HIGH PRECISION PIEZOELECTRIC LINEAR MOTORS FOR OPERATIONS AT CRYOGENIC TEMPERATURES AND VACUUM

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The Jet Propulsion Laboratory evaluated the use of an electromechanical device for optically positioning a mirror system during the pre-project phase of the Pluto-Fast -Flyby (PFF) mission. The device under consideration was a piezoelectric driven linear motor functionally dependent upon a time varying electric field which induces displacements ranging from submicrons to millimeters with positioning accuracy within nanometers. Using a control package, the mirror system provides image motion compensation and mosaicking capabilities. While this device offers unique advantages, there were concerns pertaining to its operational capabilities for the PFF mission. These issues include irradiation effects and thermal concerns. A literature study indicated that irradiation effects will not significantly impact the linear motors operational characteristics. On the other hand, therms! concerns necessitated an in depth study.

To address the thermal issue, we constructed an exact electro-elastic-thermal analytical solution, a finite element model and conducted experimental tests to evaluate the operation of the linear motor at cryogenic temperatures. This study indicated that severe problems arise when operating this device at low temperatures related to thermal mismatches in the materials causing the motor to "lock up" and degradation of the strain coefficients causing a loss in the motor's efficiency. To address these issues, we conducted a parametric study to investigate the impact of geometrical changes and material substitutions on the thermal response of the linear motor. This study indicated that the thermal mismatch problem could be overcome with several possible reconfiguration. We also evaluated the response of the motor's drive element (PZT-5h) at temperatures down to 157 Kelvin. Experimental results indicate that mechanical limitations of the piezoelectric ceram ic are strain dependent and electric field independent. Thus, degradation in the piezoelectric strain coefficients at cryogenic temperatures are easily overcome with appropriate modification s to the applied voltage. These preliminary results suggest that the appropriate state variable for modeling/predicting nonlinear and long term response of solid state motors containing piezoelectric material could be strain. Experimental tests on an augmented linear motor at 157 Kelvin demonstrated both clamping and elongation/contraction capabilities supporting the analytical results. Therefore, both analytical and experimental evidence has led to the conclusion that an augmented linear motor can intelligently engineered to operate at the temperature levels of the PFF mission.

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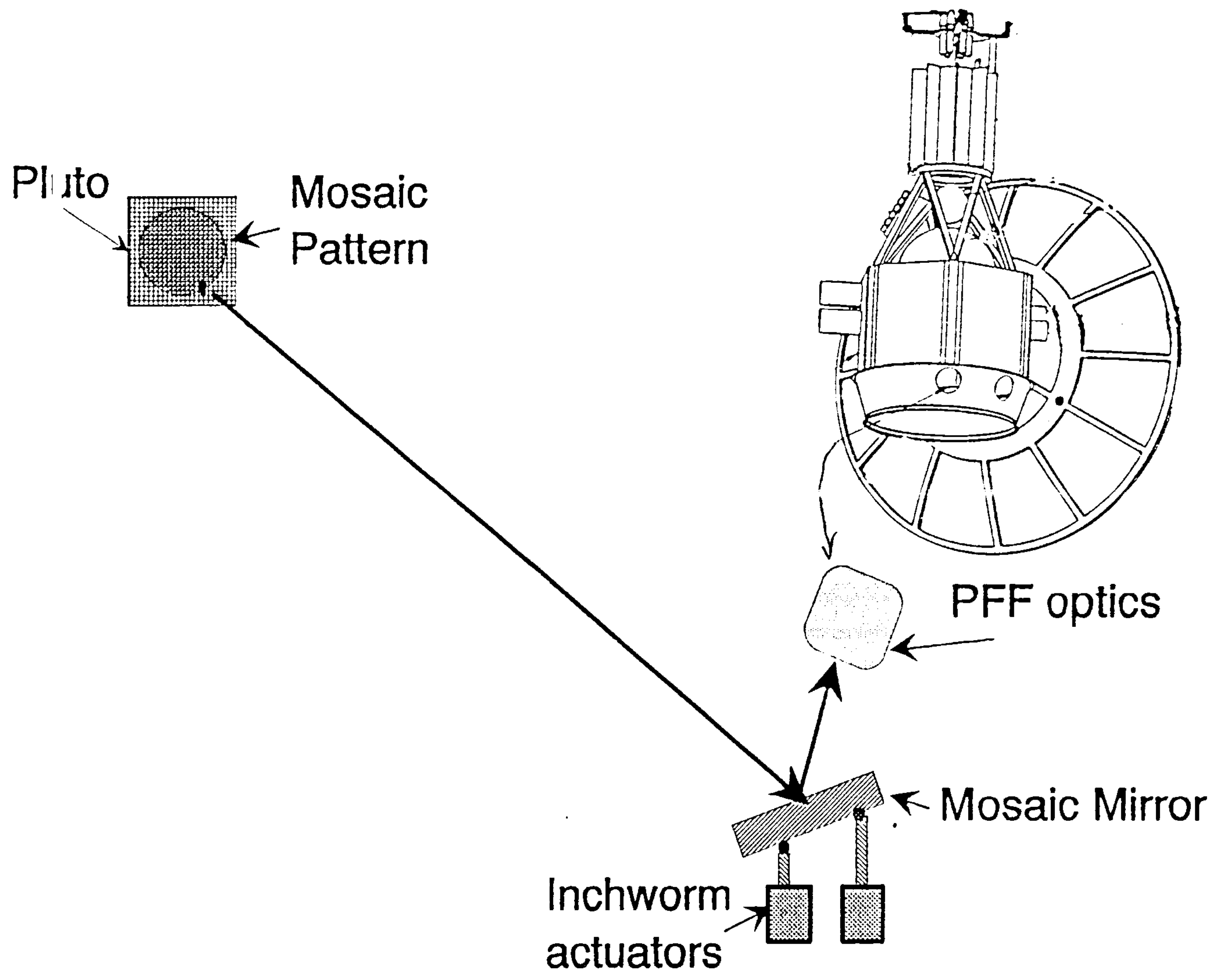
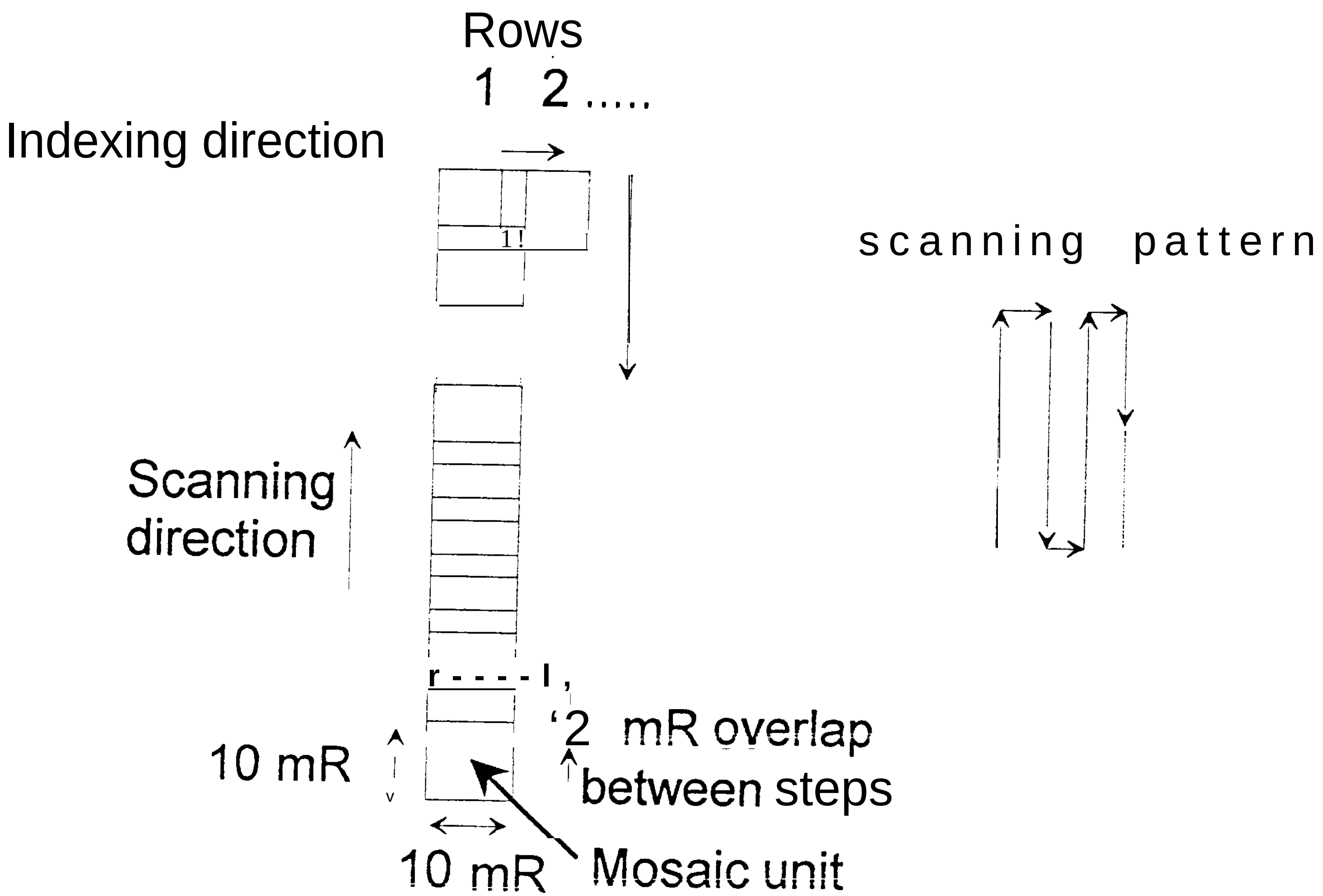
PLUTO FAST FLYBY SCANNING USING AN ARTICULATED MOSAIC MIRROR





MOSAIC MIRROR SCANNING PATTERN

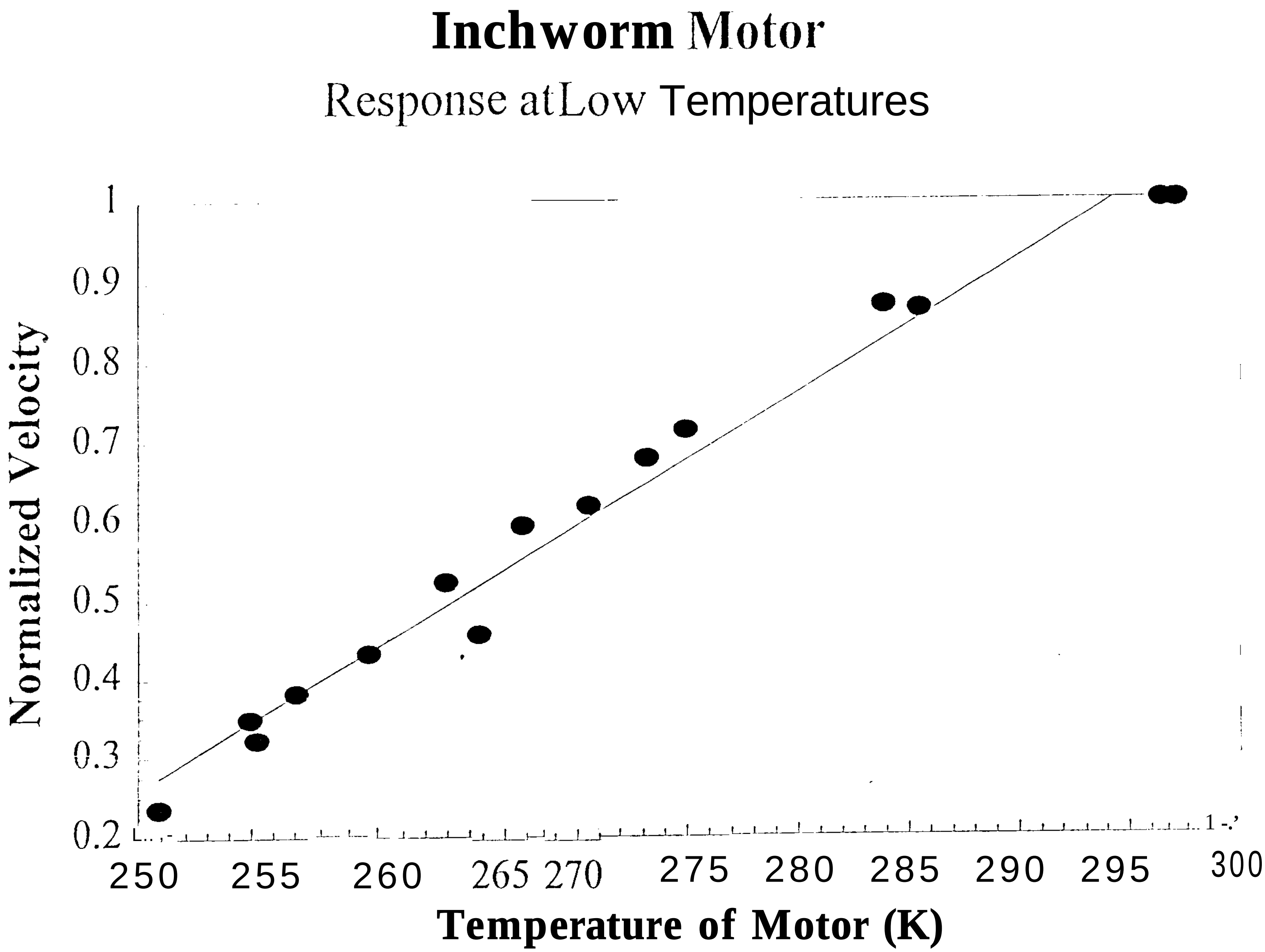
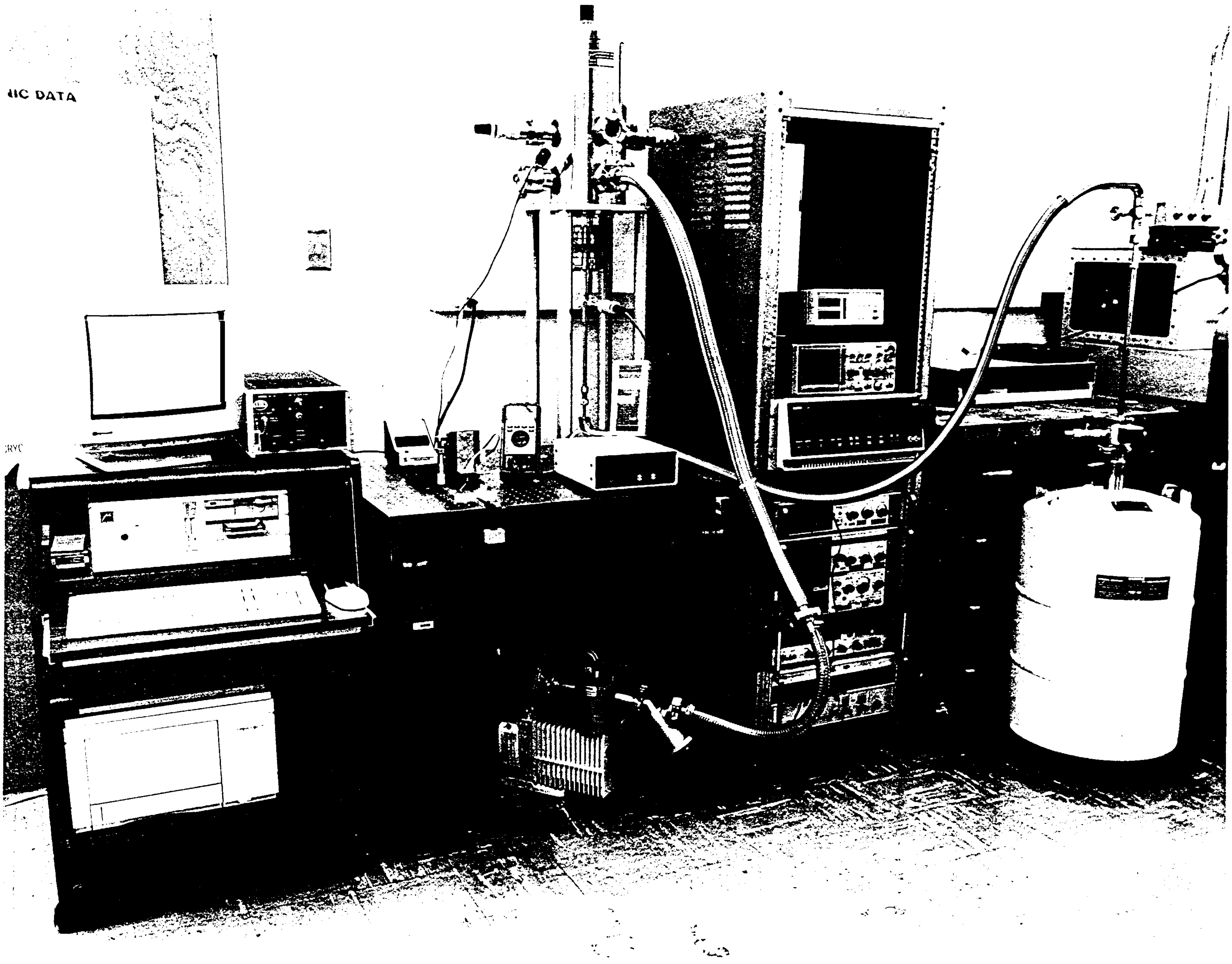

Inchworm Motor
Response at Low Temperatures
Normalized Velocity
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
250
255
260
265
270
275
280
285
290
295
300
Temperature of Motor (K)

FIGURE 6



OBJECTIVES

Develop an Articulation System for the Scanning Mirror of Fast Pluto Flyby Preproject with the following requirements:

- Large tilting and tipping angles with milliradian resolution.
- Capability to operate at cryogenic temperatures (>120K), Vacuum and exposure to radiation.
- Available system power limited to 4Watts.

Presentation Outline

- analytical solution including temperature dependent piezoelectric coefficient
- Power requirement for linear motor using Fourier series
- Experimental results
  - Coefficients of thermal expansion
  - Nonlinearity of piezoelectric coefficient
  - Depoling behavior w.r.t. strain and electric field
- Analytical results
  - Stress due to temperature and electric field
  - Effects of liner thickness changes
  - Temperature dependence of piezoelectric coefficient
  - Design plot
- Analytical vs. experimental

Modified Constitutive Relations

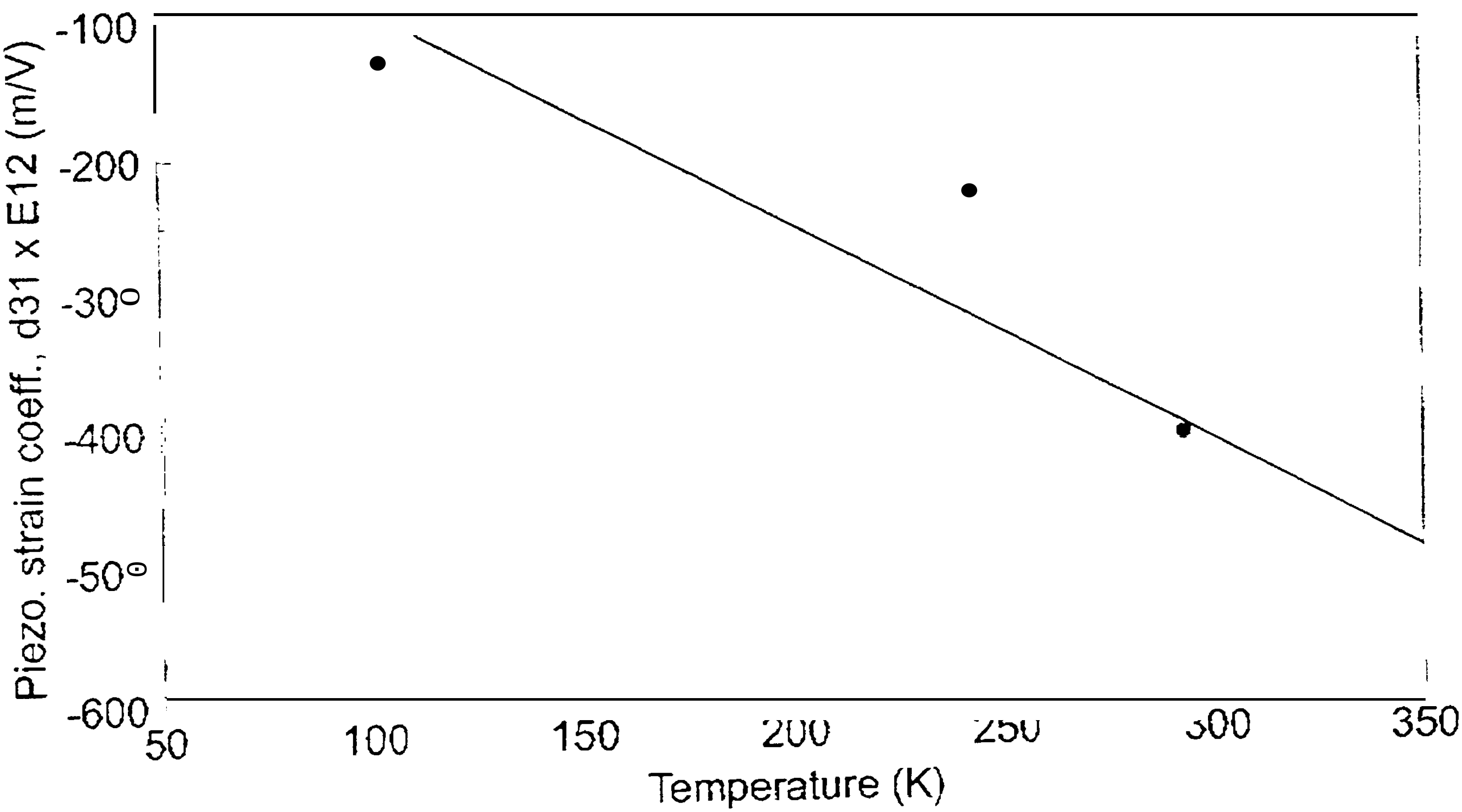
Stress

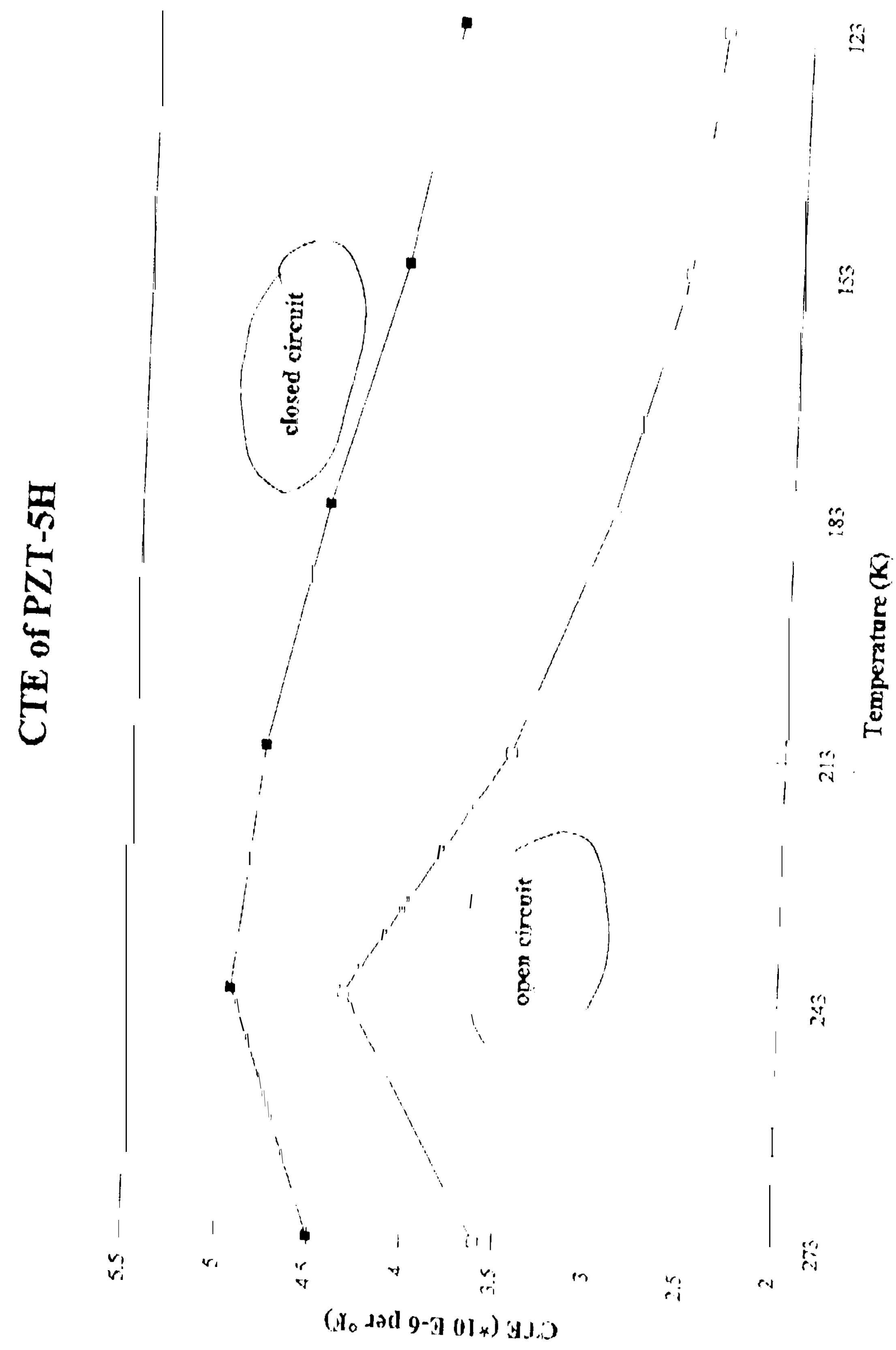
$$\begin{Bmatrix}\sigma_\theta\\ \sigma_x\\ \sigma_r\end{Bmatrix}=\begin{bmatrix}C_{\theta\theta} & C_{\theta x} & C_{\theta r}\\ C_{x\theta} & C_{xx} & C_{xr}\\ C_{r\theta} & C_{rx} & C_{rr}\end{bmatrix}\begin{Bmatrix}\varepsilon_\theta-\alpha_\theta\Delta T\\ \varepsilon_x-\alpha_x\Delta T\\ \varepsilon_r-\alpha_r\Delta T\end{Bmatrix}-\begin{bmatrix}0 & 0 & \left(g_{r\theta}+g_{r\theta}\Delta T\right)\\ 0 & 0 & \left(g_{rx}+g_{rx}\Delta T\right)\\ 0 & 0 & \left(g_{rr}+g_{rr}\Delta T\right)\end{bmatrix}\begin{Bmatrix}0\\ 0\\ E_r\end{Bmatrix}$$

Electric Displacement

$$D_r=\left(g_{r\theta}+\bar{g}_{r\theta}\Delta T\right)\varepsilon_\theta+\left(g_{rx}+\bar{g}_{rx}\Delta T\right)\varepsilon_x+\left(g_{rr}+\bar{g}_{rr}\Delta T\right)\varepsilon_r+\varepsilon_{rr}E_r+p_r\Delta T$$

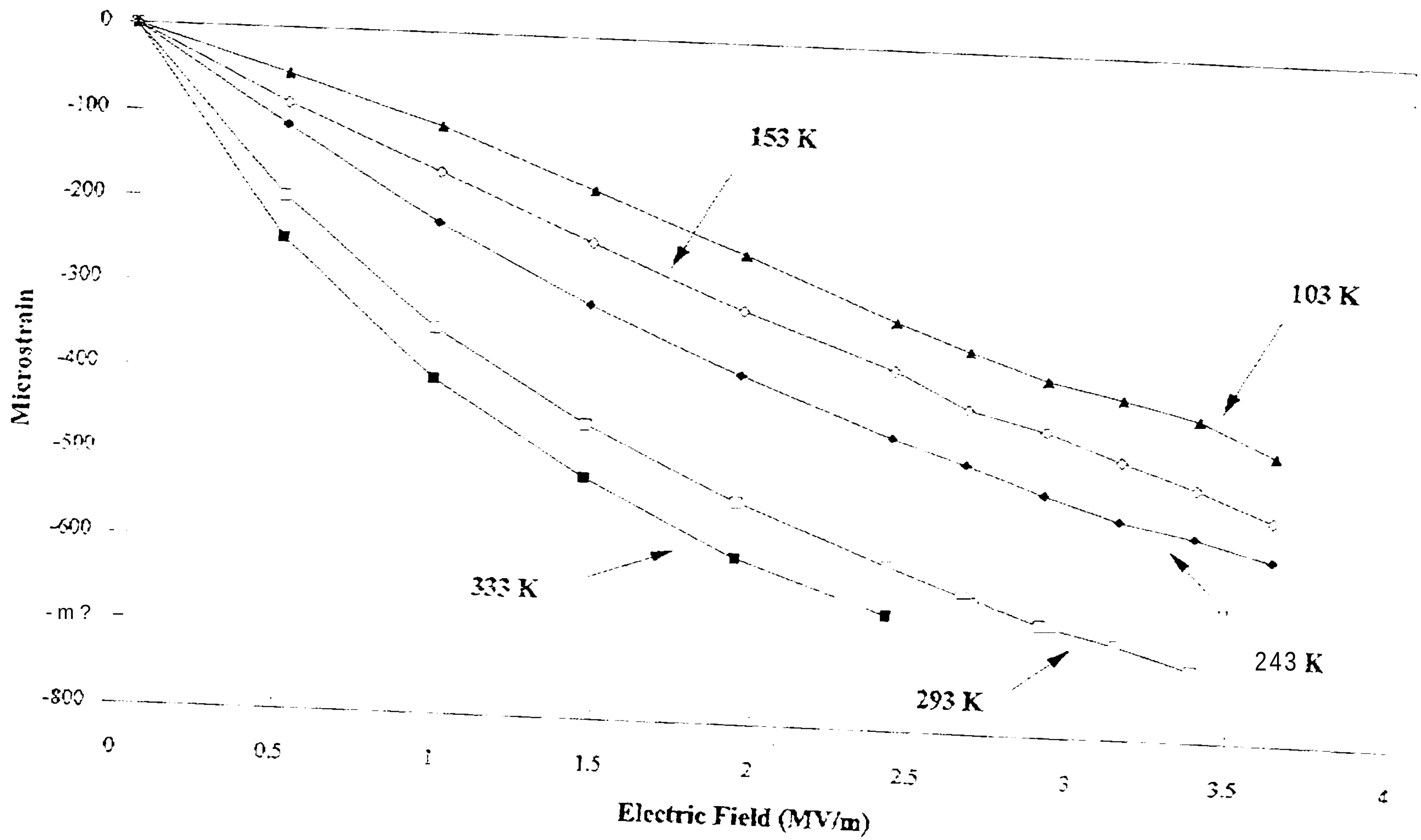
Linearized Piezoelectric Strain Coefficient, d31




CTE of PZT-5H
closed circuit
open circuit
Temperature (K)
CTE (*10 E-6 per °K)
5.5
5
4.5
4
3.5
3
2.5
2
273
243
213
183
153
123

Saturation attain strain

Nonlinearity of the d31 Piezoelectric Strain Coefficient



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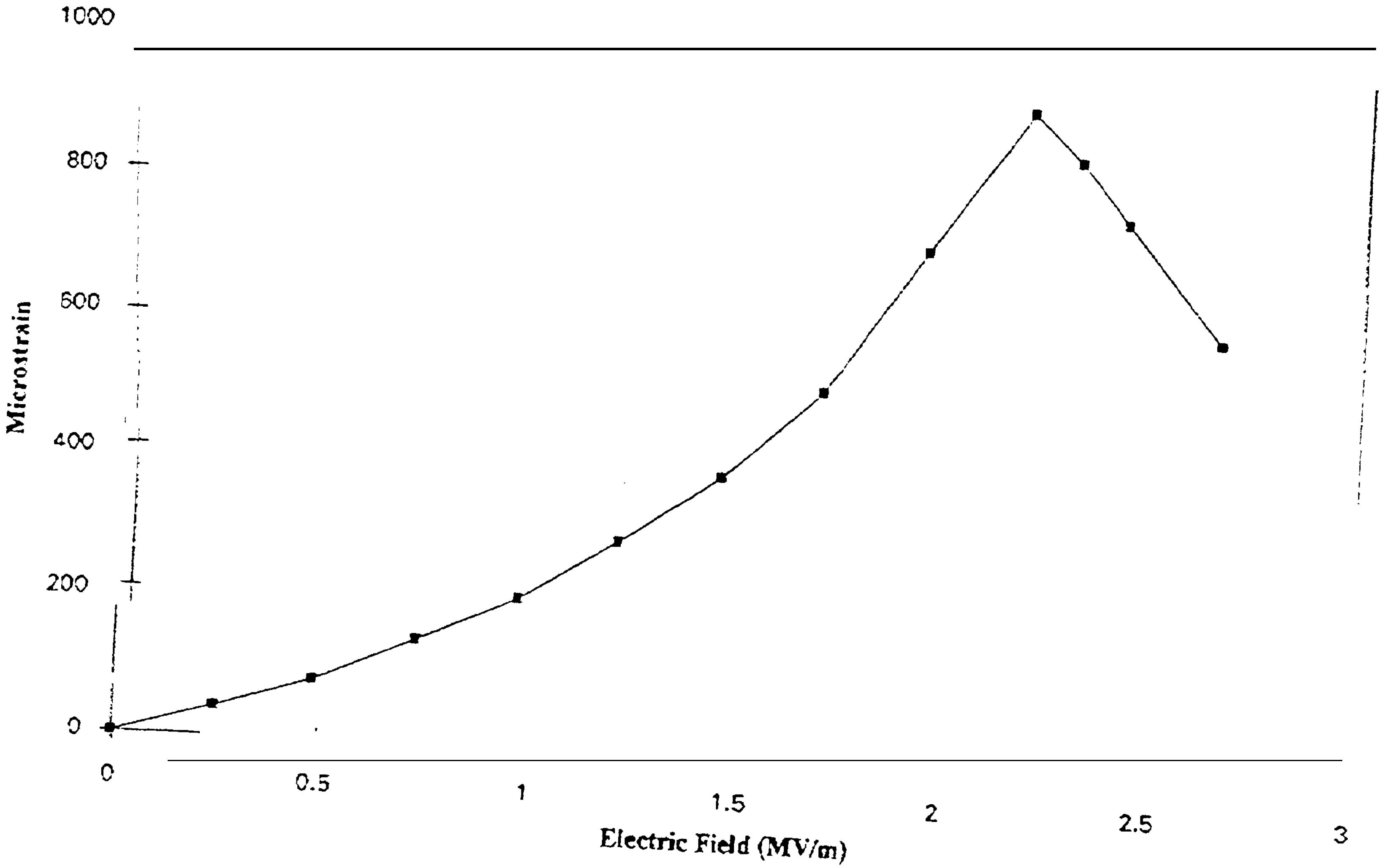
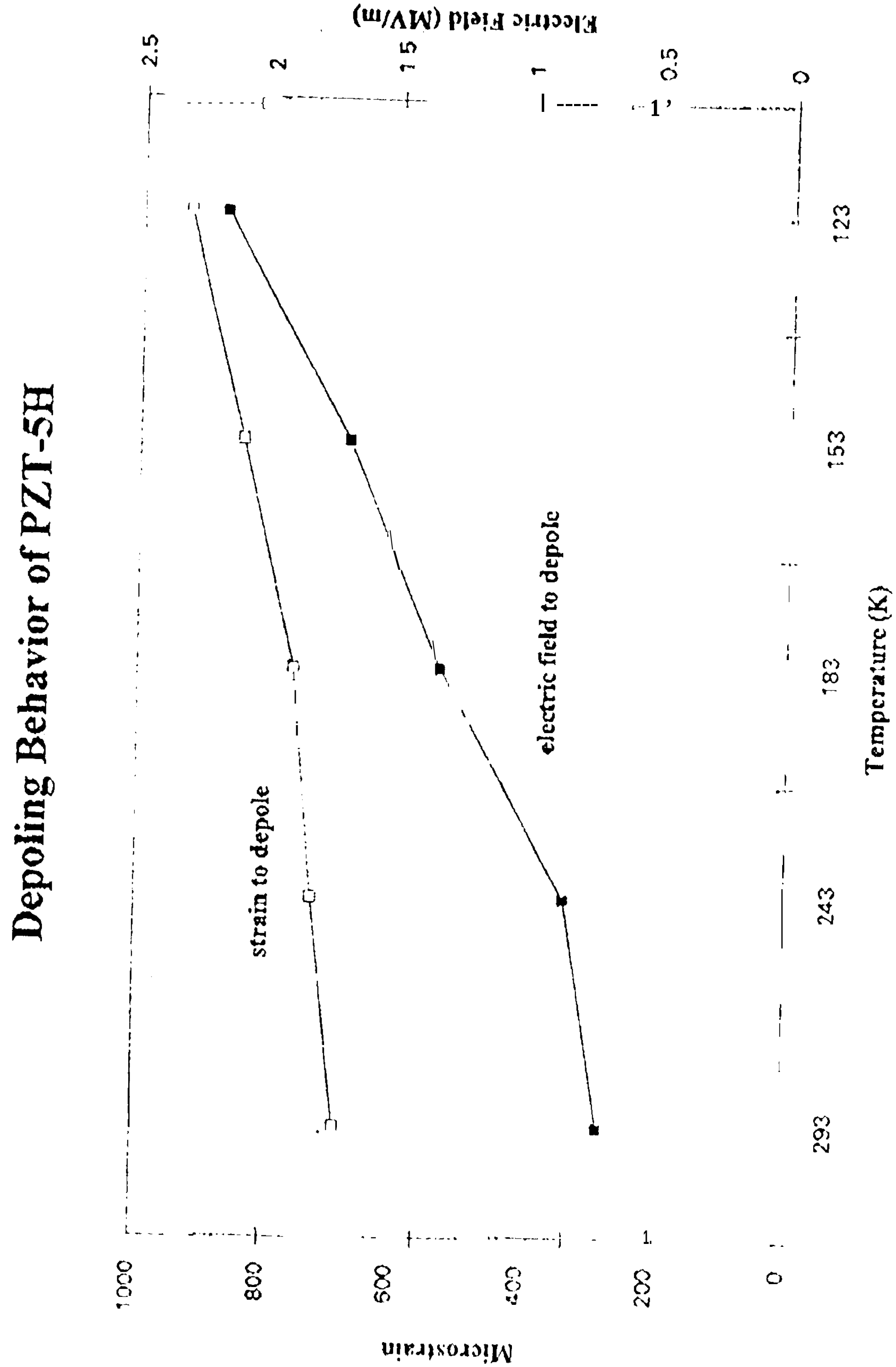
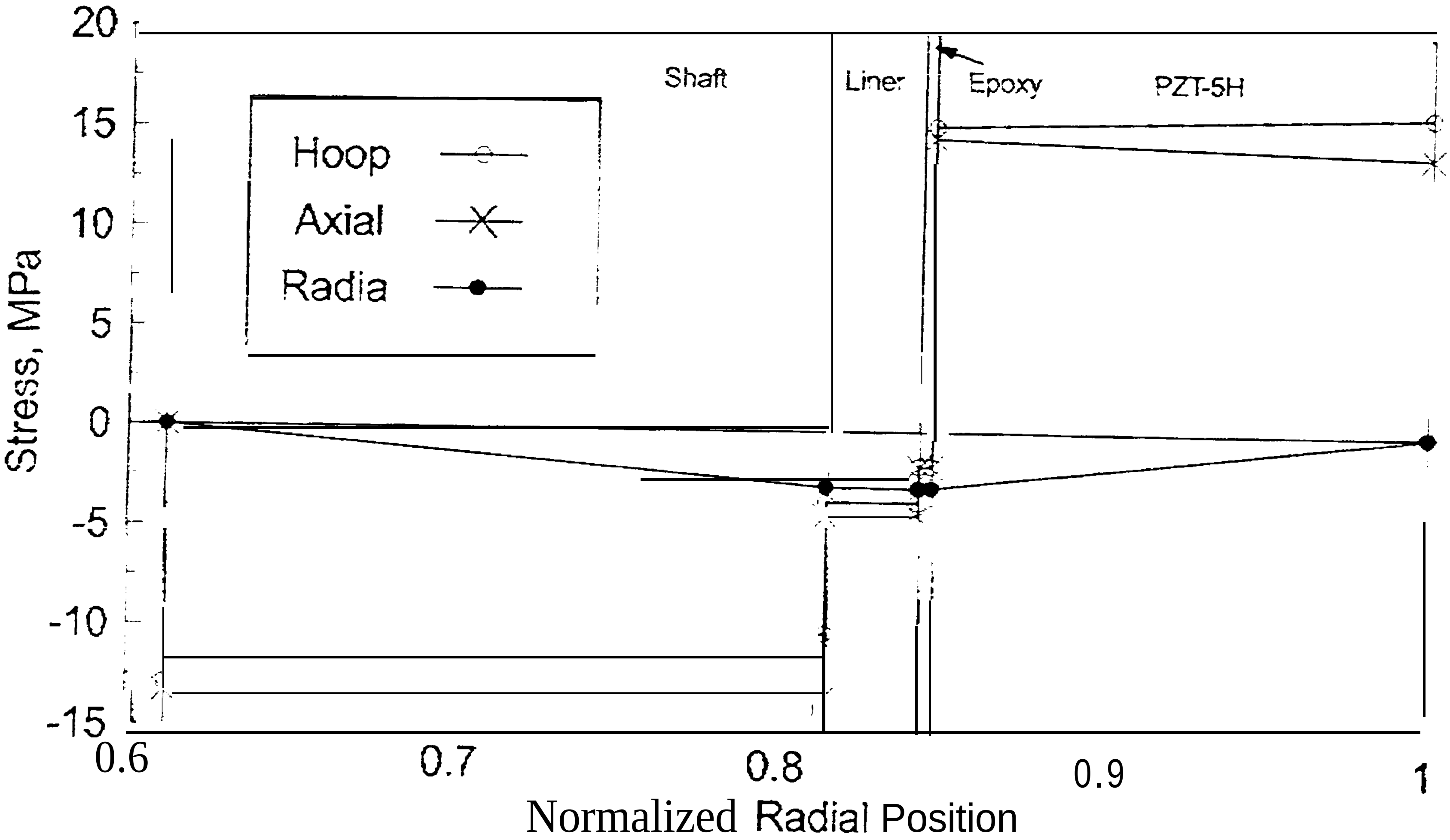
Depoling of PZT-5H at 123 K



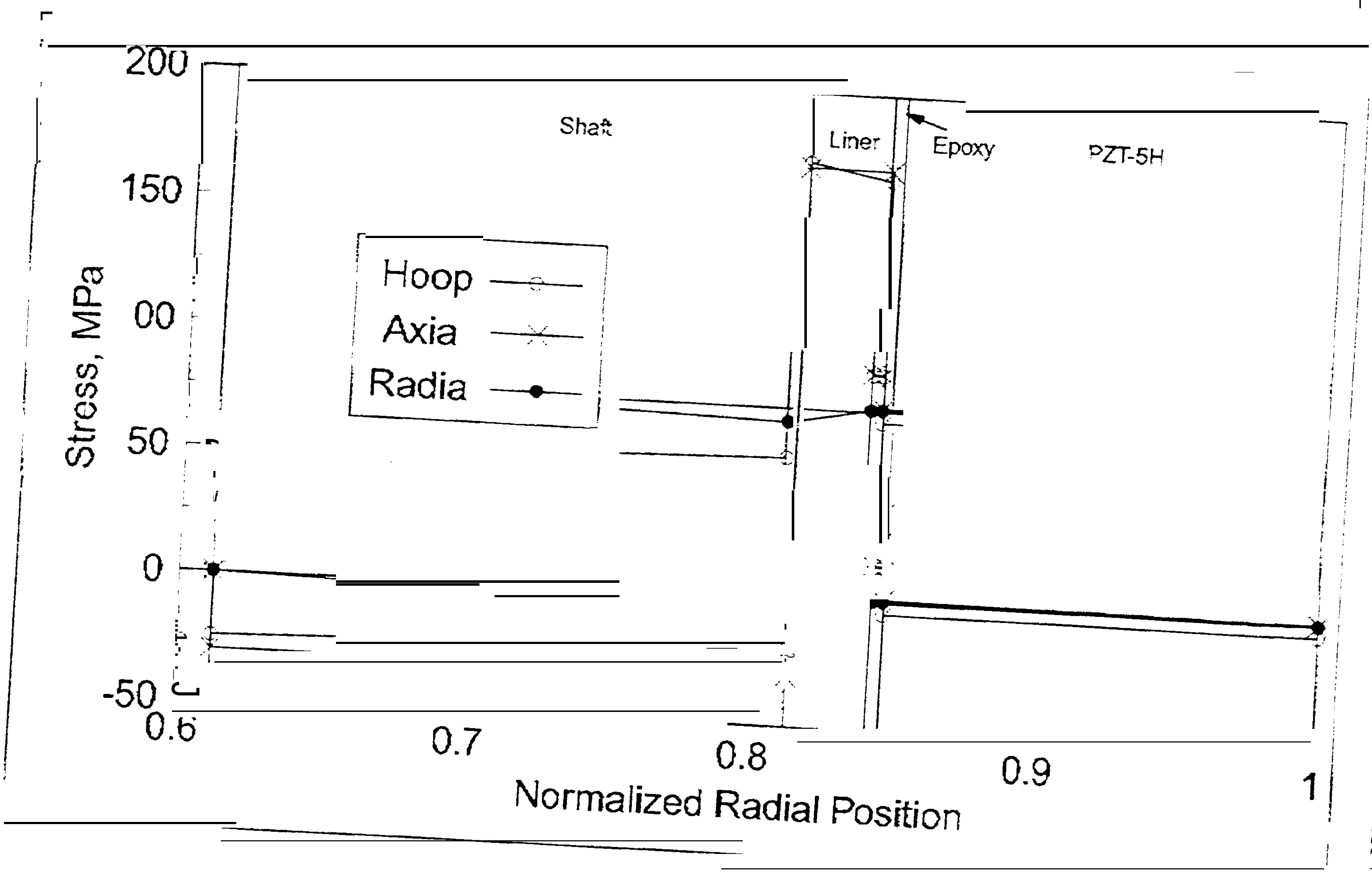

Depoling Behavior of PZT-5H
Electric Field (MV/m)
2.5
2
1.5
1
0.5
0
strain to depole
electric field to depole
123
153
183
243
293
Temperature (K)
1000
800
600
400
200
0
Microstrain

Electric Field Stress in Linear Motor

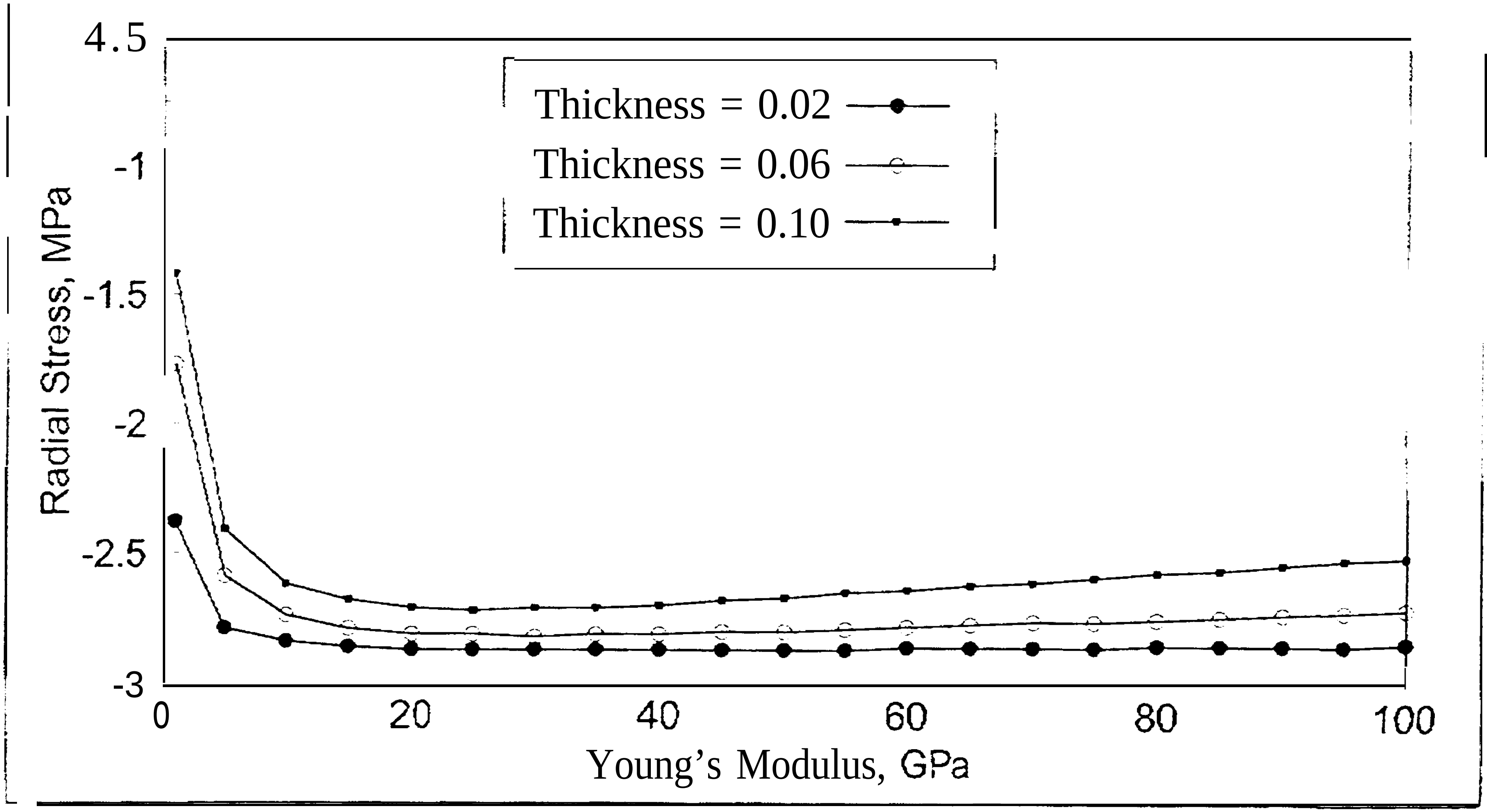
E Field = -0.59 Mvolts/m



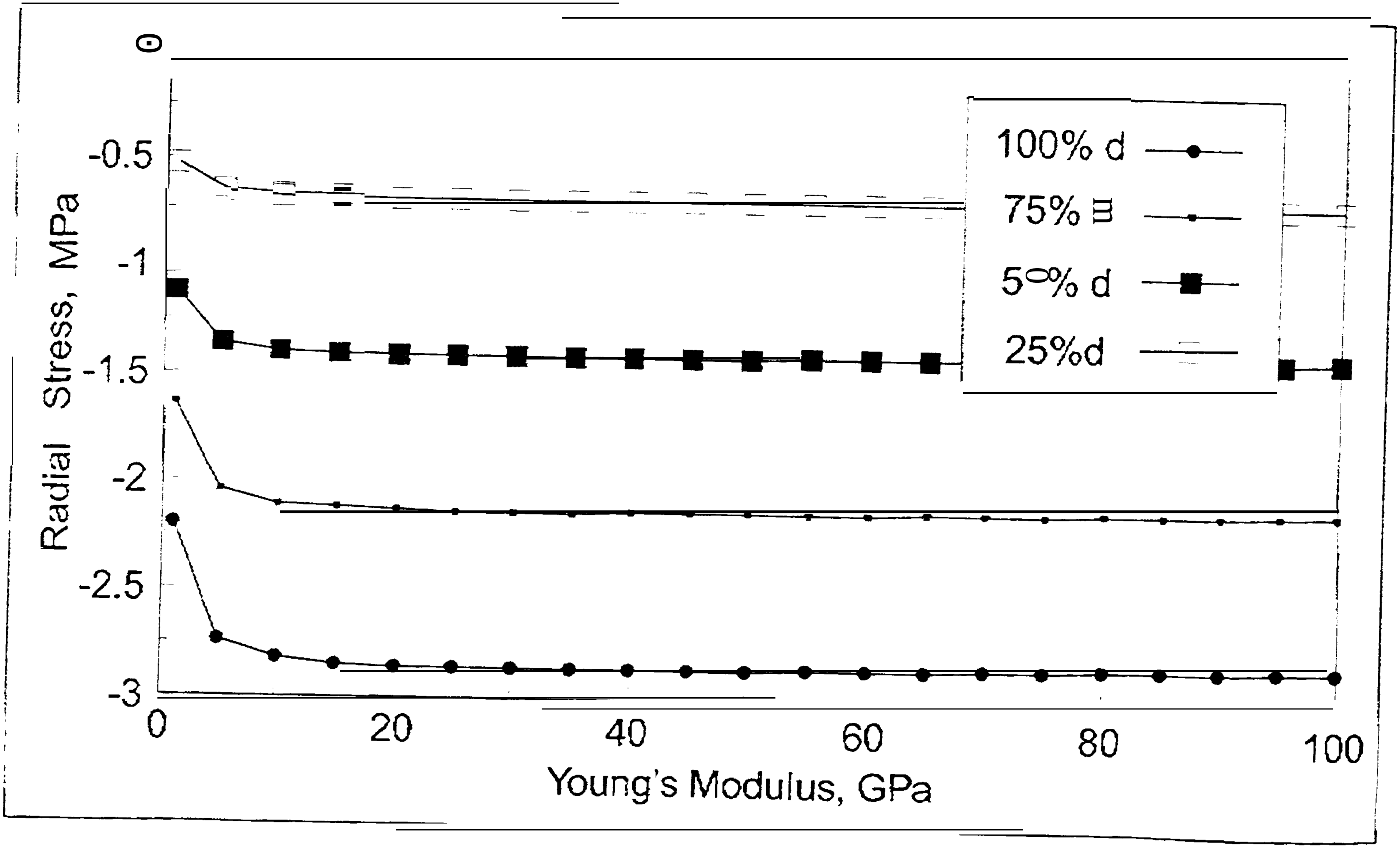
Thermal Stress in Linear Motor T = -100 C



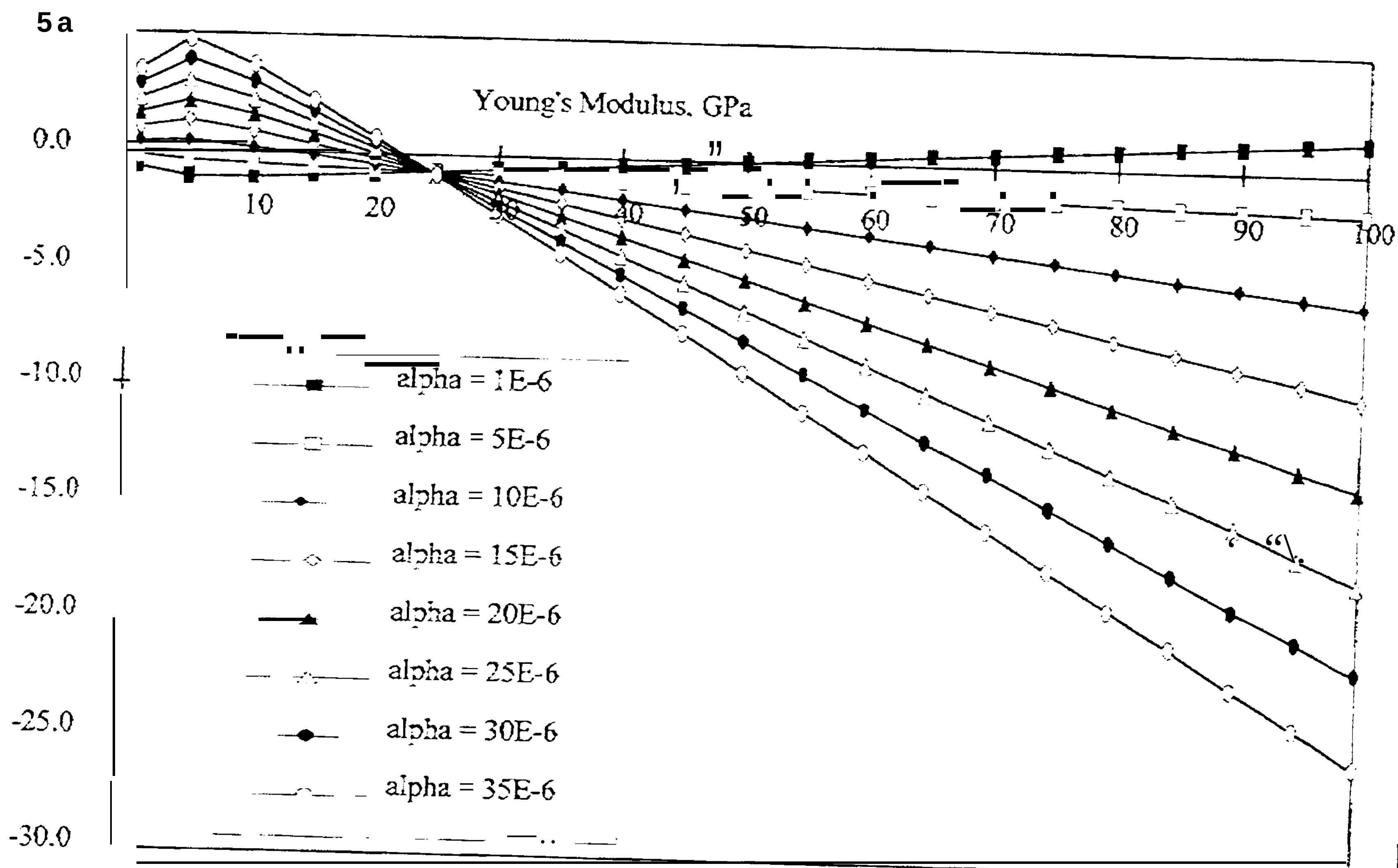
Radial Stress at Shaft/Liner Interface Varying Liner Thickness, E Field = -0.59 MV/m



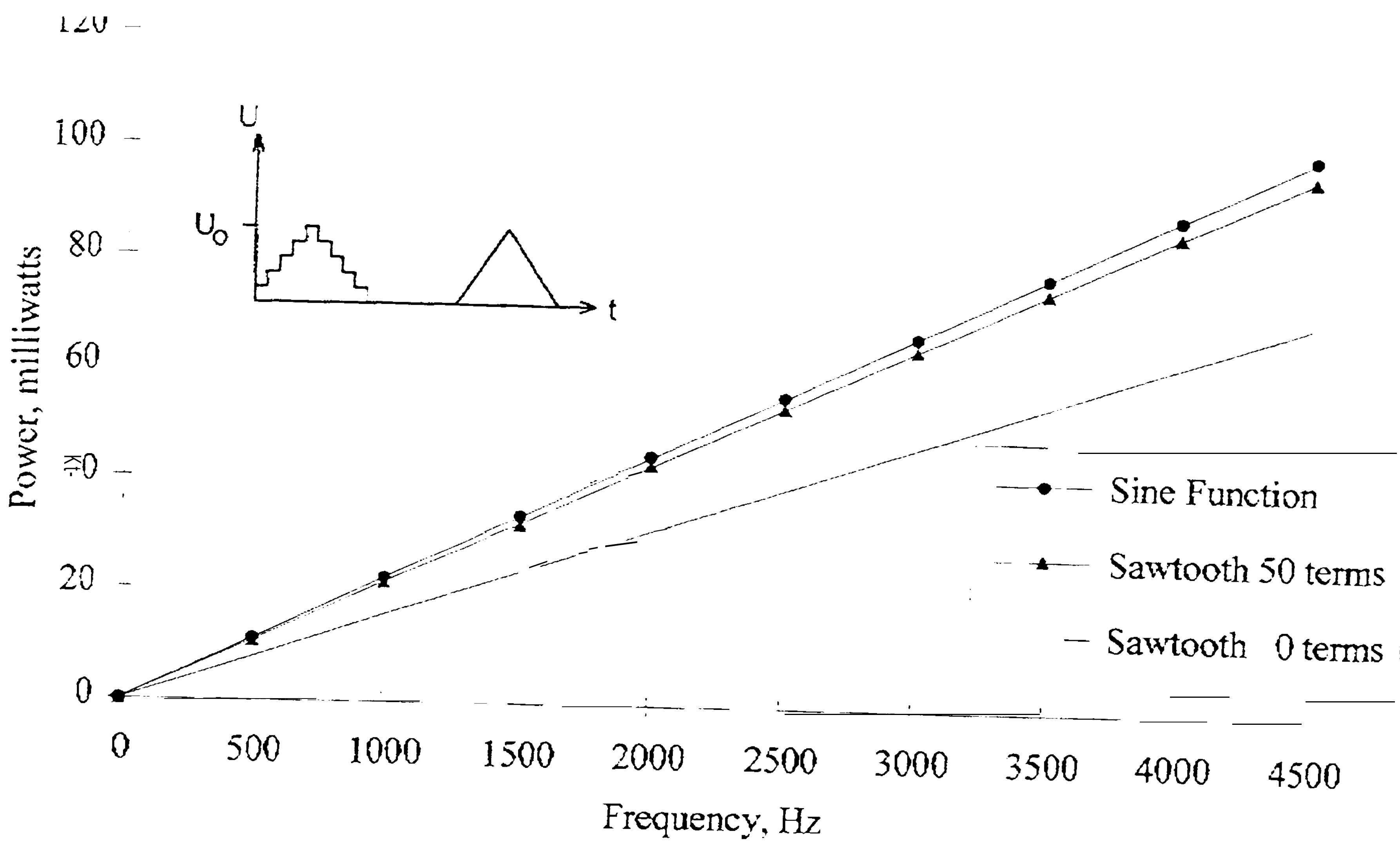
Radial Stress at Shaft/Liner Interface Varying Piezo Strain Constant, E Field = -0.59 Mv/m



Radial Stress at Shaft/Liner Interface
Varying Liner CTE T= -100 C



Piezoelectric Power Consumption
Room Temoerature

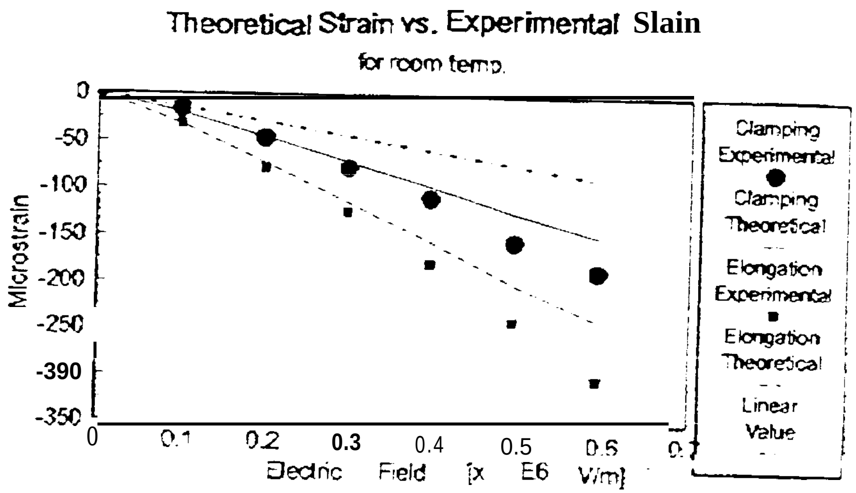


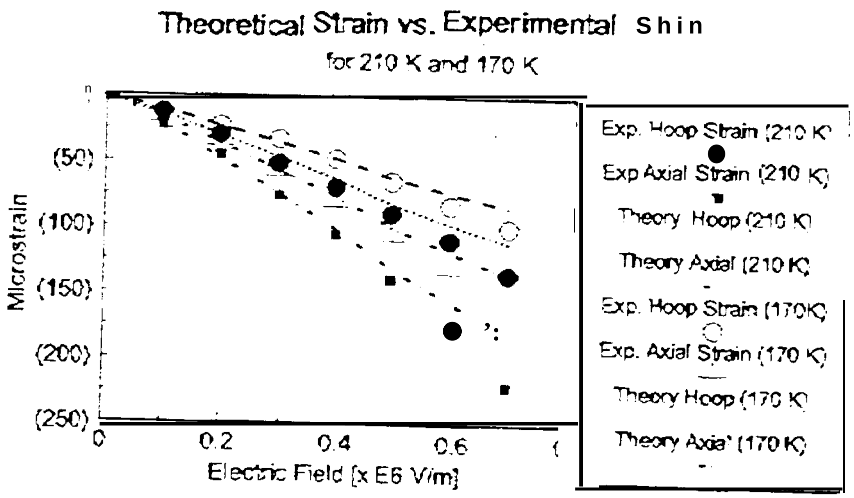
Theoretical vs. Experimental

-Temperature dependent piezoelectric coefficient included in model

. Experimental values correlated with theoretical model incorporating nonlinear dependence **between** field **and** strain

·FEM vs. model shows **good agreement for non-symmetric geometries** (split liner)





Linear motor

Conclusions

- Analytical model incorporates thermal dependence of piezoelectric coefficients
- Analysis correlates with experiment results
- Depoling and Saturation of PZT-5H is strain dependent
- Power requirements are in the sub-watt regime

SUMMARY

- An analytical model was developed that incorporates the thermal dependence of the materials coefficients of piezoelectric elements.
- Analysis was correlated with experimental results
- Depoling and saturation of PZT-5H is strain dependent
- Power requirements are determined to be in the sub-watt-regime