Mission Statement

OUR MISSION AS A COMPANY IS TO BECOME THE LEADING MANUFACTURER OF SMALL AND SPECIALTY PIEZOELECTRIC CERAMIC ELEMENTS AND ASSEMBLIES. WE INTEND TO ACCOMPLISH OUR MISSION BY USING OUR DYNAMIC WORK ETHIC AND VISION AND BY PROVIDING SUPERIOR PRODUCT QUALITY AND CUSTOMER SUPPORT.

BY "QUALITY" WE MEAN COMPLETE, ABSOLUTELY RELIABLE CONFORMANCE TO CUSTOMERS' SPECIFICATIONS, INCLUDING DELIVERY REQUIREMENTS, WHETHER STATED OR IMPLIED.

BY "CUSTOMER SUPPORT" WE MEAN CONSTANTLY DEMONSTRATED WILLINGNESS AND ABILITY TO ENGINEER OUR PARTS INTO OUR CUSTOMERS' APPLICATIONS, PROVIDING MAXIMUM EFFECTIVENESS, RELIABILITY, AND VALUE.

Table of Contents

Our Company's Evolution

For the last twenty years, Piezo Kinetics Inc. (PKI) has manufactured **PIEZOELECTRIC CERAMIC ELEMENTS** and assemblies used in a wide variety of applications and industries, including aerospace, biomedical, and ultrasonics.

PKI's roots date back to 1979. In 1996, we became a member of Crest Ultrasonics Corporation.

Crest is an international ultrasonic cleaning and welding corporation and a heavy user of PZT. Crest's acquisition was due to their belief in PKI's superior products — also noting our high reliability and exceptional on-time delivery.

This acquisition was a great vote of confidence and a perfect match.

One of PKI's responsibilities is to supply Crest and its other divisions with PZT ceramics.

Though part of this remarkable multimillion-dollar corporation, PKI remains a small, independent operation which can provide **CUSTOM** piezoceramics and assemblies cost effectively, even in smaller quantities.

Our proximity to Penn State University's main campus has allowed us to use their renowned resources for research and development. We have a cooperative relationship with the **PENN STATE** University Materials Research Laboratory, giving us a unique competitive edge in the forefront of technology.

We are confident that we can be responsive, timely, and economical for companies developing new uses for piezoelectric ceramics, as well as those who have been using them for decades. You can count on us being a dedicated part of your team.

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**

1 **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.

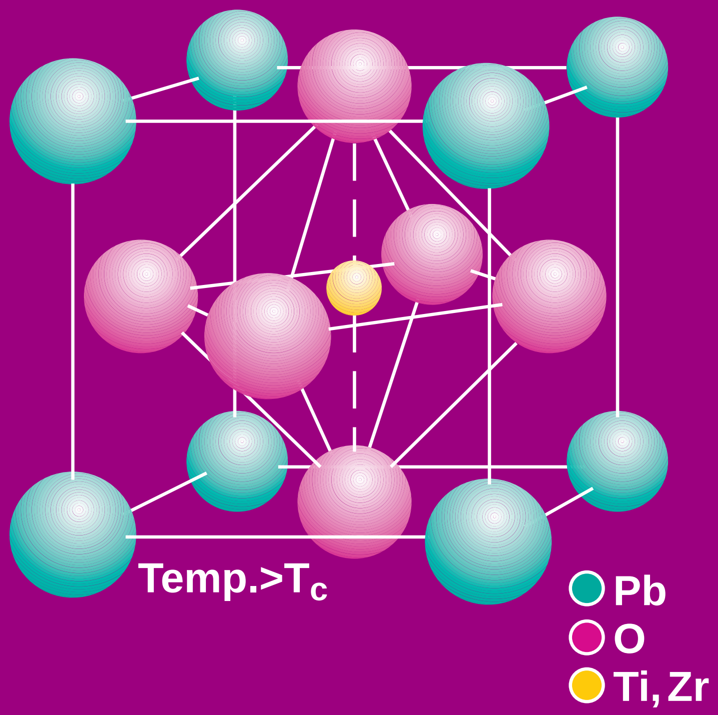
It could also be induced in some polycrystalline materials, such as lead-zirconate-titanate (PZT), barium titanate, and lead metaniobate.

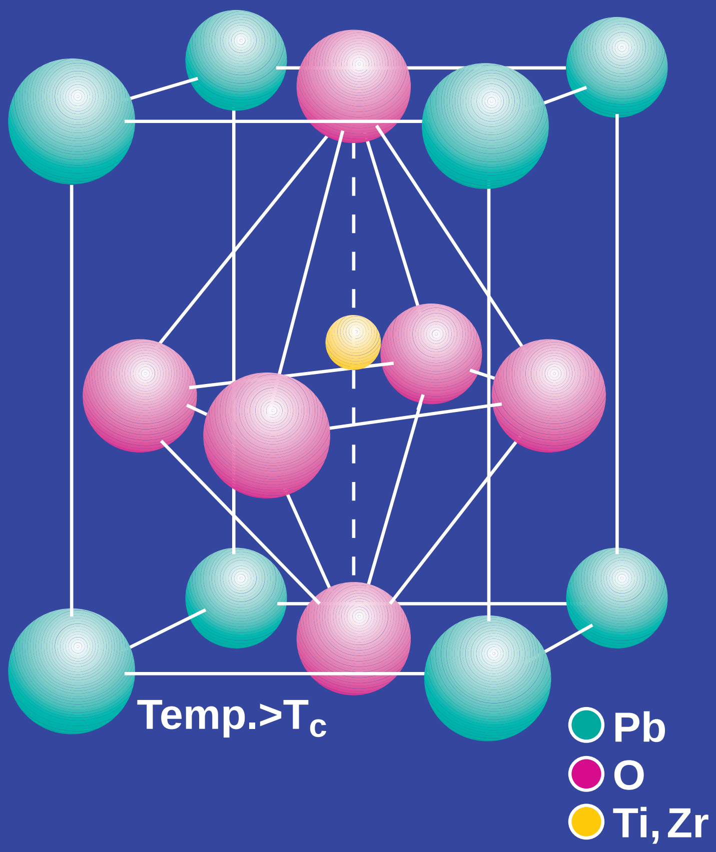
POLING PZT TO BEST ADVANTAGE

PZT is a ceramic material with a polycrystalline structure. It has a basic chemical composition of $PbTiO_3$ and PbZ_RO_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 II — PKI 502**
- **DOD TYPE III — PKI 802, 804**
- **DOD TYPE V — PKI 532**
- **DOD TYPE VI — PKI 552, 556**
- **LEAD METANIOBATE — PKI 100**
- **SPECIALTY MATERIALS — PKI 700, 906**

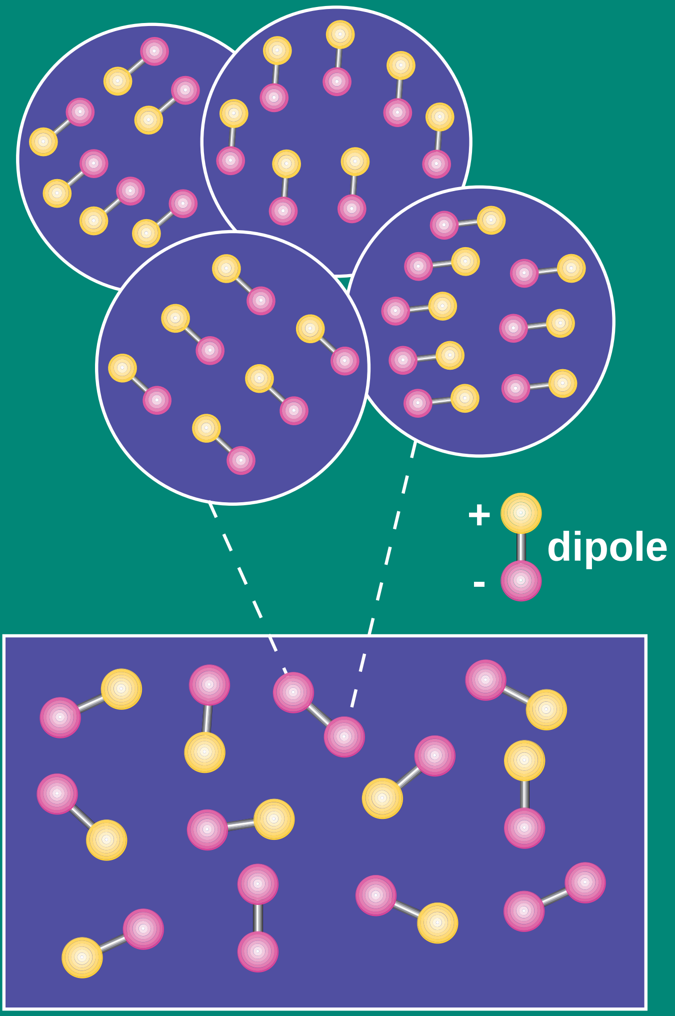
Above a certain temperature, called the **Curie Temperature** (T_c), the crystal structure is cubic and has no electric dipole moment (right).

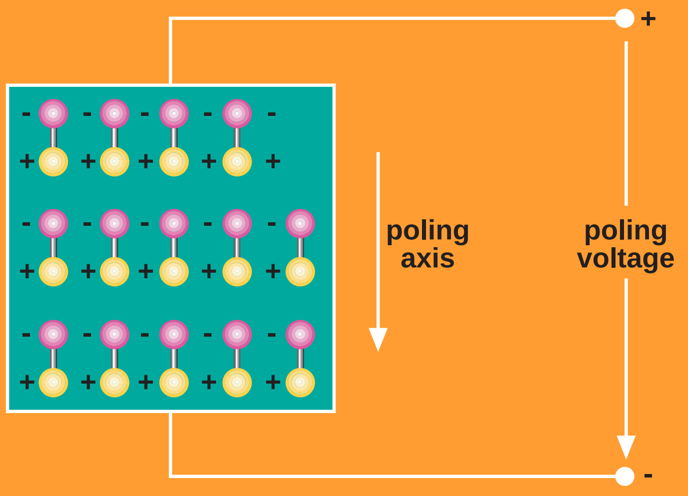




However, below this temperature the positively charged Ti/Zr ion shifts from its central location along one of several allowed directions. This slightly **Distorts** the crystal lattice into a perovskite structure (a tetragonal/rhombohedral shape), and produces an electric dipole with a single axis of 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:

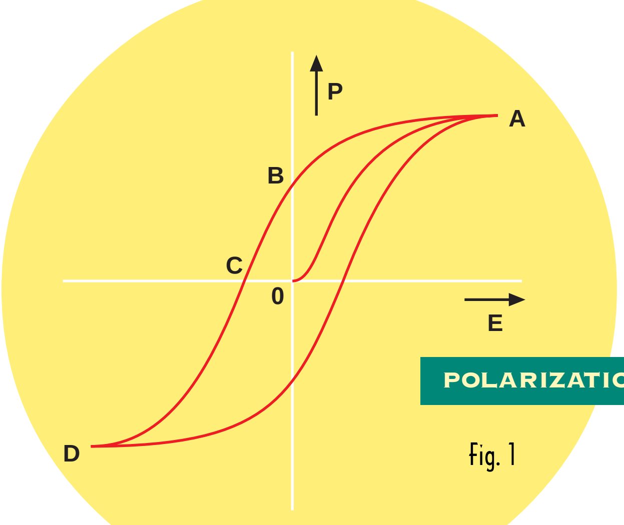
1. **HARD PZT MATERIALS** — THESE HAVE CURIE TEMPERATURES ABOVE 300 DEGREES C AND ARE NOT EASILY POLED OR DEPOLED EXCEPT AT HIGHER TEMPERATURES. THESE MATERIALS GENERALLY HAVE SMALL d CONSTANTS, GOOD LINEARITY, LOW HYSTERESIS, HIGH Q VALUES AND ARE ABLE TO WITHSTAND HIGH LOADS AND VOLTAGES.
2. **SOFT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



POLARIZATION P

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).**

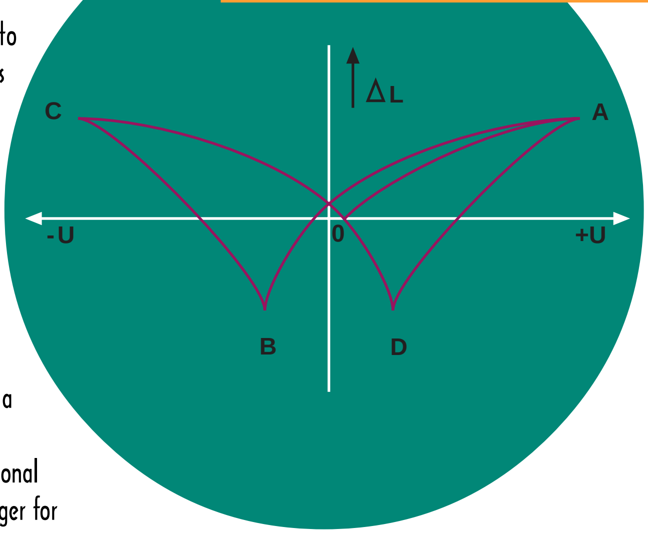
Material composition is the main determiner of coercive field strength. For common actuator materials, it is in the range of one hundred to several hundred volts/mm. A consequence of hysteresis in the P-E diagram is dissipative loss, which occurs during dynamic operation of the actuators leading to actuator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

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

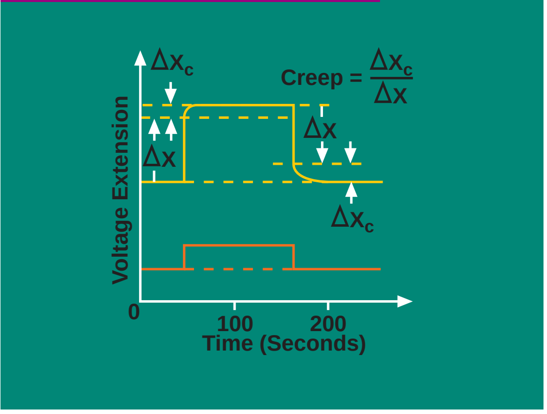
Polarized materials show contraction when the voltage is reversed, but re-expansion occurs up to Point C when the coercive limit is exceeded. Therefore, the principal limit of total movement is determined by saturation and coercive effects, but usually actuators are operated far away from these points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

Fig. 2

Schematic Butterfly



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: $S_{33}^E = 20 \times 10^{-12}\ \mathrm{m^2/Newton}$

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

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

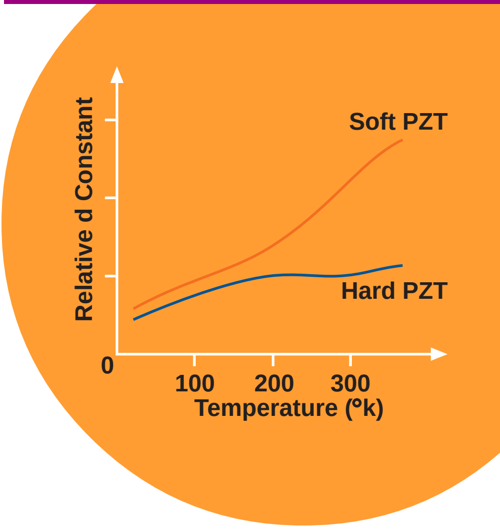
$S_{11}^E = 12 \times 10^{-12}\ \mathrm{m^2/Newton}$

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.

PZT TEMPERATURE SENSITIVITY



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 10^{11} 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.

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

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)**

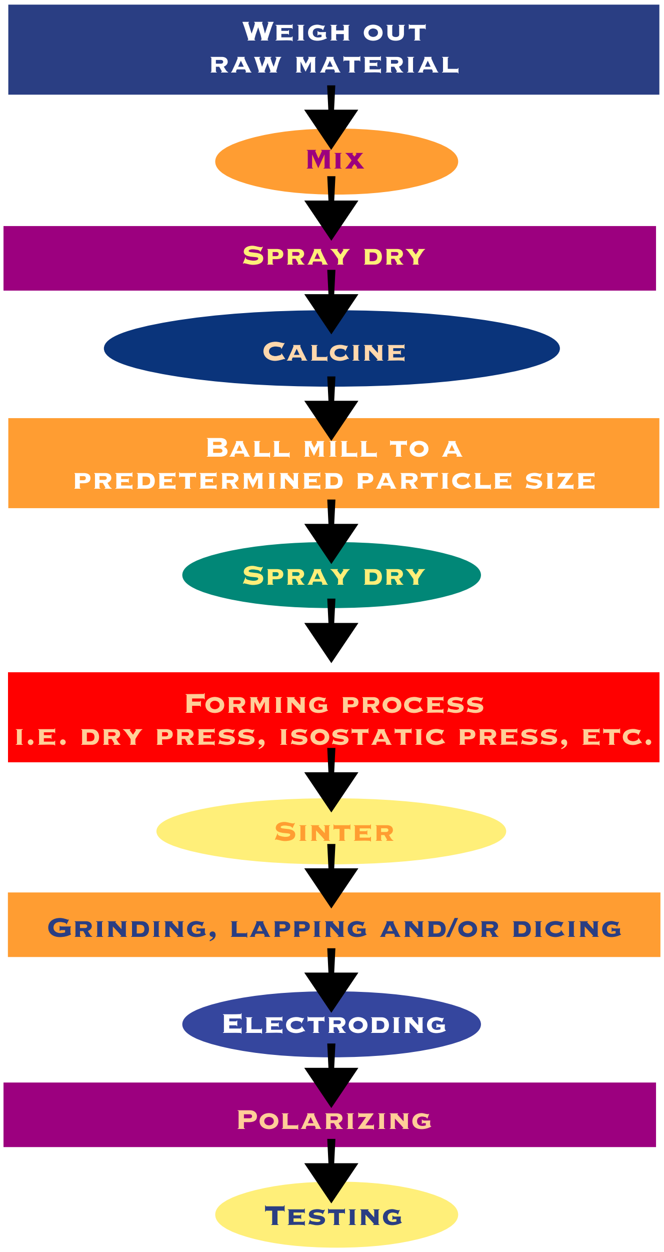
The equations pertaining to the material's power-handling capacities may be derived from lumped equivalent circuits. The acoustic power density P per cubic meter is given by this formula:

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

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.

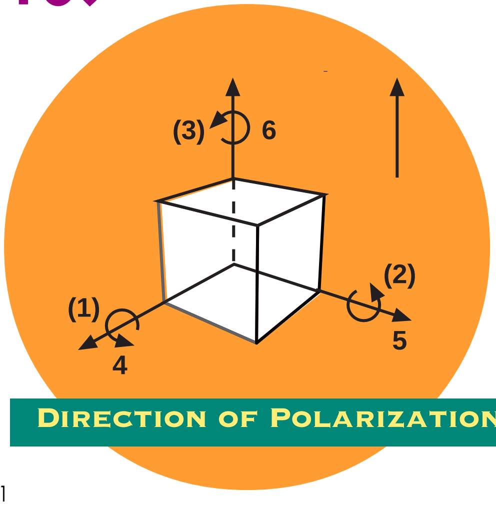
STRESS

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



DIRECTION OF POLARIZATION

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. $Q = CV$ **2.** $d_{33} = K_3 \varepsilon_0 g_{33}$ **3.** $d_{31} = K_3 \varepsilon_0 g_{31}$ **4.** $d_{15} = K_1 \varepsilon_0 g_{15}$

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.