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Piezoelectric

Given today's remarkable array of applications for piezoelectrics, it is hard to **IMAGINE** an area in which these products cannot make a positive difference in design and function. Our ceramic elements can be manufactured to your specifications — to be both **TECHNICALLY ADVANTAGEOUS** and economically efficient. PKI offers a wide range of lead zirconate titanate (PZT) and lead metaniobate ceramic elements, produced in ring, tube, disc, or plate form. We offer custom cutting, dicing, grinding, lapping, and polishing, along with precise rounding and core drilling. Another beneficial and useful service PKI offers is our **ASSEMBLY CAPABILITIES**. We have all the necessary resources to assemble or sub-assemble products reliably and inexpensively for your particular application. When considering applications for our piezo products, take a look at the **MANY WAYS** others have used piezoceramics to great advantage:

APPLIANCE

Contact microphone
Vibration

AUTOMOTIVE

Air bag
Suspension
Passenger compartment
Security

COMPUTER (INPUT/OUTPUT)

Keyboards
Printers
Disk drives

CONSUMER

Musical instruments
Sports equipment
Toys/games
Audio
Speakers & microphones
Other
Telephones
Humidifiers
Igniters
Security devices

INDUSTRIAL

Switches
Physical security & energy management
Robotics
Fans
Flow/level
Traffic sensors
Other
Ultrasonic welders
Flow meters
Alarms
Process control sensors
Cleaners

INSTRUMENTATION

Machine health monitor
Weather sensors
Active vibration damping
Non-destructive testing
Adaptive optics
Oil exploration
Power generation

MEDICAL

Diagnostic
Apnea monitor
Blood pressure cuff
Fetal heart monitors
Phaco emulsification
Electronic stethoscope
Sleep disorder sensors
Solid state respiration air flow
Infusion pumps
Ultrasound
Catheter ultrasound sensors
Biological
Chemical assays

MILITARY

Hydrophones
Ballistics

TELECOMMUNICATIONS

Microphones
Speakers

Piezo History

Harnessing Nature's Electricity

It's been more than a century since Pierre and Jacques Curie discovered the unusual properties of certain natural crystals.

A remarkable find for the 1880s, the Curies noticed

TWO THINGS APPLYING PRESSURE OR MECHANICAL STRESS ON CERTAIN NATURAL NONSYMMETRICAL CRYSTALS PRODUCES ELECTRICAL CHARGE IN PROPORTION TO THAT PRESSURE.

2 THE SAME CRYSTALS, WHEN SUBJECTED TO AN ELECTRIC FIELD, EXPAND OR CONTRACT.

This unique property is known as the piezoelectric effect. The materials exhibiting these properties can be used as electromechanical transducers, converting electrical energy to mechanical energy and vice-versa.

The effect was first observed in single **CRYSTALS** like quartz, Rochelle salt, and tourmaline.

It could also be induced in some polycrystalline materials, such as lead-zirconate-titanate (PZT), barium titanate, and lead metaniobate.

POLING PZT TO BEST ADVANTAGE

PZT is a ceramic material with a polycrystalline structure. It has a basic chemical composition of $PbTiO_3$ and $PbZrO_3$ which is modified by adding dopants of other elements. Adding those dopants to PZT enhances certain characteristics producing

several material types to meet a **WIDE VARIETY OF REQUIREMENTS.** Our material types include the following:

DOD TYPE I — PKI 402, 406

DOD TYPE V — PKI 532

DOD TYPE II — PKI 502

DOD TYPE VI — PKI 552, 556

DOD TYPE III — PKI 802, 804

LEAD METANIOBATE — PKI 100

SPECIALTY MATERIALS — PKI 700, 906

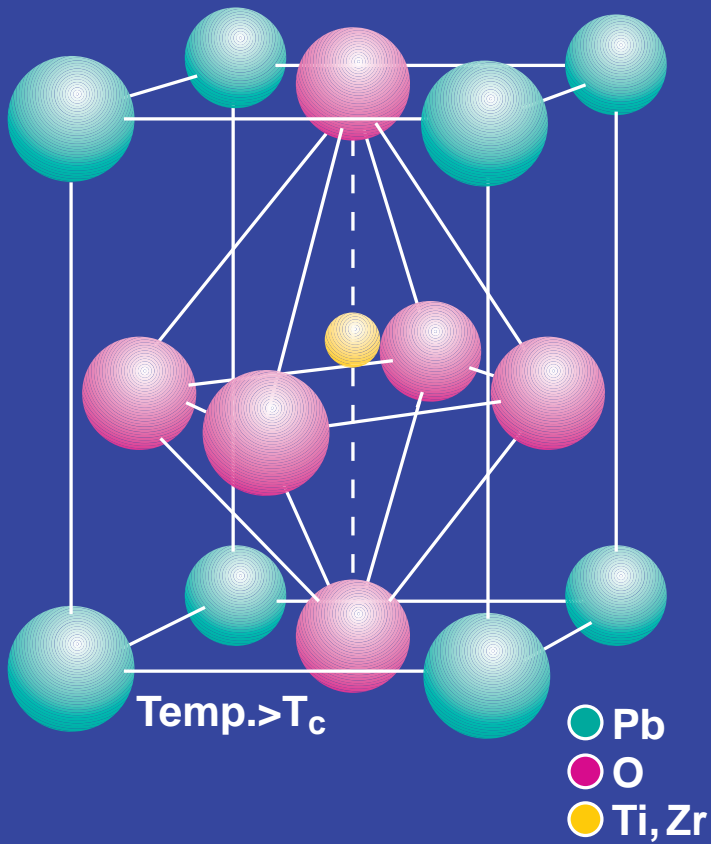
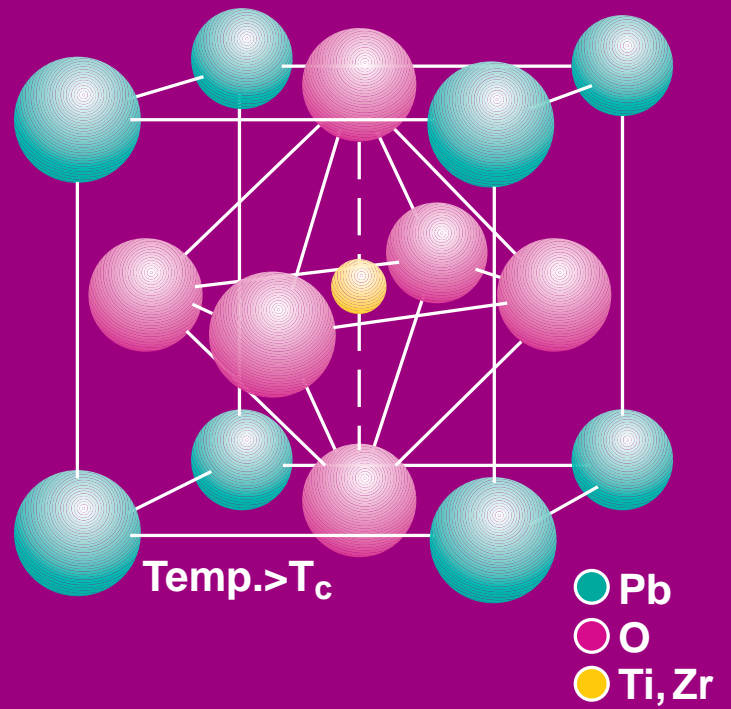
A

bove a certain temperature, called the

CURIE TEMPERATURE

(T_c), the crystal structure is cubic and has no electric

dipole moment (right).



H

owever, below this temperature the positively charged Ti/Zr ion shifts from its central location

along one of several allowed directions. This slightly

DISTORTS

the crystal lattice into a perovskite structure

(a tetragonal/rhombohedral shape), and produces an

electric dipole with a single axis of symmetry (left).

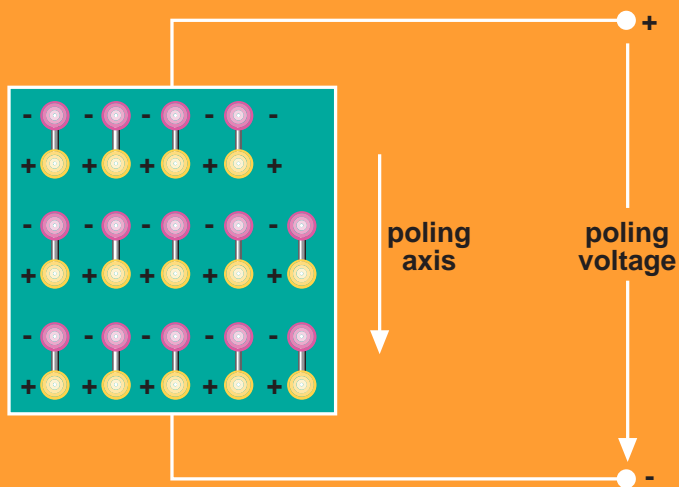
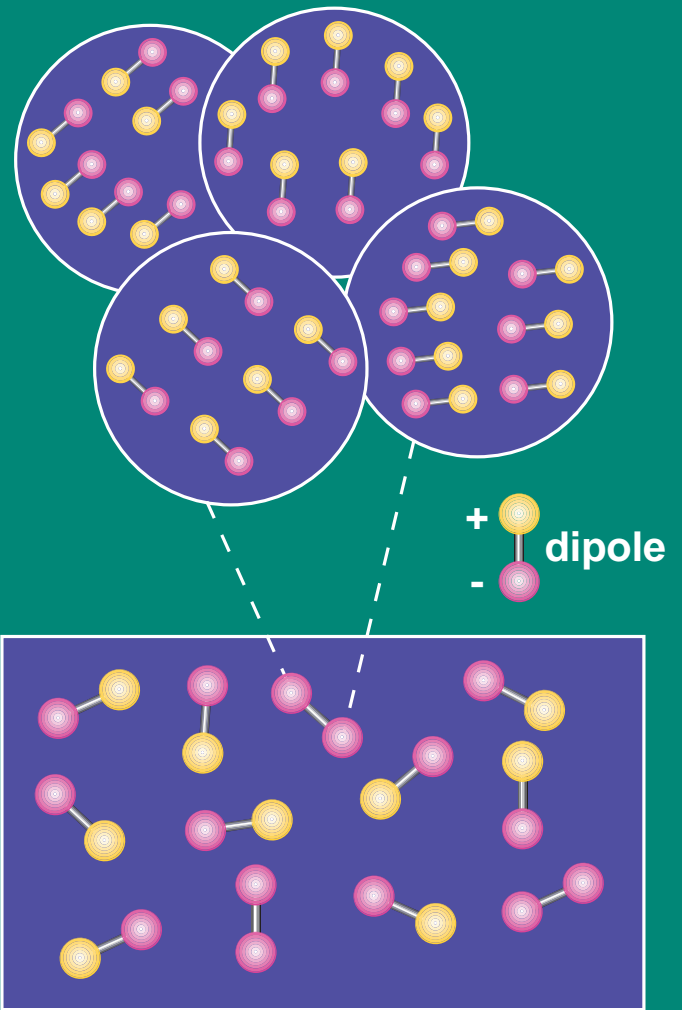
Immediately after sintering, groups of molecular dipoles align within small areas, or domains, to form large dipole moments.

PZT is made up of many such domains; however, as they are

RANDOMLY ORIENTED,

their net external electric dipole

is zero (right).



If PZT is subjected to a large electric field at elevated

temperatures, the domain dipoles align in the

allowed direction most closely in line with the field.

This process is called **POLARIZATION**

and causes the PZT to exhibit the piezoelectric

phenomenon (left). The dipoles will maintain this

orientation even after the dc field is removed

(remanent polarization), a necessary condition for

the piezoelectric behavior of ferroelectric ceramics.

Applications Data

Though the linear piezoelectric equations give us a description of the piezoelectric **PHENOMENON**, they do not predict the actual characteristics in relation to nonlinearity, hysteresis, frequency, and time dependence.

Of the many ceramic compositions in use, most can be placed into one of these two categories:

1 HARD PZT MATERIALS — THESE HAVE CURIE TEMPERATURES ABOVE 300 DEGREES C AND ARE NOT EASILY POLED OR DEPOLED EXCEPT AT HIGHER TEMPERATURES. THESE MATERIALS GENERALLY HAVE SMALL d CONSTANTS, GOOD LINEARITY, LOW HYSTERESIS, HIGH Q VALUES AND ARE ABLE TO WITHSTAND HIGH LOADS AND VOLTAGES.

2 SOFT PZT MATERIALS — THESE USUALLY HAVE LOWER CURIE TEMPERATURES AND ARE READILY POLED OR DEPOLED AT ROOM TEMPERATURE WITH STRONG ELECTRIC FIELDS. THE PIEZOELECTRIC ACTIVITY IS GREATER, BUT THE LINEARITY AND HYSTERESIS SUFFERS. IN GENERAL, SOFT PZT HAS LARGE DIELECTRIC CONSTANTS AND DISSIPATION FACTORS WHICH MAY LIMIT THE ABILITY TO DRIVE THEM WITH HIGH ELECTRIC FIELDS AT HIGH FREQUENCIES.

Here we take a look at the **MOST IMPORTANT** piezoelectric properties for applications in positioning systems, referencing both hard and soft PZT materials.

HYSTERESIS

PZT ceramics exhibit different properties depending on their material composition and treatment during manufacture,

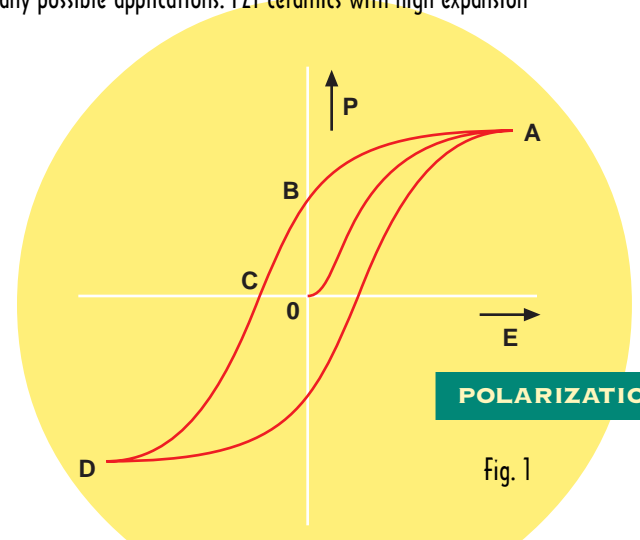
so a material can be designed to **OPTIMALLY SUIT** one of many possible applications. PZT ceramics with high expansion

efficiency are generally used for actuator applications.

Because they are ferroelectric, PZT ceramics show the

following polarization characteristics

when an electric field is applied. (Fig. 1)



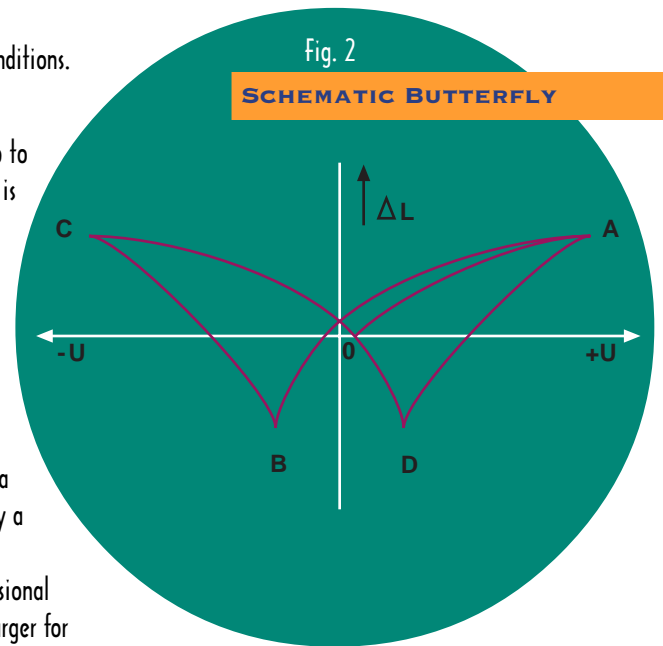
The essential characteristics follow:

- ▶ **UNPOLARIZED MATERIAL (POINT O) IS POLARIZED BY AN ELECTRIC FIELD. SATURATION IS OBSERVED FOR STRONG FIELDS (POINT A).**
- ▶ **THE REMANENT POLARIZATION IS MAINTAINED (POINT B) AFTER REMOVING THE ELECTRIC FIELD (E).**
- ▶ **THE REMANENT POLARIZATION IS REMOVED BY A COMPENSATING FIELD, CALLED A COERCIVE FIELD (POINT C).**
- ▶ **POLARIZATION CHANGES TO THE OPPOSITE DIRECTION BY INCREASING THE INVERSE FIELD, LIMITED BY SATURATION (POINT D).**

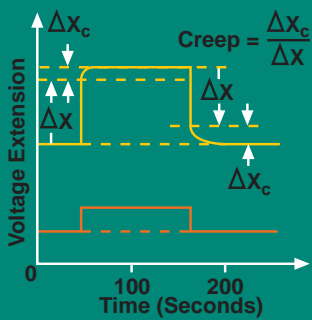
Material composition is the main determiner of coercive field strength. For common actuator materials, it is in the range of one hundred to several hundred volts/mm. A consequence of hysteresis in the P-E diagram is dissipative loss, which occurs during dynamic operation of the actuators leading to actuator warm-up.

This butterfly diagram (Fig. 2) shows the characteristic motion of an actuator under cycling conditions.

Polarized materials show contraction when the voltage is reversed, but re-expansion occurs up to Point C when the coercive limit is exceeded. Therefore, the principal limit of total movement is determined by saturation and coercive effects, but usually actuators are operated far away from these points to reduce nonlinearities and hysteresis.



PZT CREEP



CREEP

Following a change in voltage, all piezoelectric materials exhibit a short-term dimensional stabilization known as creep. A step-change in the applied voltage will produce an initial response in a fraction of a millisecond. However, it is followed by a smaller change on a much longer time scale.

Creep is always in the same direction as the dimensional change caused by the voltage step, but is usually larger for decreasing voltage. It is specified by the additional extension (Δx_c) expressed as a percentage of the initial response (Δx) and an associated time constant. Typical values range from 1% to 20%, with time constants between 10 and 100 seconds. As long as both are fully poled, there is no great difference between hard and soft PZTs, because creep is measured as a percentage of extension.

COMPLIANCE

When you apply stress to any material, it responds by changing its dimension due to its elastic properties. The compliance witnessed in piezoelectric ceramics is different in an important way: it exhibits different compliance perpendicularly than it does along its parallel poling axis. For linear positioning applications, the most important compliance tensor elements are those in the direction of the PZT extension: S_{33}^E for strain due to uniaxial stress along the poling direction, and S_{11}^E for strain due to the perpendicular stress. Normally S_{33}^E is 25% greater than S_{11}^E . As you might guess from the name, soft PZT is somewhat more compliant than hard PZT.

The compliance values shown to the right are for piezoelectric ceramic materials alone. The compliance can be much greater for devices assembled using these ceramics with adhesives, epoxies, and other materials.

Values for soft PZT: $S_{33}^E = 20 \times 10^{-12} \text{ m}^2/\text{Newton}$

$S_{11}^E = 15 \times 10^{-12} \text{ m}^2/\text{Newton}$

Values for hard PZT: $S_{33}^E = 15 \times 10^{-12} \text{ m}^2/\text{Newton}$

$S_{11}^E = 12 \times 10^{-12} \text{ m}^2/\text{Newton}$

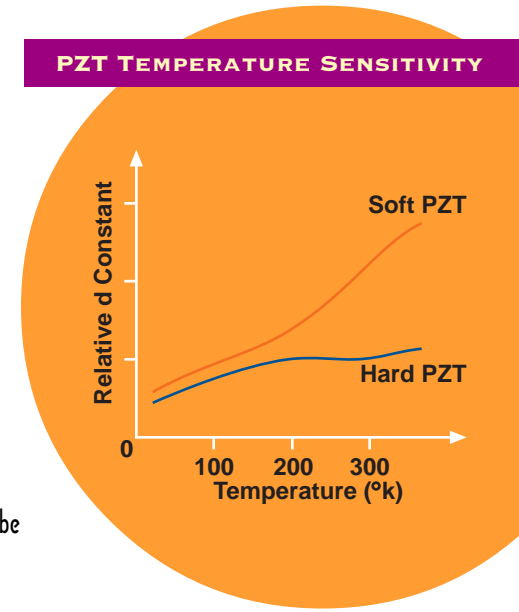
THERMAL PROPERTIES

PZT materials need to be used well below their Curie temperature for the material to remain stable. If you raise the temperature close to the Curie temperature, the material will become partially or completely depoled, thus losing its piezoelectric properties. If you have applications that require operation or bake-out at high temperatures, you should choose a PZT with a comparably high Curie temperature.

When considering low temperature use, note that piezoelectric ceramics have been integrated into assemblies requiring operation at temperatures as low as 4 degrees Kelvin. Both hard and soft PZT loses sensitivity at cryogenic temperatures, as shown.

So that you don't damage the materials or strain their performance, cryogenic devices using PZT elements should be designed for the proper thermal contraction differential.

Thermal stability is a major concern with high-resolution positioning applications under normal operating temperatures. The thermal expansion coefficients for PZT materials are on the order of 1-5ppm/degree C, similar to many ceramics and glasses. A major difference is that the thermal expansion coefficient is anisotropic with respect to the poling direction, particularly just below the Curie temperature. The change in piezoelectric d constants (see illustration) may also be important in applications where the temperature varies during normal operation.



POWER DISSIPATION

Piezoelectric elements are essentially capacitors. Their natural internal resistance is about 10¹¹ ohms when used at temperatures well below their Curie temperature. No current is drawn or power is consumed while the device is under static operation. Changing the voltage requires power.

The perfect capacitor wouldn't dissipate any energy while charging and discharging. Piezoelectric ceramics dissipate energy in the form of heat proportional to the dissipation factor (tan δ), the tangent of the loss angle for the material. This is similar to the reaction of any type of elastic material under stress; it becomes hot when stretched repeatedly.

The dissipation factor is actually a measure of the breadth of the hysteresis loop. For comparison purposes, the dissipation factor is usually specified for low electric fields and at 1000 Hz. As you can see in the hysteresis illustration earlier, soft PZT materials have large dissipation factors of .02 and hard PZT dissipation is about .004.

This equation will help you figure power dissipation per unit volume, using a capacitance C, driven at an RMS voltage V, and frequency f.

$$P = 2\pi f C (\tan \delta) V^2 = V^2/R_e \quad (9)$$

where $R_e = (2\pi f C \tan \delta)^{-1}$ is the equivalent series resistance (ESR). The resultant temperature rise depends on the device's heat capacity and the means used to transfer that heat to the surroundings, be it convection, conduction, or radiation.

Due to increase in the dielectric constant, the capacitance may increase rapidly in soft PZT materials as the temperature rises toward its Curie temperature. Be careful when running at high frequency so that thermal runaway does not damage the actuator.

AGING RATE

Time can slowly erode the poling process of piezoelectric ceramics. It can lose sensitivity with time. As with other natural forms of decay, PZT aging is a logarithmic function of time. The aging rate is the change in the material's parameters per decade of time. For example, a 1% aging rate implies a 1% drop in the piezoelectric properties between 1 hour and 10 hours after poling, and another 1% drop between 10 hours and 100 hours after poling.

Hard PZT materials age slowly, but for extended periods of time. Soft PZT materials age rapidly, but quickly (within 48 hours). This loss of polarization can be regained, however, by applying a high voltage at room temperature for a short time before reuse.

Operating Limitations

The chemical composition of the piezoelectric material determines its operating limits. These limits include voltage, stress, temperature, and power. If you operate outside these limits, the material can become partially or completely depoled, losing its piezoelectric properties. Here we explain each of these limitations.

VOLTAGE

A strong electric field with polarity opposite the original poling voltage can depolarize the material. The field strength limit depends on the material type, the application time, and the operating temperature.

MECHANICAL STRESS

A piezoelectric ceramic can also become depolarized with high mechanical stress. The stress limit depends on the material itself and the length of time stress is applied. With dynamic stress, like impact ignition, the material has less of a limit. Materials with higher energy output, or high g-constant, can be used.

The material behaves in a nonlinear way for pulse durations of a microsecond or more. The effect is linear when the duration is less than a microsecond, because of the short application of time compared with the domains' relaxation time.

TEMPERATURE

The Curie temperature is the term for the material's absolute maximum exposure temperature. A complete deterioration of the polarization occurs when the material reaches its Curie temperature. In fact, its performance decreases as the operating temperature increases toward Curie. Each ceramic has its own maximum temperature, after which its properties are lost.

It would be best for the material to be operated substantially below this maximum. This limitation decreases with more continuous operation or exposure. Also, higher temperatures speed the aging process, reducing its piezoelectric performance and its maximum safe stress level.

POWER

The following factors limit the acoustic power handling capacity of a radiating transducer:

1. THE CERAMIC'S DYNAMIC MECHANICAL STRENGTH
2. REDUCTION IN EFFICIENCY DUE TO DIELECTRIC LOSSES
3. REDUCTION IN EFFICIENCY DUE TO MECHANICAL LOSSES
4. DEPolarization DUE TO ELECTRIC FIELD
5. DEPolarization DUE TO TEMPERATURE RISE
6. INSTABILITY DUE TO POSITIVE FEEDBACK BETWEEN INTERNAL HEATING AND DIELECTRIC LOSSES (2 AND 5)

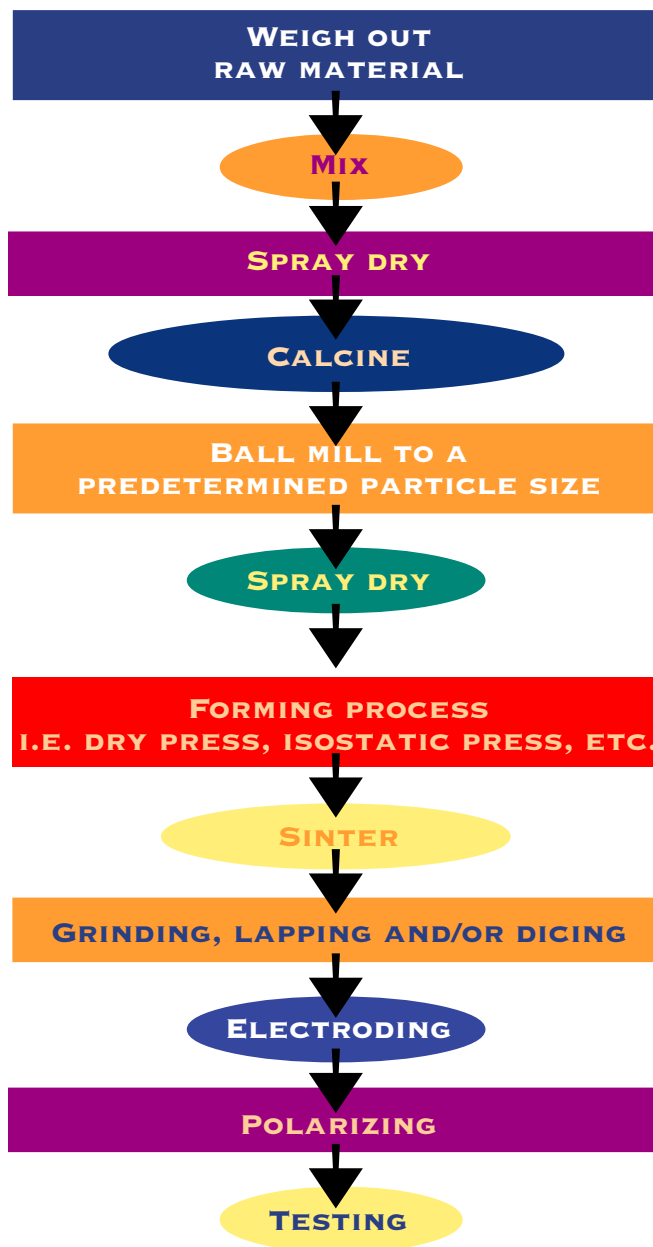
The equations pertaining to the material's power-handling capacities may be derived from lumped equivalent circuits. The acoustic power density P per cubic meter is given by this formula:

$$P = 2\pi f_r E^2 k^2 e_{33}^2 Q_M$$

where k is equal to k_{33} for a stack of axially poled rings or plates or k_{31} for a radially poled cylinder, E is the rms electric field, and f_r is the resonance frequency.

The Ceramic Manufacturing Process

It may be helpful to understand the stages of the ceramic **MANUFACTURING PROCESS** shown briefly as follows:



Piezoelectric Limitations



All materials have certain limitations, and piezoelectric materials are no exception. The three major limitations for piezoelectric ceramics are temperature, voltage, and stress.

TEMPERATURE

Temperature plays an important role in the **PROPER ORIENTATION** of our material. As the temperature of the ceramic is elevated, the piezoelectric performance decreases steadily until no activity is noticed. This temperature is called the Curie temperature or Curie point. Each different ceramic composition has its own Curie point. For design engineers, it is recommended, as a rough rule of thumb, that the maximum operational temperature be kept at approximately half of the stated Curie temperature. This should provide the necessary safeguard for the proper operation of the component.

VOLTAGE

Voltage plays an important role as well. Piezoelectric materials can be depolarized by **STRONG ELECTRIC FIELDS** that have opposite polarity with respect to the original poling polarity. Once again, as with temperature, each ceramic type has differing field strengths. There are no typical operating limits because there are many variables to consider, such as: AC or DC field, frequency, duty cycle, temperature, humidity, etc.

STRESS

Mechanical stress can also depolarize a piezoelectric ceramic. As stated earlier, the stress limitations are different for different compositions. However, typically "hard" compositions have much **GREATER STABILITY** than "soft" when subjected to high mechanical stress. Please consult a PKI engineer for additional information regarding your specific application.

For dynamic stress (impact ignition), the limit is less severe and therefore a high-energy output ceramic (high g constant) can be used. For these applications it is also notable that the material behaves quasi-statically (nonlinearly) for pulsed durations of a few milliseconds or more. When the pulse duration approaches a microsecond, the piezoelectric effect becomes linear, due to the short application of time compared with the relaxation time of the domains within the ceramic.

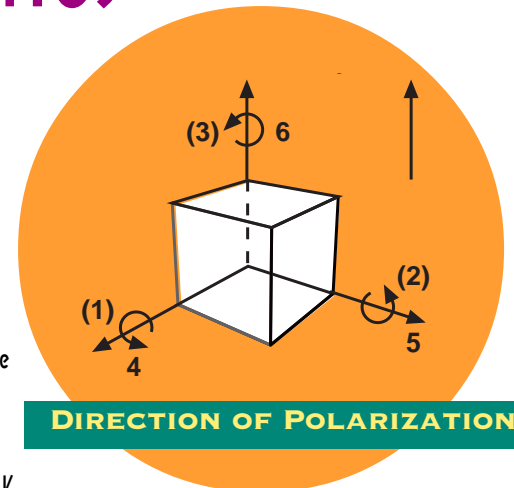
Piezoelectric Material Properties

AXES

Piezoelectric materials are anisotropic — the electrical and mechanical properties differ for differing electrical or mechanical excitation along different directions. Therefore, a means to identify standard directions is as follows:

1=X, 2=Y, 3=Z. See illustration.

Before the ceramic is poled, it is isotropic and therefore also not piezoelectric. The poling process actually creates the anisotropy. The direction of polarization is conventionally taken as the 3 axis with the 1 and 2 axes perpendicular to this. In the illustration, the terms 4, 5, and 6 refer to shear strains associated with the 1, 2, and 3 directions.



DIELECTRIC CONSTANT (k)

In the following equations, K_3 is the relative dielectric constant (relative to the vacuum) in the 3 direction. K_1 is the relative dielectric constant in the 1 direction. Multiplying these by ϵ_0 , the dielectric permittivity of free space, (8.85×10^{-12} Farads/meter), yields the absolute permittivity constant.

PIEZOELECTRIC VOLTAGE COEFFICIENT (g)

The g constant expresses the ratio of the field developed along a specific axis to the stress applied along a specific axis, when all other external stresses are constant. The g constant also expresses the ratio of strain developed along a specific axis, to the electric charge per unit-area of electrode applied, to electrodes which are perpendicular to a specific axis. A 33 subscript indicates that the electric field and the mechanical stress are both along the polarization axis. A 31 subscript signifies that pressure is applied at right angles to the polarization axis, but the voltage appears on the same electrodes as in the 33 case.

PIEZOELECTRIC CHARGE COEFFICIENT (d)

The d constant expresses the ratio of strain developed along a specific axis to the field parallel to a specific axis, when all external stresses are constant. The d constant also expresses the ratio of short-circuit charge per unit-area of electrode, flowing between connected electrodes, which are perpendicular to a specific axis, to the stress applied along a specific axis when all other external stresses are constant.

A special case is noted when the ceramic is subject to equal stresses along all three axes. This is termed hydrostatic stress. In this case, d is represented as d_h — the hydrostatic d constant. Substantial charge is developed under this scenario and the electrodes in this case are understood to be perpendicular to the 3 axis.

RELATIONSHIP BETWEEN (g) AND (d) CONSTANTS

At frequencies far below resonance, piezoelectric transducers are fundamentally capacitors. Consequently, the voltage constant g is related to the charge constant d by the dielectric constant K as, in a capacitor, the voltage V is related to the charge Q by the capacitance C. The equations are:

$$1. Q = CV \quad 2. d_{33} = K_3 \epsilon_0 g_{33} \quad 3. d_{31} = K_3 \epsilon_0 g_{31} \quad 4. d_{15} = K_1 \epsilon_0 g_{15}$$

COUPLING CONSTANTS

Electromechanical coupling k_{33} , k_{31} , k_{15} etc., describe the conversion of energy by the ceramic from electrical to mechanical or vice versa. The ratio of stored converted energy of one kind to the input energy of the second kind is defined as the square of the coupling coefficients. Subscripts denote the relative directions of electrical and mechanical quantities and the kind of motion involved.

Except in the special case noted hereafter, the coupling coefficients generally used are for cases when all external stresses are constant. The special case of considerable **PRACTICAL IMPORTANCE** involves use of the thickness vibrations in plates and discs at frequencies above the resonant frequencies, determined by the length and width of the element. Under these conditions, the inertia of the piezoelectric material effectively prevents lateral vibrations.

The effect would be the same as if infinitely ridged clamps were applied to the plate to prevent length and width vibrations. These clamps would apply opposing dynamic stresses as the element "tried" to vibrate laterally. Thus the qualification that "all external stresses are constant" is not met. Therefore, k_{33} does not define the electromechanical coupling under these conditions. The coupling in this special case is k_T .

Another case of importance involves coupling between the electric field in the 3 direction and the mechanical action simultaneously in the 1 and 2 directions. This coupling is identified by the symbol k_p (planar coupling). It is important because of the ease with which it may be measured with high accuracy, yielding a simple measure of the effectiveness of the poling of the ceramic.

Definition of Terms

DIELECTRIC CONSTANT

$$K = \frac{\text{permittivity of material}}{\text{permittivity of free space}}$$

DENSITY

The ratio of mass to volume (Kg/m^3)

COUPLING COEFFICIENT

$$k = \frac{\text{mechanical energy stored}}{\text{electrical energy stored}} \text{ or vice versa}$$

“d” CONSTANT

$$d = \frac{\text{strain developed}}{\text{applied force}} \text{ or } \frac{\text{short circuit charge density}}{\text{applied stress}}$$

“g” CONSTANT

$$g = \frac{\text{open circuit field}}{\text{applied stress}} \text{ or } \frac{\text{strain developed}}{\text{applied charge density}}$$

MECHANICAL Q (Q_M)

The ratio of reactance to resistance in the equivalent electric circuit, representing the mechanical vibrating resonant system.

YOUNG'S MODULUS (Y)

The ratio of stress to strain, while vibrating at its resonant frequency (N/m^2).

CURIE TEMPERATURE (T_c)

The temperature for a piezoelectric element, above which no piezoelectric action is detected. The crystal suffers permanent and complete depolarization, and changes from nonsymmetrical to symmetrical form.

FREQUENCY CONSTANT

Defined as the resonant frequency (f_r) x the controlling dimension, expressed in $\text{KHz}\cdot\text{m}$ or $\text{KHz}\cdot\text{in}$.

STRAIN

The ratio of change in length to the original length.

$$\text{Strain} = \frac{\Delta L}{L}$$

STRESS

The ratio of applied force to the cross sectional area.

AGING RATE

Aging is the attempt of the ceramic to change back to its original state prior to polarization. Aging is a logarithmic function with time. The aging rate defines the change in material parameters per decade of time, i.e., 1-10 days, 10-100 days, 100-1,000 days.

Conversions & Symbols

METRIC/ENGLISH CONVERSION

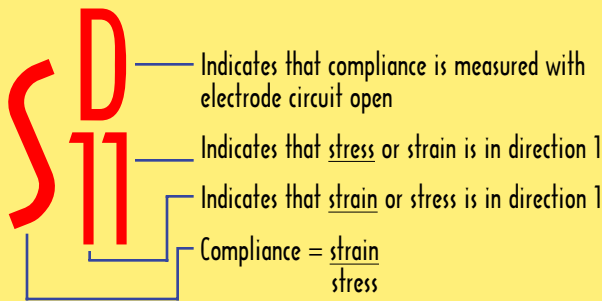
	Multiply	By	To Obtain
AREA	Meters ²	1550	Inches ²
	Meters ²	10.76	Feet ²
	Centimeters ²	0.1550	Inches ²
DENSITY	Grams/Cm ³	1000	Kilograms/Meters ³
	Pounds/Inches ³	27,680	Kilograms/Meters ³
	Pounds/Feet ³	16.02	Kilograms/Meters ³
	Pounds/Inches ³	27.68	Grams/Centimeters ³
FORCE	Newtons	10 ⁵	Dynes
	Dynes	1.020 x 10 ⁻⁶	Kilograms
	Kilograms	2.205	Pounds
	Newtons	0.2248	Pounds
	Grams	0.03527	Ounces
LENGTH	Meters	39,370	Mils
	Meters	39.37	Inches
	Meters	3.281	Feet
PRESSURE	Dynes/Cm ²	0.1	Newtons/Meters ²
	Dynes/Cm ²	1.450 x 10 ⁻⁵	Pounds/Inches ²
	Pounds/Inches ²	6895	Newtons/Meters ²
VOLUME	Meters ³	61,020	Inches ³
	Meters ³	35.31	Feet ³
	Centimeters ³	0.06102	Inches ³
	Feet ³	1728	Inches ³

SYMBOL DESIGNATIONS

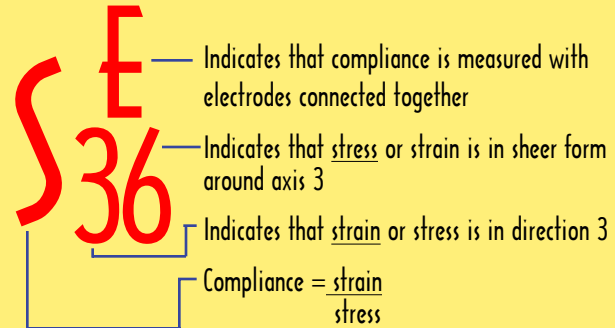
V	VOLTAGE
Q	ELECTRIC CHARGE
C	CAPACITANCE
F	FORCE
T, W, L & D	DIMENSIONS: Thickness, width, length and diameter, respectively
ΔT, ΔL & ΔD	SMALL CHANGES IN DIMENSIONS
d ₃₃	The DIRECT CHARGE COEFFICIENT
d ₃₁	The TRANSVERSE CHARGE COEFFICIENT
d ₁₅	The SHEAR CHARGE COEFFICIENT
g ₃₃	The DIRECT VOLTAGE COEFFICIENT
g ₃₁	The TRANSVERSE VOLTAGE COEFFICIENT
g ₁₅	The SHEAR VOLTAGE COEFFICIENT
P↓	The DIRECTION OF THE POLING AXIS. The arrow is parallel to the poling electric field, pointing toward the negative poling electrode.
k ₃₃	The DIRECT ELECTROMECHANICAL COUPLING COEFFICIENT
k ₃₁	The TRANSVERSE ELECTROMECHANICAL COUPLING COEFFICIENT
k ₁₅	The SHEAR ELECTROMECHANICAL COUPLING COEFFICIENT
k _p	The PLANAR ELECTROMECHANICAL COUPLING COEFFICIENT
K ₃	RELATIVE DIELECTRIC CONSTANT MEASURED ALONG THE POLING AXIS
K ₁	RELATIVE DIELECTRIC CONSTANT MEASURED AT RIGHT ANGLES TO THE POLING AXIS
ρ	DENSITY OF CERAMIC
Y _{ij} ^E	Young's MODULUS measured at constant electric field
Q _m	MECHANICAL Q (QUALITY FACTOR)
P _r	REMANENT POLARIZATION
E _c	COERCIVE FIELD
Z _m	IMPEDANCE AT RESONANCE
ε ₁₁ ^T	FREE PERMITTIVITY
ε ₁₁ ^S	CLAMPED PERMITTIVITY
f _r	RESONANCE FREQUENCY
f _a	ANTIRESONANCE FREQUENCY

TYPICAL SYMBOLS EMPLOYED IN DESCRIBING PROPERTIES OF PIEZOELECTRIC MATERIALS

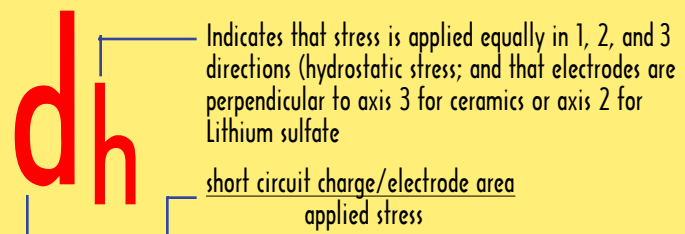
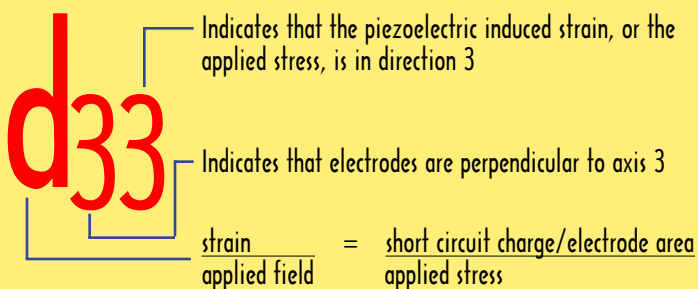
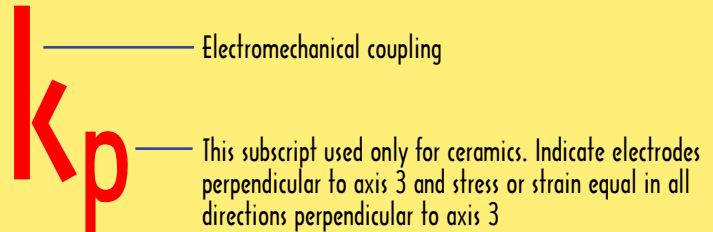
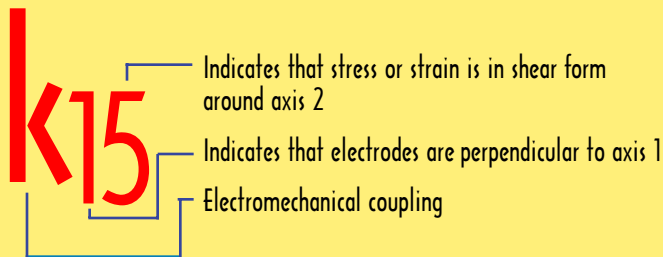
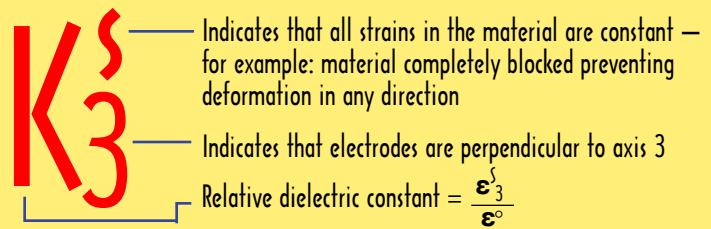
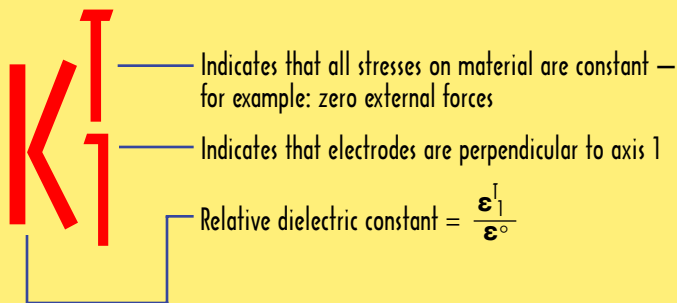
Strictly speaking, these symbols are used to identify properties of materials only, and should not be used to describe characteristics of actual physical elements made of these materials. However, for convenience, some liberties have been taken in the explanations — electric boundary conditions are identified by indicating locations and connections of electrodes.



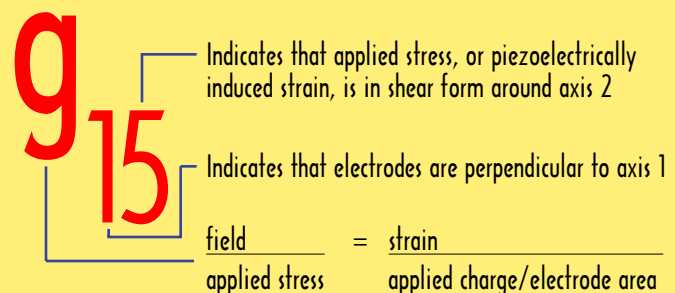
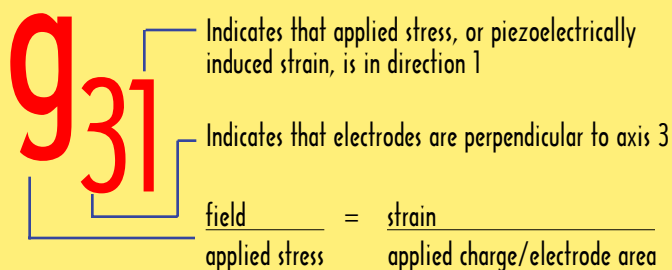
(All stresses, other than the stress involved in one subscript, are constant.)



(All stresses, other than the stress involved in one subscript, are constant.)



(All stresses, other than the stress involved in the second subscript, are constant.)



(All stresses, other than the stress involved in the second subscript, are constant.)

(All stresses, other than the stress involved in the second subscript, are constant.)

Lead Zirconate Titanate

NAVY TYPE I (PKI-402 AND PKI-406)

It is designed to serve as a driver where high power and low losses are dictated by design. It is primarily well suited for ultrasonic cleaners, fish finders and sonars. PKI 406 is suitable for medical applications.

NAVY TYPE II (PKI-502)

It is designed for applications that require high electromechanical activity and high dielectric constant. These are used primarily as receivers, e.g. hydrophones, phono pickups, sound detectors, accelerometers, delay lines, flow detectors, and flow meters.

NAVY TYPE III (PKI-802 AND PKI-804)

It is specifically used as a driver that exhibits low losses under extreme driving conditions and has a high Q. PKI 804 is well suited for medical applications.

NAVY TYPE V (PKI-532)

It is used as sensors that require low impedance, high dielectric constant and high sensitivity.

NAVY TYPE VI (PKI-552 AND PKI-556)

Denoted as Navy Type VI, this ceramic is used as sensors that require extremely high dielectric constant and large displacements. PKI 556 material has been slightly modified to give a higher g_{33} value, higher k_{33} , and lower loss factor. This formulation aids the design engineer by giving more flexibility within the type VI class of materials.

PKI 700

This material has low dielectric constant, high Q_M , high shear coupling coefficient, good temperature stability and low aging characteristics. Common use of this material is in delay lines and accelerometers.

Lead Metaniobate

PKI 100

Lead metaniobate exhibits properties not usually present in other types of piezoelectric ceramics. The noteworthy facts are its low mechanical Q_M , negligible aging, wide range of operating temperatures, and small values for lateral and planar coupling compared to longitudinal coupling. The low Q_M enhances the use of PKI 100 material in the construction of wide bandwidth sensors for high frequency pulse echo measurements that require a short pulse and critical resolution. Its negligible aging helps simplify circuit design. Wide variations in temperature have limited effect on its dielectric and piezoelectric properties, making it ideal for high temperature applications. Its high longitudinal coupling compared to lateral and planar coupling allows it to generate a better response under hydrostatic pressures and makes it useful for underwater sonar equipment.

Lead Nickel Niobate

PKI 906

PKI 906 is slightly different in composition than the "general" PZT formulations. Its PZT-doped lead nickel niobate composition was developed to enhance the d_{33} and dielectric properties of Navy Type VI materials. These enhanced properties make it the optimum choice for ultrasound or actuator applications. The increased dielectric constant allows engineers to use the material in smaller (higher frequency) applications while still maintaining the desired or necessary capacitance. The increased d_{33} allows for higher displacement applications.

Modes of Vibration, Displacement,

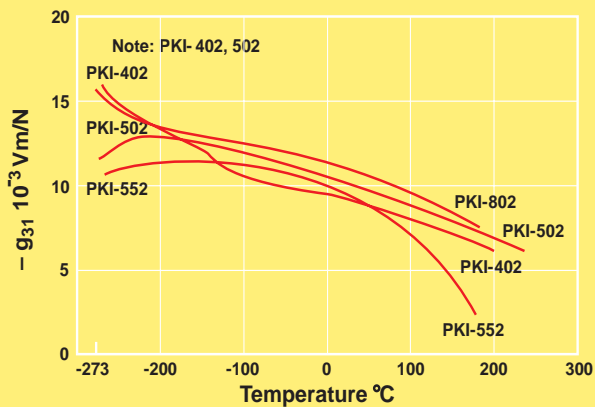
SHAPE	AXES	POLARIZATION DIRECTION	APPLIED FIELD	MODE OF VIBRATION OR DISPLACEMENT
			VOLTAGE OUTPUT	APPLIED STRESS
PLATE				LENGTH OR TRANSVERSE (L or W) THICKNESS (thk)
THIN DISC				RADIAL (r) THICKNESS (thk)
RING				RADIAL (r) THICKNESS (thk)
TUBE				LENGTH (L) RADIAL (r)
BAR				LENGTH (L)
ROD				LENGTH (L)
SHEAR PLATE				SHEAR (L or W)

and Voltage Output

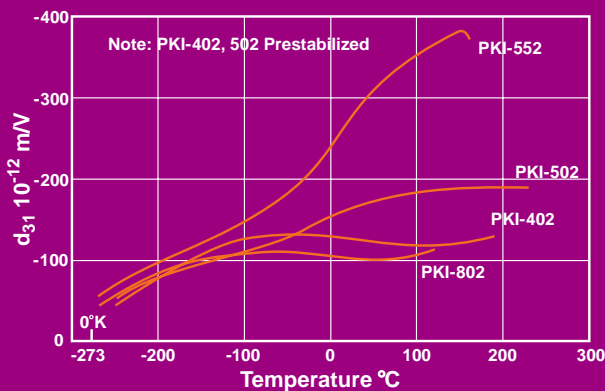
FREQUENCY CONSTANT	CAPACITANCE	(STATIC) DISPLACEMENT	(STATIC) VOLTAGE
$N_1 = f_r L$ $N_1 = f_r W$ $N_t = f_r thk$	$C_{ap} = \frac{K_{33}^T \epsilon_0 LW}{thk}$	$\Delta W = \frac{d_{31} VW}{thk}$ $\Delta L = \frac{d_{31} VL}{thk}$ $\Delta thk = d_{33} V$	$V = \frac{g_{31} F_1}{W}$ $V = \frac{g_{31} F_2}{L}$ $V = \frac{g_{33} F_3 thk}{LW}$
$N_p = 2f_r$ $N_t = f_r thk$	$C_{ap} = \frac{K_{33}^T \epsilon_0 \pi r^2}{thk}$	$\Delta r = \frac{2d_{31} Vr}{thk}$ $\Delta thk = d_{33} V$	$V = \frac{g_{31} F_1}{2\pi r}$ $V = \frac{g_{33} F_3 thk}{\pi r^2}$
$N_p = f_r (OD+ID)$ $N_t = f_r thk$	$C_{ap} = \frac{K_{33}^T \epsilon_0 \pi (OD^2-ID^2)}{4 thk}$	$\Delta r = \frac{d_{31} V (OD-ID)}{2 thk}$ $\Delta thk = d_{33} V$	$V = \frac{g_{31} F_1}{2\pi (OD-ID)}$ $V = \frac{4g_{33} F_3 thk}{\pi (OD^2-ID^2)}$
$N_1 = f_r L$ $N_t = \frac{f_r (OD-ID)}{2}$	$C_{ap} = \frac{2K_{33}^T \epsilon_0 \pi L}{\ln\left(\frac{OD}{ID}\right)}$	$\Delta L = \frac{2d_{31} VL}{(OD-ID)}$ $\Delta r = d_{33} V$	$V = \frac{g_{31} F_1 (OD-ID)}{L (OD+ID)}$ $V = \frac{g_{33} F_3 (OD-ID)}{2(OD^2-ID^2)}$
$N_3 = f_r L$	$C_{ap} = \frac{K_{33}^T \epsilon_0 W thk}{L}$	$\Delta L = d_{33} V$	$V = \frac{g_{33} F_3 L}{W thk}$ $V = \frac{g_{31} F_1}{W} \quad V = \frac{g_{31} F_2}{thk}$
$N_3 = f_r L$	$C_{ap} = \frac{K_{33}^T \epsilon_0 \pi r^2}{4L}$	$\Delta L = d_{33} V$	$V = \frac{g_{33} F_3 L}{\pi r^2}$ $V = \frac{g_{31} F_1}{2\pi r}$
$N_5 = f_r thk$	$C_{ap} = \frac{K_{33}^T \epsilon_0 LW}{thk}$	$\Delta W = d_{15} V$	$V = \frac{g_{15} F_3}{L}$

Electromechanical vs. Temperature

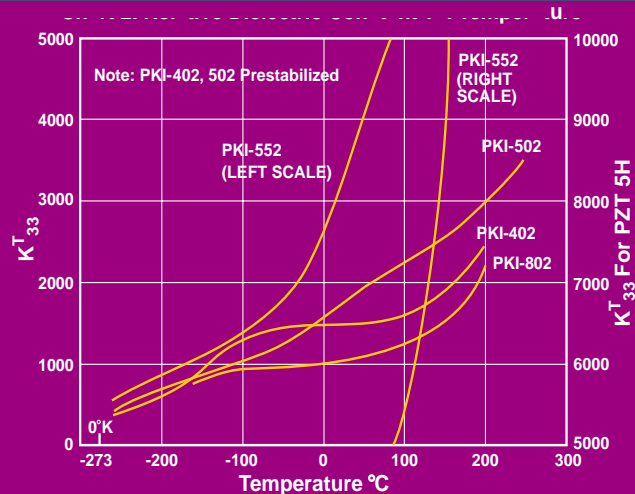
g_{31} VS. TEMPERATURE



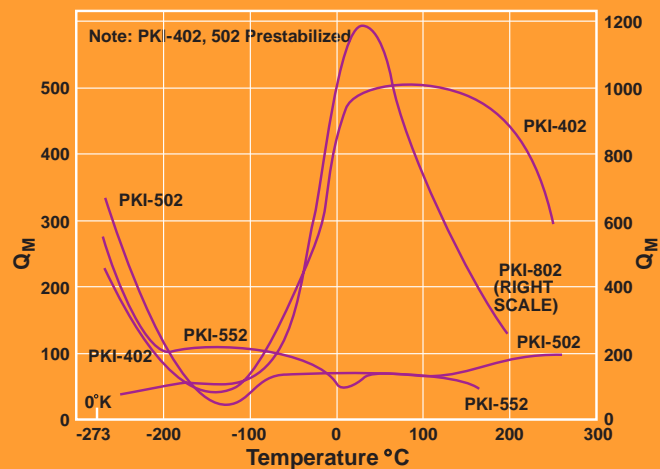
d_{31} VS. TEMPERATURE



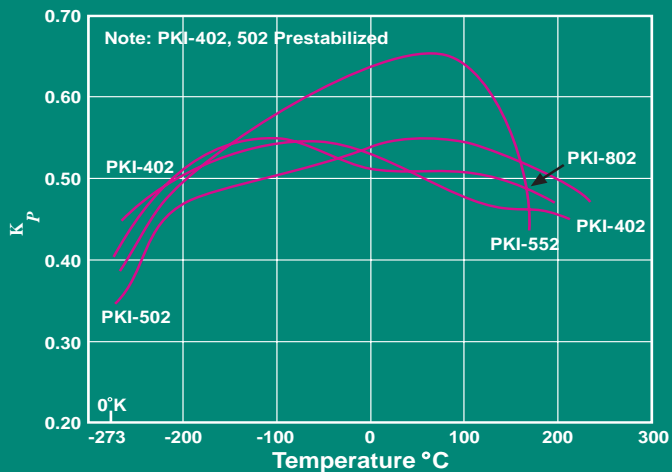
RELATIVE DIELECTRIC CONSTANT VS. TEMPERATURE



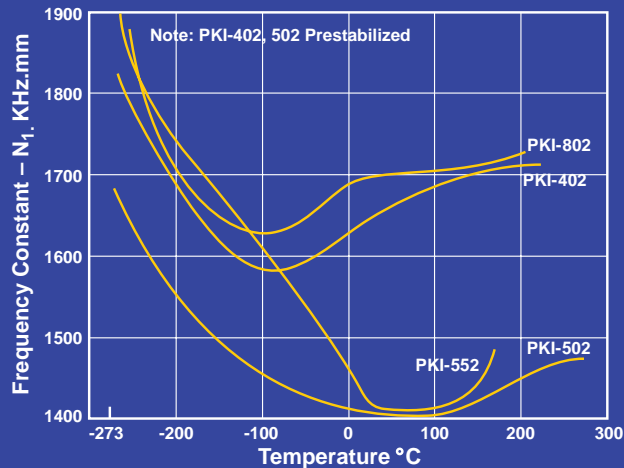
MECHANICAL Q VS. TEMPERATURE



PLANAR COUPLING FACTOR VS. TEMPERATURE



FREQUENCY CONSTANT VS. TEMPERATURE



General Information

RESONANT FREQUENCY

Though special tolerances to $\pm 1\%$ are possible, standard tolerances are 5%-10%. If their nominal frequency is not as important as matching transducers, specify the permissible deviation, allowing greater latitude in the group's coverage frequency. If you desire a specific frequency within close limits, leave the associated dimension variable to achieve the necessary control.



**YOU CAN PRECISELY SET ONLY ONE:
THE FREQUENCY OR A PERTINENT DIMENSION.**

Resonant frequencies are inversely proportional to the size of a single dimension only for transducers of simple, ideal shapes. The resonant frequencies of intermediate shapes, such as short bars or thick discs, are less predictable. The pattern of vibration may become confused by closely spaced multiple resonances. The two modes may also mutually interfere when two dimensions produce coinciding or proximate resonances. This would happen in a tube with a length of nearly 1.5 times the mean diameter, for example. At this point, frequencies do not follow simple formulas and vibrations become complex.

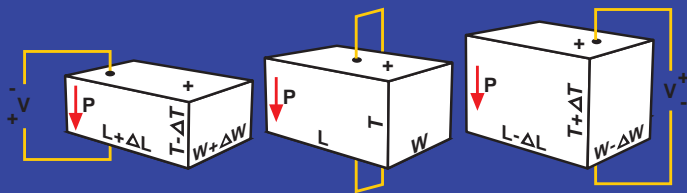
MODES OF VIBRATION

DC OR LOW FREQUENCY RELATIONS

Quantities inserted in the following equations must be in compatible units. Since piezoelectric coefficients are usually given in MKS units, the system is most convenient. X, L, W and T should then be in meters, V in volts, Q in Coulombs, F in Newtons, d coefficient in Coulombs/Newton or meters/volt, and g coefficients in volt-meters/Newton.

Equations give magnitudes only. Signs of charge, voltage and displacement are shown on drawing.

EXPANSION OR CONTRACTION

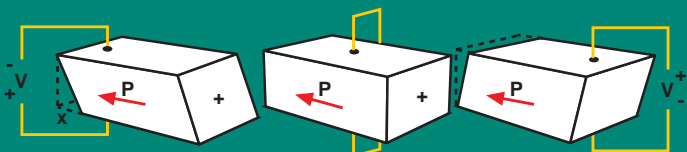


MOTOR

$$\text{DIRECT } \Delta T = V d_{33}$$

$$\text{TRANSVERSE } \frac{\Delta L}{L} = \frac{\Delta W}{W} = \frac{V}{T} d_{31}$$

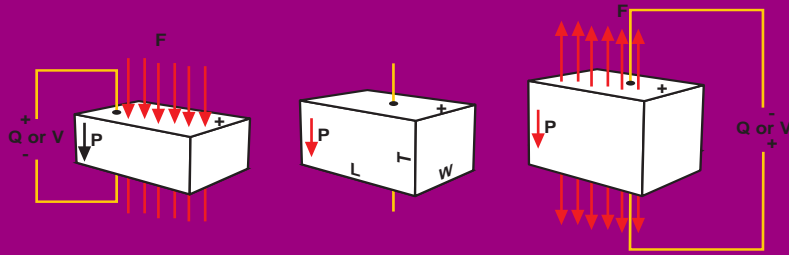
EXPANSION OR CONTRACTION



MOTOR

$$X = V d_{15}$$

PARALLEL COMPRESSION OR TENSION

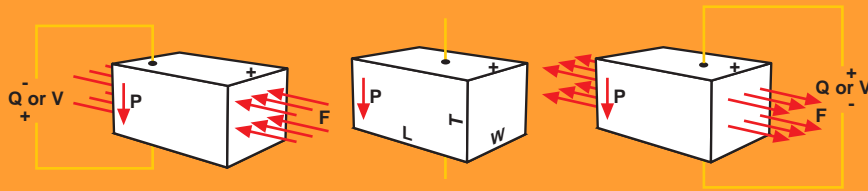


GENERATOR

$$Q = Fd_{33}$$

$$\frac{V}{T} = \frac{Fg_{33}}{LW}$$

TRANSVERSE COMPRESSION OR TENSION

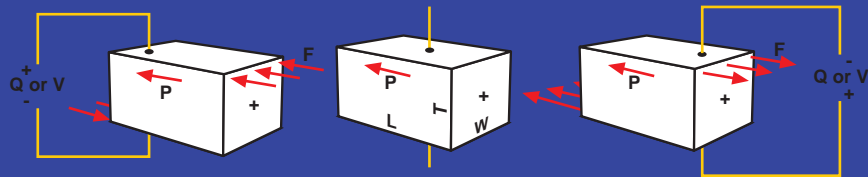


GENERATOR

$$\frac{Q}{LW} = \frac{F}{TW} d_{31}$$

$$\frac{V}{T} = \frac{F}{TW} g_{31}$$

PARALLEL SHEAR

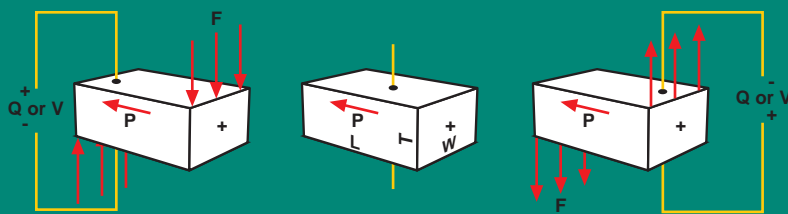


GENERATOR

$$Q = Fd_{15}$$

$$\frac{V}{T} = \frac{F}{LW} g_{15}$$

TRANSVERSE SHEAR



GENERATOR

$$\frac{Q}{LW} = \frac{F}{TW} d_{15}$$

$$\frac{V}{T} = \frac{F}{TW} g_{15}$$

ELECTRODES & LEADS

PKI's piezoelectric ceramics come with electrodes of fired silver or electroless nickel. Silver electrodes are flat-white and the nickel electrodes are gray. Thicknesses are:

Silver 0.0003 - 0.001"

Nickel 0.00005 - 0.0002"

In addition, special electrodes such as electroplated gold and sputtered gold and nickel are available upon request for your special applications.

You can order almost any electrode combination you want. Leads are not normally furnished unless you specify them. The electrode quality is based on the adhesion of the soldered leads, the surface finish, and the conductivity.

SOLDERING

Because improperly attaching the leads can affect performance, here are some procedures for soldering:

NICKEL ELECTRODE & SILVER SOLDERING

MATERIAL REQUIRED:

Soldering iron: 15-25 watts with a few tip sizes

Solder: SN 60, 60% tin, 40% lead, .032" diameter OR

Solder: SN 62, 2% silver, 62% tin, 36% lead, .032" diameter

Flux: Kester 1571, or equivalent

Common pencil eraser, Q-tip, and isopropyl alcohol

1. PREHEAT YOUR SOLDERING IRON.
2. GENTLY BURNISH A SMALL AREA TO BE SOLDERED WITH THE ERASER.
3. USING A Q-TIP, CLEAN THE SURFACE TO BE SOLDERED WITH ISOPROPYL ALCOHOL AND LET DRY.
4. MELT SOME SOLDER ON THE TIP OF THE PREHEATED SOLDERING IRON.
4. TIN THE LEAD WITH THE SOLDER.
5. DIP THE TINNED LEAD INTO THE FLUX.
6. PLACE THE LEAD ON THE ELECTRODE AREA.
7. USING MILD PRESSURE, PLACE THE TIP OF THE SOLDERING IRON ON THE LEAD UNTIL THE SOLDER FLOWS ONTO THE ELECTRODE.
8. REMOVE THE SOLDERING IRON, BUT HOLD THE WIRE UNTIL THE SOLDER SOLIDIFIES, APPROXIMATELY 2.5 SECONDS.
9. REMOVE FLUX RESIDUE BY RINSING WITH ISOPROPYL ALCOHOL.

SOLDERING TIPS

REMEMBER, EXCESSIVE TEMPERATURES CAN ACTUALLY DEPOLARIZE YOUR CERAMIC. MAKE YOUR SOLDERING JOINTS QUICKLY AND KEEP THEM AS SMALL AS POSSIBLE.

USE A NON-CORROSIVE FLUX, NOT CONTAINING ZINC CHLORIDE OR OTHER CORROSIVE AGENTS.

A GOOD SOLDER JOINT WILL FLOW RAPIDLY, WET AROUND THE WIRE AND SHINY UPON SOLIDIFYING.

FREQUENTLY CLEAN AND REMOVE EXCESS SOLDER FROM THE IRON'S TIP, USING A DAMP SPONGE.

IF YOU'D LIKE TO BE CONSISTENT IN YOUR SOLDER-DOT SIZE, PRECUT YOUR BITS OF SOLDER AND CLEAN THE TIP AFTER EACH USE BEFORE PICKING UP THE NEXT ONE.