PIEZOCERAMIC MICROACTUATION FOR ROBOTIC SPACE EXPLORATION

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OUTLINE

- OVERVIEW: CURRENT SURFACE MOBILITY FOR PLANETARY EXPLORATION
- INSECT EXPLORERS: NEW PARADIGM FOR MOBILITY
- APPROACH
    - FLEXIBLE MICROACTUATORS
    - ELECTRICAL/OPTICAL ACTIVATION
    - ENHANCED BIMORPH: LOW POWER, HIGH FORCE

- APPLICATIONS
    - ADVANCED MOBILITY
    - OPTICAL SHAPE CONTROL
    - MICROVALVES
    - PRECISION MEDICAL TREATMENT/DIAGNOSTICS

- CONCLUSIONS/ SUMMARY

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OVERVIEW: CURRENT SURFACE MOBILITY SYSTEMS

- Current approach for realization of small vehicles is evolutionary: through the miniaturization 1 of existing wheeled/legged vehicles based on state Of the art in miniature actuators and motors. However, such miniaturization does not lend itself to cost reduction concomitant with the size reduction because cost of the individual mobility components goes up by an order of magnitude or more for such miniature motors etc which often need to be precisely hand assembled.
- An alternate approach with significant potential advantages, especially when traversing unusual and difficult terrain such as loose granular surfaces, is to imitate the mobility attributes of insects. Mimicking biology, such artificial insects may possess varied mobility modes: surface-roving, burrowing, hopping, hovering, or flying, to accomplish surface, subsurface, and atmospheric exploration”. They would combine the functions of advanced mobility and sensing with a choice of electronic and/or photonic control. Preprogram’nmed for a specific function, they could serve as "no-uplink, one-way communicating” beacons, spread over the exploration site, autonomously looking for the object of interest.

OVERVIEW: MOBILITY APPROACHES

- CURRENT APPROACH:

  ENERGY SOURCE (SUN)-----SOLAR CELLS/BATTERY ------- **MOTORS** -------- **PASSIVE** MOBILE COMPONENTS

  EFFECTIVE EFFICIENCY ~**3-5%**

- NEW PARADIGM (INSECT EXPLORERS):

  ENERGY SOURCE (SUN) -------- ACTIVE MOBILE COMPONENTS

  EFFECTIVE EFFICIENCY ~**10%**

VISION:

ADVANCED MOBILITY . . . . . . the size of small insects

. . . . with the same mobility agility

When coupled with dedicated microsensors/ microimagers -

INSECT EXPLORERS

They will be ideal for:

- SCOUTING MISSIONS - IN-SITU SENSING
- HAZARDOUS AREA EXPLORATION
- REACH NARROW CREVICES

Such "artificial" insects will enable that couldn't be easily done today

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PAY_OFF - WHY INSECT EXPLORERS

- Extremely small size - allows reach to places never reached before for in-situ sensing
- Expendable due to low cost - will be used to explore high risk zones
- Science return /$ would be tremendous, unprecedented.

JPL WHY PIEZOCERAMIC ACTUATION?

(AS WE SCALE DOWN TO THIN FILM PIEZOCERAMICS)

			POLYMERIC MATERIALS		
	PIEZOCERAMIC	SHAPE MEMORY ALLOY	PVDF	Polymides PMMA Polyurethane	MAGNETO-STRICTIVE
MECHANISM	PIEZOELECTRIC & ELECTROSTRICTIVE	THERMAL: MARTENSITIC → AUSTENITIC PHASE CHANGE	PIEZOELECTRIC, PHASE TRANSITION	ELECTRO-STRICTIVE	MAGNETIC FIELD INDUCED BY COIL
STRAIN	10^{-4} TO $0.3\text{X}10^{-2}$**	10^{-6} TO 10^{-1}	10^{-4} TO 10^{-1}	10^{-9} TO 10^{-2}	10^{-6} TO 10^{-2}
DISPLACEMENT	LOW TO HIGH*	MEDIUM TO HIGH***	LOW TO HIGH	LOW TO MEDIUM	MEDIUM
FORCE	HIGH ~100 kgm FORCE	LOW-MEDIUM ~1 kgm FORCE	SMALL	SMALL	HIGH
HYSTERISIS	TAILORABLE BY COMPOSITION	SMALL	LARGE	SMALL TO MEDIUM	LARGE
AGING	COMPOSITION DEPENDENT	VERY SMALL	LARGE	LARGE	SMALL
TEMPERATURE RANGE OF OPERATION	–196°C → 300°C WIDE	–196°C → 100°C WIDE	–10°C → 60°C LIMITED	–10°C → 80°C LIMITED	-273°C → 100°C WIDE
RESPONSE SPEED	µsec-msec	seconds	msec	msec	µsec-msec
ACTIVATION MODE	BOTH OPTICAL AND ELECTRICAL	THERMAL AND ELECTRICAL	ELECTRICAL	ELECTRICAL	MAGNETIC
POWER REQUIREMENT	LOW	LOW	MEDIUM	LOW TO MEDIUM	HIGH
RADIATION HARDNESS	YES	TBD	TBD	TBD	YES
CYCLABILITY	EXCELLENT	GOOD	FAIR	FAIR–POOR	GOOD
PROSPECT OF MINIATURIZATION	GOOD	GOOD	GOOD	GOOD	FAIR

PIEZOELECTRICS REPRESENT A LEADING CANDIDATE FOR ADVANCED MICROACTUATION

- •With amplification techniques (e. g. optically or electrically activated bimorph, flextensional elements and combination thereof to obtain double amplification)

** Antiferroelectric phase transition materials

•** Limited by Thermal Energy Input

COMPARISON ACTUATION TECHNOLOGIES

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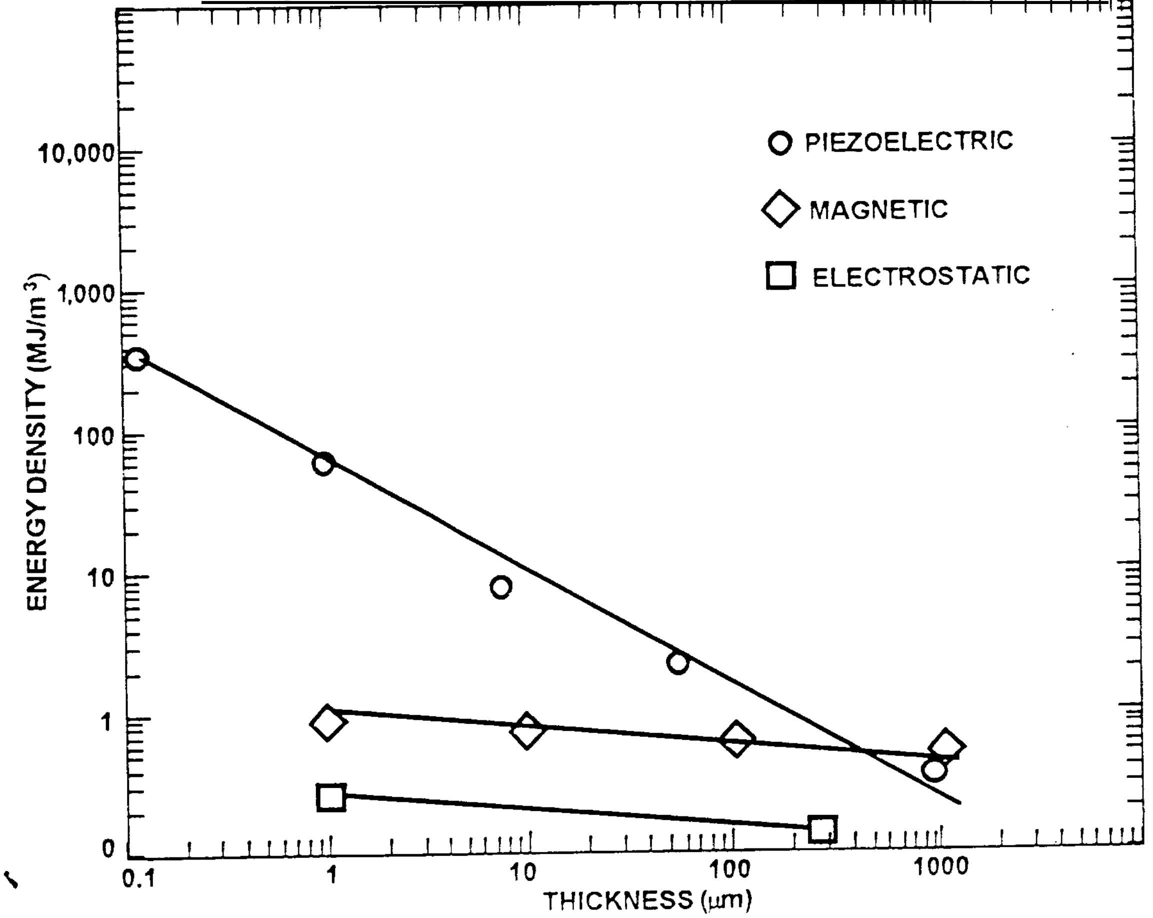
ENERGY DENSITY AS FUNCTION OF THICKNESS

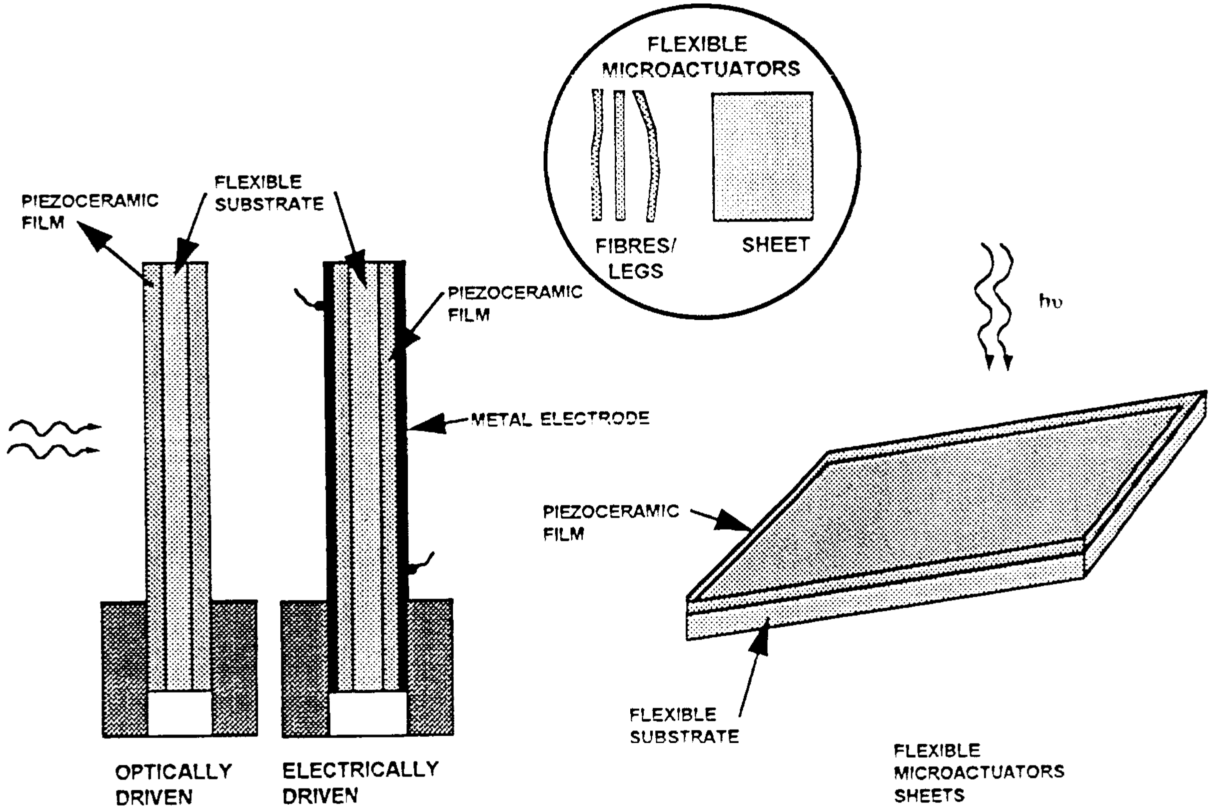


FLEXIBLE MICROACTUATORS

Flexible microactuators are envisioned by depositing tailored thick (~ 2-10 micron) films of active materials on judiciously chosen, strong flexible (polymeric) substrates. Flexible microactuators would provide a combination of high force and displacement and be operable over a wide temperature range as is required for a variety of advanced mobility applications. Potential advantages of flexible microactuators are:

- low power (low voltage operation, <5 V), low mass, low volume
- low cost, batch production of the components compatible with VLSI processing
- high force/volume even with low voltage operation
- higher deflection
- flexible. miniaturizable microactuator: scaleable for MEMS/MOMS
- excellent cyclability -more than million cycles
- amenable to both electrical or optical activation

JPL Flexible Micro Actuators For Advanced Mobility



FLEXIBLE MICROACTUATORS

Flexible microactuators would enable a new generation of microelectro- mechanical and micro-opto-mechanical systems where the actuation will not be restricted by the clamping effect due to the rigid substrate as in the current silicon based micromachined structures. Also in the current micromachined structures, the actuation force out of the structure is limited by the thickness to which the micromachined structures could be grown. Deposition of tailored piezoceramic thin films on flexible substrates would substantially eliminate the substrate clamping effect and thicker films can be deposited by high rate deposition processes, leading to mobile elements with substantially higher force to input power ratio with the option of contact-less optical activation.

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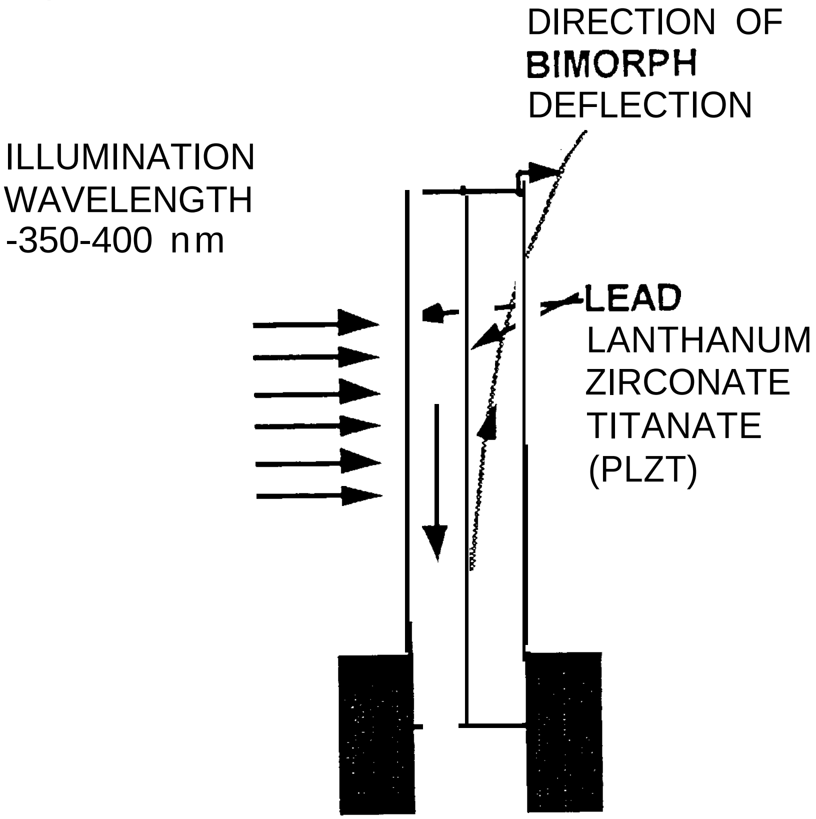
FLEXIBLE MICROACTUATORS

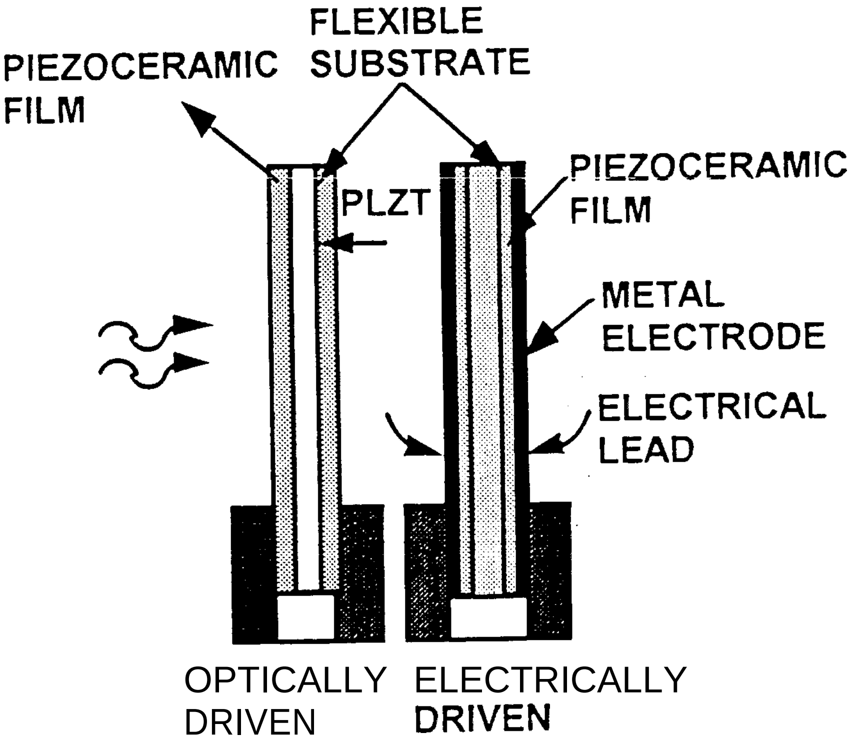
- Optimization of the Piezoceramic films:
  - Optical quality enhancement
  - Polarization direction& intensity optimization
  - Optimization of the optical penetration effect



CERAMIC BIMORPH

ceramic thickness: 200 micron

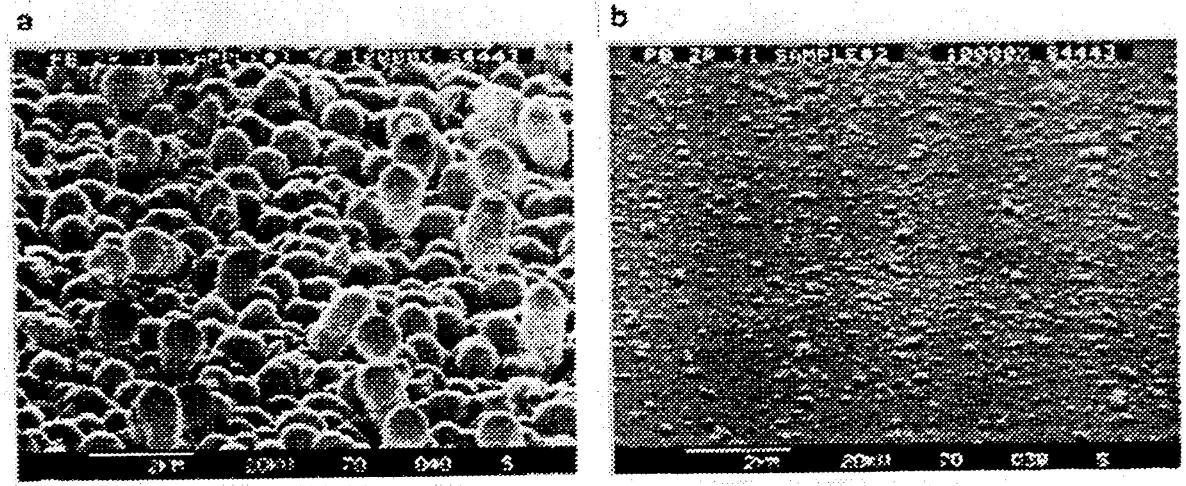
(a)

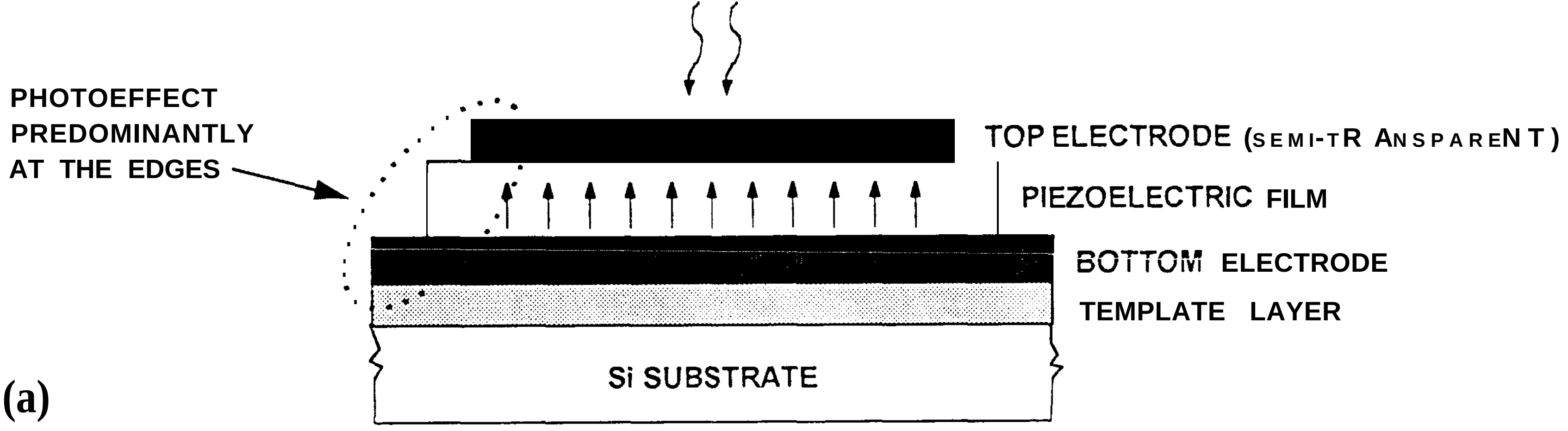


FLEXIBLE MICROACTUATOR

film thickness: 2 micron

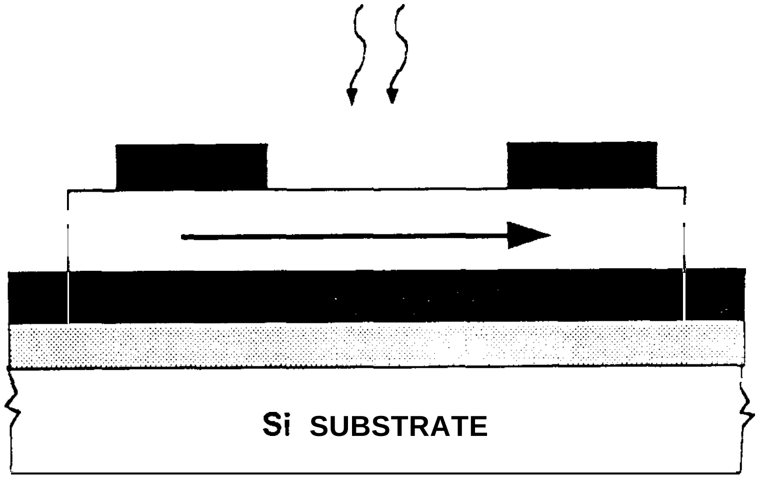
(b)


a
b
SAMPLE#2
2μm
20KV



(a)

➪ **HYPOTHESIS: EFFECT WOULD BE MAXIMUM FOR NORMAL INCIDENCE OF PHOTONS WHEN C-AXIS IS PARALLEL TO SUBSTRATE**

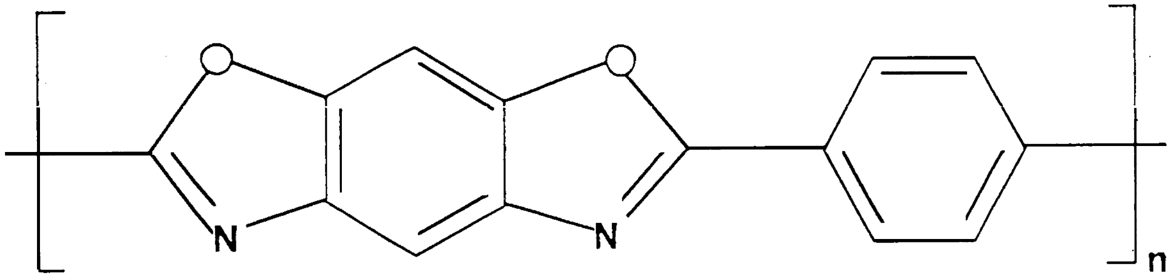


(b)

TABLE 4: Flexible film microactuators, matrix of improvement

		Current Status Ceramic Bimorph	Projected Improvement Film Bimorph
ELECTRICAL ACTUATION PARAMETERS	Thickness	200 microns	! microns: Thickness reduced. material tailored
	Operating Voltage	100 V	5 V : Operational voltage reduced
	Energy Density	1X	25 x : inherent advantage of reduced thickness
	Force/Volume	1X	5X enhancement for film bimorph
OPTICAL ACTUATION PARAMETERS	Optical Power	80 mW/cm^2	3 mW/ cm^2 : Illumination Intensity
	Power Ratio	10X	1 x
	Photonic to Mechanical Conversion Efficiency	0.1 % 1x	10/0 - 100/0 : significant enhancement in overall efficiency
	Force./Energy	F	2F to 20F : Multifold enhancement in the film bimorph
	Force/Power	1x	20X to 200X

CHEMICAL STRUCTURE OF POLYBENZOXAZOLE (PBO)



CIS-PBO

PBO IS A CONJUGATED AROMATIC HETEROCYCLIC LIQUID CRYSTALLINE POLYMER (LCP) WITH OPERABILITY DEMONSTRATED AT 460°C. THE HIGH STRENGTH AND SUPERIOR PHYSICAL PROPERTIES OF PBO ARE DUE TO THE ROD-LIKE NATURE OF THE PBO MOLECULE AND THE ORIENTATION THAT CAN BE BUILT INTO THE POLYMER FILM. PBO FILM'S SELF-REINFORCING MICROSTRUCTURE RESULTS IN A "MOLECULAR FABRIC" WITH PROPERTIES COMPARABLE TO THOSE OF ADVANCED, FIBER-REINFORCED MATERIALS. BUT WITHOUT THE DRAWBACKS OF DISTINCT FIBER AND MATRIX COMPONENTS

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COMPARATIVE DATA FOR FILMS

PROPERTY	UNIT	KAPTON	ARAMID	PET	PEN	PBO
DENSITY	g/ cm^3	1.420	1.500	1.395	1.355	1.54
MELTING TEMP	°C	NONE	NONE	263	272	NONE
GLASS TRANSITION TEMP	°C	350	280	68	113	NONE
YOUNG' S MODULUS	kg/mm^2	300	1000-2000	500-850	650-1400	4900
TENSILE STRENGTH	kg/mm^2	18	50	25	30	56-63
TENSILE ELONGATION	%	70	60	150	95	1-2
LONG-TERM HEAT STABILITY	°C	230	180	120	155	>300
HEAT SHRINKAG E (200°C x % min)	%	0.1	0.1	5-10	1.5	<0.1
COEFFICIENT OF THEW EXPANSION	ppm/°C	20	15	15	13	-2
COEFFICIENT OF HYDROSCOPIC EXPANSION	ppm/% RH	20	18	10	10	0.8
MOISTURE ABSORPTION	%	2.9	1.5	0.4	0.4	0.8

PROPERTIES OF HIGH-PERFORMANCE FIBERS

PROPERTY	PBO	PBO HIGH MODULUS	ARAMID	STEEL	SPECTRA® (HDPE)	CARBON (HI-TENSILE)	GLAS (s-2)
TENSILE STRENGTH (ksi)	820	800	400-500	250	435	500-700	665
TENSILE MODULUS (Msi)	25-30	40-45	10-25	29	25	30-40	12.6
COMPRESSIVE STRENGTH (ksi)	40	65	65	250	10	300-400	>150
ELONGATION, BREAK (%)	3.0	1.5	1.5-4.0	2.0	3.5	1.5-2.0	5.4
DENSITY (g/cc)	1.56	1.56	1.44	7.86	0.97	1.8-1.9	2.4
SPECIFIC TENSILE STRENGTH (ksi)	525	510	280-350	32	450	270-380	280
SPECIFIC TENSILE MODULUS	16	26	7-18	4	26	16-22	5
LIMITING OXYGEN INDEX (LOI: %)	56	56	30		19	50-65	

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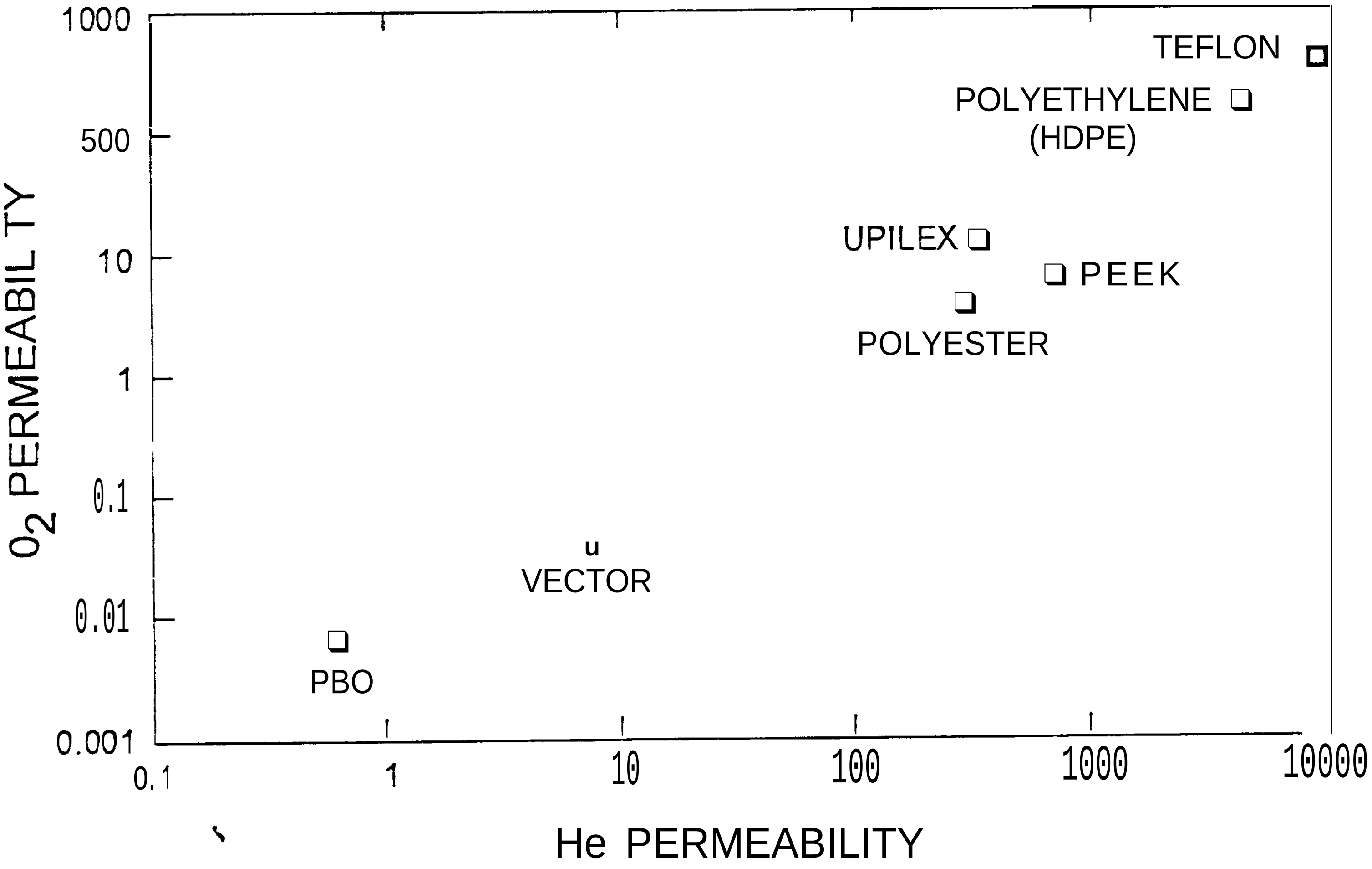
PERMEABILITY COMPARISON DATA



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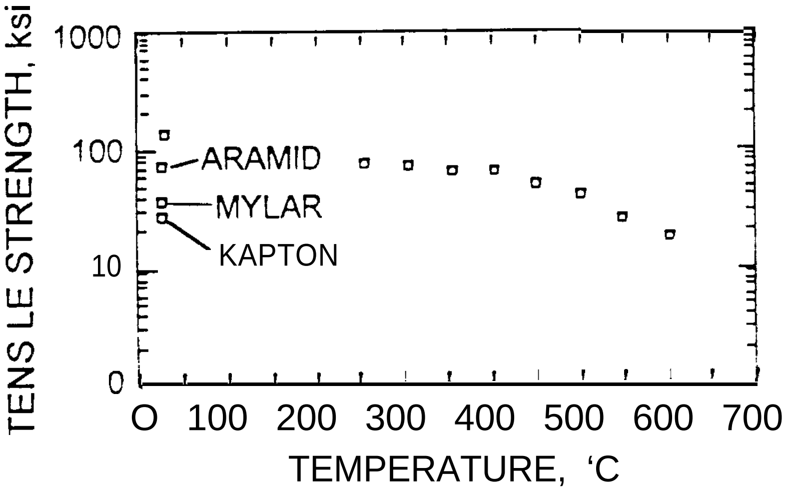
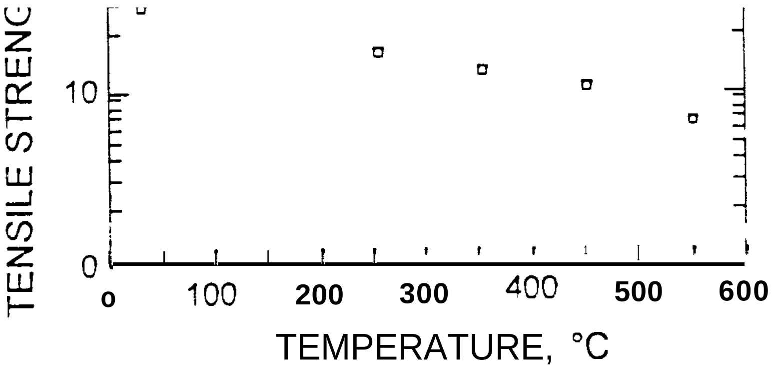
TEMPERATURE DEPENDENCE OF FILM TENSILE STRENGTH

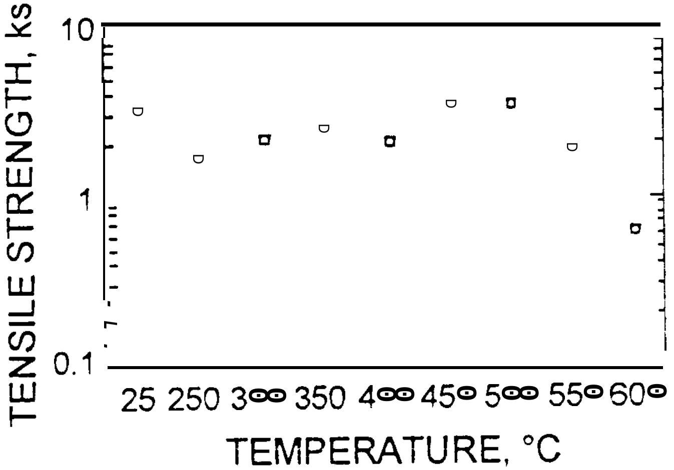


FILM TENSILE STRENGTH
IN MACHINE DIRECTIONS

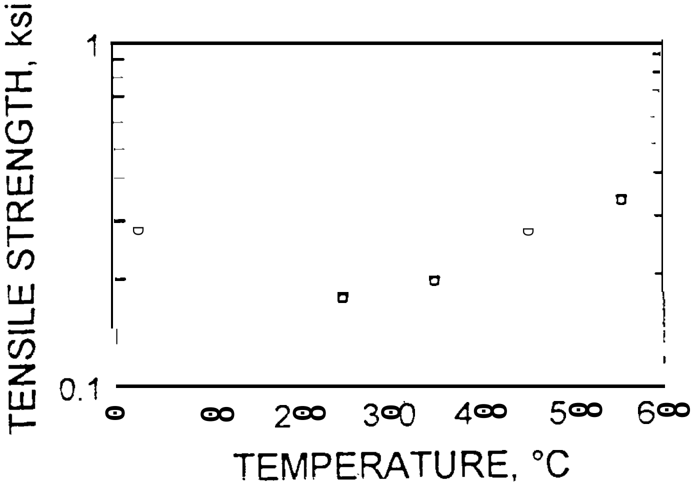


FILM TENSILE STRENGTH
IN TRANSVERSE DIRECTIONS

TEMPERATURE DEPENDENCE OF FILM TENSILE MODULUS FOR PBO FILM

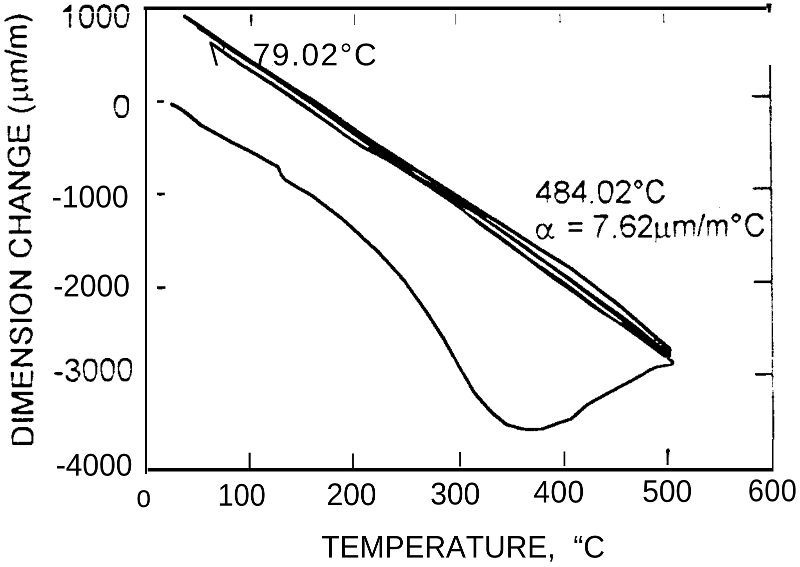


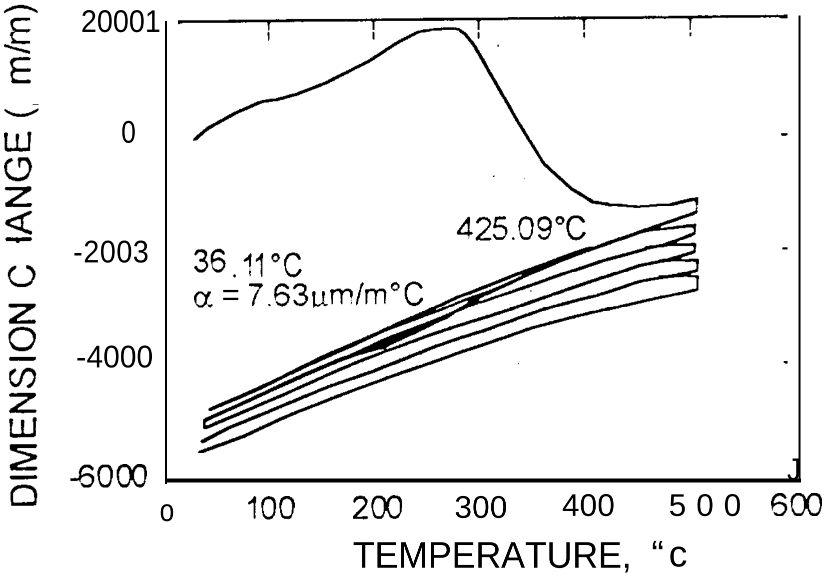
FILM TENSILE MODULUS IN MACHINE DIRECTIONS



FILM TENSILE MODULUS IN TRANSVERSE DIRECTIONS

COEFFICIENT OF THERMAL EXPANSION (CTE) OF PBO FILM





MACHINE DIRECTION
(NEGATIVE CTE)

TRANSVERSE DIRECTION
(POSITIVE CTE)

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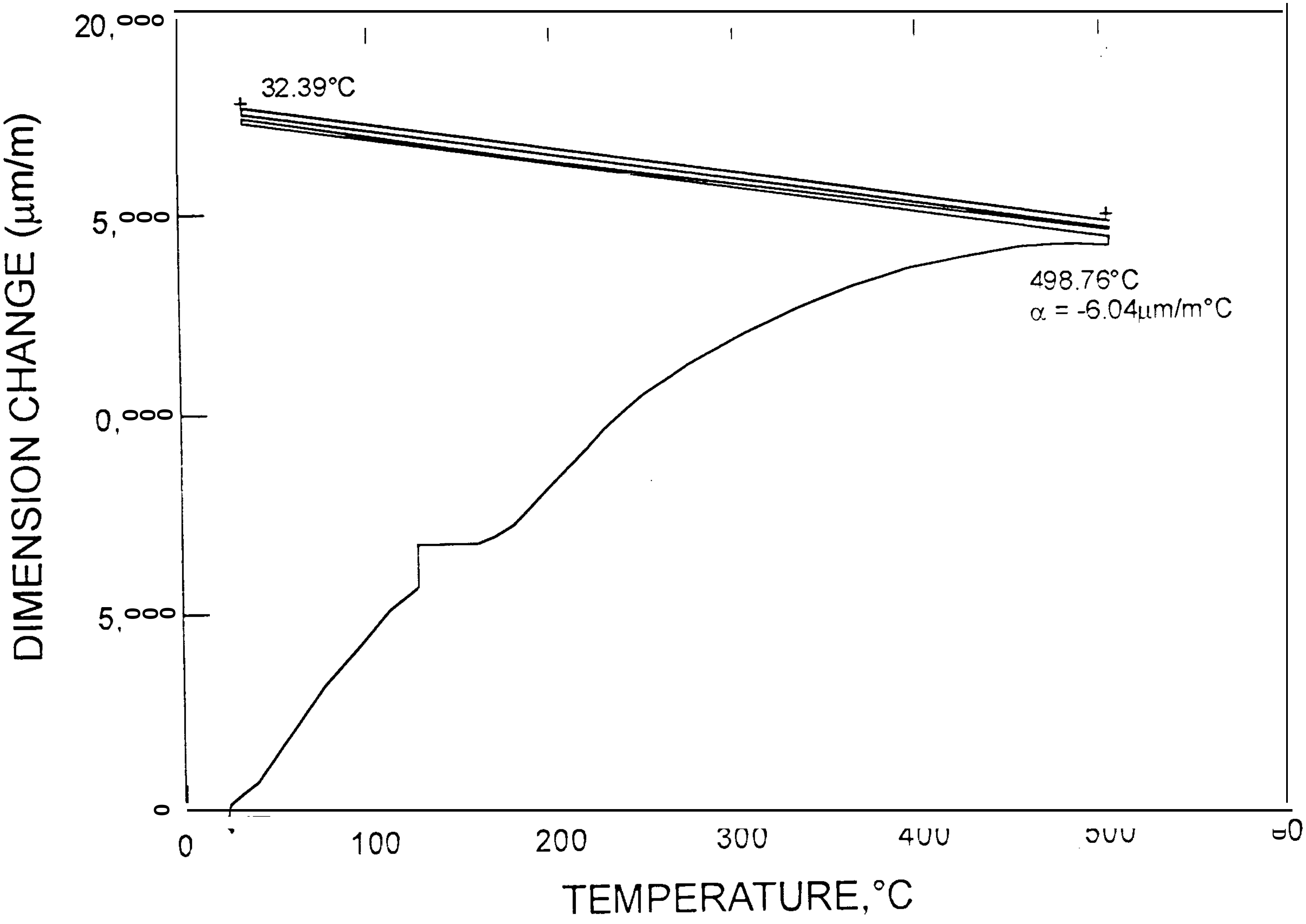
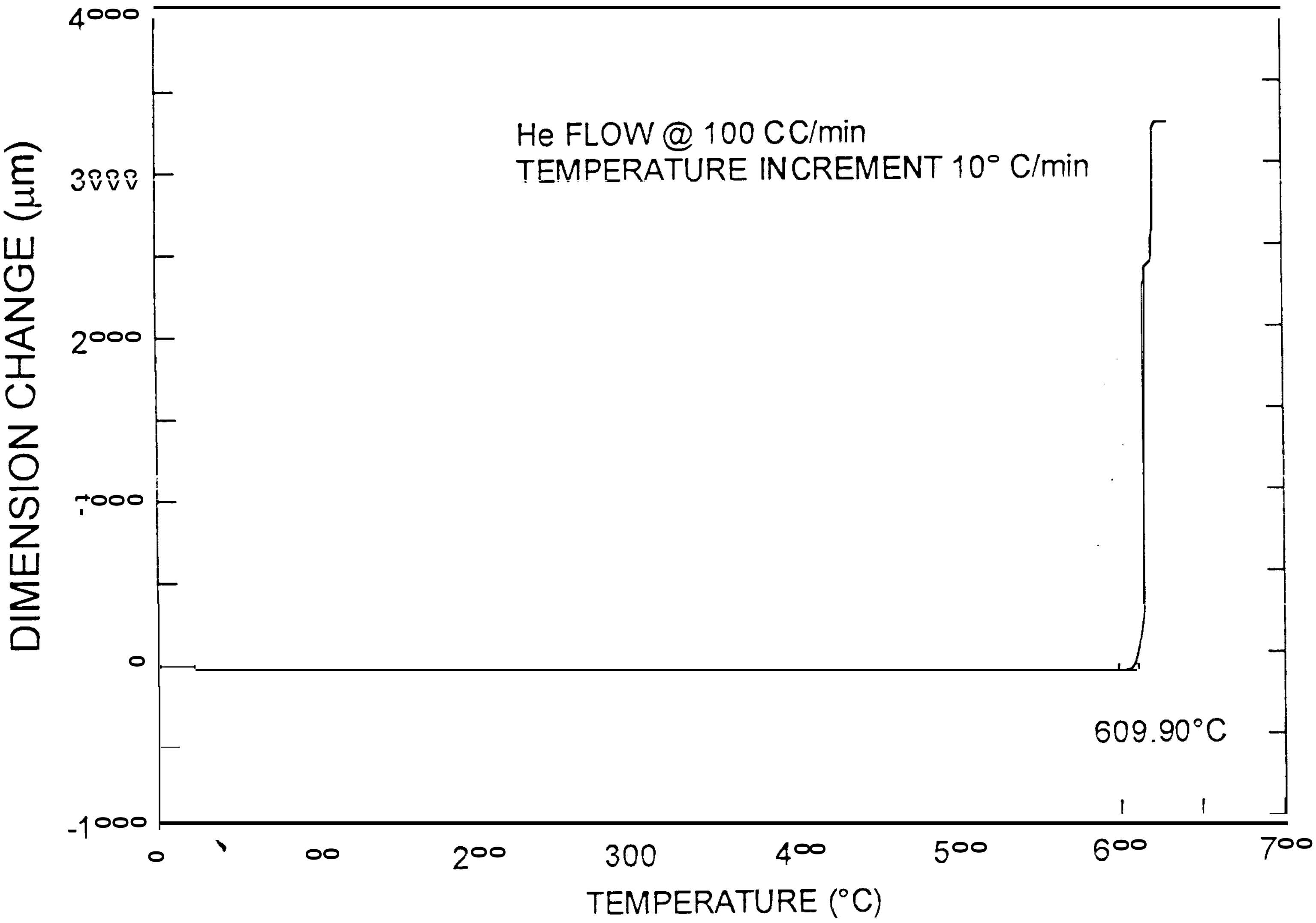
CTE OF PBO FIBER BUNDLE



THERMAL ANNEALING OF PEO



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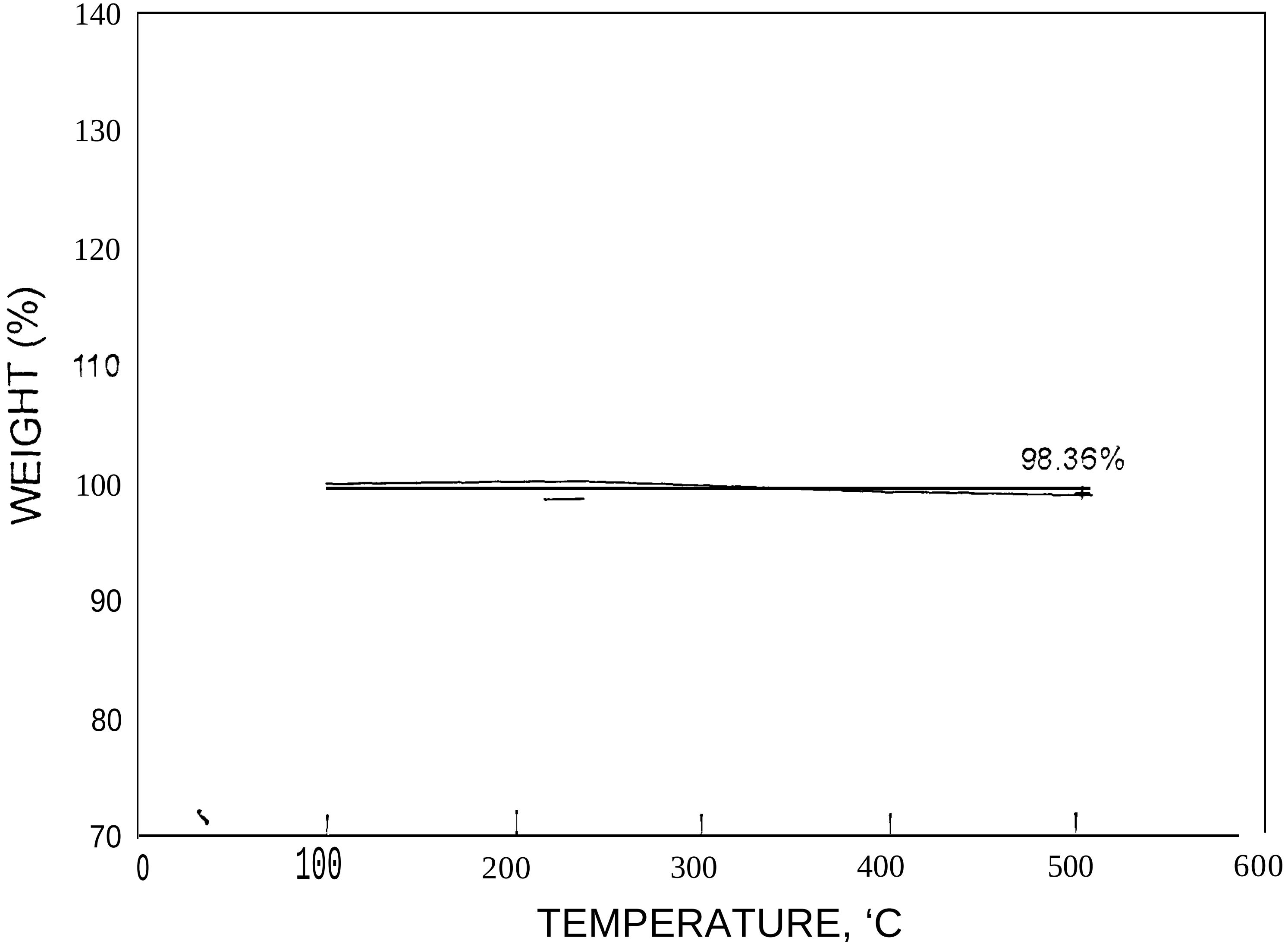
THERMOGRAVIMETRIC ANALYSIS (TGA)
OF DRIED ?60 FILMS



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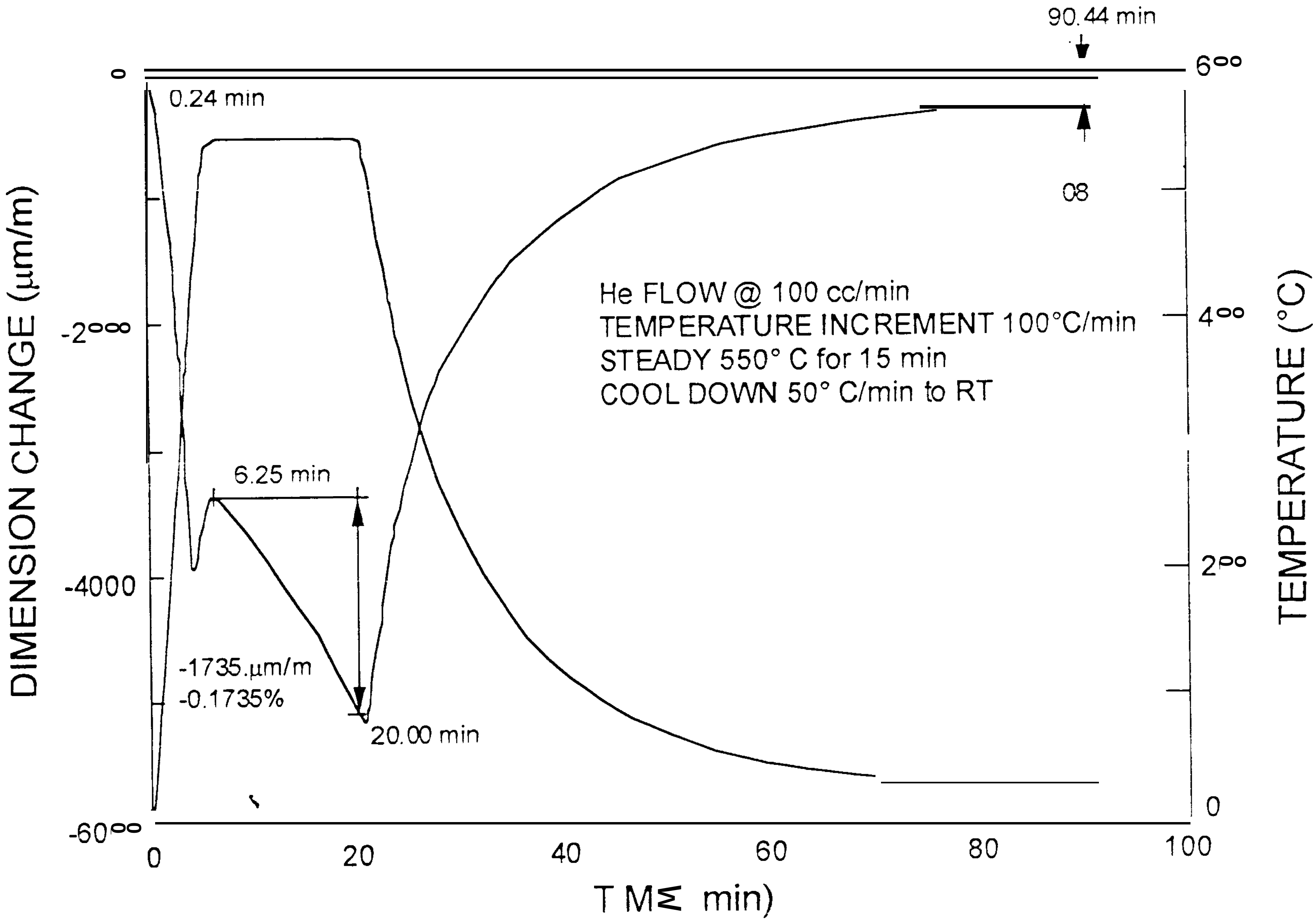
THERMAL ANNEALING OF PEO



He FLOW @ 100 cc/min
TEMPERATURE INCREMENT 100°C/min
STEADY 550° C for 15 min
COOL DOWN 50° C/min to RT

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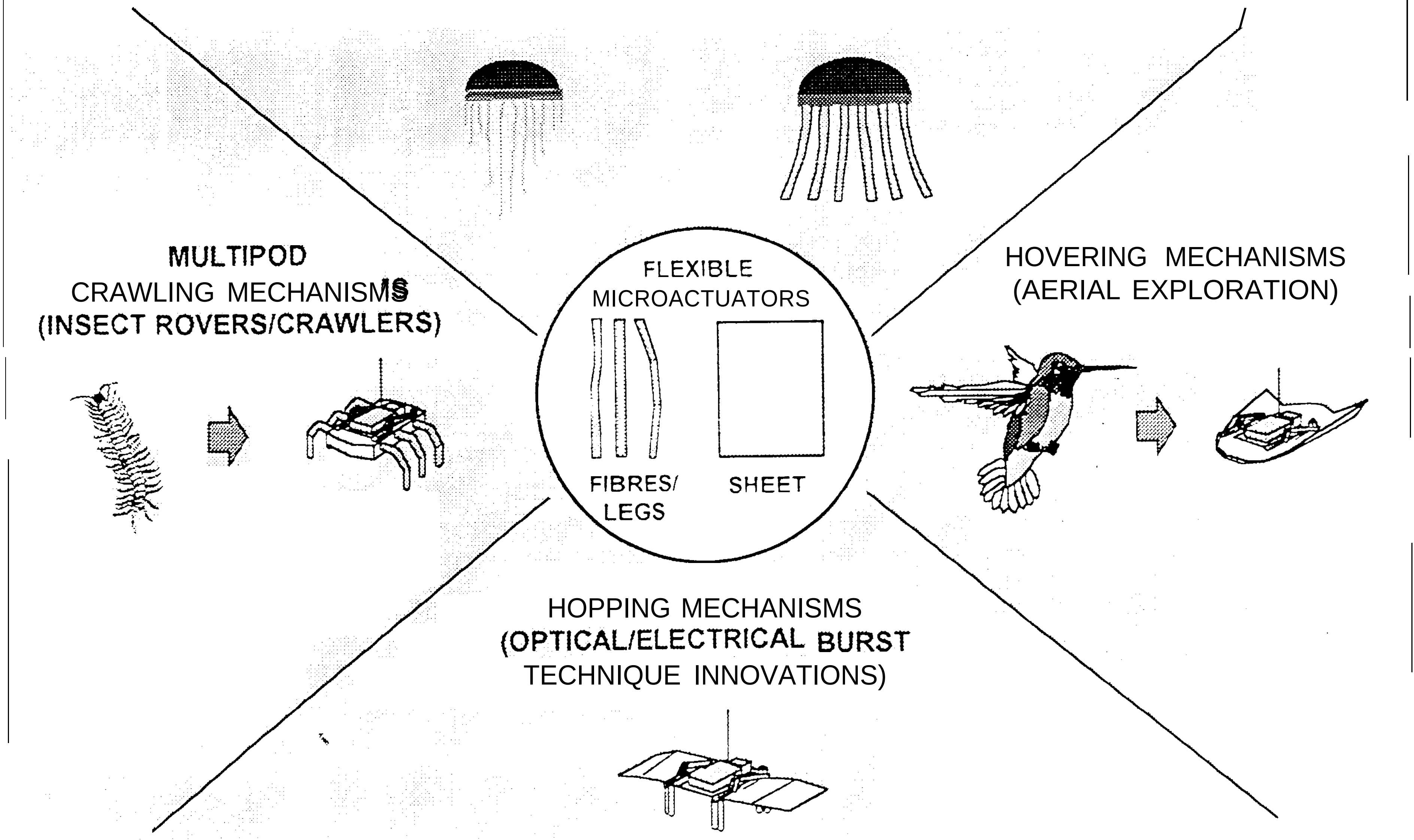
JPL ADVANCED MOBILITY FOR INSECT EXPLORERS



CILIARY/FLAGELLAR MECHANISMS FOR FLUID NAVIGATION

MULTIPOD
CRAWLING MECHANISMS
(INSECT ROVERS/CRAWLERS)

FLEXIBLE
MICROACTUATORS

FIBRES/
LEGS

SHEET

HOVERING MECHANISMS
(AERIAL EXPLORATION)

HOPPING MECHANISMS
(OPTICAL/ELECTRICAL BURST
TECHNIQUE INNOVATIONS)

CONCLUSION

- FLEXIBLE MICROACTUATORS OFFER A COMBINATION OF HIGH FORCE AND DISPLACEMENT WITH POTENTIAL OF OPERABILITY OVER A WIDE TEMPERATURE RANGE AND A CONTACT-LESS OPTICAL ACTIVATION

- PIEZOCERAMIC BASED FLEXIBLE MICROACTUATORS FORM AN ENABLING TECHNOLOGY FOR A VARIETY OF APPLICATIONS:
  - ADVANCED MOBILITY
  - SHAPE CONTROL
  - MICROVALVES
  - MINIMALLY INVASIVE PRECISION MEDICAL TREATMENT/DIAGNOSTICS

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