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Macro Fiber Piezocomposite Actuator Poling Study

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ABSTRACT

The performance and advantages of Piezocomposite Actuators are to provide a low cost, in-situ actuator/sensor that is flexible, low profile and high strain per volt performance in the same plane of poled voltage. This paper extends reported data for the performance of these Macrofiber Composite (MFC) Actuators to include 4 progressively narrower Intedigitized electrode configurations with several line widths and spacing ratios. Data is reported for max free strain, average strain per applied volt, poling (alignment of the electric dipoles of the PZT ceramic) voltage vs. strain and capacitance, time to poling voltage 95% saturation. The output strain per volt progressively increases as electrode spacing decreases, with saturation occurring at lower poling voltages. The narrowest spacing ratio becomes prone to voltage breakdown or short circuits limiting the spacing width with current fabrication methods. The capacitance generally increases with increasing poling voltage level but has high sensitivity to factors such as temperature , moisture and time from poling which limit its usefulness as a simple indicator. The total time of applied poling voltage to saturate or fully line up the dipoles in the piezo-ceramic was generally on the order of 5-20 seconds. Less sensitivity to poling due to the applied rate of voltage increase over a 25 to 500 volt/second rate range was observed.

1. Introduction

The purpose of this research project is to characterize the performance of different Electrode configurations of the Piezo-ceramic Macrofiber Composite (MFC) Actuators fabricated at NASA Langley Research Center. The MFC consists of a sandwich of 2 layers of inter-digitized electrodes etched on Pyralux film with a rectangular Piezo-ceramic sheet made of diced longitudinal fibers in the middle. These Actuators have been previously described in the paper *Low-Cost Piezocomposite Actuator for Structural Control Applications* [1] in which details of the construction are laid out along with performance data including strain per volt, operational endurance, and fabrication variability for Electrode configurations with pitch (centerline distance between inter-digitized electrodes) of .042 inches (42 mils) and .021 inches consisting of 7 mil and 5 mil line widths respectively. In this paper electrode configurations 7-42,6-30,5-21,and 4-12 are fabricated and performance tested. In describing the Actuators, The electrode line width is stated followed by a 'dash' with the pitch. Thus 7-42 refers to a electrode line with of 7 mils with the electrode centerlines 42 mils apart, leaving a Pyralux insulation width of 35 mils. Longitudinal strain gages [1]are used on the top and bottom electrode/Pyralux layers to indicate microstrain (mils deflection/inch) The stain /volt output, Piezo modulus or strain coefficient (d_{11}) is higher with greater coupling than previous configurations such as perpendicular poling to strain (d_{31}). Testing consists of the parameters of poling voltage levels vs. strain/volt output and effects of total time of applied poling voltages. Capacitance is compared to strain as a indication of poling voltage effects. Finally the Stain performance of the actuators is shown with a low frequency (0.1 Hz Sine wave of positive and negative applied voltage to a specimen that is a least 95% fully poled. This Plot is referred to as Butterfly Plot due to the shape of the hysteresis curve of Microstrain vs. applied voltage.

2. Procedure

[1] Sigma Plot 5.0 SPSS Inc. 233 South Wacker Dr. Chicago, Ill.

The Micro-fiber Composite (MFC) Actuators were fabricated as previously described in detail [1] and will only be summarized below:
Identical electrode patterns consisting of Copper deposited on polyamide film (Pyralux LF 8510) [2] are placed on either side of rectangular cross sectional separated longitudinal fiber sheet with an active piezo-ceramic area of 3.375 by 2.25 inches of Lead Zirconate titanate (PZT) ceramic [3]. A 2-part Epoxy [4] is used between the fibers and with a thin bondline to ‘glue’ the layers together. The laminate is cured with two steps of pressure applied with Aluminum/Teflon/elastic layered plates at elevated temperature and vacuum under 300-400 psi. Wire leads are soldered on and strain gages [5] bonded to the Actuator Longitudinal center line top and bottom. The interdigitized electrodes consist of alternating positive and negative lines which under an applied voltage generate an electric field through the longitudinal piezo-ceramic fibers. Table 1 below are the Samples fabricated for this project. The Samples were made in batches of 1-3. See Figure 1 for the completed Actuator with strain gage.

Table 1 Fabrication/ Testing Summarized

Batch (date)	**Types (identifying marks)**	**Press force (lbf)**	**Test performed (date)**
1 (8/22)	7-42	5000	Poll ,cap, strain cycle (9/4)
2 (9/19)	6-30 (●)	5000	Poll,cap,strain cycle (9/26)
2	7-42 (●●)		Poll, cap, strain cycle (10/4)
2	7-42 (●●●)	5000	Timed Poll ,cap, strain cycle (12/11)
3 (9/20)	6-30 (●)	5000	Poll ,cap, strain cycle (10/11)
3	5-21 (●●)	5000	Poll ,cap, strain cycle (10/16)
3	5-21 (●●●)	5000	Poll ,cap, strain cycle (11/16)
4 (9/29)	4-12 (●+)	5000	Poll ,cap, strain cycle (10/26)
4	4-12 (●●+)	5000	Poll ,cap, strain cycle (10/30)
4	3-6 (●●●+)	5000	Shorted electrodes
5 (10/12)	3-6 (+)	5000	Shorted
5	3-6 (++)	5000	Shorted
6 (10/18)	6-30 (*)	5000	Timed poll,cap,Strain cycle
6	6-30 (**)	5000	Timed poll,cap,Strain cycle
7 (10/25)	3-6 (Δ)	5000	Shorted
7	3-6 (ΔΔ)	5000	Shorted
8 (11/7)	4-12 (◊)	5000	Poll,.cap strain cycle
8	4-12 (◊◊)	5000	Shorted
9 (11/21)	4-12 (xxx)	5000	Poll.cap, stain cycle
9	4-12 (xx)	5000	Timed poll, cap, strain cycle
9	5-21 (x)	5000	Timed poll, cap, strain cycle
10 (12/6)	7-42 (F2)	4000	Poll.cap, stain cycle
10	4-12 (F1)	4000	Poll.cap, stain cycle

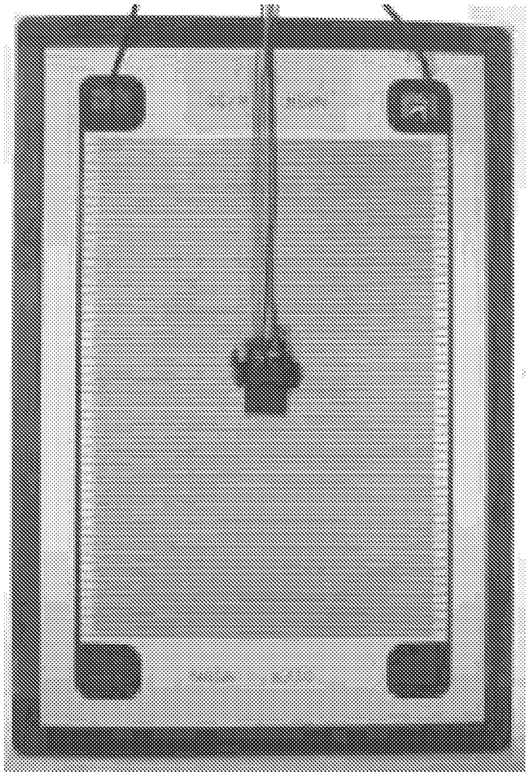


Figure 1 6-30 Actuator with top strain gage

A test fixture was designed to keep the actuators from flexing out of plane while allowing for non-constrained motion in both the longitudinal and transverse axis. This fixture was a 6 inch diameter PVC pipe with a loose friction ring on one end. The sides of the MFC and the top were loosely held in place with Scotch ® tape in order to maintain curvature of the MFC. These edge restraints were flexible enough to effectively maintain a free strain condition. See Figure 2.

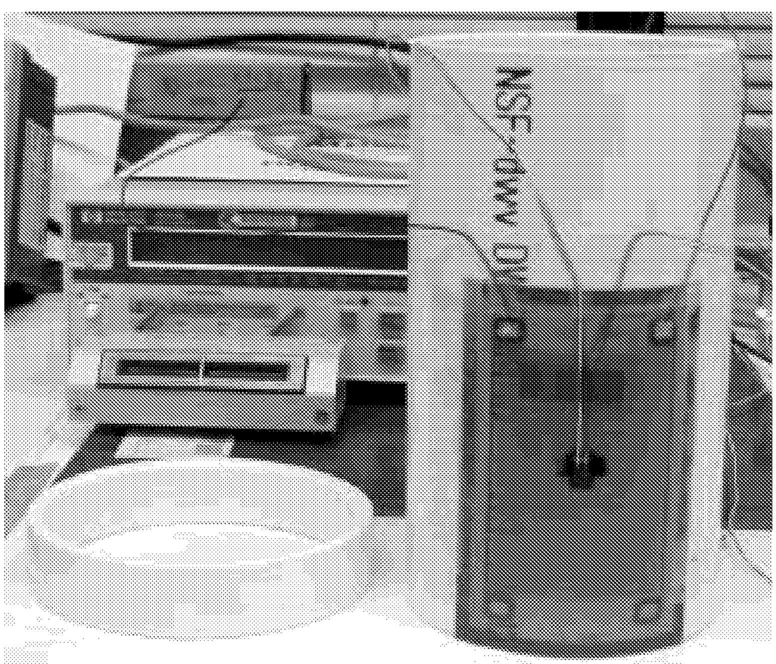


Figure 2 Mounted Actuator on PVC Pipe with End Ring

Computer controlled testing sequences:

Poling : To poll or apply a DC electrical field that enhances the piezoelectric effect inherent to the PZT, a test setup with an PC running Labview[2] data acquisition software was used to control and acquire data using a Trek power amp through a digital interface card.

Strain Cycling Tests: A similar setup is used with a PC running Labview[3] data acquisition through a Trek power amplified to provide controlled voltage. Also the top and bottom or back Strain gages are wired into a bridge completion circuit and monitored with the units recorded in Microstrain (x 10^{-6} inch per inch). The Software controls the frequency and amplitude of the applied sine wave voltage and reads current, voltage and Microstrain with the results stored and displayed on the Screen after the last complete cycle. See Figure 3 and 4.

Figure 3 Strain Cycling Test Setup

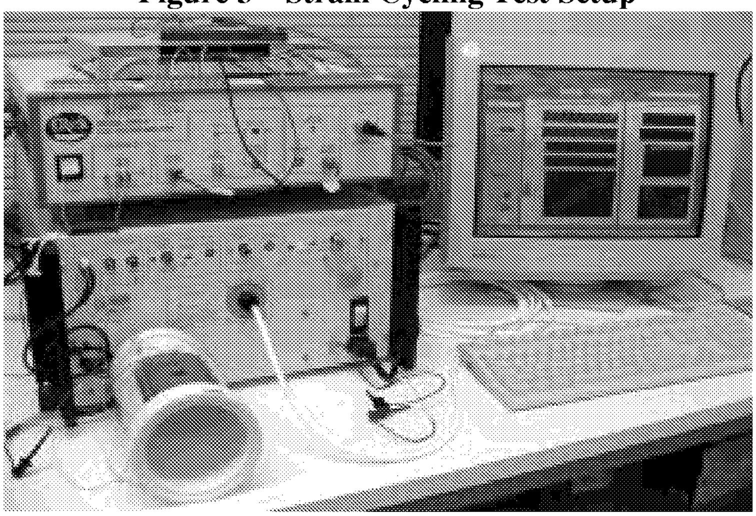
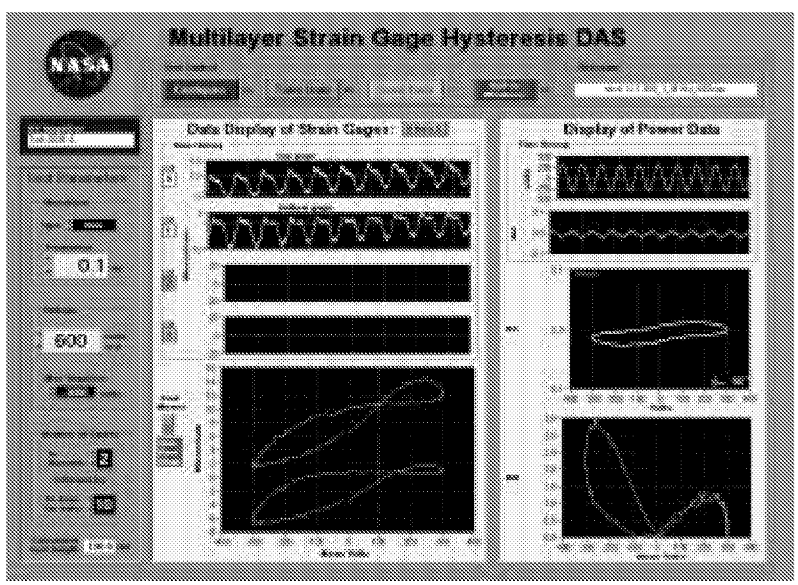


Figure 4 Computer post test Display Screen



[2] Labview software National Instruments
11500 N. Mopac Expwy Austin, Texas

Figure 5 Capacitance Testing:

The capacitance is measured following Poling and prior to the Strain Cycle Testing,
The HP 4263B Meter is hooked up to the actuator leads and read with 3 minutes allowed for the reading to stabilize for consistency see Figure 5.

Testing Sequence:
The Poling of the samples consisted of applying a DC voltage using a Computer running Labview [6] software controlling and acquiring data through an data acquisition interfaced Trek Amplifier.
The voltage was applied at a rate of 25 volts/sec and held for 1 minute at the specified voltage as shown in Table 2. After each poling voltage level the sample capacitance in Nanofaradays (nf) was measured using a HP Capacitance Meter performed after a 3 minute interval.

The specimens were tested for free microstrain vs. applied voltage using a PC with Labview [6] controlled amplifier applying a sine wave with voltage of 600 Volts peak-to-peak at 0.1 HZ -low Frequency to minimize higher frequency effects. Strain gage outputs were recorded at 128 points per cycle, averaged and displayed following 10 cycles. The Table shows the samples vs. Poled applied voltage DC for one minute:

Table 2

Configuration	7-42	6-30	5-21	4-12
Volts DC	300	250	200	150
	600	500	400	300
	900	750	600	450
	1200	1000	800	600
	1500	1250	1000	750
	1800	1500	1200	900
	2100	1750	1400	1050
	2400	2000	1600	1200
	2700	2250	1800	1350
	3000	2500	2000	1500

Timed Poling Sequence:

Based on the results of the poled sequence study a 95% value of fully saturated poling applied voltage for each electrode configuration are selected. Top and bottom strain gage Microstrain levels were averaged after averaging the Ten 0.1 Hz 600 volt Sine wave cycles used for the Strain cycle test. The 95% of full poling levels were read off the resultant graphs and also calculated by using Polynomial curve fitting per Sigma Plot software[7]. See table 3 below for the values used:

Table 3

Configuration	7-42	6-30	5-21	4-12
95% saturation Vdc	1840	1750	1290	700
rate of increases volts/sec)	(470)	(440)	(325)	(250)
Time voltage applied (secs)	10	10	10	10
	15	15	15	15
	20	20	20	20
	30	30	30	30
	45	45	45	45
	60	60	60	60
	120	120	120	120
	180	180	180	180
	240	240	240	240
	300	300	300	300

Strain Gage Cycle test (600 volt Sine wave at 0.1 Hz)was used to arrive at the average (top and bottom strain gage over 10 cycles) microstrain after each time step from Table 3

The 95% saturation level was selected by combing the poling tests level data and averaging 2 samples per electrode configuration. The curves produced were fit with polynomial curve fit equations to minimize error . As a check the graphs were also interpolated visually.

Butterfly Final Test:

Named after the shape of the hysterics curve , each sample configuration was tested using the Strain Gage cycle but at Saturation Voltage or above for 10 cycles at 0.1 HZ same as always. See Table 4.

Table 4

Configuration	7-42	6-30	5-21	4-12
saturation Volts peak to peak @ 0.1 HZ Sine	1840	1750	1290	700 and 1500

3. Results

The four electrode configurations will be compared by analyzing the following parameters:

1. Poling level/ Microstrain Cycle Test:

Strain in thousandths of an inch is measured by The Strain gages bonded to the top and bottom sides of the samples. The strain follows the input voltage Sine wave over a 10 second period. Twelve cycles are collected with the first two discarded. 128 data pints are written to a disk file per cycle by the software. The voltage excursions used are +/– 300 volts. The top and bottom gages should show the same values if everything were perfectly in balance with no bending strain. However due to small differences in construction, poling and other factors differences are measured. To minimize small effects the following averaging is done in the following data graphs unless otherwise stated:
Each cycle of 128 points take maximum –minimum strain gage value
Average 10 cycles
Average top and bottom gages
For each sample configuration average 2-3 samples to account for fabrication variability some Samples had visible or explainable flaws and were not included, These will be discussed later in the report.

Graphic results are shown in **Graphs 1 and 2** as microstrain vs. poling voltage and Percent strain vs. poling voltage. Microstrain increases as expected when poling voltage is increases up to saturation as indicated by the knee in the curves for all configurations. Also for the 7-42, 6-30 and 5-21 configurations, this saturation point occurs at progressively higher stain levels and lower voltage. The 4-12 configuration does not follow the increases Microstrain trend, and also easily shorted prior to the poling steps above 1000 VDC, The 3-6 configuration was fabricated 5 times with all shorted even before poling. In checking the 3-6 electrode patterns before fabrication over 90% were shorted. Shorting occurs between opposite polarity interdigitized electrodes allowing current conduction and charring. **Graph 3** shows all 4-12 samples, samples 2 and 3 are not averaged in Graph 1 and 2 due to deviant behavior.

2. Poling level/ Capacitance:

Following each poling voltage level and prior to the Strain Cycle test, the sample capacitance was measured with values recorded after 3 minutes due to fluctuations in readings. The capacitance always increased from un-poled to the first poled voltage level . In general, the capacitance continued to go up with increasing poling voltage to saturation. However, the values have also gone down or varied up and down. Apparently environmental effects time dependent variations are affecting capacitance, making it a relatively poor measure of actuator performance. A detailed study of theses effects are a subject for further research. **Graphs 4 ,5 and 6** show capacitance of the samples separately. **Graph 7** shows capacitance for the same 4-12 samples Shown in Graph 3.

3. Timed Poling level/ Strain Test:

A sample of each electrode spacing was used for the timed poling test followed by capacitance and strain cycle testing. **Graph 8** shows microstrain vs. total poling seconds for the complete timed test (300 seconds) while **Graph 9** shows the first 60 seconds. As can be seen, in the first seconds of the applied poling voltage most of the ceramic dipole saturation has taken place. The voltage rise rate was varied per electrode configuration and corresponding level (95% of full saturation) so as to provide approximately the same rise time--4 seconds to each voltage level.

Curve fit equations used for Timed poling test voltage levels:

This Polynomial Equation was used with the order adjusted and applied by trail and error Methods over the all or part of the equation to achieve the best fit.

$$Y = -b0+b1*X-b2*X^2+b3*X^3-b4*X^4+b5*X^5-b6*X^6+b7*X^7-b8*X^8+b9*X^9$$

Maximum microstrain values from the previous poling voltage step test results were used times .95 and inserted in the equation above for the variable x. The resulting values were used as the poling voltage level on the timed poling test for each configuration. The Polynomial coefficients used are listed below:

Table 5
Polynomial Coefficients for best fit equations over (microstrain range)

Coefficients	7-42 (226-263)	6-30 (8-374)	5-21 (21-638)	4-12 (19-332)
b[0]	2.726713E+07	2.885333E+02	1.963886E+02	9.185409E+01
b[1]	-4.483620E+05	-8.181464E+00	-1.518608E-01	3.175825E+00
b[2]	2.763139E+03	4.388486E-01	2.225249E-02	-8.256413E-03
b[3]	-7.564201E+00	-5.212691E-03	-8.058858E-05	1.402319E-05
b[4]	7.761908E-03	2.686297E-05	8.116138E-08	
b[5]		-6.389453E-08		
b[6]		5.788540E-11		
r^2	0.995078	0.9937881	0.9875045	0.9999644

Capacitance Values from timed poling test:

Capacitance was recorded after 3 minutes before the strain cycle test as shown in **Graphs 10 and 11**. Like the results of the Poling voltage step test, the capacitance shows trends but there are exceptions such as for the 4-12 electrode configuration which has an unusual low change similar to its relatively low Microstrain values.

'Butterfly' Strain cycle Test:

The butterfly Strain cycle test is the same testing as the strain cycle test previously described with a separate sample poled to the 95% saturation level with 0.1 Hz Sine wave applied for 10 cycles at peak to peak (pp) voltage equal to the 95% saturation level.
Graph 12 shows Microstrain based on averaged top and bottom strain gages, averaged over 10 cycles each . Note that two samples are shown for the 4-12 configuration, 700 volts pp and 1500 volts pp. The sample was tested at 700 based on the previously shorted sample which was not 95% saturated, when tested at 1500 this sample shorted after about 8 cycles as shown with the uneven trace.
The hysteresis due to dipole redirection produces the characteristic 'butterfly' appearance. As shown in previous data, the 4-12 sample does not follow the increasing strain vs. applied volt trend as would be expected when electrode spacing is decreased.

4. Conclusions

Summarized in the table below are several important parameters for comparison between the configurations tested. The 4-12 electrode spacing showed deviant behavior in that samples shorted early and were highly variable in performance. Six 4-12 samples were fabricated with 3 Batches, with no trend apparent. To an even greater degree the 3-6 electrode were virtually all shorted even prior to fabrication. The polyamide layer copper electrodes could show bridging of the copper from manufacturing.
It is supposed that these fabrication processes could be further improved by minimizing contamination. Other shorts developed dynamically during poling looked under 10X magnification like a breakdown in the epoxy filler. The dielectric strength of the polyamide is about 6000 volts per .001 inches[2] vs. 600 volts for the epoxy[4] per manufacture datasheets. A failure analysis of the shorts will be conducted in the near future with the results disseminated in a short report.
The 5-21 Actuators appear optimum from this admittedly small batch fabrication dataset. The performance exceeds previous reported values, confirming the high performance and usefulness of the macrofiber composite actuators.
The effect of time on the poling levels is in the order of seconds to effect saturation, with 95% of saturation attained in less than 20 seconds of applied voltage.
Capacitance shows increasing values with saturation, but is an inconsistent method with observed sensitivity to heat, temperature, other environmental effects (moisture) and has A time varying quality also making it a relatively poor poling indicator vs. strain.

Sample	Longitudinal strain coefficient (d_{11}) Microstrain/volt	Max Free Microstrain	Max time (seconds) to 95% pole Saturation
4/12	0.42*	1170**	20
5/21	1.1	2430	20
6/30	.625	2140	10
7/42	0.45	2340	10

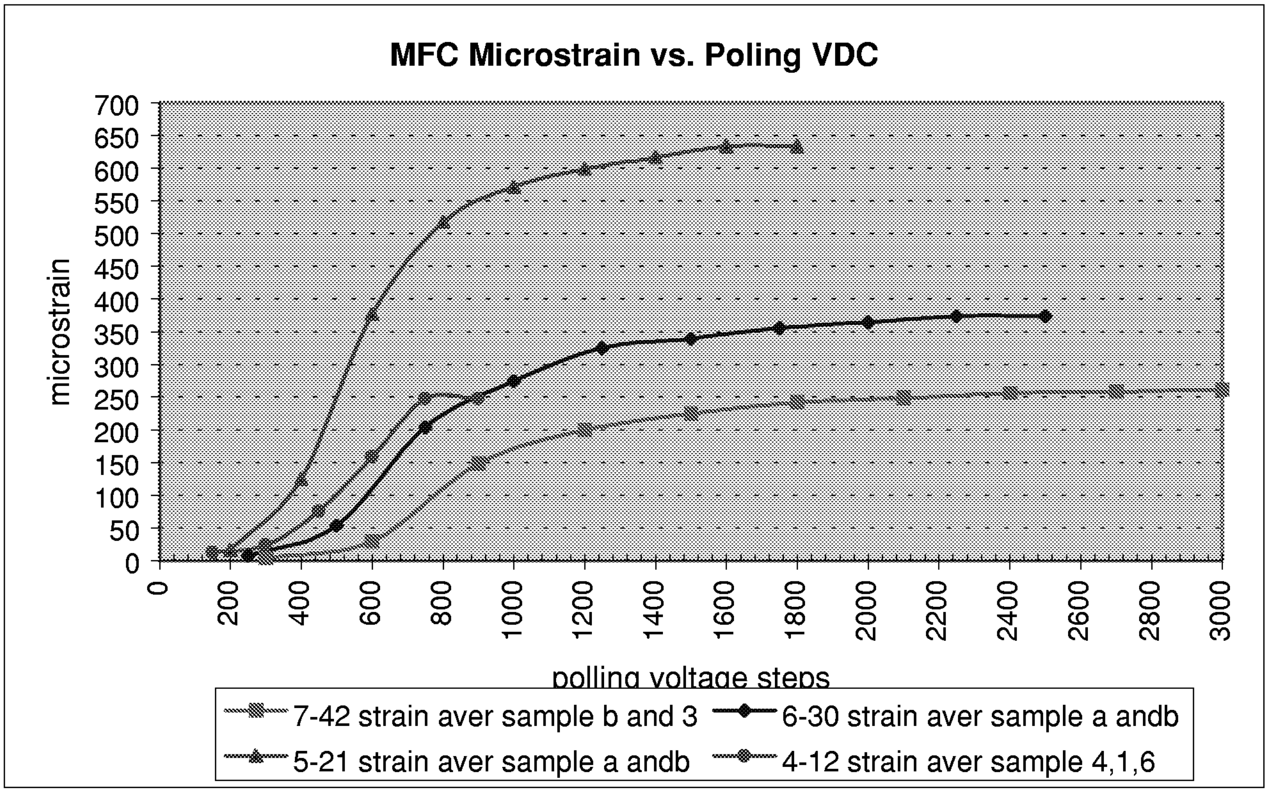
* 4-12 samples shorted at 900, 1050 Volts   ** 4-12 shorted at 1500 Volts

5. Acknowledgments

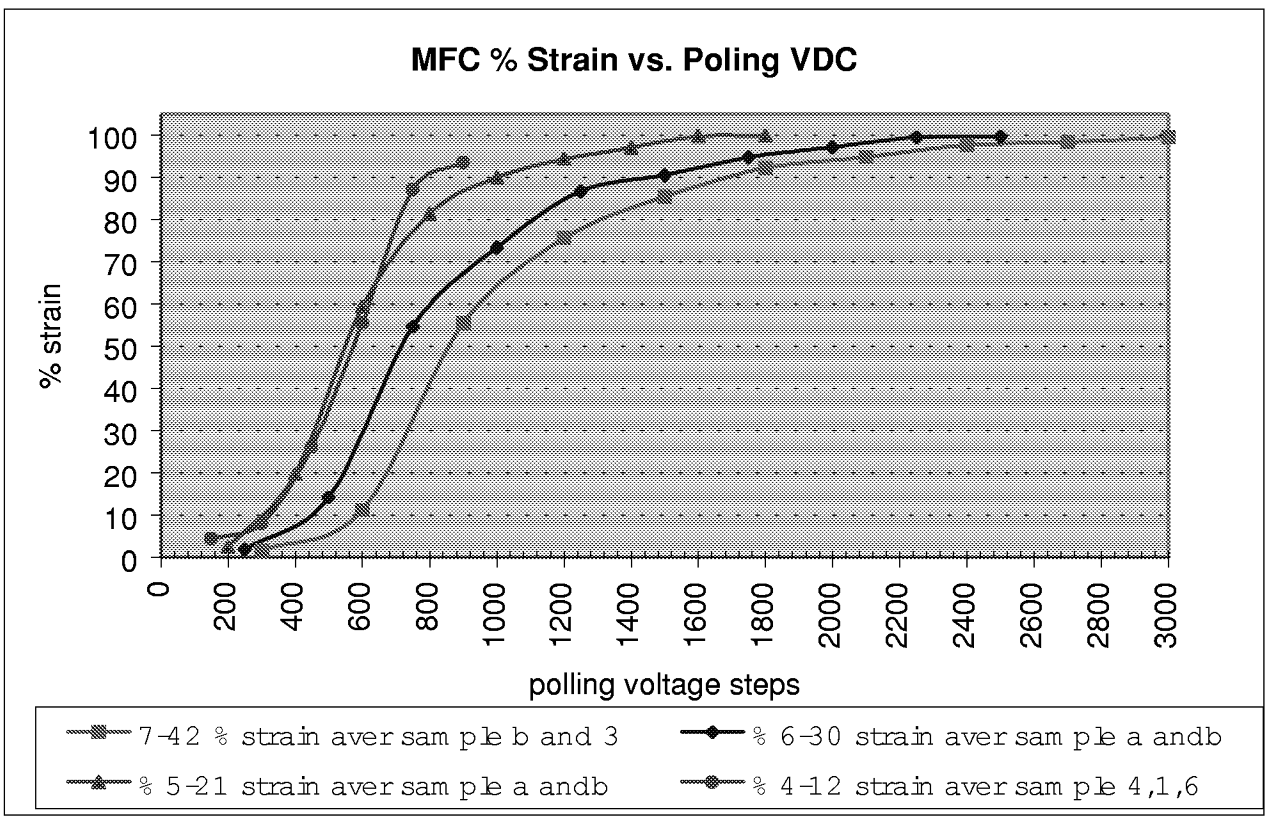
I wish to thank Ben Copeland of the Microelectronics Section, NASA Langley Research Center for the training on MFC fabrication and expert attachment of Strain gages.

6. References

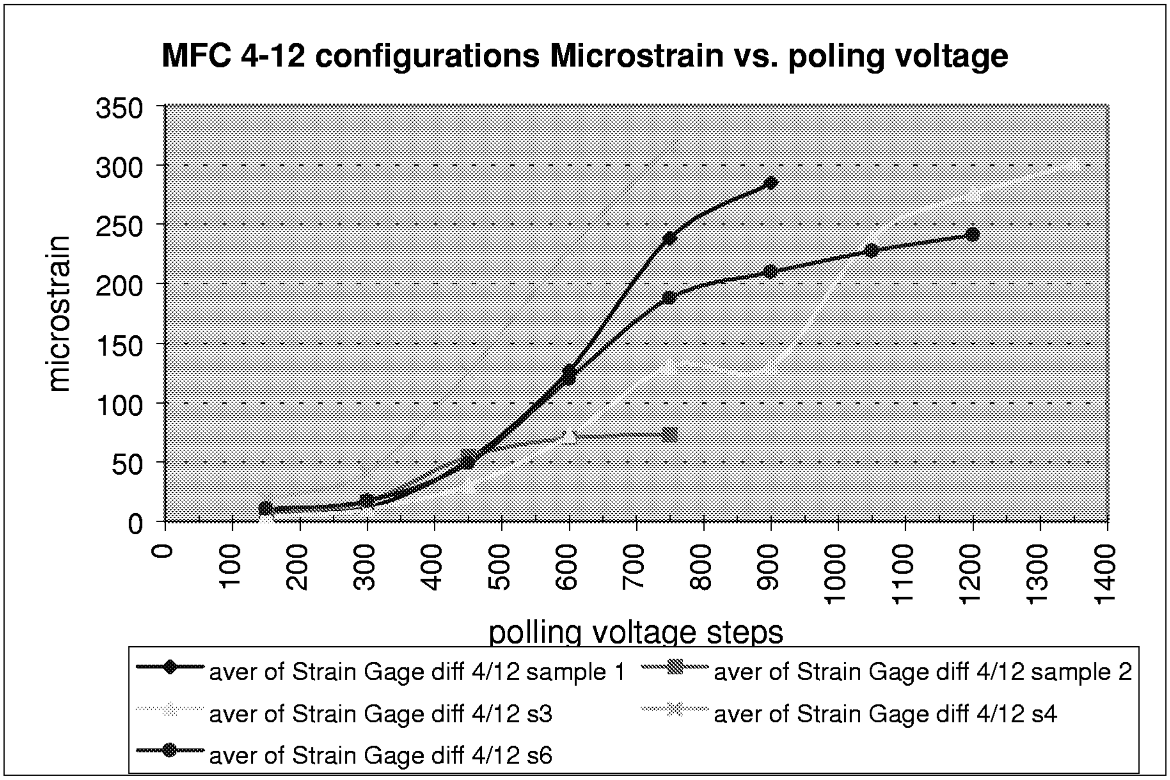
1. W. Keats, Robert G. Bryant, et al, *Low-Cost Piezocomposite Actuator for Structural Control Applications,* SPIE 7th annual International Symposium on Smart Structures and Materials, Newport Beach, CA, March 5-9,2000.
2. DuPont High Performance Materials P.O. Box 89 Route 23 South and DuPont Road Circleville, OH 43113, Pyralux Specifications http://www.dupont.com/fcm/products/H-91906.pdf
3. CTS Wireless Components 4800 Alameda Blvd. N.E. Albuquerque, NM , Data sheet for PZT 3195 HD April 2000
4. Loctite Corporation 1001 Trout Brook Crossing Rocky Hill, CT 06067, Technical Data Sheet Hysol Product E-120 HP August 2001
5. TSM LTD 48 Cloyfin Rd. Coleraine Co. Londonderry Precision Strain Gauges PN# 6/350/PC11/B Gauge factor 2.1



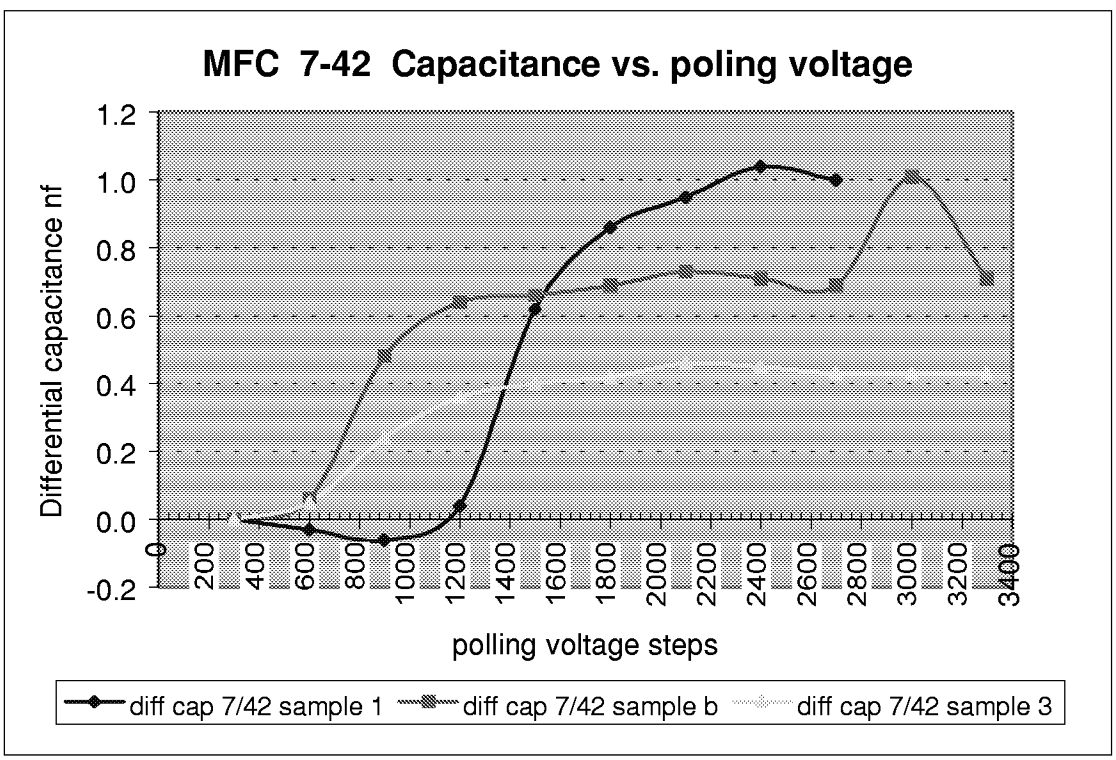
Graph 1
Averaged Microstrain vs. poling voltages per electrode configuration



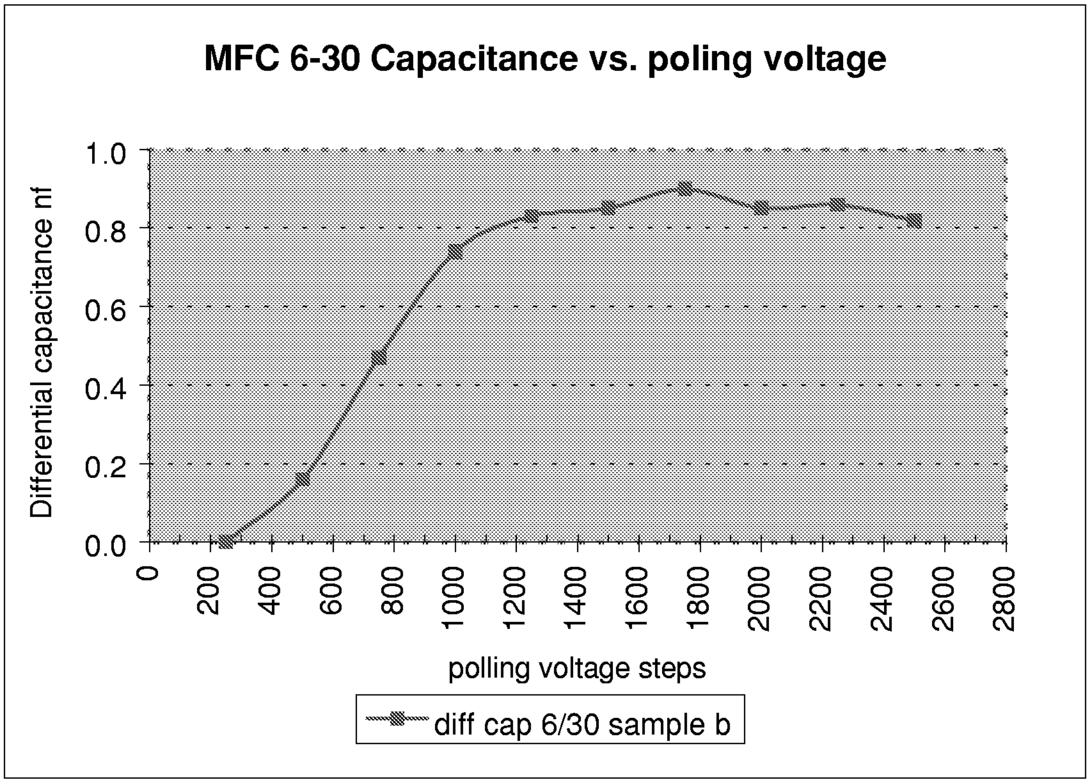
Graph 2 % Averaged data showing strain vs. poling voltages



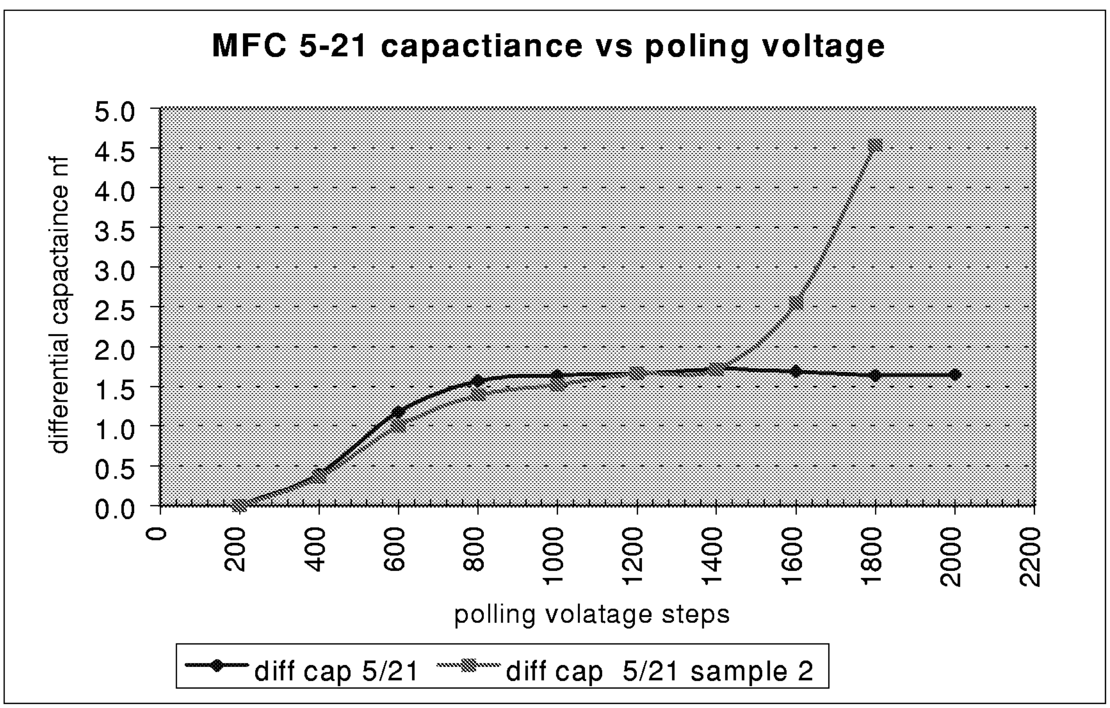
Graph 3 4-12 Samples showing microstrain vs. shorting voltage level (sample 2,3 not averaged in graph 1,2)



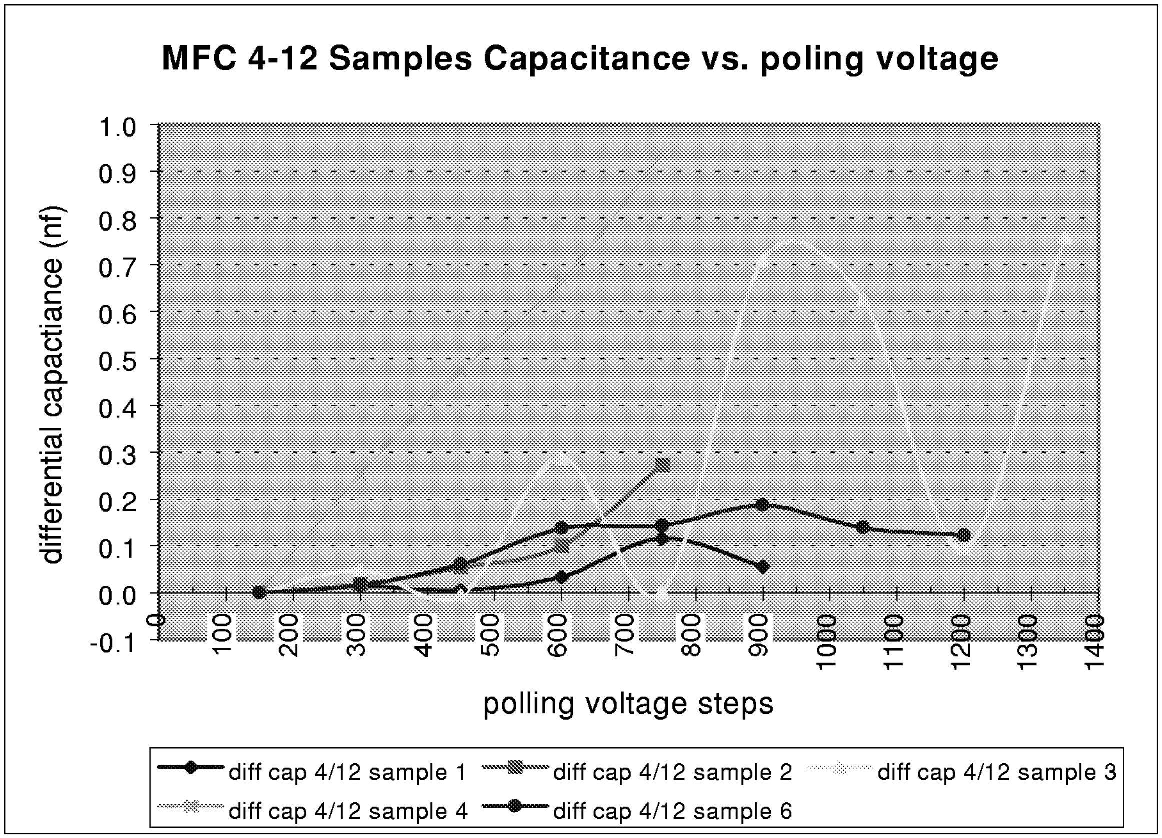
Graph 4 Differential Capacitance 7-42 samples



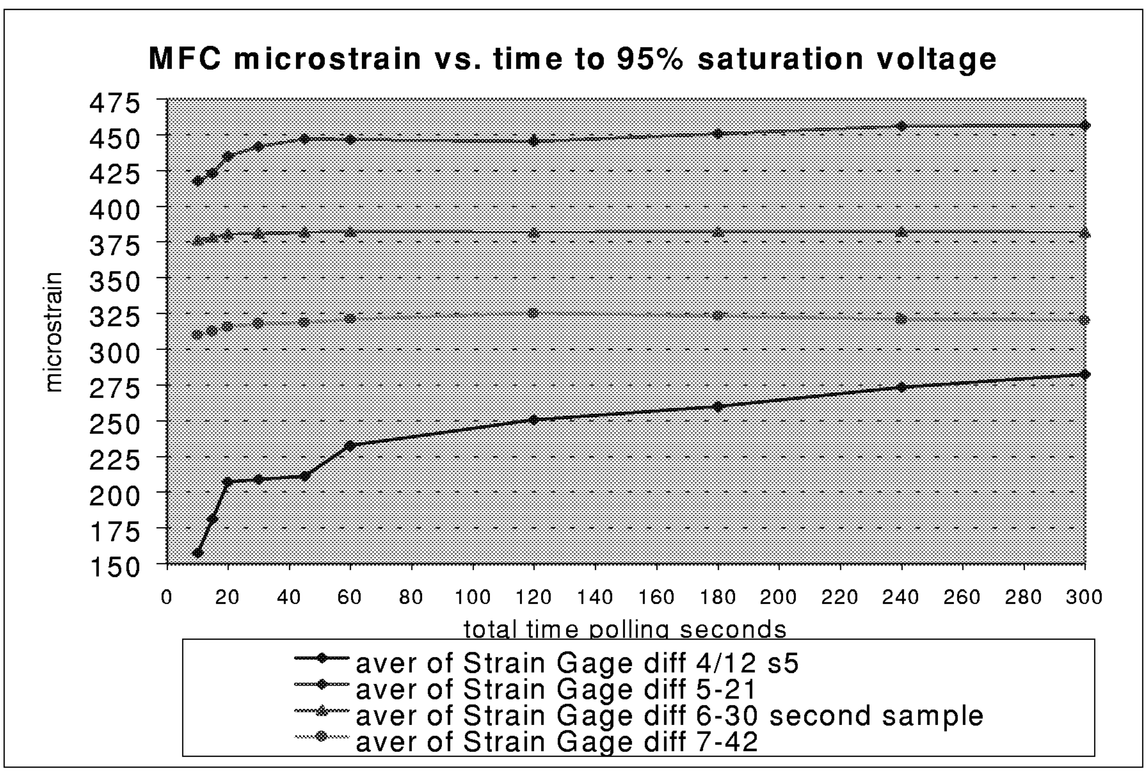
Graph 5 Differential Capacitance 6-30 samples



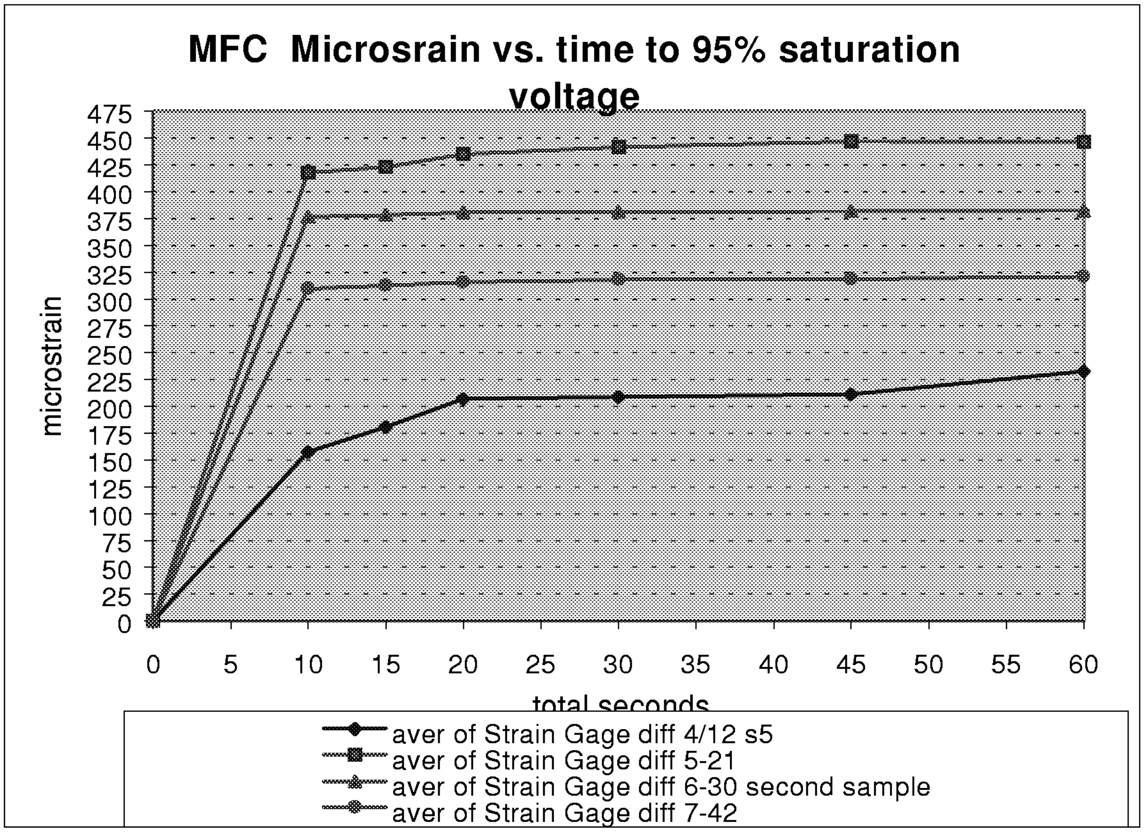
Graph 6 Differential Capacitance 7-21 samples



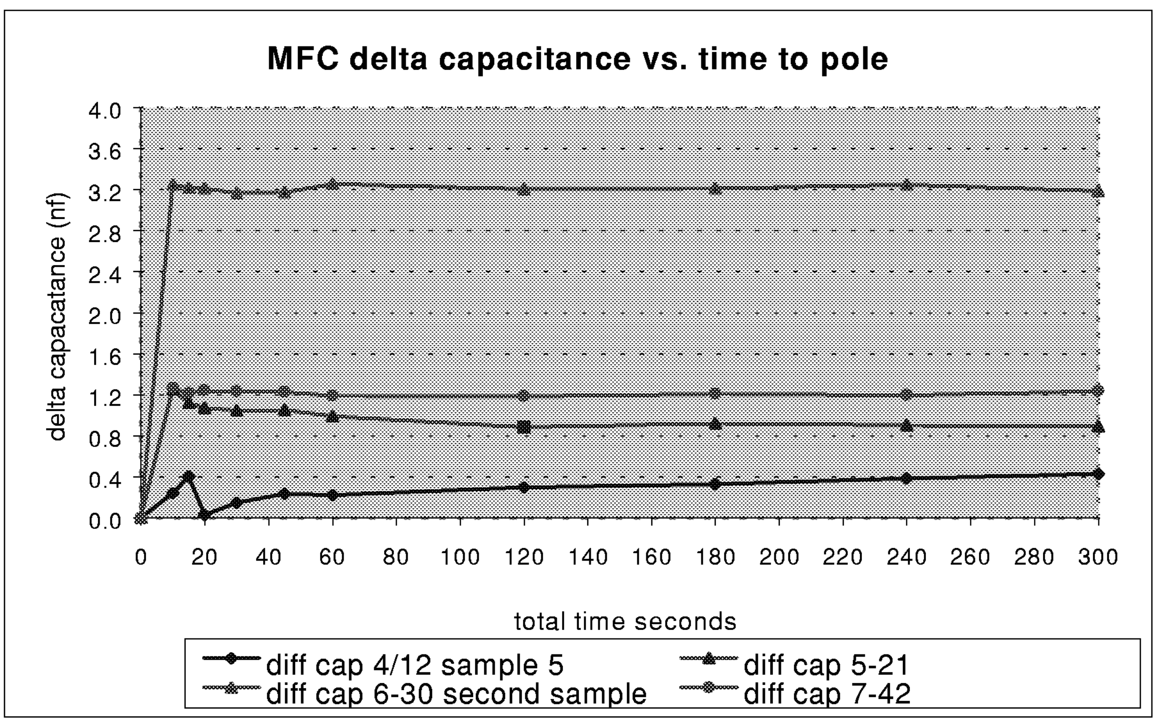
Graph 7 Differential Capacitance 4-12 samples



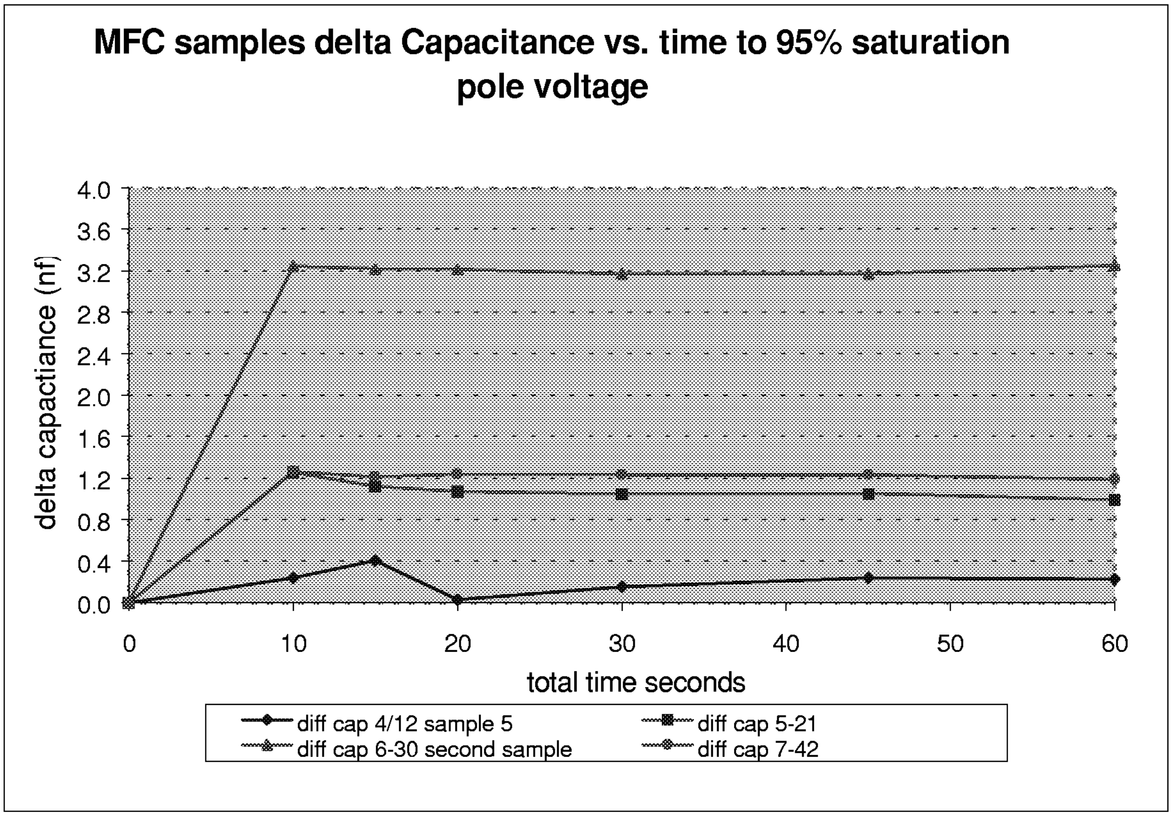
Graph 8 Microstrain vs. total time 300 seconds poling voltage applied



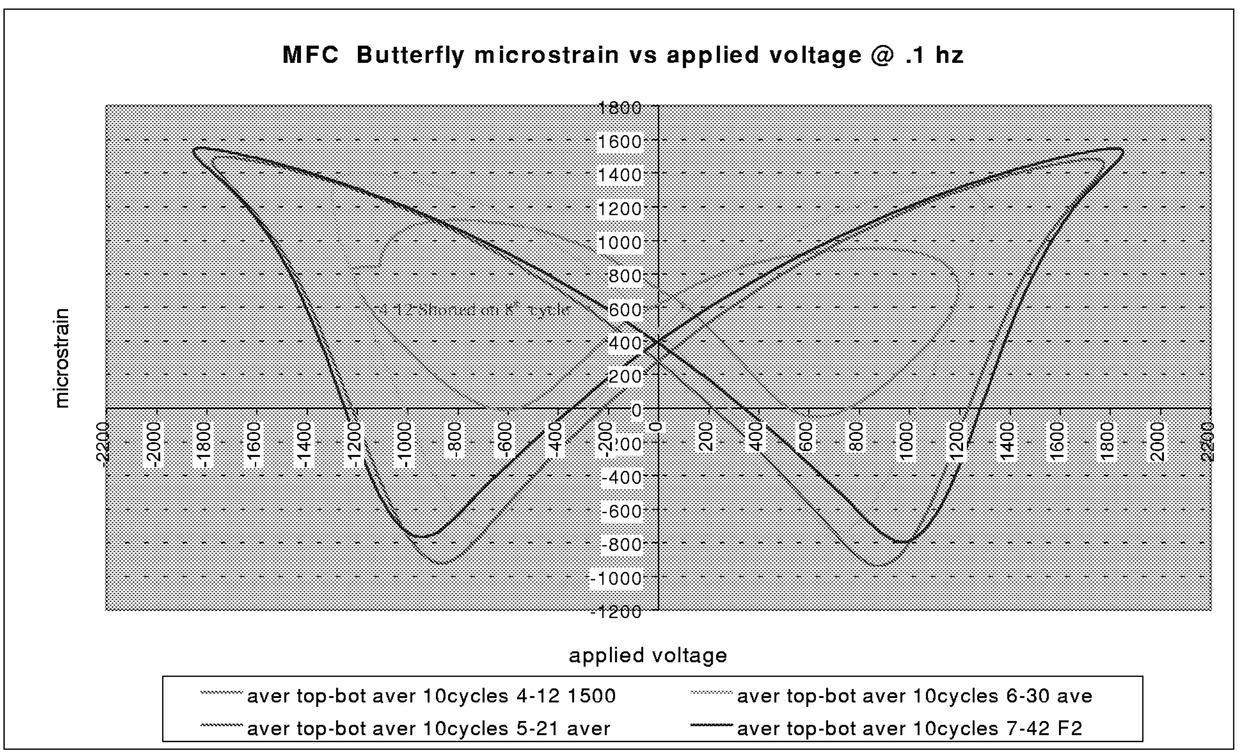
Graph 9 Microstrain vs. first 60 seconds of applied voltage



Graph 10 MFC Samples Timed poll Test capacitance values



Graph 11 MFC Samples Timed pole Test capacitance values first 60 seconds



Graph 12 MFC 'Butterfly' Plots samples poled to 95% saturation prior to 0.1 Hz applied voltage

Micro Fiber Piezocomposite Poling Study Appendix

Rudy Werlink NASA Langley Research Center Hampton, VA

7-42 sample b and 3 curve fit Coefficients:		6-30 sample a and b curve fit Coefficients:		5-21 sample a and b ave. curve fit Coefficients:		4-12 sample 4 curve fit Coefficients:		4-12 sample 5 (150-750 vdc range) after butterfly test and curve fit Coefficients:	
b[0]	27267126.44	b[0]	288.53	b[0]	196.39	b[0]	91.85	b[0]	0.00
b[1]	-448361.98	b[1]	-8.18	b[1]	-0.15	b[1]	3.18	b[1]	1.00
b[2]	2763.14	b[2]	0.44	b[2]	0.02	b[2]	-0.01	r^2	1.00
b[3]	-7.56	b[3]	-0.01	b[3]	0.00	b[3]	0.00		
b[4]	0.01	b[4]	0.00	b[4]	0.00	r^2	1.00		
r^2	1.00	b[5]	0.00	r^2	0.99				
		b[6]	0.00						
		r^2	0.99						

Function Values:

Microstrain x	polling volts f(x)	Microstrain x	polling volts f(x)	Microstrain x	polling volts f(x)	Microstrain x	polling volts f(x)	Microstrain x	polling volts f(x)
225.35	1499.97	7.39	250.01	21.34	202.52	19.05	149.45	900.00	900.00
226.09	1433.42	14.72	247.79	33.67	213.53	25.31	167.18	912.00	912.00
226.83	1381.28	22.06	271.68	46.00	229.01	31.57	184.34	924.00	924.00
227.57	1342.26	29.39	313.51	58.33	248.19	37.83	200.95	936.00	936.00
228.31	1315.12	36.73	366.51	70.66	270.35	44.10	217.04	948.00	948.00
229.05	1298.68	44.06	425.19	82.99	294.83	50.36	232.64	960.00	960.00
229.79	1291.79	51.40	485.17	95.32	321.00	56.62	247.75	972.00	972.00
230.53	1293.39	58.73	543.09	107.65	348.28	62.88	262.39	984.00	984.00
231.27	1302.45	66.06	596.48	119.98	376.13	69.14	276.60	996.00	996.00
232.01	1318.02	73.40	643.63	132.31	404.06	75.40	290.39	1008.00	1008.00
232.75	1339.19	80.73	683.50	144.64	431.63	81.67	303.78	1020.00	1020.00
233.49	1365.11	88.07	715.61	156.97	458.43	87.93	316.80	1032.00	1032.00
234.23	1394.98	95.40	739.96	169.30	484.11	94.19	329.45	1044.00	1044.00
234.98	1428.06	102.73	756.91	181.63	508.36	100.45	341.77	1056.00	1056.00
235.72	1463.68	110.07	767.14	193.96	530.91	106.71	353.77	1068.00	1068.00
236.46	1501.21	117.40	771.54	206.29	551.54	112.97	365.48	1080.00	1080.00
237.20	1540.07	124.74	771.16	218.62	570.08	119.24	376.91	1092.00	1092.00
237.94	1579.75	132.07	767.14	230.95	586.39	125.50	388.09	1104.00	1104.00
238.68	1619.79	139.41	760.66	243.28	600.40	131.76	399.04	1116.00	1116.00
239.42	1659.79	146.74	752.89	255.61	612.05	138.02	409.77	1128.00	1128.00
240.16	1699.41	154.07	744.94	267.94	621.36	144.28	420.31	1140.00	1140.00
240.90	1738.35	161.41	737.83	280.27	628.38	150.54	430.68	1152.00	1152.00
241.64	1776.37	168.74	732.46	292.60	633.18	156.81	440.90	1164.00	1164.00
242.38	1813.31	176.08	729.61	304.93	635.93	163.07	450.99	1176.00	1176.00
243.12	1849.03	183.41	729.85	317.26	636.80	169.33	460.97	1188.00	1188.00
243.86	1883.47	190.75	733.63	329.59	636.02	175.59	470.86	1200.00	1200.00
244.60	1916.62	198.08	741.20	341.92	633.87	181.85	480.68	1212.00	1212.00
245.34	1948.52	205.41	752.63	354.25	630.66	188.11	490.45	1224.00	1224.00
246.08	1979.28	212.75	767.85	366.58	626.76	194.37	500.20	1236.00	1236.00
246.82	2009.05	220.08	786.64	378.91	622.58	200.64	509.94	1248.00	1248.00
247.56	2038.04	227.42	808.64	391.24	618.57	206.90	519.69	1260.00	1260.00
248.30	2066.53	234.75	833.41	403.57	615.24	213.16	529.48	1272.00	1272.00
249.04	2094.84	242.08	860.44	415.90	613.13	219.42	539.33	1284.00	1284.00
249.78	2123.35	249.42	889.20	428.23	612.82	225.68	549.25	1296.00	1296.00
250.52	2152.50	256.75	919.21	440.56	614.96	231.94	559.27	1308.00	1308.00
251.26	2182.78	264.09	950.06	452.89	620.22	238.21	569.41	1320.00	1320.00
252.00	2214.74	271.42	981.47	465.22	629.33	244.47	579.69	1332.00	1332.00
252.74	2248.99	278.76	1013.39	477.55	643.05	250.73	590.12	1344.00	1344.00

253.49	2286.18	286.09	1046.06	489.88	662.21	256.99	600.74	1356.00	1356.00
254.23	2327.03	293.42	1080.08	502.21	687.66	263.25	611.55	1368.00	1368.00
254.97	2372.32	300.76	1116.50	514.54	720.30	269.51	622.59	1380.00	1380.00
255.71	2422.88	308.09	1156.94	526.87	761.09	275.78	633.86	1392.00	1392.00
256.45	2479.58	315.43	1203.64	539.20	811.03	282.04	645.40	1404.00	1404.00
257.19	2543.38	322.76	1259.61	551.53	871.14	288.30	657.23	1416.00	1416.00
257.93	2615.26	330.09	1328.72	563.86	942.52	294.56	669.35	1428.00	1428.00
258.67	2696.29	337.43	1415.85	576.19	1026.30	300.82	681.80	1440.00	1440.00
259.41	2787.56	344.76	1526.96	588.52	1123.64	307.08	694.60	1452.00	1452.00
260.15	2890.25	352.10	1669.28	600.85	1235.78	313.35	707.76	1464.00	1464.00
260.89	3005.57	359.43	1851.42	613.18	1363.97	319.61	721.31	1476.00	1476.00
261.63	3134.81	366.77	2083.50	625.51	1509.53	325.87	735.26	1488.00	1488.00
262.37	3279.29	374.10	2377.36	637.84	1673.81	332.13	749.65	1500.00	1500.00

poll vdc	aver of Strain Gage diff 7/42 sample 1	%aver of Strain gage diff 7/42 sample 1	capacitance(nf) 7/42 sample 1	diff cap 7/42 sample 1	% capacitance 7/42 sample 1
300.00	5.14	2.54	4.10	0.00	0.00
600.00	7.65	3.78	4.07	-0.03	-2.97
900.00	21.33	10.56	4.04	-0.06	-5.94
1200.00	50.81	25.14	4.14	0.04	3.96
1500.00	126.61	62.65	4.72	0.62	61.39
1800.00	164.28	81.28	4.96	0.86	85.15
2100.00	177.92	88.03	5.05	0.95	94.06
2400.00	184.37	91.23	5.14	1.04	102.97
2700.00	202.10	100.00	5.10	1.00	99.01

poll vdc	aver of Strain Gage diff 7/42 sample b	%aver of Strain gage diff 7/42 sample b	capacitance(nf) 7/42 sample b	diff cap 7/42 sample b	7-42% capacitance 7/42 sample b
300.00	5.21	1.81	3.28	0.00	0.00
600.00	38.81	13.51	3.34	0.06	5.94
900.00	197.34	68.69	3.76	0.48	47.52
1200.00	234.14	81.51	3.92	0.64	63.37
1500.00	259.30	90.27	3.94	0.66	65.35
1800.00	266.97	92.93	3.97	0.69	68.32
2100.00	275.01	95.73	4.01	0.73	72.28
2400.00	279.78	97.39	3.99	0.71	70.30
2700.00	283.65	98.74	3.97	0.69	68.32
3000.00	286.48	99.73	4.29	1.01	100.00
3300.00	287.27	100.00	3.99	0.71	70.30

poll vdc	aver of	%aver of	capacitan	diff cap 7/42 sample	% capacitance 7/42	7-42	7-42

	Strain Gage diff 7/42 sample3	Strain gage diff 7/42 sample 3	ce(nf) 7/42 sample 3	3		sample 3		strain aver	%strain aver	
0.00			3.39		7-42 diff cap aver sample b and 3		7-42 %diff cap aver sample b and 3	sample b and 3	sample b and 3	stddev
300.00	3.48	1.47	3.40	0.00	0.00	0.00	0.00	4.35	1.64	1.22
600.00	21.36	9.00	3.45	0.05	0.06	10.87	8.41	30.09	11.25	12.34
900.00	100.32	42.25	3.64	0.24	0.36	52.17	49.85	148.83	55.47	68.60
1200.00	165.49	69.69	3.76	0.36	0.50	78.26	70.81	199.82	75.60	48.54
1500.00	191.39	80.60	3.80	0.40	0.53	86.96	76.15	225.35	85.43	48.02
1800.00	217.31	91.51	3.82	0.42	0.56	91.30	79.81	242.14	92.22	35.12
2100.00	222.96	93.89	3.86	0.46	0.60	100.00	86.14	248.98	94.81	36.80
2400.00	232.59	97.94	3.85	0.45	0.58	97.83	84.06	256.18	97.67	33.37
2700.00	232.32	97.83	3.83	0.43	0.56	93.48	80.90	257.98	98.29	36.29
3000.00	235.79	99.29	3.83	0.43	0.72	93.48	96.74	261.14	99.51	35.85
3300.00	237.47	100.00	3.83	0.43	0.57	93.48	81.89	262.37	100.00	35.22

poll vdc	aver of Strain Gage diff 6/30 sample a	%aver of Strain gage diff 6/30 sample a	capacitance(nf) 6/30 sample a	diff cap 6/30 sample a	% capacitance 6/30 sample a
250.00	7.29	1.99	4.81	0.00	0.00
500.00	70.20	19.17	4.81	0.00	0.00
750.00	249.61	68.15	4.66	-0.15	25.42
1000.00	298.82	81.58	4.22	-0.59	100.00
1250.00	333.81	91.13	4.22	-0.59	100.00
1500.00	333.81	91.13	4.26	-0.55	93.22
1750.00	346.23	94.52	4.24	-0.57	96.61
2000.00	357.53	97.61	4.23	-0.58	98.31
2250.00	362.71	99.02	4.22	-0.59	100.00
2500.00	366.29	100.00	4.70	-0.11	18.64

poll vdc	aver of Strain Gage diff 6/30 sample b	%aver of Strain gage diff 6/30 sample b	capacitance(nf) 6/30 sample b	diff cap 6/30 sample b	% capacitance 6/30 sample b	6-30 strain aver	%6-30 strain aver
						sample a and b	sample a and b
250.00	7.49	1.94	4.61	0.00	0.00	7.39	1.97
500.00	36.25	9.42	4.77	0.16	17.78	53.23	14.29
750.00	158.81	41.25	5.08	0.47	52.22	204.21	54.70
1000.00	250.85	65.16	5.35	0.74	82.22	274.83	73.37
1250.00	316.78	82.29	5.44	0.83	92.22	325.30	86.71
1500.00	346.23	89.94	5.46	0.85	94.44	340.02	90.54
1750.00	365.83	95.03	5.51	0.90	100.00	356.03	94.78
2000.00	372.04	96.64	5.46	0.85	94.44	364.79	97.13
2250.00	384.96	100.00	5.47	0.86	95.56	373.83	99.51
2500.00	381.92	99.21	5.43	0.82	91.11	374.10	99.61

poll vdc	aver of Strain Gage diff 5/21	%aver of Strain gage diff 5/21	capacitance(nf) 5/21	diff cap 5/21	% capacitance 5/21
200.00	12.42	1.94	9.24	0.00	0.00
400.00	119.81	18.71	9.64	0.40	23.26
600.00	411.70	64.29	10.42	1.18	68.60
800.00	547.57	85.50	10.81	1.57	91.28
1000.00	588.39	91.88	10.88	1.64	95.35
1200.00	610.73	95.37	10.90	1.66	96.51
1400.00	627.87	98.04	10.96	1.72	100.00
1600.00	637.29	99.51	10.93	1.69	98.26
1800.00	638.40	99.69	10.88	1.64	95.35
2000.00	640.41	100.00	10.89	1.65	95.93

poll vdc	aver of Strain Gage diff 5/21 sample 2	%aver of Strain gage diff 5/21 sample 2	capacitance(nf) 5/21 sample 2	diff cap 5/21 sample 2	% capacitance 5/21 sample 2	5-21 strain aver sample a and b	%5-21 strain aver sample a and b
0.00			8.68				
200.00	19.70	3.13	8.85	0.00	0.00	16.06	2.53
400.00	130.59	20.72	9.21	0.36	7.88	125.20	19.71
600.00	342.06	54.26	9.85	1.00	22.08	376.88	59.27
800.00	487.25	77.29	10.25	1.39	30.78	517.41	81.40
1000.00	554.69	87.99	10.37	1.52	33.54	571.54	89.93
1200.00	588.27	93.32	10.52	1.67	36.87	599.50	94.34
1400.00	605.13	95.99	10.57	1.71	37.84	616.50	97.02
1600.00	630.39	100.00	11.40	2.55	56.30	633.84	99.76
1800.00	629.78	99.90	13.38	4.53	100.00	634.09	99.79
2000.00	57.25	9.08	0.00	-8.85	-195.43		

poll vdc	aver of Strain Gage diff 4/12 sample 1	%aver of Strain gage diff 4/12 sample 1	capacitance(nf) 4/12 sample 1	diff cap 4/12 sample 1	% capacitance 4/12 sample 1
150.00	8.77	3.08	13.76	0.00	0.00
300.00	12.05	4.23	13.78	0.01	11.97
450.00	51.98	18.24	13.77	0.01	5.13
600.00	126.90	44.52	13.80	0.03	29.06
750.00	238.47	83.66	13.88	0.12	100.00
900.00	285.05	100.00	13.82	0.06	48.72

poll vdc	aver of Strain Gage diff 4/12 sample 2	%aver of Strain gage diff 4/12 sample 2	capacitance(nf) 4/12 sample 2	diff cap 4/12 sample 2	% capacitance 4/12 sample 2
0.00			11.43		
150.00	6.13	8.38	11.42	0.00	0.00
300.00	16.93	23.14	11.44	0.02	6.99
450.00	54.81	74.89	11.47	0.05	19.85
600.00	70.54	96.39	11.52	0.10	36.76
750.00	73.18	100.00	11.69	0.27	100.00

poll vdc	aver of Strain Gage diff 4/12 s3	%aver of Strain gage diff 4/12 sample 3	capacitance(nf) 4/12 sample 3	diff cap 4/12 sample 3	% capacitance 4/12 sample 3
0.00			7.75		
150.00	4.63	1.54	7.63	0.00	0.00
300.00	10.46	3.48	7.68	0.05	6.46
450.00	30.83	10.25	7.62	-0.01	-0.79
600.00	72.25	24.02	7.91	0.29	37.99
750.00	130.62	43.43	7.63	0.00	0.26
900.00	130.62	43.43	8.34	0.71	93.67
1050.00	238.72	79.38	8.25	0.63	82.59
1200.00	275.53	91.62	7.72	0.10	100.00
1350.00	300.72	100.00	8.38	0.76	100.00
1500.00	234.04	77.83	14.57	6.95	916.62

poll vdc	aver of Strain Gage diff 4/12 s4	%aver of Strain gage diff 4/12 sample 4	capacitance(nf) 4/12 sample 4	diff cap 4/12 sample 4	% capacitance 4/12 sample 4
0.00			14.89		
150.00	19.05	6.02	15.03	0.00	0.00
300.00	41.35	13.08	15.29	0.25	27.08
450.00	125.74	39.77	15.51	0.48	50.64
600.00	228.79	72.36	15.70	0.67	71.00
750.00	316.20	100.00	15.97	0.94	100.00

900.00	45.78	14.48	0.00	-15.03	-1602.56

poll vdc	aver of Strain Gage diff 4/12 s5 after timed polling test	%aver of Strain gage diff 4/12 sample 5	capacitance(nf) 4/12 sample 5	diff cap 4/12 sample 5	% capacitance 4/12 sample 5
0.00			5.51		
750.00	360.20	86.15	7.66	0.00	0.00
900.00	362.06	86.60	7.67	0.01	-3.43
1050.00	394.51	94.36	7.64	-0.02	9.14
1200.00	417.87	99.95	7.60	-0.06	34.86
1350.00	418.10	100.00	7.53	-0.13	72.57
1500.00	412.01	98.54	7.48	-0.18	100.00

poll vdc	aver of Strain Gage diff 4/12 s6	%aver of Strain gage diff 4/12 sample 6	capacitance(nf) 4/12 sample 6	diff cap 4/12 sample 6	% capacitance 4/12 sample 6	4-12 strain aver	%4-12 strain aver
0.00			10.87			sample 4,1,6	sample 4,1,6
150.00	10.74	4.45	10.85	0.00	0.00	12.85	4.52
300.00	17.45	7.23	10.87	0.02	8.56	23.62	8.18
450.00	49.30	20.44	10.92	0.06	32.62	75.67	26.15
600.00	120.17	49.82	10.99	0.14	73.80	158.62	55.56
750.00	188.07	77.97	11.00	0.14	77.01	247.58	87.21
900.00	209.81	86.99	11.04	0.19	100.00	247.43	93.49
1050.00	227.54	94.33	10.99	0.14	74.33		
1200.00	241.20	100.00	10.98	0.12	65.78		

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13. ABSTRACT *(Maximum 200 words)*

The performance and advantages of Piezocomposite Actuators are to provide a low cost, in-situ actuator/sensor that is flexible, low profile and high strain per volt performance in the same plane of poled voltage. This paper extends reported data for the performance of these Macrofiber Composite (MFC) Actuators to include 4 progressively narrower Intedigitized electrode configurations with several line widths and spacing ratios. Data is reported for max free strain, average strain per applied volt, poling (alignment of the electric dipoles of the PZT ceramic) voltage vs. strain and capacitance, time to poling voltage 95% saturation. The output strain per volt progressively increases as electrode spacing decreases, with saturation occurring at lower poling voltages. The narrowest spacing ratio becomes prone to voltage breakdown or short circuits limiting the spacing width with current fabrication methods. The capacitance generally increases with increasing poling voltage level but has high sensitivity to factors such as temperature , moisture and time from poling which limit its usefulness as a simple indicator. The total time of applied poling voltage to saturate or fully line up the dipoles in the piezoceramic was generally on the order of 5-20 seconds. Less sensitivity to poling due to the applied rate of voltage increase over a 25 to 500 volt/second rate range was observed.

14. SUBJECT TERMS
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