Reliability & Lifetime of Multilayer Piezo Actuators
PICMA® multilayer piezo actuators are based on a special PZT (lead zirconate – lead titanate) ceramic, which ideally combines the desired characteristics of the components such as high stiffness, low electrical capacity, high specific displacement, low load and temperature dependence of the specifications and long lifetime.

The internal electrodes and the ceramic are jointly sintered (co-fired technology) to create a monolithic piezoceramic block (Fig. 1). This block is protected against humidity and damage from increased leak current by a ceramic isolation layer. Therefore, PICMA® actuators are far superior in terms of reliability and lifetime to conventional, polymer-coated, multilayer, piezoelectric actuators. The construction with the ceramic insulation layer results also in a high resonance frequency, making the actuators ideally suited for high-dynamic operation.

Large Temperature Range – Optimum UHV Compatibility – Minimal Outgassing – Neutral in Magnetic Fields

The particularly high Curie temperature of 320°C allows for a usable temperature range of up to 150°C, far beyond the 80°C limit of conventional multilayer actuators. This and the exclusive use of inorganic materials provide the optimum conditions for use in ultra-high vacuums: No outgassing and high bake-out temperatures. PICMA® piezoelectric actuators even work in the cryogenic temperature range, although at a reduced travel.

Low Operating Voltage

In contrast to most commercially available multilayer piezo actuators, PICMA® actuators achieve their nominal displacement at operating voltages significantly below 150 V. This is achieved by using a particularly fine-grained ceramic material which allows a lower depth of the internal layers. The products described in this document are at least partially protected by the following patents:

- German patent no. 10021919
- German patent no. 10234787
- German patent no. 10348836
- German patent no. 102005015405
- German patent no. 102007011652
- US patent no. 7,449,077

100 Billion Cycles: PICMA® actuators were life tested by NASA/JPL before they were sent to the Mars. No failures were seen after the extensive tests. Results are available here: http://www.ncbi.nlm.nih.gov/pubmed/21507759

Influences on the Lifetime of a Piezo-Ceramic Actuator

Three essential factors affect the lifetime of piezo ceramics in positioning applications: Humidity, operating voltage and temperature.

Ingressing moisture and the electric field applied can cause electro-chemical transport processes in the component, which are accelerated by higher temperatures. The result is a short circuit between the electrodes, which can cause irreparable damage to the actuator.

The actual application determines the extent to which the individual factors have an impact.

Optimized Electrodes for high Electric Currents

Research on the control electrodes led to a further improved design. The patented, meandering form of the external electrodes supplies the electric current evenly to the internal electrodes (Fig. 2). The contact here is chosen so that it remains electrically stable and mechanically flexible even at high currents up to 20 A and more, for extreme dynamic requirements. This improves the lifetime of the actuator in applications with rapidly changing fields.
Ceramic vs. Polymer Coating

In positioning applications, the piezoelectric actuator is typically operated at constant voltage to maintain one position over an extended period of time. The lifetime of piezoelectric actuators in this application is mainly affected by the voltage and humidity.

Protective Ceramic Layer
The most important feature which protects PICMA® actuators against ingressing moisture is the monolithic construction with the ceramic insulation layer. The ingestion of water molecules is effectively suppressed, which is impressively documented by measurements of the leak current (Fig. 3). Increased values are a sign of deteriorating insulation resistance and thus of a decrease in lifetime, as can be seen with polymer-coated actuators.

Tests Under Realistic and Extreme Loads
The high reliability makes it virtually impossible to experimentally measure the lifetime of PICMA® actuators under realistic operating conditions. To estimate the lifetime, tests under extreme loading conditions are used. These tests are then confirmed in a long-term series of tests that are carried out under realistic conditions (see “Realistic study”).

Realistic Study

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Failure Rate of PICMA® Actuators with Ceramic Insulation</th>
<th>Failure Rate of Conventional, Polymer-Coated Actuators</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 V DC</td>
<td>0 % (calculated MTTF: 1.3 · 10E6 h)</td>
<td>75 %</td>
</tr>
<tr>
<td>120 V DC</td>
<td>0 % (calculated MTTF: 178,000 h)</td>
<td>100 %</td>
</tr>
<tr>
<td>135 V DC</td>
<td>0 % (calculated MTTF: 49,000 h)</td>
<td>100 %</td>
</tr>
<tr>
<td>150 V DC</td>
<td>25 % (calculated MTTF: 15,500 h)</td>
<td>100 %</td>
</tr>
</tbody>
</table>

Tests under realistic conditions clearly confirm the high reliability of the ceramic-insulated PICMA® piezo actuators. Multilayer actuators were operated under conventional environmental conditions with different DC voltages. In this case, as well, PICMA® actuators with ceramic insulation convince by quite a margin: First failures occur only at 150 V, i.e. far above their specified nominal voltage, while after an 18-month test period only a small number of conventional polymer-insulated piezoelectric actuators are still functional. Test conditions: 22°C, 55% RH, testing period 18 months (13,400 h)

Accelerated Life Test
An increased relative humidity combined with high ambient temperatures and control voltages sometimes above the nominal voltage range leads here to an accelerated degradation of the piezoelectric actuators. The boundary conditions are subsequently corrected using a mathematical model and this results in a specification for the average lifetime (Mean Time To Failure, MTTF) in a realistic application. Conventional, polymer-coated piezoelectric actuators typically survive continuous use at increased humidity for about 30 days (Fig. 4), whereas PICMA® multilayer piezoelectric actuators are still working reliably after more than four years!

The results were obtained from a representative random sample of PICMA® 5 x 5 x 18 (P-885.50) and are typical for the complete PICMA® product range.

Tests on PICMA® actuators under realistic operating conditions revealed the following voltage failure rates (calculated MTTF: Mean Time To Failure):

- 100 V DC: 0 % (MTTF: 75 · 10E6 h)
- 120 V DC: 0 % (MTTF: 178,000 h)
- 135 V DC: 0 % (MTTF: 49,000 h)
- 150 V DC: 25 % (MTTF: 15,500 h)

Fig. 3. PICMA® piezoelectric actuators (bottom curve, red) compared to polymer-coated multilayer piezoelectric actuators. The high insulation resistance of the PICMA® actuators remains stable over several time decades, whereas conventional, polymer-coated actuators exhibit a significantly increased leak current after a few hours. (Test conditions: 100 V DC, 25°C, 70 % relative humidity [RHI])

Fig. 4. Comparison of PICMA® and conventional piezo actuators insulated with a polymer coating. Results of an accelerated life test with increased humidity for accelerated aging (Test conditions: 100 V DC, 22°C, 90 % RH). Statistical methods can be used to derive values under normal climatic operating conditions from this. The extrapolated average lifetime (MTTF) for PICMA® actuators is more than 400,000 h (approx. 45 years). All polymer-coated comparison samples fail, at the most, after only 1,600 hours (MTTF = 890 hours, about 1 month)
The DC-test results of PICMA® actuators are the basis for the lifetime calculations under predefined conditions. The individual factors which can have an impact here must be taken into consideration: Temperature, relative humidity and applied voltage. These were gathered through an extensive series of tests still in progress. The dependencies are shown in the adjacent diagrams (Fig. 5).

Long-Term Cryogenic Test Results
Test on the lifetime of PICMA® actuators for a 10-year cryogenic application were also conducted by Dr. Bosotti, University of Milano, Italy in 2005.

Calculating the Lifetime in the Application
In the selected simplified presentation, the average lifetime of a PICMA® multilayer actuator can be directly derived for the intended operating conditions. The effect on the lifetime of each individual factor can be read off the diagrams. The the lifetime calculated in hours simply results as the product of all three values read off the diagrams. This calculation can also be used to optimize a new application in terms of its lifetime as early as in the design phase. A decrease in the control voltage or the control of temperature and humidity with flushing air or encapsulation can be very important here.

The impact that the applied voltage has, is particularly important. The lifetime to be expected at 80 V DC, for example, is 10 times higher than that to be expected at 100 V DC.

Example
The simple formula MTTF = A_u * A_T * A_H provides a quick estimate of the reliability in hours. In concrete terms: The values for 75 % RH (A_H=14), 100 V DC (A_u=75) and 45°C (A_T=100) result in an approximate average lifetime of 105,000 h, i.e. more than 11 years (see markings on the diagrams).

Fig. 6: The diagrams show the interdependency between the mean lifetime of a PICMA® actuator and the value of the voltage applied, the ambient temperature and the relative humidity. Important: With decreasing voltage the lifetime increases exponentially. This must always be taken into consideration in an application.
Dynamic Operation / Patented Design Reduces Stress

Dynamic Continuous Operation
Cyclic demands with a rapidly alternating electrical field and high control voltages (typically > 50 Hz; > 50 V) are common conditions for multilayer piezoelectric actuators, for example when used in valves, pumps or ultrasonic transducers.

The lifetime of the piezo element is in this case dominated by different factors to those affecting DC operation:
The impact of the dynamic forces and the changing state of the mechanical stress increases. Therefore, this can lead to the formation of cracks in the stack construction and hence to electrical discharges. The impact of the humidity, on the other hand, is negligible because it is reduced locally by the warming-up of the piezoceramic.

The most important factors affecting the lifetime are therefore the voltage and the type of the signal. In AC operation, the lifetime itself is not expressed as a time period but more sensibly as a number of cycles.

Extraordinarily Robust: 10¹⁰ Working Cycles
Due to the stability of the material behavior and their mechanical construction, PICMA® actuators exhibit no signs of wear even after many billions of load cycles (Fig. 6).

The target of 10¹⁰ working cycles is especially important for industrial use. The proof for the reliability of the PICMA® technology is obtained by means of a test with particularly high control frequency.

Preloaded PICMA® actuators with dimensions of 5 x 5 x 36 mm were loaded at room temperature and average humidity with a sinusoidal signal of 120 V unipolar voltage at 1,157 Hz. This produces 10⁸ cycles per day!
Even at this high voltage and frequency there was not a single failure and the actuators showed no significant changes in displacement.

Longer Operating Periods and Higher Control Frequencies
The dynamic operation of PICMA® piezo elements benefits significantly from the large range of operating temperatures of up to 150°C. The intrinsic warming of the elements when dynamically controlled is proportional to the operating frequency. A higher operating temperature thus also allows higher control frequencies and longer periods of operation. Additionally, the displacement of the PICMA® piezoceramics exhibits only a low dependence on temperature.
**P-882 · P-888 PICMA® Multilayer Piezo Stack Actuators**

**Ceramic-Insulated High-Power Actuators**

- Superior lifetime even under extreme conditions
- Very large operating temperature range
- High humidity resistance
- Excellent temperature stability
- High stiffness
- Peak current up to 20 A
- UHV compatible to 10⁻⁶ hPa
- Sub-millisecond response / Sub-nanometer resolution
- Ideal for dynamic operation

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**Prepared for Closed-Loop Operation**

PICMA® actuators achieve positioning resolutions in the sub-nanometer range and response times in the microsecond range. The ceramic surface of the actuators is highly suitable for mounting sensors, e.g. piezo resistive strain gauges. Due to the lack of polymer coating, the sensor can be applied directly to the ceramic of the PICMA® actuator, allowing for higher stability, linearity and measuring accuracy.

---

**Technical Data/Product Order Numbers**

<table>
<thead>
<tr>
<th>Order Numbers*</th>
<th>Dimensions A x B x L [mm]</th>
<th>Nominal Displacement [µm] ±20% (0 – 100 V)</th>
<th>Max. Displacement [µm] ±20% (0 – 120 V)</th>
<th>Blocking Force [N] (0 – 120 V)</th>
<th>Stiffness [N/µm]</th>
<th>Electrical Capacitance [µF] ±20%</th>
<th>Resonant Frequency [kHz] ±20%</th>
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</thead>
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<tr>
<td>P-882.11</td>
<td>2 x 3 x 9</td>
<td>6.5 ±20%</td>
<td>8 ±20%</td>
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<td>135</td>
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<td>18 ±10%</td>
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<td>0.31</td>
<td>70</td>
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<tr>
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<td>70</td>
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<tr>
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<tr>
<td>P-887.31</td>
<td>7 x 7 x 13.5</td>
<td>11 ±20%</td>
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<tr>
<td>P-887.51</td>
<td>7 x 7 x 18</td>
<td>15 ±10%</td>
<td>18 ±10%</td>
<td>1750</td>
<td>100</td>
<td>3.1</td>
<td>70</td>
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<tr>
<td>P-887.91</td>
<td>7 x 7 x 36</td>
<td>32 ±10%</td>
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<td>50</td>
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<td>P-888.31</td>
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<td>11 ±20%</td>
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<td>15 ±10%</td>
<td>18 ±10%</td>
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<td>200</td>
<td>6.0</td>
<td>70</td>
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<tr>
<td>P-888.91</td>
<td>10 x 10 x 36</td>
<td>32 ±10%</td>
<td>38 ±10%</td>
<td>3800</td>
<td>100</td>
<td>13.0</td>
<td>40</td>
</tr>
</tbody>
</table>

* Standard piezo ceramic type: 252
* For optional solderable contacts, change order number extension to .x0 (e.g. P-882.10)
* Recommended preload for dynamic operation: 15 MPa
* Maximum preload for constant force: 30 MPa
* Resonant frequency at 1 V pp, unloaded, free at both sides. The value is halved for unilateral clamping
* Capacitance at 1 Vpp, 1 kHz
* Operating voltage: -30 to +130 V; the lifetime depends on the voltage applied.
* Operating temperature range: -40 to +150°C
* Standard mechanical interfaces: Ceramics
* Available options: strain gauge sensors, special mechanical interfaces, etc.
* Other specifications on request.
PIEZO® Nano® Positioning

**PL112 · PL140 PICMA® Bender Actuators**

*Multilayer Piezo Bender Actuators with High Travel and Low Operating Voltage*

- Ceramic Encapsulation for Better Protection and Longer Lifetime
- Positioning Range up to 2 mm
- Fast Response (10 msec)
- Nanometer-Range Resolution
- Low Operating Voltage
- Vacuum-Compatible Versions to $10^4$ hPa
- Available with Integrated Position Sensor
- Special OEM- and Bench-Top Amplifiers Available

**Advantages**

PICMA® Bender piezo actuators offer several advantages over classic bimorph components manufactured by gluing together two ceramic plates (0.1 to 1 mm thick): faster response time and higher stiffness. The main advantage, however, is the drastically reduced (by a factor of 3 to 10) operating voltage of only 60 V. The reduced voltage allows smaller drive electronics and new applications, such as in medical equipment. Additionally, these devices offer improved humidity resistance due to the ceramic encapsulation.

**Technical Data / Product Order Numbers**

<table>
<thead>
<tr>
<th>Order number*</th>
<th>Operating voltage [V]</th>
<th>Nominal displacement [µm] ±20 %</th>
<th>Free length [mm]</th>
<th>Dimensions L x W x T [mm]</th>
<th>Blocking force [N]</th>
<th>Electrical capacitance [µF] ±20 %</th>
<th>Resonant frequency [Hz] ±20 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>PL112.10**</td>
<td>0 - 60 (±30)</td>
<td>±80</td>
<td>12</td>
<td>17.8 x 9.6 x 0.65</td>
<td>±2.0</td>
<td>2 x 1.1</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>PL122.10</td>
<td>0 - 60 (±30)</td>
<td>±250</td>
<td>22</td>
<td>25.0 x 9.6 x 0.65</td>
<td>±1.1</td>
<td>2 x 2.4</td>
<td>660</td>
</tr>
<tr>
<td>PL127.10</td>
<td>0 - 60 (±30)</td>
<td>±450</td>
<td>27</td>
<td>31.0 x 9.6 x 0.65</td>
<td>±1.0</td>
<td>2 x 3.4</td>
<td>380</td>
</tr>
<tr>
<td>PL128.10**</td>
<td>0 - 60 (±30)</td>
<td>±450</td>
<td>28</td>
<td>35.5 x 6.3 x 0.75</td>
<td>±0.5</td>
<td>2 x 1.2</td>
<td>360</td>
</tr>
<tr>
<td>PL140.10</td>
<td>0 - 60 (±30)</td>
<td>±1000</td>
<td>40</td>
<td>45.0 x 11.0 x 0.60</td>
<td>±0.5</td>
<td>2 x 4.0</td>
<td>160</td>
</tr>
</tbody>
</table>

*For optional PTFE insulated wire leads change order number extension to .x1 (e.g. PL112.11)
Operating temperature range: -20 to +85 °C;
**to +150 °C Resonant frequency at $V_{pp}$, capacitance at 1 $V_{pp}$, 1 kHz

All parameters depend on actual clamping conditions and applied load.
Ask about custom designs and further specifications.
**PL022 · PL033 · PL055 PICMA® Chip Actuators**

**Miniature Multilayer Piezo Stack Actuators**

- Superior Lifetime Even Under Extreme Conditions
- Ultra-Compact: from 2 x 2 x 2 mm
- Ideal for Dynamic Operation
- Sub-Millisecond Response
- Sub-Nanometer Resolution
- Vacuum Compatible to 10⁹ hPa
- High Humidity Resistance

**Smallest Dimensions – High Performance**

PICMA® Chip actuators sized from 2 x 2 x 2 mm are the smallest monolithic multilayer piezo stack actuators available. Providing sub-nanometer resolution and sub-millisecond response, they are ideally suited to high-level dynamic applications.

**Technical Data / Product Order Numbers**

<table>
<thead>
<tr>
<th>Order number*</th>
<th>Dimensions A x B x TH in mm</th>
<th>Nominal displacement [µm @ 100 V ±20 %]</th>
<th>Blocking force [N]</th>
<th>Electrical capacitance [nF] ±20 %</th>
<th>Resonant frequency [kHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PL022.30</td>
<td>2 x 2 x 2</td>
<td>2.2</td>
<td>&gt;120</td>
<td>25</td>
<td>&gt;300</td>
</tr>
<tr>
<td>PL033.30</td>
<td>3 x 3 x 2</td>
<td>2.2</td>
<td>&gt;300</td>
<td>50</td>
<td>&gt;300</td>
</tr>
<tr>
<td>PL055.30</td>
<td>5 x 5 x 2</td>
<td>2.2</td>
<td>&gt;500</td>
<td>250</td>
<td>&gt;300</td>
</tr>
</tbody>
</table>

* For optional PTFE insulated wire leads change order number extension to .x1 (e.g. PL022.31)

Resonant frequency at 1 Vpp, unloaded, free at both sides. The value is halved for unilateral clamping

Capacitance at 1 Vpp, 1 kHz
Operating voltage: -20 to +100 V
Operating temperature range: 150 °C
Standard electrical interfaces: Solderable pads
Other specifications on request. Recommended preload for dynamic operation: 15 MPa
Maximum preload for constant force: 30 MPa

**Application Examples**

- Static and dynamic precision positioning
- Laser tuning
- Micro-dispensing
- Metrology / Interferometry
- Life science, Biotechnology
- Photonics
PI Ceramic: Piezoelectric Actuators from PI's Piezo Division

Leaders in Piezoelectric Technology

PI Ceramic is one of the world’s market leaders for instrumentation grade piezoelectric actuators and sensors. PIC currently employs 150 staff, including 30 engineers, in piezo research, development and ceramics manufacturing. A broad range of expertise in the complex development and manufacturing process of functional ceramic components combined with state of the art equipment ensures the high quality, flexibility and adherence to supply deadlines.

Core Competences of PI Ceramic
- Standard piezo components for actuator, ultrasonic and high-power ultrasonic applications, system solutions
- Manufacturing of components of up to several 100,000 units per year
- Development of custom-engineered solutions
- High degree of flexibility in the engineering process, short lead times
- All key technologies and state of the art equipment for ceramic production available in-house
- ISO 9001-2000, ISO 14001 and OHSAS 18001 certified

PI Ceramic supplies piezo-ceramic solutions to all important high-tech markets:
- Industrial automation
- Semiconductor industry
- Medical engineering
- Mechanical and precision engineering
- Aviation and aerospace
- Automotive industry

Award-Winning PICMA® Technology: A Revolution in Durability

PICMA® piezoelectric actuators from PI Ceramic are the only monolithic, multilayer, piezoelectric actuators in the world which are completely encapsulated in a ceramic insulation layer. The patented PICMA® technology makes it possible to manufacture components with a particularly long lifetime. Decades of experience with PICMA® series in various applications show that the lifetime has been increased by at least a factor of 10 compared to previously used, conventional, polymer-coated, multilayer piezoelectric actuators.

Flexibility with a Complete Ceramic Seal

PI Ceramic can manufacture almost any shape of PICMA® multilayer piezoelectric actuator using the latest production technology. All surfaces are hereby covered with a ceramic isolation layer. Not only are variable basic shapes possible, such as round or triangular cross-sections, but also insulated internal bores on benders, chips or stack actuators, therefore making their integration easier.

Hermetic Encapsulation for the Harshest Environments

PICMA® actuators are also available in an encapsulated version. Hermetically sealed in a compact stainless steel case, these actuators resist extreme environmental conditions such as splash water or very high humidity.

Some PICMA® Applications
- Precision mechanics / precision machining
- High-speed switches
- Active and adaptive optics
- Active vibration damping
- Adaptronics, smart materials
- Pneumatic and hydraulic valves
- Metrology / interferometry
- Life science, biotechnology
- Nanotechnology

Equipment for fully automated screen printing of electrodes on piezoelectric and dielectric ceramics.
The current edition of the main PI catalog “Piezo – Nano – Positioning: Inspirations 2009” is now available. The catalog demonstrates the broad PI product range and new technical solutions in the areas of:

Nanopositioning systems/scanning systems
Fast scanning stages for microscopy
Piezo actuators
Piezo motors
Piezo controllers
Motorized micro-translation stages and linear actuators
Motor controllers
Six-axis adjustment systems, hexapods

For more information, about piezo-ceramic materials and elements see the PI Ceramic catalog or visit their website (www.piceramic.de)