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An INCHWORM® Actuator for the Next Generation Space Telescope Phase II SBIR Quarterly Technical Report (April - June, 2000)

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1.0 CURRENT STATUS

During this reporting period, the prototype stack actuators have been tested at cryogenic temperatures. The actuators were tested at room temperature and 20 K to measure the piezoelectric displacement under voltage. Data has been obtained at 20 degree intervals from 20 K to 300 K. Initial results show a lower than expected displacement of the PZN-8%PT single crystal actuators at 20K. The conventional material actuators performed within 10% of the expected values. The impact of the lower displacement of the single crystal actuators will affect the final design of the mechanism – most importantly, the design of the clamping mechanism.

The 2nd generation prototype mechanism has been built and initial performance testing completed. The motor was assembled and operated using the phase I prototype controller. The initial evaluation consisted of measuring the motion profile, glitch, push force, and power off hold force. The motor was designed using conventional PZT-5H actuators. The length of the actuators were increased to account for the loss of piezoelectric strain at cryogenic temperatures. By reducing the voltage, operation at cryogenic temperatures was simulated.

With anticipation that the single crystal actuators may not produce sufficient displacement at cryogenic temperatures, new clamp designs are being evaluated. Specifically, this includes designs which use electromagnetic devices in place of the piezoelectric actuators for the clamping mechanism. Piezoelectric actuators will still be used for the extension actuator in order to maintain the high resolution and stiffness characteristics. A prototype clamp mechanism and motor has been designed using solenoids for the clamp actuating means and conventional piezoelectric actuators for the extension actuation means. Components for the device are being manufactured and the prototype will be built in July, 2000.

2.0 CRYOGENIC PIEZOELECTRIC ACTUATOR DEVELOPMENT

2.1 PROTOTYPE STACK ACTUATOR SPECIFICATIONS AND DESIGN

In order to verify the analytical models and measure cryogenic performance, prototype stack actuators made from single crystal PZN-8%PT have been designed and built. The baseline design for the prototype stacks actuators is shown in Table 1. In addition to the PZN-8%PT single crystal stacks, stacks actuators made from PZT-5H material have also been built to verify the analytical models and to evaluate the thermal displacement (CTE). Testing performed to date consisted of room temperature measurement of displacement under voltage and cryogenic testing down to 20 K to measure the CTE, and displacement under voltage. Additional testing will be performed at room temperature and cryogenic temperatures to measure actuator stiffness, electrical properties, and reliability.

Table 1: Baseline Specifications for Piezoelectric Stack Actuators

Function	Prototype	Clamping	Extension	Prototype
Plate Specification				
Material (single crystal)	**PZN-8%PT**	PZN-8%PT	PZN-8%PT	**PZT-5H***
d33 @ RT (x 10^{-12} m/V)	2231	2231	2231	575
d33 @ 20 K (x 10^{-12} m/V)	500	500	500	115
Field strength (kV/mm)	1	2	2	1
Strain @ full voltage, RT	0.22%	0.45%	0.45%	0.06%
Strain @ full voltage, 20 K	0.05%	0.1%	0.1%	0.01
Dimensions (mm)	5 x 5 x 0.5	3 x 3 x 0.25	3 x 3 x 0.25	5 x 5 x 0.5
Stack Specification				
Number of active layers	10	15	15	10
Dimensions (mm)	5 x 5 x 6	3 x 3 x 4.3	3 x 3 x 4.3	5 x 5 x 6
Max voltage (V)	500	500	500	500
Displacement @ RT (µm)	9.5	14.2	14.2	2.8
Displacement @ 20 K (µm)	2.2	3.2	3.2	0.67
*Note: actual material used for PZT-5H was Pz29 from Ferroperm Ceramics. Pz29 strain is approximately 0.09% at 1 kV/mm field strength.				

2.2 PZN-8%PT SINGLE CRYSTAL PROTOTYPE STACK ACTUATORS

2.2.1 DISPLACEMENT MEASUREMENTS AT ROOM TEMPERATURE

Room temperature displacement measurements were made for each actuator at both Burleigh and PMIC. The room temperature testing consisted of energizing the actuator by ramping up to a maximum voltage and continuously measuring the displacement. The Burleigh test setup included the stack actuator mounted in the preload test fixture (described in the previous report) and preloaded to 15 lb. The voltage was applied using a ramp generator and amplifier with sinusoidal input at <10 Hz. The displacement was measured using an Eddy current sensor. The accuracy and repeatability of this test setup is on the order of ±0.2 um and is primarily governed by thermal drift of the sensor.

PMIC utilized the same setup and equipment for both room temperature and cryogenic testing. The actuators were mounted in the Burleigh preload test fixture and installing in a thermal chamber. Displacement measurements were made with a laser interferometer which measured the difference in displacement between the top and bottom of the stack actuator. The voltage input to the stack actuator was applied utilizing the same equipment used at Burleigh. For cold testing, the chamber was pulled to a high vacuum (<10^{-4} torr) and cooled with liquid helium. Cooling was computer controlled and took approximately 1 day to reach 20 K.

Table 2 shows a summary of the room temperature displacement measurements. For each measurement, the motion efficiency of the stack is calculated based on the sum of the individual plates used to build the actuator. The motion efficiency value defines how much the bond design reduces the motion of the stack due to in-plane clamping (see previous reports). Also included in this table is the expected displacement at 20 K. For each actuator, measurements were made at Burleigh prior to delivery of the stacks to PMIC. These tests are signified by the 'a' prefix. The 'b' and higher tests were measured at PMIC. The 'b' measurements were prior to cool down to 20 K. The 'c' and higher measurements were after warm up from 20 K. In comparison, the Burleigh and PMIC measurements agree well, verifying that the two test setups and equipment produced valid results. For actuator #1 (shim design), the motion efficiency is approximately 85%, this agreed well with analytical predictions. For actuator #2 (full epoxy), the motion efficiency is approximately 71%. For actuator #3 (Indium bonds), the motion efficiency is approximately 80%.

The only major discrepancy between the measured data is for actuator #3. The Burleigh measurement for the preloaded actuator was 10.4 um while PMIC measured 8.3 um. The unpreloaded measurement made at Burleigh was 8.4 um. PMIC did not measure unpreloaded stacks. This actuator will be re-tested at Burleigh to determine if the 10.4 um value was due to errors in test setup.

Table 3 shows the calculated strain and D33 of each stack actuator. D33 is calculated as displacement divided by voltage divided by the number of plates used to make up the stack. For the prototype stacks, 10 plates were used. The D33 values are lower than the individual plate measurements due to the clamping effect of the bonds.

Table 2: Performance Summary for PZN-8%PT Single Crystal Prototype Stack Actuators at Room Temperature

Test	Actuator	Voltage	Field	Disp	Efficiency	Expected 20 K Disp. @500 V
		(V)	(kV/mm)	(um)	%	(um)
1a	1	360	0.72	10.8	89%	3.15
1b	1	360	0.72	9.7	80%	3.15
1c	1	360	0.72	10.2	84%	3.15
1d	1	360	0.72	10.4	85%	3.15
1e	1	360	0.72	10.3	85%	3.15
2a	2	360	0.72	7.7	73%	2.5
2b	2	360	0.72	7.4	71%	2.5
2c	2	360	0.72	7.2	69%	2.5
3a	3	330	0.66	8.4, 10.4†	82-98%	2.4 (330 V)
3b	3	330	0.66	8.3	80%	2.4 (330 V)
3c	3	330	0.66	8.3	80%	2.4 (330 V)

Note: 1a, 2a, 3a from Burleigh test data: 1b, 2b, 3b from PMIC data prior to cooldown to 20 K: 1c-e, 2c, 3c from PMIC data after warm up from 20 K
† 8.4 um measured w/o preload, 10.1 um w/ preload

Table 3: Calculated Strain and D33 for PZN-8%PT Single Crystal Prototype Stack Actuators at Room Temperature

Actuator	Field	Strain	d33
	(kV/mm)	%	($*10^{12}$ m/V)
1	0.72	0.22%	3000
1	0.72	0.19%	2694
1	0.72	0.20%	2833
1	0.72	0.21%	2889
1	0.72	0.21%	2861
2	0.72	0.15%	2139
2	0.72	0.15%	2056
2	0.72	0.14%	2000
3	0.66	0.17%	2545
3	0.66	0.17%	2515
3	0.66	0.17%	2515

2.2.2 DISPLACEMENT MEASUREMENTS AT CRYOGENIC TEMPERATURES

Using the same test setup and equipment, each actuator was cooled to cryogenic temperatures (20 K) and the displacement under voltage was measured at 20 K. Table 4 is a summary of the cryogenic displacement measurements for each single crystal stack actuator at 20 K. Actuator #1 was energized to 500, 725, 850, and 1000 V while at 20 K; this corresponds to a field strength of 1-2 kV/mm. Actuator #2 was tested at 500 and 850 V, while actuator #3 was tested to only 330 V. Actuator #3 was suspected to electrically short at voltages greater than 360, therefore the input was limited to 330 V. Also shown in Table 4 is the expected displacement at 20 K for each actuator along with the percent difference between the expected and measured values.

As with the room temperature results, actuator #1 had the greatest displacement at 20 K, followed by actuator #3 (if scaled to 500 V), and lastly by actuator #2. The displacement of actuators #1 and #2, was very linear with input voltage. For actuator #1 at 500 V, the displacement was 1.3 um and 2.75 um at 1000 V. For actuator #2 at 500 V, the displacement was 1.1 um and 1.9 at 850 V. Comparing with the expected displacement at 20 K, the measured displacement was less than 50% of the expected value for each actuator. In addition, the strain and D33 was calculated and is shown in Table 5. As seen in this Table, the D33 coefficient is approximately 10% of the room temperature value. Previous testing of individual single crystal PZN-8%PT plates predicted that the D33 coefficient at 20 K would be 500 pm/V or 18% of the room temperature value.

At room temperature, the field induced phase transition occurs at a much lower field strength than at cryogenic temperatures. For PZN-8%PT, the field induced phase transition occurs at approximately 1.5 kV/mm at room temperature. At 20 K, the field required to induce phase transition increases well above 2 kV/mm. This was verified by testing actuator #1 to 1000 V (2 kV/mm). As previously discussed, the displacement was very linear with input voltage, verifying that a phase transition did not occur at 2 kV/mm or below.

Table 4: Performance Summary for PZN-8%PT Single Crystal Prototype Stack Actuators at 20K

Test	Actuator	Voltage	Field	Temp.	Disp.	Expected Disp.	Diff.
		(V)	(kV/mm)	(K)	(um)	(um)	%
1f	1	500	1	21	1.3	3.15	-58%
1g	1	725	1.45	18	1.9	4.6	-59%
1h	1	850	1.7	23	2.3	5.4	-57%
1i	1	1000	2	21	2.75	6.3	-56%
2d	2	500	1	20	1.1	2.5	-56%
2e	2	850	1.7	20	1.9	4.3	-56%
3d	3	330	0.66	21	0.77	2.4	-68%
3e	3	330	0.66	21	0.80	2.4	-67%

Table 5: Calculated Strain and D33 for PZN-8%PT Single Crystal Prototype Stack Actuators at 20K

Actuator	Field	Strain	D33	% of RT D33
	(kV/mm)	%	($*10^{12}$ m/V)	%
1	1	0.026%	260	9.2%
1	1.45	0.038%	262	9.3%
1	1.7	0.046%	269	9.5%
1	2	0.055%	274	9.7%
2	1	0.022%	218	10.6%
2	1.7	0.038%	224	10.8%
3	0.66	0.015%	233	9.3%
3	0.66	0.016%	242	9.6%

2.2.3 DISPLACEMENT MEASUREMENTS VS. TEMPERATURE

After measurements were taken at 20 K, the test chamber was slowly warmed to room temperature (295 K). During warm up, the actuator was energized and the displacement measured at 20° C intervals. This data was used to produce the displacement vs. temperature curve for each actuator shown in Figure 1. For these measurements, the maximum voltage at each temperature was limited to the maximum room temperature of the actuator. For actuators #1 and #2, the maximum voltage was 360 V. For actuator #3, the maximum voltage was 330 V. For comparison purposes, the measurements for actuator #3 were scaled up to 360 V.

The shape of the curve is similar for each actuator. There are two distinct linear regions, one from 300K down to 140 K, and a steeper slope from 140 K down to 20 K. As the temperature approaches 20 K, the response of all three actuators converge. If extrapolated to absolute zero, the displacement under voltage would also approache zero. This trend is similar to measurements made with other piezoelectric ceramic compositions. Shown in Figure 2 is the calculated D33 coefficient based on the measured displacement.

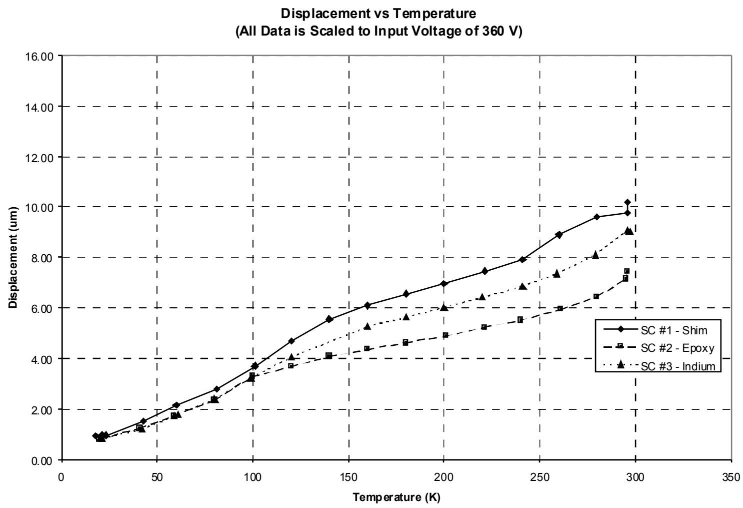

Figure 1: Displacement vs Temperature for PZN-8%PT Single Crystal Prototype Stack Actuators

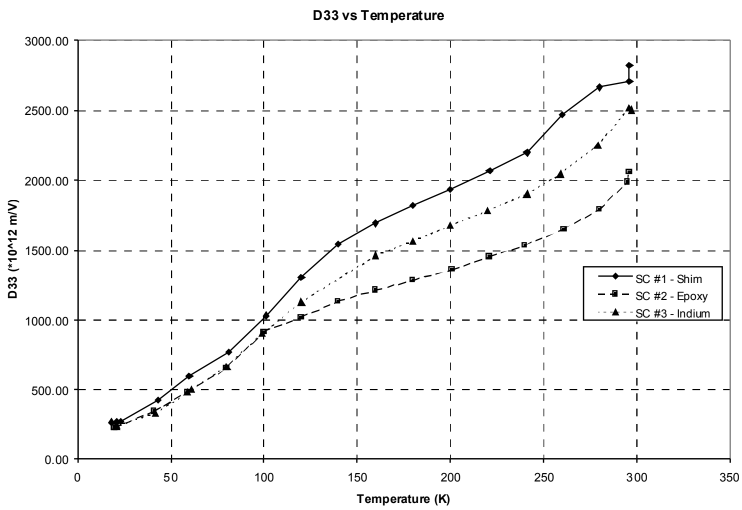

Figure 2: Calculated D33 vs Temperature for PZN-8%PT Single Crystal Prototype Stack Actuators (1 kV/mm Field)

2.3 CONVENTIONAL MATERIAL (Pz-29) PROTOTYPE STACK ACTUATORS

2.3.1 DISPLACEMENT MEASUREMENTS AT ROOM TEMPERATURE

For thermal displacement testing (CTE measurements) and comparison with known data, three Pz-29 stack actuators were built using the same manufacturing method as actuator #1 (shim design). The actual material used was Pz29 from Ferroperm Ceramics, which is similar to PZT-5H. The reported strain, from Ferroperm, for this material at 1 kV/mm is 0.09%.

Table 6 shows a summary of the room temperature displacement measurements. For each measurement, the motion efficiency of the stack is calculated based on the sum of the individual plates used to build the actuator. The motion efficiency value defines how much the bond design reduces the motion of the stack due to in-plane clamping (see previous reports). Also included in this table is the expected displacement at 20 K. For each actuator, measurements were made at Burleigh prior to delivery of the stacks to PMIC. These tests are signified by the 'a' prefix. The 'b' and higher tests were measured at PMIC. The 'b' measurements were prior to cool down to 20 K. The 'c' and higher measurements were after warm up from 20 K. In comparison, the Burleigh and PMIC measurements agree well, verifying that the two test setups and equipment produced valid results. The motion efficiency of each actuator was greater than 100%. Previous finite element analysis had predicted motion efficiencies over 100% for some designs due to poisson's effect and could partially explain these results.

Table 7 shows the calculated strain and D33 of each stack actuator. D33 is calculated as displacement divided by voltage divided by the number of plates used to make up the stack. For the prototype stacks, 10 plates were used. The strain values are very close to what the manufacturer states as the nominal value of 0.09%.

Table 6: Performance Summary for Pz29 Prototype Stack Actuators at Room Temperature

Test	Actuator	Voltage	Field	Disp	Efficiency	Expected 20 K Disp. @500 V
		(V)	(kV/mm)	(um)	%	(um)
4a	4	500	1.0	4.00	102%	0.79
4b	4	500	1.0	4.50	115%	0.79
4c	4	500	1.0	4.21	107%	0.79
5a	5	500	1.0	3.20	90%	0.69
5b	5	500	1.0	3.77	106%	0.69
5c	5	500	1.0	3.55	100%	0.69
6a	6	500	1.0	4.90	125%	0.98
6b	6	500	1.0	4.06	103%	0.98
6c	6	500	1.0	3.87	98%	0.98

Note: 4a, 5a, 6a from Burleigh test data
4b, 5b, 6b from PMIC data prior to cooldown to 20 K
4c, 5c, 6c from PMIC data after warm up from 20 K
† 8.4 um measured w/o preload, 10.1 um w/ preload

Table 7: Calculated Strain and D33 for Pz-29 Prototype Stack Actuators at Room Temperature

Actuator	Field	Strain	d33
	(kV/mm)	%	(*10^{12} m/V)
4	1.0	0.08%	800
4	1.0	0.09%	900
4	1.0	0.08%	842
5	1.0	0.06%	640
5	1.0	0.08%	754
5	1.0	0.07%	710
6	1.0	0.10%	980
6	1.0	0.08%	812
6	1.0	0.08%	774

2.3.2 DISPLACEMENT MEASUREMENTS AT CRYOGENIC TEMPERATURES

Using the same test setup and equipment, each actuator was cooled to cryogenic temperatures (20 K) and the displacement under voltage was measured at 20 K. Table 8 is a summary of the cryogenic displacement measurements for each Pz-29 stack actuator at 20 K. Each actuator was energized to 500 V while at 20 K; this corresponds to a field strength of 1 kV/mm. Also shown in Table 8 is the expected displacement at 20 K for each actuator along with the percent difference between the expected and measured values.

On average, the displacement at 20 K was 20% greater than expected. The only actuator which displaced less than expected was #6 at -15%. As mentioned previously, these actuators were built to identical designs and techniques to test for variations in manufacture. From this set of data, the amount of variation seen is approximately ±0.07 um, or ±9% of the total displacement. The strain and D33 was calculated and is shown in Table 9. As seen in this Table, the D33 coefficient is approximately 20% of the room temperature value. This agrees well with published data.

Table 8: Performance Summary for Pz-29 Prototype Stack Actuators at 20K

Test	Actuator	Voltage	Field	Temp.	Disp.	Expected Disp.	Diff.
		(V)	(kV/mm)	(K)	(um)	(um)	%
4d	4	500	1	25	0.94	0.79	19%
4e	4	500	1	25	0.93	0.79	18%
4f	4	500	1	26	0.96	0.79	22%
5d	5	500	1	23	0.85	0.69	23%
5e	5	500	1	28	0.79	0.69	14%
6d	6	500	1	24	0.83	0.98	-15%

Table 9: Calculated Strain and D33 for Pz-29 Prototype Stack Actuators at 20K

Actuator	Field	Strain	D33	% of RT D33
	(kV/mm)	%	(*10^{12} m/V)	%
4	1	0.019%	188	22.2%
4	1	0.019%	186	22.0%
4	1	0.019%	192	22.7%
5	1	0.017%	170	24.2%
5	1	0.016%	158	22.5%
6	1	0.017%	166	19.4%

2.3.3 DISPLACEMENT MEASUREMENTS VS. TEMPERATURE

After measurements were taken at 20 K, the test chamber was slowly warmed to room temperature (295 K). During warm up, the actuator was energized and the displacement measured at 20° C intervals. This data was used to produce the displacement vs. temperature curve for each actuator shown in Figure 3. For each measurement, the voltage applied was 500 V. Unlike the single crystal material, the displacement vs. temperature curves have a constant curvature throughout the entire temperature range. Also, if extrapolated to absolute zero, the displacement crosses at a point above zero. From a variability point of view, the curves are almost identical in form suggesting that if the absolute displacement of each actuator was identical, they would perform with very little variation. Shown in Figure 4 is the calculated D33 vs. temperature.

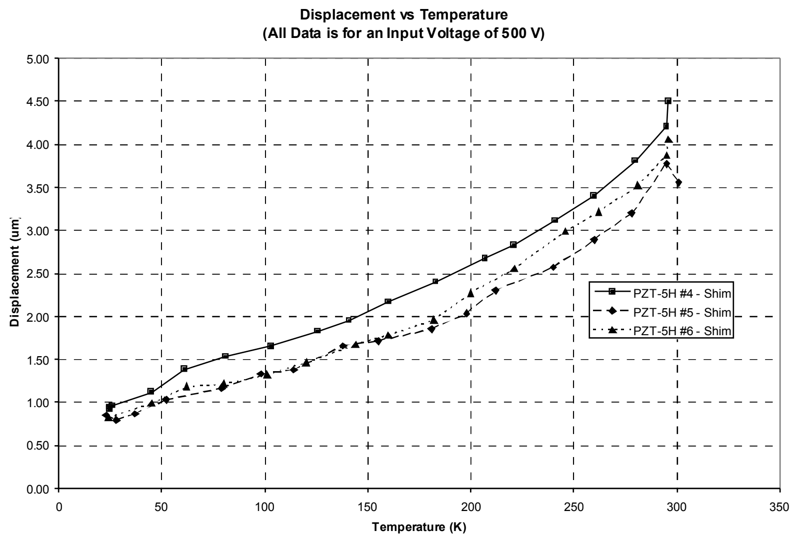

Figure 3: Displacement vs Temperature for Pz-29 Prototype Stack Actuators

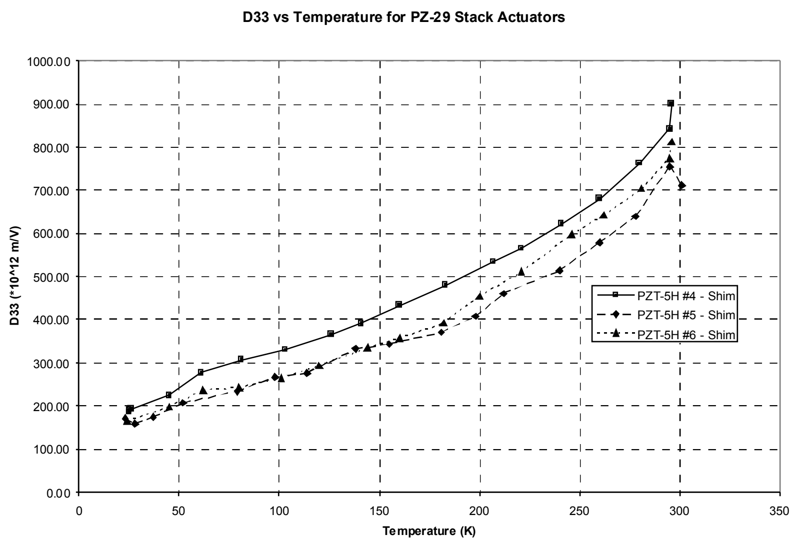

Figure 4: Calculated D33 vs Temperature for Pz-29 Prototype Stack Actuators (1 kV/mm Field)

2.4 DISCUSSION OF TEST RESULTS

Preliminary results of the cryogenic testing show a much lower than expected performance of the PZN-8%PT single crystal material when built into stack actuators. The expected displacement was more than twice the measured results. At room temperature, the displacement under voltage correlated very well with analytical predictions for each actuator design. In comparison, the stack actuators made from conventional PZT material (PZT-5H equivalent) performed as expected at cryogenic temperatures with little variation between the three actuators. For a direct comparison between single crystal material and conventional PZT material, the representative D33 vs temperature for each material is shown in Figure 5. The D33 data for the single crystal actuators were scaled up from 360 V to 500 V.

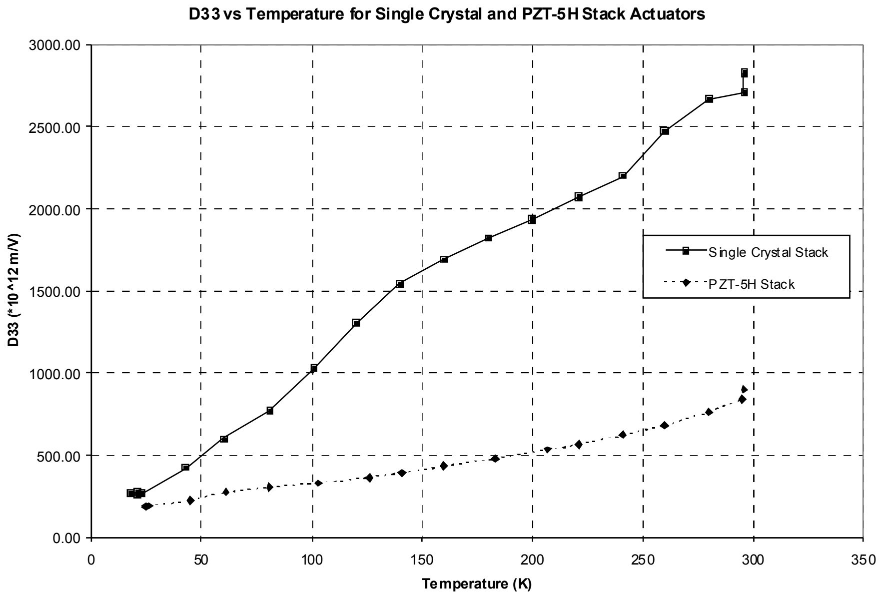

Figure 5: Comparison of Calculated D33 vs Temperature for PZN-8%PT Single Crystal and Pz-29 Prototype Stack Actuators (PZN-8%PT Actuator Data is Scaled up to 1 kV/mm)

From Figure 5, at room temperature the single crystal actuator D33 is approximately 3.5 times greater than the conventional material actuators. As the temperature approaches 20 K, the performance of the two types of actuators begin to converge. At best, it appears that the single crystal actuators was only 40% better than the conventional material actuators at 20 K. These conclusions are drawn based on preliminary evaluation of the data. In order to fully understand what may have caused the reduced performance, the following questions and observations will need to be addressed:

- Questionable test equipment and setup?
  Observations:
  - Same test setup was used for RT and cryogenic measurements
  - PMIC reported RT displacements within 0.1 um of Bii results
  - Before and after RT measurements agree
  - Displacement is linear from 0-1000 V
  - PZT-5H stacks performed as expected

- Stiffening of bonding material at 20K?
  Observations:
  - Bond interface of stacks #1, #2, #3 were progressively more compliant. Stack #3 was

bonded with Indium which is very compliant even at 20K. Expected change in Indium modulus is less than 10%.

– PZT-5H stacks were built using design #1 with predicted results

- Change in electrical conductivity to the electrodes at 20K?
  Observations:
  – Bond interface of stacks #1, #2, #3 were progressively more conductive. Stack #3 was bonded with Indium which provided a fully conductive surface between the plates.
  – PZT-5H stacks were built using design #1 with predicted results

- Unexpected reduction of in-plane elastic properties is PZN-8%PT resulted in more clamping by the electrodes?
  Observations:
  – Previous analysis is showed that stack actuator design was very sensitive to the in-plane elastic properties. Although a very drastic change in properties would be required to result in the low efficiencies presented above.
  – In-plane clamping would not be noticed in testing involving individual plates. Electrode thickness was less than 1500 A
  – Bond interface of stacks #1, #2, #3 were progressively more compliant. Stack #3 was bonded with Indium which is very compliant even at 20K. Expected change in Indium modulus is less than 10%. This would suggest that the efficiencies would increase for actuator #3. It decreased…

In addition to displacement measurements, CTE measurements were also made. This data has not been finalized at this time and will be analyzed for the next reporting period.

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Additional Testing On MLA by John Fasick in early 2001

Extension Mechanism

The extension actuator mechanism design is shown in Figure 15. The design consists of the PZT extension actuator, the front and rear clamp guides, bearing rails, and the preload spring and tightening screw. The extension actuator is mounted between the clamp guides and preloaded by tightening the screw and compressing the spring. To eliminate moment forces into the PZT actuator, a spherical/cone interface is used. Mounted to both ends of the PZT actuator is a spherical cap which mates into a cone on the clamp guides.

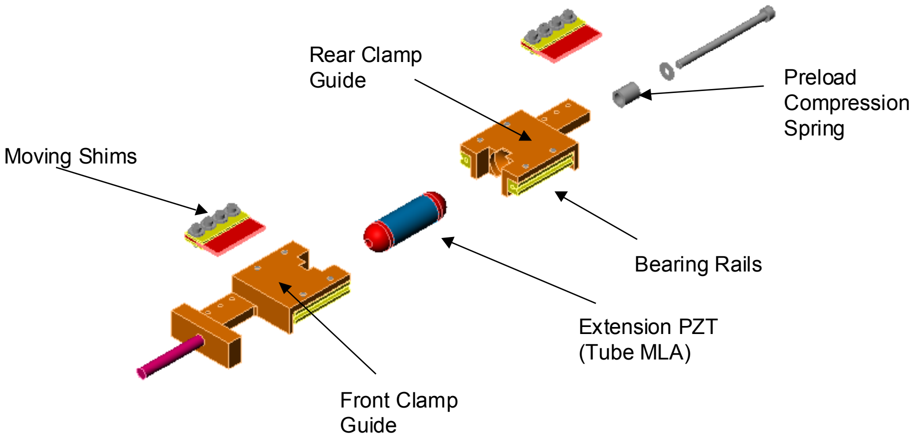

Figure 15: Extension Actuator Mechanism Design

The extension actuator consists of a built-up stack of seven co-fired multi-layer PZT actuators. The specifications for the extension actuator are shown in Table 5. The PZT actuators are a ring shape geometry with a ⌀3mm ID and ⌀6mm OD. Seven actuators are stacked together and bonded with cryogenic epoxy to form the extension actuator. The ring shape design allows a shaft to pass through the center for preloading. The actuator operates at 200 V with a maximum displacement of 17 μm at room temperature and 2.8 μm at 20K. The axial stiffness of the actuator is 88 N/μm.

Table 5: Extension Actuator Specifications

Expected Displacement 20K	2.8 μm
Displacement RT	17 μm
Dimensions	⌀3mm ID x ⌀6mm OD x 2mm thk
No. Actuators	7
Total Length	16.5 mm
Max Voltage	200 V
Capacitance	1.4 μF
Blocking Force	1500 N
Stiffness	88 N/μm

By the nature of their design, co-fired multi-layer actuators develop internal stresses for a given change in temperature. The internal stress is due to the CTE mismatch between the piezoelectric ceramic and metallic electrodes. The initial build of this motor used external wire leads soldered directly to the external electrodes on the PZT actuators. When first cooled to 77 K, the actuators worked intermittently and short circuited the electronics. Upon inspection, it was discovered that the external electrodes delaminated from the piezoelectric ceramic in the vicinity of the solder joints. This in turn exposed the internal electrodes and produced intermittent contact. An evaluation determined that the high stiffness of the solder did not allow the electrode to shrink with the piezoelectric material and therefore high stresses were developed which tore the electrode from the ceramic. To solve this problem, the external wire leads were attached to the electrodes using a conductive epoxy. The epoxy used was Cryobond 620 with 60% by volume addition of silver coated glass spheres. The resistance was less than 5 ohm. This new design was tested at both 77 K and 30 K and the actuator performed as expected.

Cryogenic test results of this project are encouraging and prove that co-fired multi-layer actuators operate at cryogenic temperatures and behave as expected, but the overall reliability of co-fired multi-layer actuators were not tested during this project. Extensive testing is required and necessary to evaluate the life of these actuators at cryogenic temperatures.

2.4.1 PZT Displacement Testing at Room Temperature and 30 K

The displacement of the center extension PZT actuator was measured at both room temperature and 30 K. For both measurements, the motor was commanded to move 50000 motor steps, or 0-150 V. This range assured that a clamp change would not occur. For each test, the actuator was commanded to 150 V held for several seconds then return to 0 V. This was repeated several times to obtain an average displacement. The measured displacement for both tests is shown in Figure 24. At room temperature, the displacement was 12.9 um. For full stroke, 0-200 V, the expected displacement of the extension actuator is 17.2 um. At 30 K, the measured motion of the PZT from 0-150V was 3.3 um. The open-loop resolution is therefore 0.06 nm/step. For full stroke, 0-200 V, the expected displacement of the extension actuator is 4.4 um. This means the displacement between clamp changes will nominally be 4.4 um at 30 K. Compared to the room temperature stroke, the PZT strain was reduced approximately 75% when cooled to 30 K. This reduction in strain was as expected based on data in the literature and previous testing of conventional PZT stack actuators at 20 K (ref xxx).

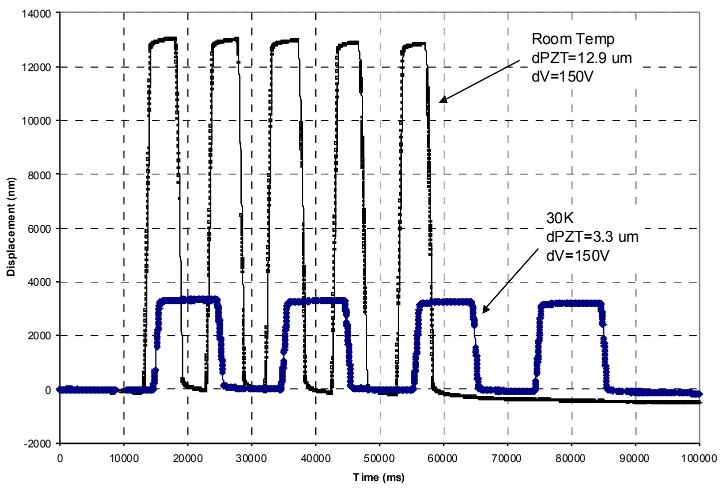

Figure 24: Extension Actuator (PZT) Displacement at Room Temperature and 30K for V=0-150V (4 & 20)