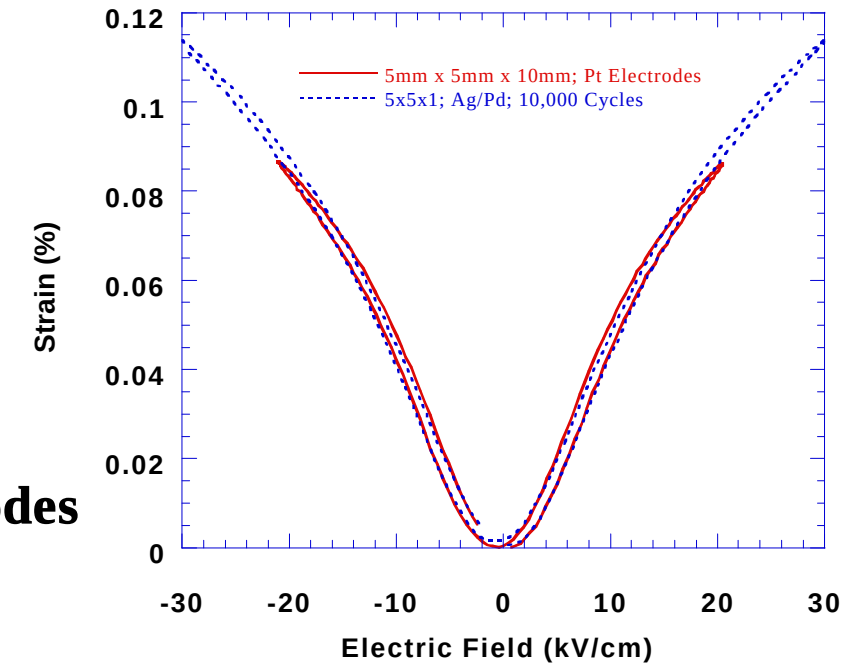




Conventional and Fine Grain Ceramic

ACT Advances in Co-Fired Actuators

- **Low Fire PMN-PT & Type II PZT**
- **Both Achieved with Fine Grain Processing**
- **Used for Cofiring with Ag/Pd Electrodes:**
  2 to 3x Cost Reduction
- **Beginning to Investigate Base Metal Electrodes**
  5 to 10x Cost Reduction



Georgia Tech. Accomplishments

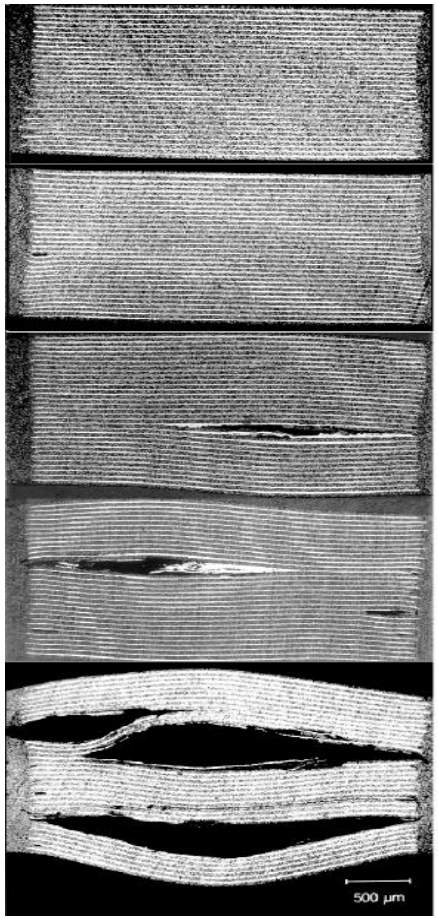
Dr. Robert Speyer: Process Characterization of Cofired Actuators

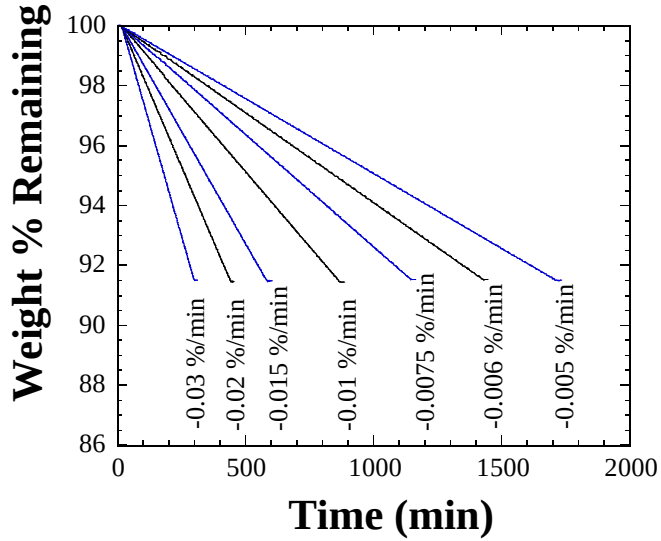
- Rate Controlled Binder Burnout
- Burnout Characterization / Optimization
- Cofiring Characterization

Dr. Chris Lynch: Material and Actuator Electromechanical Characterization

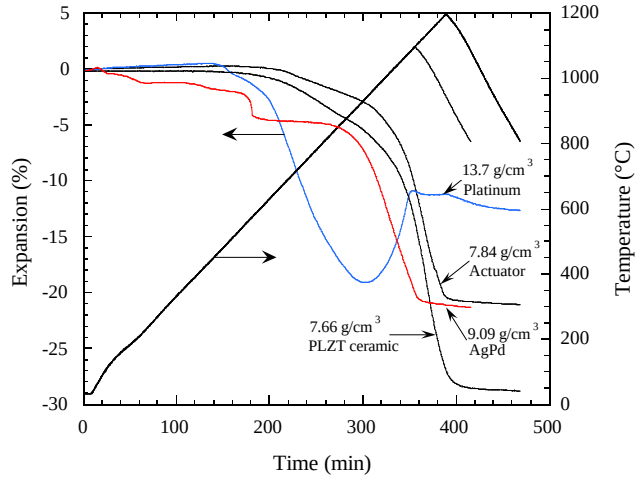
- Electromechanical Constitutive Behavior
- Actuator Efficiency
- Fracture Mechanics

Georgia Tech.: Cofiring Characterization





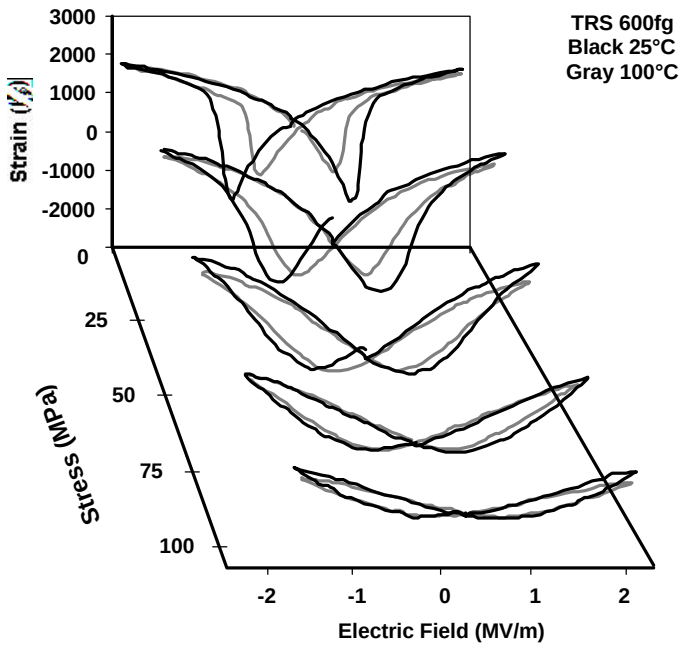
Rate Controlled Burnout

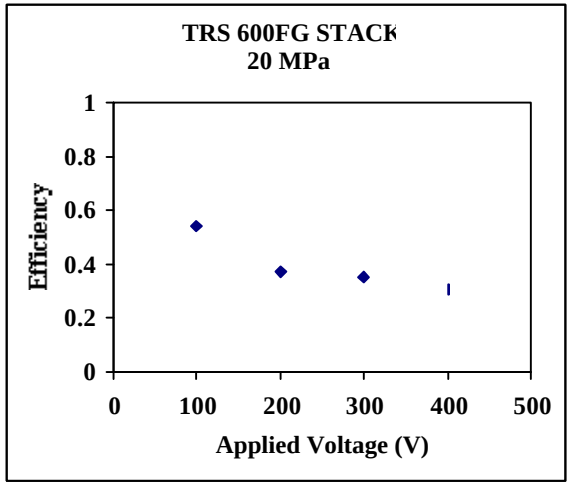


Cofiring Characterization

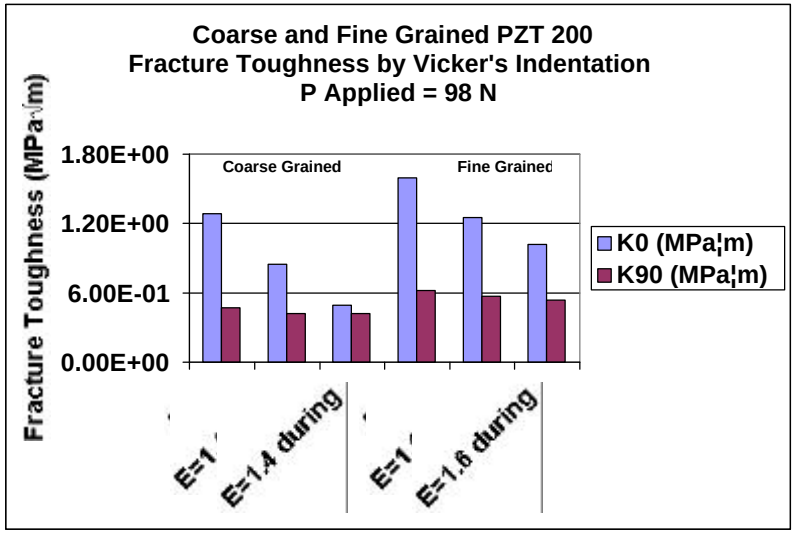
Georgia Tech.: Electromechanical Characterization

Constitutive Behavior





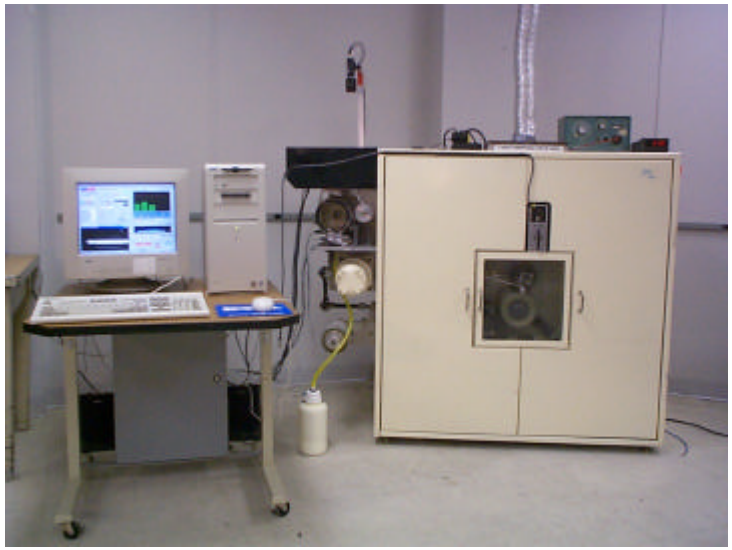
Actuator Efficiency

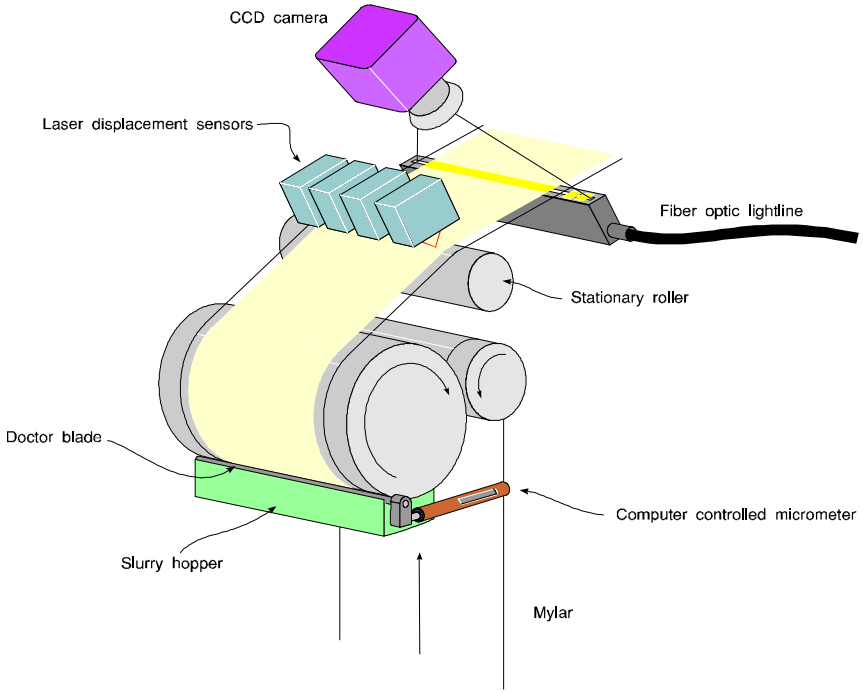


Mechanical Properties

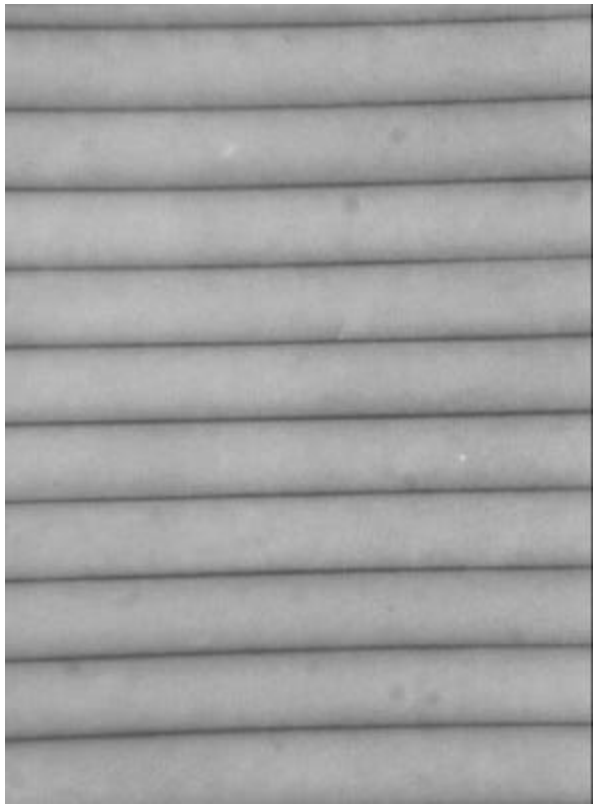
MATSYS: Intelligent Process Controls

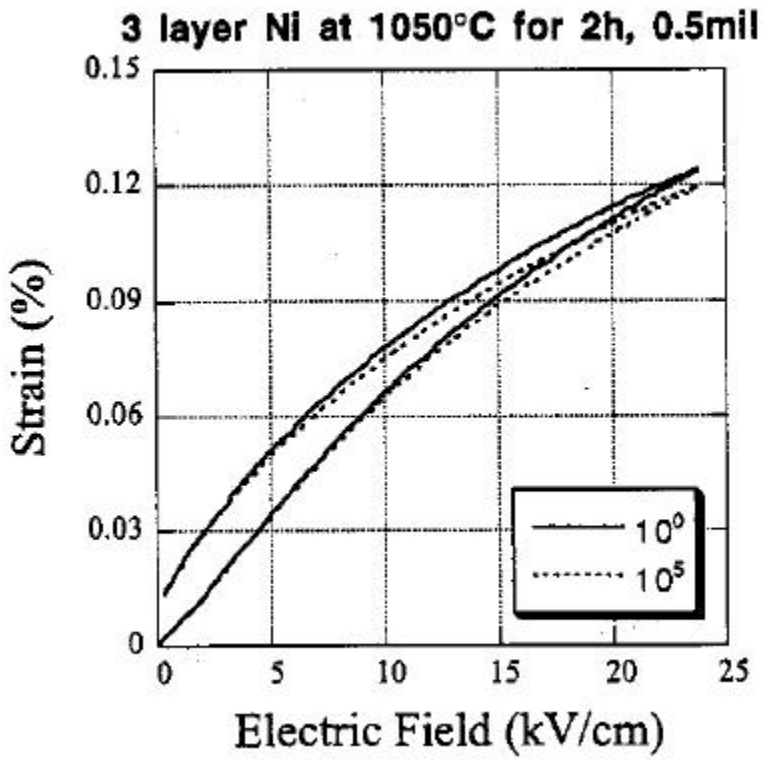
Tape Casting: Precision Thickness Control & Green Density Profiling





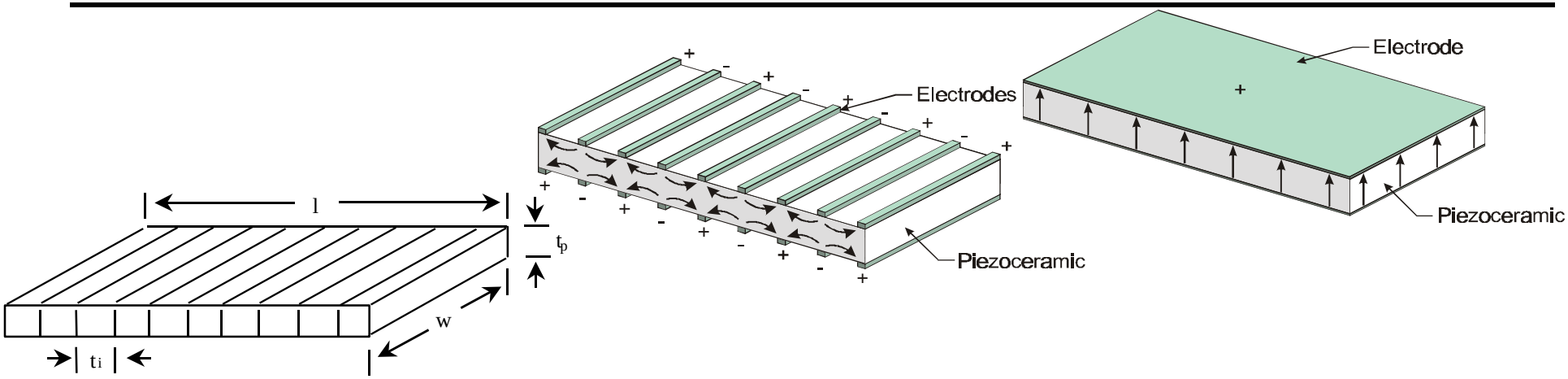
Penn State: Diffusion Bonded Stacks

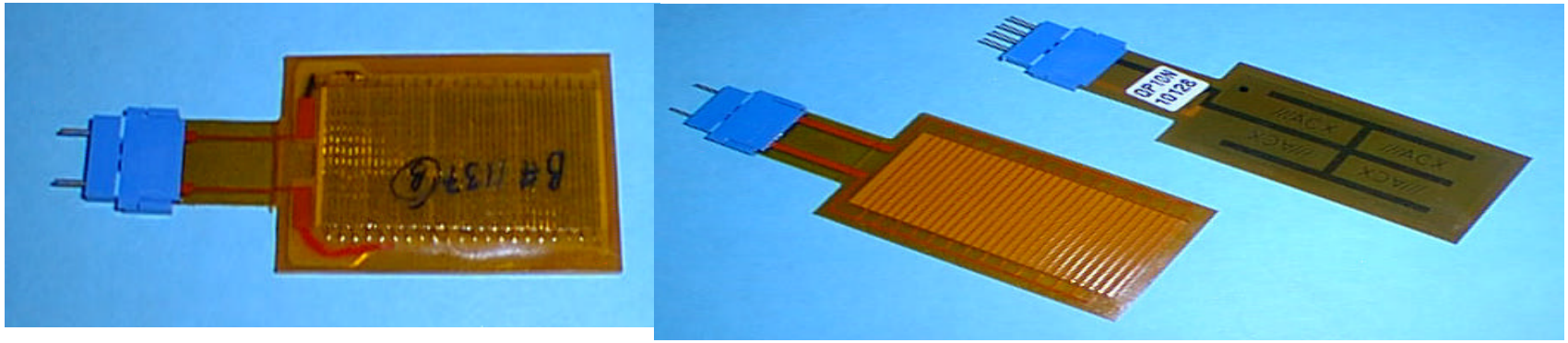




Diffusion bonded multilayer actuator of 1 mm PZT plates.

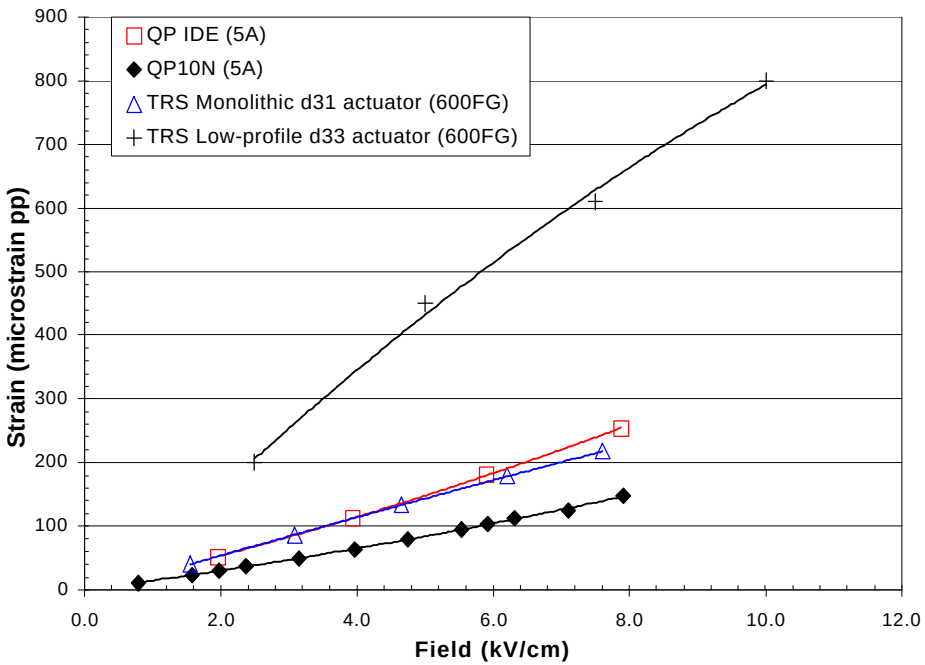
ACX: Low Profile d_{33} Actuator Patches

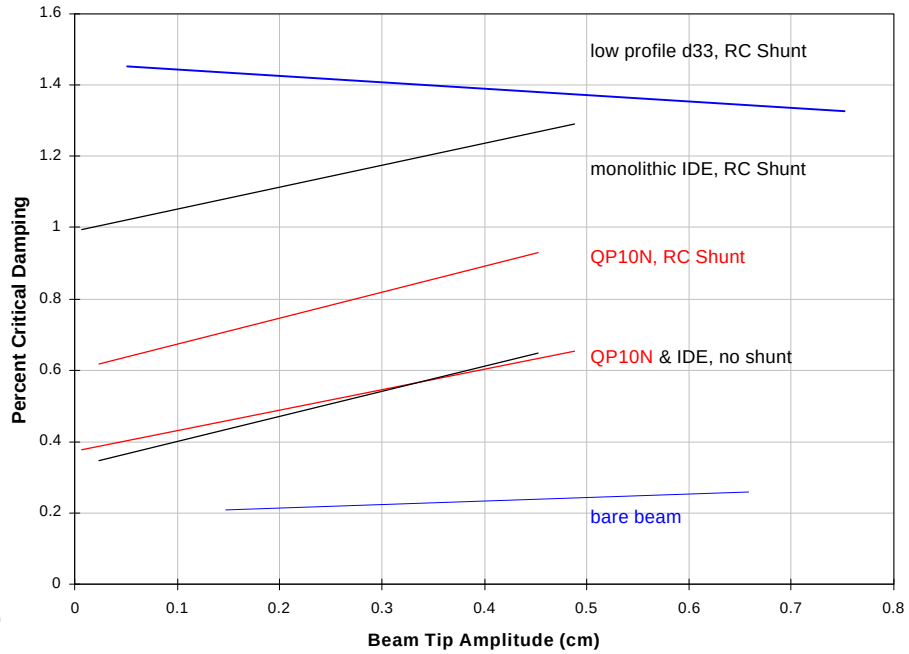




TRS low profile d_{33} stack (left), IDE electrode pattern (Middle), and conventional electrode pattern for d_{31} patch (right).

ACX: Low Profile Actuator Performance Comparison





Actuation and damping properties

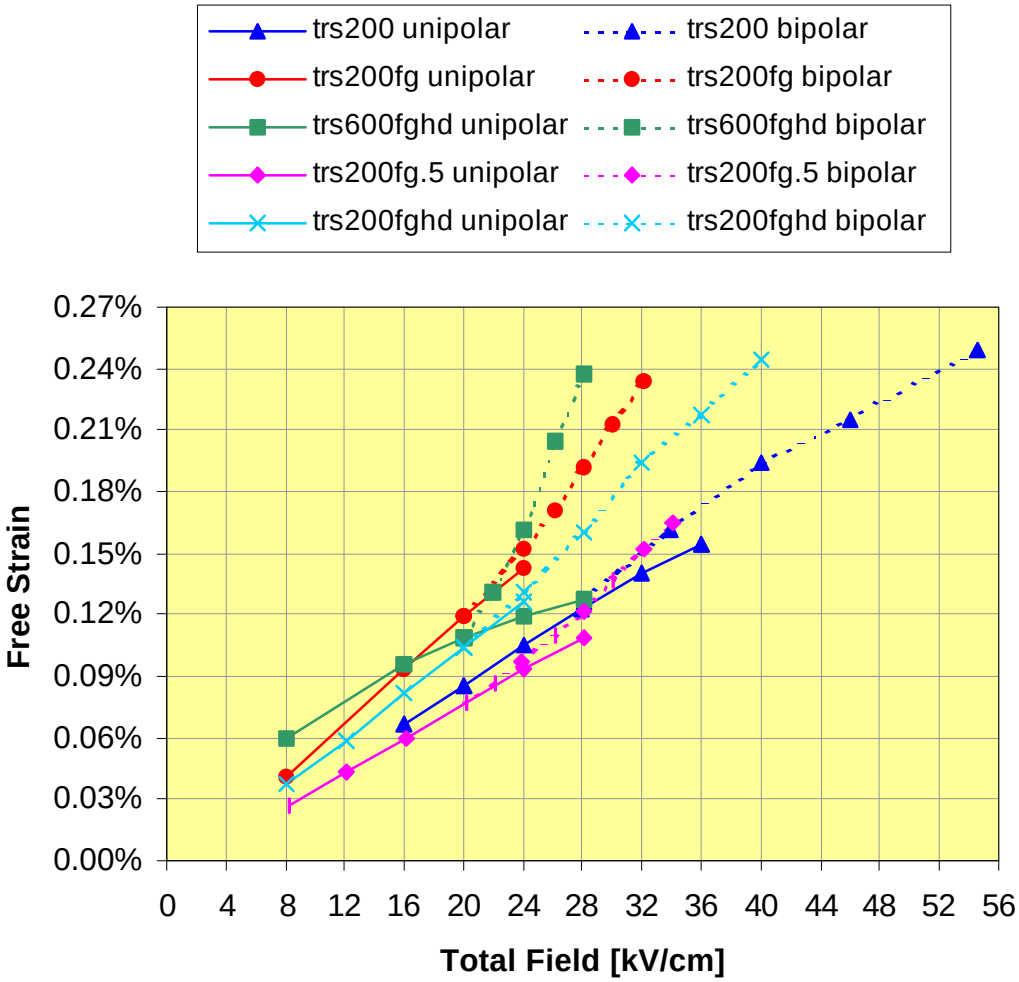
Low profile d_{33} > monolithic IDE > conventional d_{31}

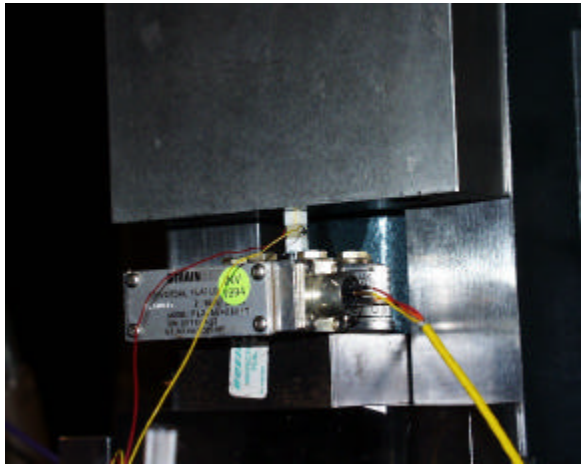
Boeing: Actuator Evaluation for Smart Structures

- Objectives:
  - Quantify metrics used for actuator evaluation
  - Identify improvements in materials and construction
  - Determine suitability for applications
- 8 different material and geometry combinations
- 3 different types of tests: free strain, blocked stress, dynamic loading
- Vary field and loading conditions
- Stack heating due to electrical excitation

	units	TRS200	TRS200FG	TRS200FG	TRS600FGHD	TRS200FGHD
equivalent		PZT-5A	PZT-5A	PZT-5A	PZT-5H	PZT-5A
batch		lot 2	C-0019	C-0020	C-0017	C-0021
L	cm	1.49	1.40	1.71	1.40	2.90
t	μm	500	500	250	500	500
C	nF	42.2	66.4	215	116	134

Boeing: Free Strain Measurements

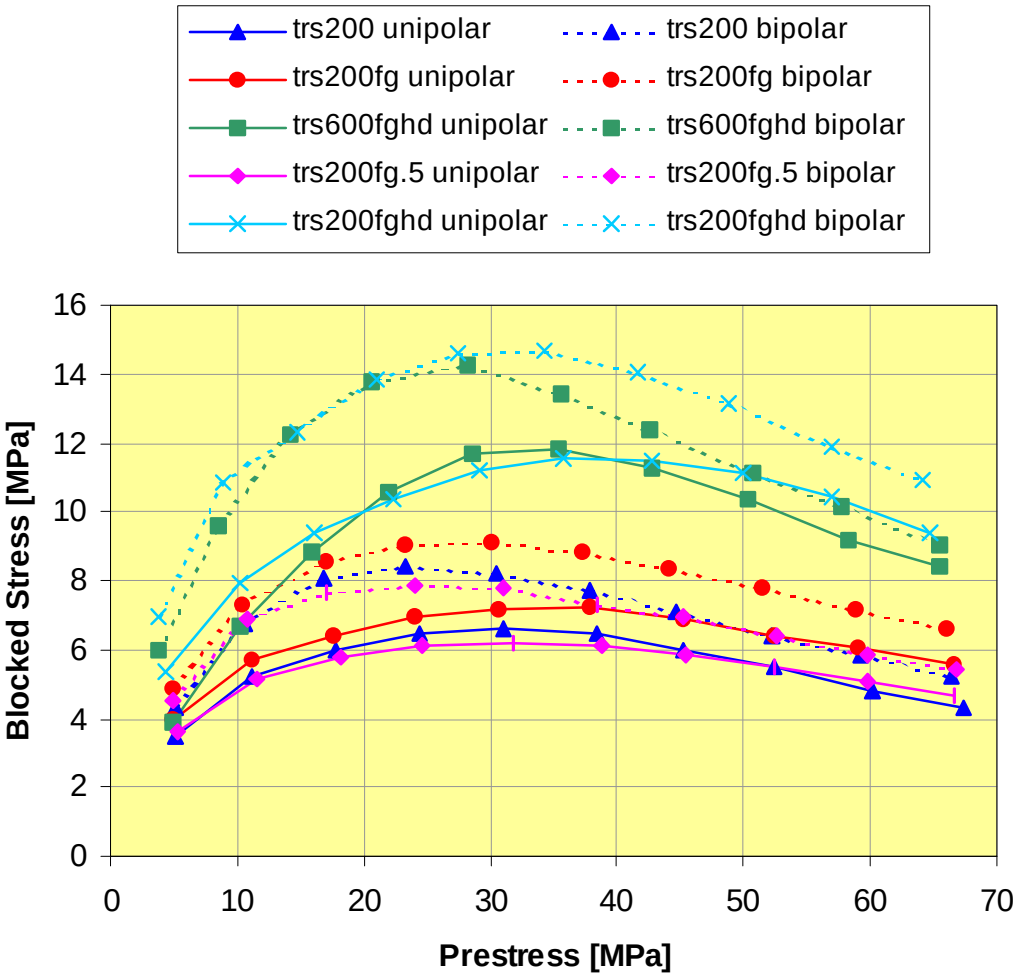




Notes:

- best unipolar at 24 kV/cm: TRS200FG
- best bipolar at 24 kV/cm: TRS600FGHD

Boeing: Blocked Stress Measurements



Notes:

- best unipolar (0 – 24 kV/cm):
  TRS600FGHD
  11.8 MPa max at 34 Mpa
  (1.7 ksi max at 5 ksi)
- best bipolar (-6 – 24 kV/cm):
  TRS200FGHD
  14.7 MPa max at 35 Mpa
  (2.2 ksi max at 5 ksi)
- all maximums occur between 24 and 36 MPa (3 and 5 ksi)

Boeing: Energy Density

- TRS200FGHD and TRS600FGHD are best overall performers based on free strain and blocked force results

TRS200FGHD pros

- more linear
- more resilient to depolarization
- more negative coercive field (allows higher peak to peak field)
- stiffer (higher blocked stress for given field)
- lower power consumption (capacitance)

TRS600FGHD pros

- less strain-field hysteresis (perhaps less heating)
- higher free strain for given applied field

stack	field (kV/cm)	blocked stress (MPa)	peak to peak strain (με)	energy density (J/m^3)	field (kV/cm)	blocked stress (MPa)	peak to peak strain (με)	energy density (J/m^3)
TRS200FGHD	0 to 24	11.6	1306	7555	-8 to 24	30.9	1978	30560
TRS600FGHD	0 to 24	11.8	1329	7848	-6 to 24	25.4	2300	29210

Summary

- **TRS Fine Grain Actuators Demonstrated to Have Very High Strain Energy Compared to Other Manufacturers**
- **Diffusion Bonded Actuators Demonstrated with Cu & Ni Electrodes**
- **Improved Passive Damping with Low Profile d_{33} Stacks**
- **Fine Grain Cofired Actuators Developed 7mm x 7mm x 10mm, 100 Layers; Ag/Pd Cofiring Demonstrated**
- **A Variety of Crystal Actuator Applications are being Investigated by the AXIS Consortium.**
- **Crystal Stacks have been Fabricated with Strain Equivalent to Bulk Crystal by using a Crystal Plate to Shim Thickness Ratio > 20.**