N91-19212

Low Cost Space Power Generation

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Introduction

Future commercialization of space will be constrained by the high cost of energy. With photovoltaic systems costing about $1,000,000 per electrical kiloWatt, space power is far more expensive than terrestrial power. From the point of view of a potential space manufacturer, the cost of electricity is over $17 per kW-hr or 170 times greater than the terrestrial rate [ref. 1]. Even with new low cost amorphous solar cell technology (or even with zero cost cells), the cost of electrical power will remain very high. The ultimate cost for any space power system is set by transportation costs (see Figure 1).

To achieve orders of magnitude cost reductions in space power, much lighter methods of generating electricity are needed.

A new method of electrical energy generation, pyroelectric conversion, promises to deliver power from a lightweight and inexpensive system.

The advantages of the pyroelectric approach include:

▷ higher power to mass ratio than photovoltaics and even nuclear reactor systems ⇒	LOWEST LAUNCH COST,
▷ active material is a polymer⇒	LOW MATERIALS COST,
▷ all condensed state device⇒	COMPACTNESS,
▷ no pressure vessels⇒	NO EXPLOSIVE HAZARD, LOW MASS CONTAINER,
▷ no single-point failure modes⇒	RELIABLE,
▷ high voltage⇒	EFFICIENT CURRENT COLLECTION AND POWER CONDITIONING,
▷ no toxic fluids⇒	SAFE FOR ASTRONAUTS AND DEVELOPMENT ENGINEERS,
▷ resistant to ionizing radiation⇒	CAN SURVIVE VAN ALLEN BELT RADIATION,

▷ resistant to ionizing radiation⇒	CAN BE USED FOR ORBIT RAISING (e.g. LEO to GEO),
▷ pyroelectric converters can be fashioned into belt radiators⇒	BUILT-IN THERMAL RADIATOR,
▷ with a thermal storage element, pyroelectrics may eventually outperform classical electrochemical batteries⇒	ENERGY STORAGE CAPABILITY,
▷ high voltage⇒	VOLTAGE MATCHED TO ION PROPULSION, and
▷ lowest mass power generation⇒	HIGHEST ACCELERATION FOR AN ELECTRIC PROPULSION SYSTEM.

The pyroelectric approach can convert collected solar heat with an efficiency approaching the Carnot limit. Advanced pyroelectric devices appear capable of exceeding 30% efficiency with materials and device improvements.

The pyroelectric converter generates electricity as a result of thermally cycling capacitor-like elements made of a polymer which will cost about $200 per electrical kiloWatt. This cost is based on the current price of a related polymer which is already commercially available.

Even more important than its inherently low materials cost, the pyroelectric approach offers dollar savings due to its light weight. Since it costs about $3000/kg to put a payload into low earth orbit (LEO) with the Shuttle [ref. 2], systems with high specific power are strongly favored. Figure 1 shows that pyroelectric power is significantly less expensive to place in orbit than photovoltaic, solar dynamic and nuclear power.

Ignoring, for the moment, the safety and reactor cost of the nearest competitor, the pyroelectric approach will clearly be less expensive to put into orbit. The transportation cost savings of a pyroelectric system will be at least $6 million for each 100 kiloWatt system delivered to LEO (compared with nuclear). In light of the Challenger disaster, the cost of assuring the safe delivery of nuclear systems into orbit would certainly be very high. Solar driven pyroelectric systems will be lighter, cheaper to manufacture and less expensive to develop.

When compared with photovoltaics, the pyroelectric approach will save 45 to 87 million dollars in delivery costs per 100 kW system.

Pyroelectric conversion represents an unusual opportunity for advanced power systems. It can provide energy storage, Carnot-limited conversion (heat to electricity), and thermal rejection. Furthermore the pyroelectric approach can provide these functions at very low specific mass and low cost.

In its simplest version, a pyroelectric converter can take the form of a rotating cylinder as shown in Figure 2. A given segment of the cylinder will alternately rotate into and out of the direct sunlight. As a result, the temperature of the segment will rise and fall during each revolution. If an externally applied voltage is raised and lowered in the appropriate phase relation to the temperature oscillation, a substantial amount of electrical power may be produced. Please refer to NASA CR-168727 for more information [ref. 3].

Pyroelectric conversion is a very promising method of making electricity in space (or on Earth). However, present pyroelectric technology must be developed before the promise can be realized. Several fundamental physical and chemical questions have already been successfully addressed.

Perhaps the most important fundamental question remaining regards the lifetime of the active polymer. These new materials had never been studied for more than a few hours of continuous thermal-electrical cycling.

Our objective was to quantify the long term stability of the energy conversion capabilities of a specific pyroelectric copolymer. We measured the thermally induced changes in the electric displacement of the copolymer vinylidene fluoride-trifluoroethylene [P(VDF-TrFE), 60% mol VDF].

We fabricated test specimens from extruded copolymer films and performed thermal-electrical cycling measurements. More specifically, we measured the effects of repetitive thermal and electrical cycling on the electrical polarization and energy density of the copolymer at elevated temperatures (20 up to 100°C).

Fundamentals of Pyroelectric Conversion

The pyroelectric effect is the flow of charge to and from the surfaces of a material resulting from a change in temperature [ref. 4]. This effect may be used for the conversion of heat directly into electrical energy. A pyroelectric converter is a form of heat engine. The thermodynamics of the pyroelectric converter are analogous to the more familiar steam engine with pressure-volume mechanical work replaced by voltage-charge electrical output.

The basic pyroelectric principle is illustrated in Figures 3 and 4. A pyroelectric material is formed into a thin film (shown edge-on in the figures) and sandwiched between two metallic electrodes to form a capacitor-like structure. At low temperature (below the Curie point), the electric dipoles of the pyroelectric material may be easily ordered or polarized by a low applied voltage.

Figure 4 shows that when the ordered pyroelectric slab is heated above its Curie temperature, the electric dipoles become thermally disordered. This causes the voltage on the electrodes to increase dramatically. If the slab electrodes are connected across a load, the high voltage forces the charge to flow through the load. The result

of heating the pyroelectric capacitor is to produce a high-voltage direct-current surge. The current flows only for a short time (the heating period of the slab). To produce more electrical power, the pyroelectric slab must be cooled, re-polarized and then re-heated. Each thermal cycle creates additional electrical energy from heat.

Pyroelectric Conversion Cycle

Figure 5 shows an overlay of the charge-voltage (electric displacement versus electric field) characteristics of a polymer pyroelectric material at two different temperatures. The shaded area of Figure 5 is a pyroelectric conversion cycle, and represents the electrical energy produced in the conversion process. The cycle is an electrical analog of the Ericsson heat engine cycle. It consists of two isothermal portions and two isostress (isoelectrical field) portions. Details of this and other cycles have been presented previously [refs. 5-7].

Poly(vinylidene fluoride-trifluoroethylene), P(VDF-TrFE), was chosen for study because it is the highest performance pyroelectric conversion material known.

Results and Discussion

Figure 8 shows a typical power cycle. Beginning at point 1 in the cold bath at low temperature and low electric field, the electric field was increased isothermally in approximately 1 second to a high value, which resulted in an increased displacement. When the high electric field was reached (point 2), the temperature of the sample was increased by moving it into the hot bath. This resulted in partial thermal depoling of the sample. When the thermal depoling stopped (point 3), the electric field was decreased to its original low value (point 4). Finally, the sample was cooled by moving it into the cold bath which caused the displacement to increase. The cycle was completed when the sample was cooled to its original low temperature (point 5). The apparent difference in displacement between point 5 and point 1 resulted from electrical conduction through the sample during the cycle.

Figure 8 also defines three quantities which describe a power cycle. The depoling displacement change is defined by the warming isofield line from point 2 to point 3. The repoling displacement change is defined by the cooling isofield line from point 4 to point 5. The conduction charge (per unit area) is given by the distance from point 1 to point 5.

To compare the durability of the strengthened samples with unenhanced samples, a pyroelectric power cycle test was applied to both types of specimens. After hysteresis poling (5 cycles), each sample was subjected to thermal cycling between room temperature and 100°C, while simultaneously electrically cycling between 20 and 50 MV/m.

In the case of the unstrengthened samples, no specimen survived more than 10 thermal-electrical cycles before suffering dielectric failure. The lifetime performance of the enhanced samples was dramatically improved. In spite of 24 hours of continuous power cycling, the strengthened sample (Sample A) was still producing electrical power as if it were new. After producing over 13,000 cycles, the power cycling experiment was halted without notable decrease in performance. The lifetime enhancement was a factor of at least 1,300 over the unstrengthened specimens.

Prior to this time, we had never encountered extended lifetime performance at such high electric fields (even with compression molded films). Due to the exceptional performance of these films we decided to try a higher frequency electrical test. We applied 60 Hz electrical cycling to provide many more electrical cycles in a short period of time.

Sample A was then subjected to 60 Hz unipolar voltage (10 to 40 MV/m) at 100°C. After 15 hours of high frequency cycling (3,240,000 cycles) the sample was subjected to power cycling and showed essentially the same displacement change performance as before. This sequence is illustrated in Figure 9.

Next, Sample A was subjected to 60 Hz unipolar voltage (10 to 60 MV/m) at 100°C. After 1 hour of high frequency cycling at this higher electric field, the sample's electrical properties were unaffected. Following a second hour of high frequency (V_{max} = 60 MV/m) cycling, the displacement changes measured in power cycles were found to have been reduced to 2/3 of their original values. This reduction was explained by 1/3 of the specimen becoming electrically disconnected (which agreed with visual observation). After being subjected to 2 more hours of high frequency cycling under these conditions, the sample remained stable.

Sample A was then subjected to 60 Hz unipolar voltage (10 to 70 MV/m) at 100°C. After 2 hours of high frequency cycling to this electric field, the sample's electrical properties were unaffected.

Finally, Sample A was subjected to 60 Hz unipolar voltage (10 to 80 MV/m) at 100°C. After 1 hour of high frequency cycling to 80 MV/m, degradation of the sample's electrical properties were found. The displacement changes had dropped to 25% of their original values. This reduction was explained by 3/4 of the specimen becoming electrically disconnected (again consistent with visual observation - the sample resembled a very highly pocked and cratered lunar surface). At this point the test was terminated.

It is important to note that the specimen degraded only after being subjected to voltages (3500 to 4000 V) which were in excess of the A.C. corona inception voltage (3000 V). Furthermore, the sample degradation appeared to be corona dominated (electrode edges were eroded by the corona process). If the maximum voltage is maintained below the corona inception voltage, this degradation pathway can be minimized if not completely eliminated.

A second sample (Sample B) from the B run was then studied. This sample was subjected to 16 hours of nonstop power cycling (thermal cycling between room temperature and 100°C, while simultaneously electrically cycling between 20 and 50 MV/m). No decrease in pyroelectric performance was detected.

Sample B was then subjected to 60 Hz unipolar voltage (10 to 40 MV/m) at 100°C. After 22 hours of high frequency cycling (4,752,000 cycles) the sample was subjected to power cycling and showed essentially the same displacement change performance as before. This sequence is illustrated in Figure 8.

The upper field limit was raised to 50 MV/m and 60 Hz cycling restarted. The sample was electrically and visually monitored for an additional 12 days. After a total of more than 67 million electrical cycles at 100°C, the electrical properties remained stable. The test was terminated to allow for other experiments. This test ended with no decrease in the pyroelectric performance of the specimen.

A third sample (Sample C) survived an even longer duration test. Sample C was subjected to simultaneous 60 Hz electrical cycling (20 to 30 MV/m) and thermal cycling (35 to 100°C) for 24 hours and showed no decrease in energy output.

Due to safety concerns, the 60 Hz cycling for Sample C was performed at room temperature [ref. 8]. After 1800 hours of continuous 60 Hz cycling, Sample C still provided full pyroelectric energy density when interrupted for an energy production test. The corresponding number of electrical cycles has already exceeded 388 million. We are preparing a dedicated chamber to allow this test to continue beyond the present study.

Summary and Conclusions

The success of this study has given us a method of fabricating durable copolymer films without size limitations. Previously, only compression molded samples (of a few cm^2 in area) were durable enough to generate electrical energy.

The strengthened specimens are very long lived materials. The lifetime was enhanced at least a factor of 1,300 in full pyroelectric conversion cycle experiments compared with extruded, non-strengthened film. The new technique proved so successful that we were not able to fully characterize the lifetime of the resultant copolymer samples.

The lifetime of these new materials is so long that we had to devise accelerated tests to probe their durability. After a total of more than 67 million high voltage electrical cycles at 100° C, the electrical properties of a copolymer sample remained stable. The test was terminated without any detectable degradation to allow for other experiments. One must be cautious in extrapolating to power cycle performance, but 67 million electrical cycles correspond to 2 years of pyroelectric cycling at 1 Hz.

In another series of experiments at reduced temperature and electrical stress, a specimen survived over one-third of a billion electrical cycles during nearly three months of continuous testing.

The radiation-limited lifetimes of the copolymer have been shown to range from several years to millions of years for most earth orbits [ref. 9]. Thus, the pyroelectric copolymer has become a strong candidate for serious consideration for future spacecraft power systems.

References

[1.] Assuming a 10 year lifetime and 5% interest, the annual cost per kiloWatt would be $100,000 for amortization and $50,000 for interest. Since there are 8760 hours in a year, the hourly cost would be $150,000/8760 = $17.12/kW-hr. Terrestrial electrical rates vary, but are of the order of $0.10/kW-hr.

[2.] D. Denais, private communication and Johnson Space Center, July, 1986.

[3.] R. B. Olsen, NASA CR 168272 , 1983.

[4.] M. E. Lines and A. M. Glass, "Principles and Applications of Ferroelectrics and Related Materials", Clarendon, Oxford, 1977.

[5.] R. B. Olsen and D. Evans, J. Appl. Phys **54**, 5941, 1983.

[6.] R. B. Olsen, D. A. Bruno, J. M. Briscoe and E. W. Jacobs, J. Appl. Phys. **57**, 5036, 1985.

[7.] R. B. Olsen, D. A. Bruno and J. M. Briscoe, J. Appl. Phys. **58**, 4709, 1985.

[8.] Our concern was that a thermocouple failure or a heat controller glitch could cause a fire during the long unattended experiment.

[9.] R. B. Olsen, NASA SBIR Phase I Report NAS7-946, 1986.

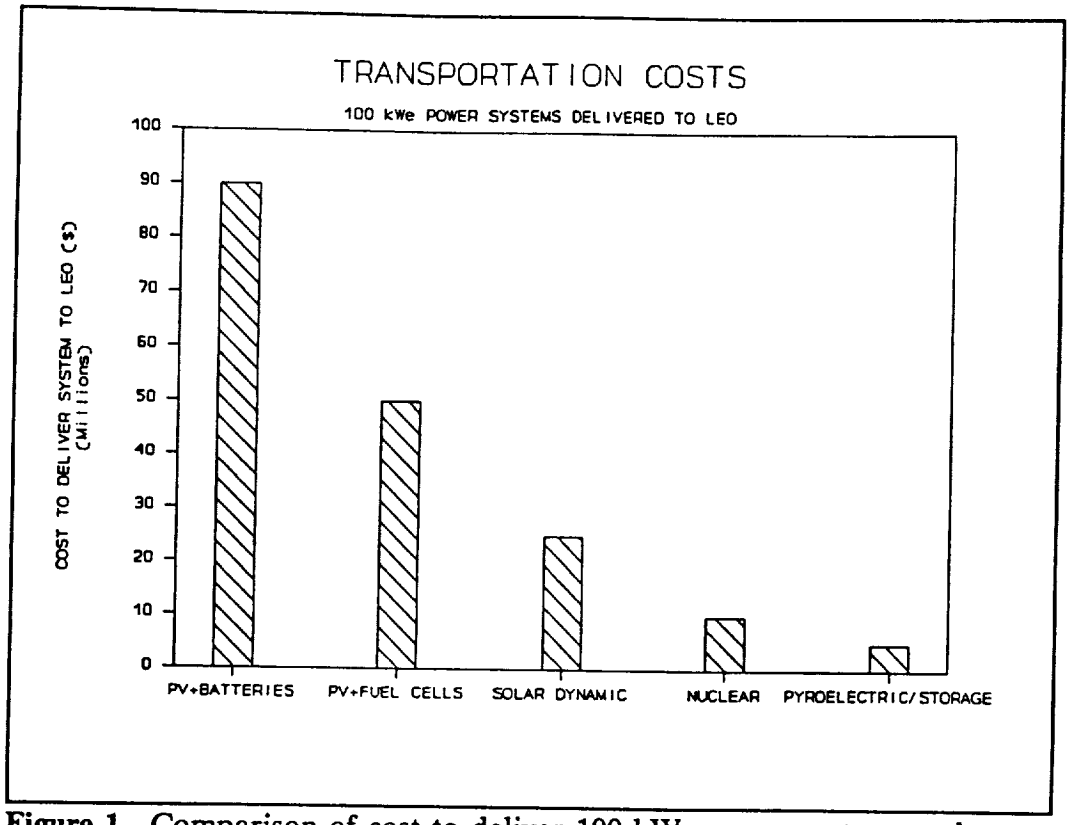

Figure 1. Comparison of cost to deliver 100 kWe power systems to low Earth orbit.

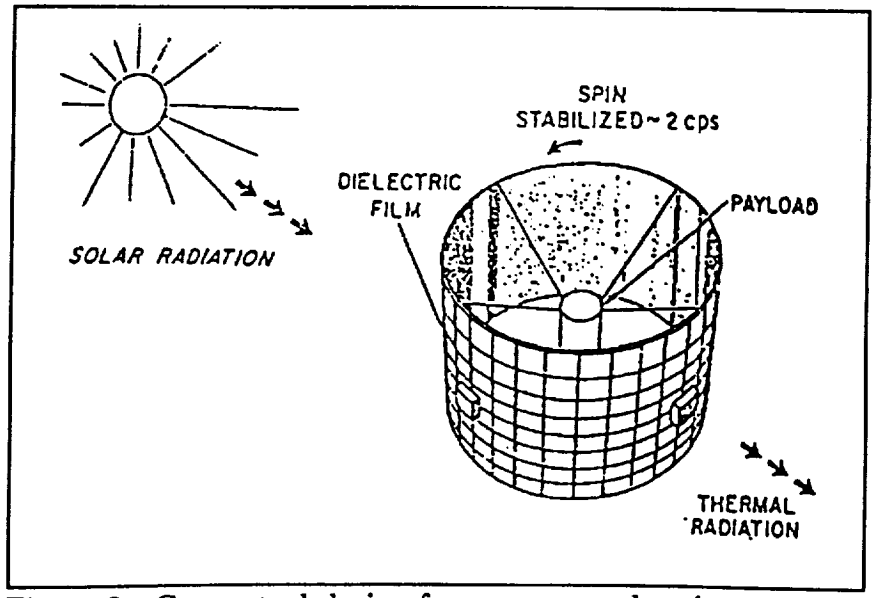

Figure 2. Conceptual design for space pyroelectric converter.

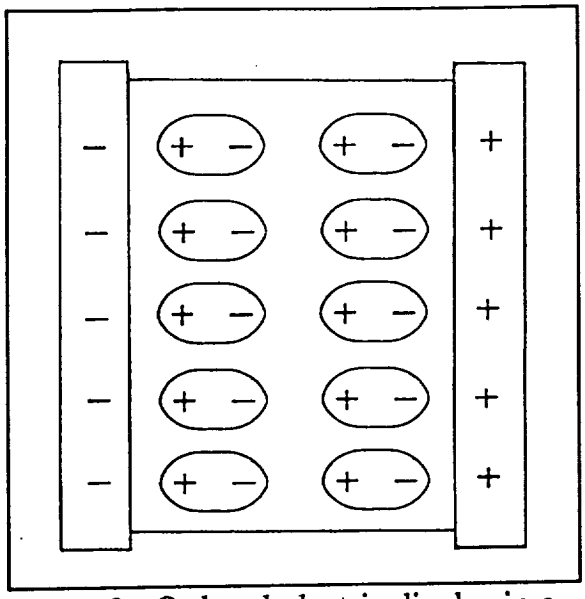

Figure 3. Ordered electric dipoles in a pyroelectric at low temperature.

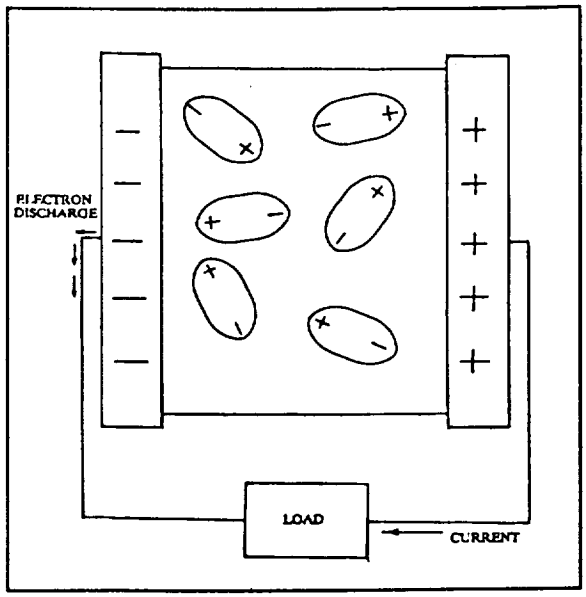

Figure 4. Heating the pyroelectric disorders the dipoles. This drives charge through a load at high voltage.

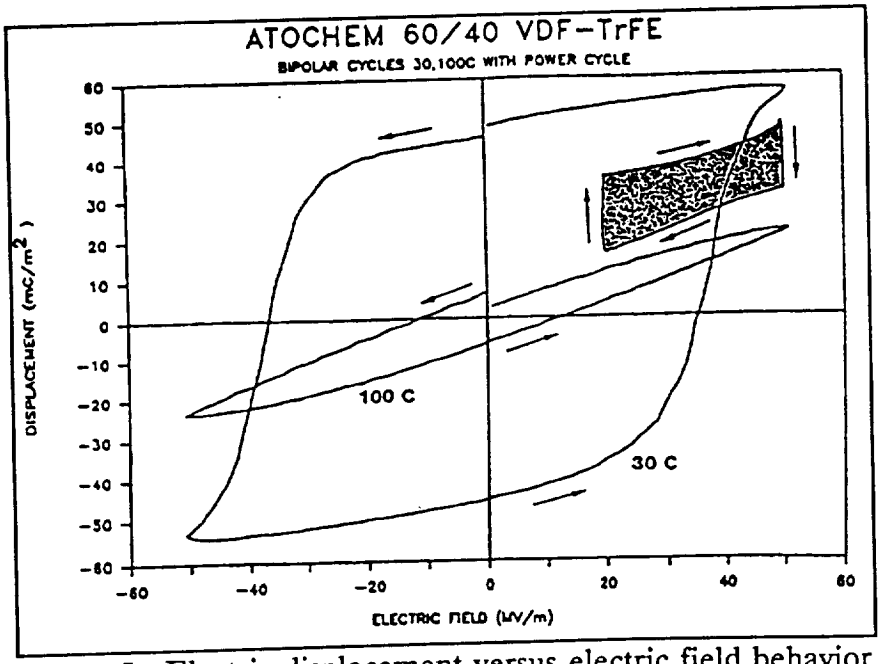

Figure 5. Electric displacement versus electric field behavior of a 60/40 mol % copolymer of vinylidene fluoride and trifluoroethylene.

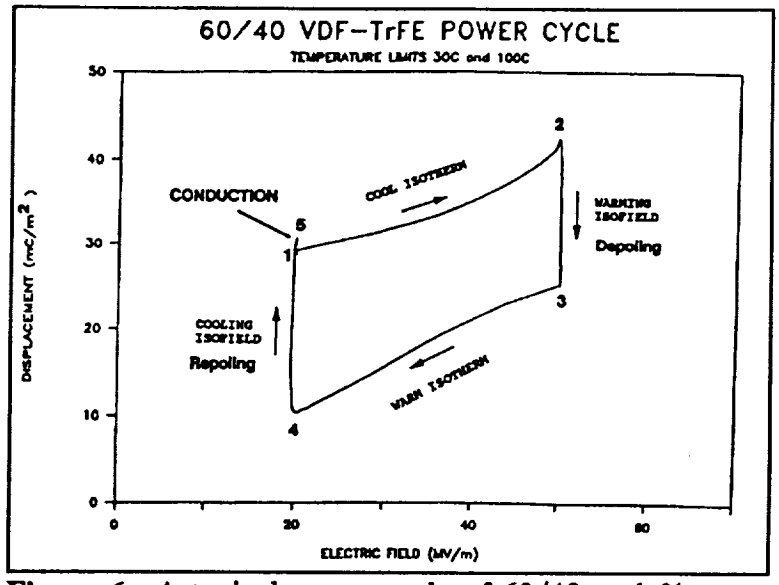

Figure 6. A typical power cycle of 60/40 mol % P(VDF-TrFE). The temperature extremes were 30 and 100°C.

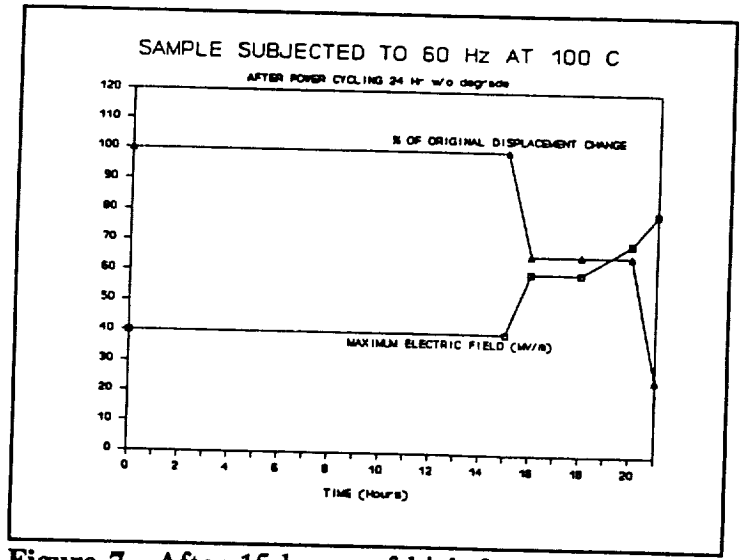

Figure 7. After 15 hours of high frequency cycling, Sample A displayed little change in displacement performance.

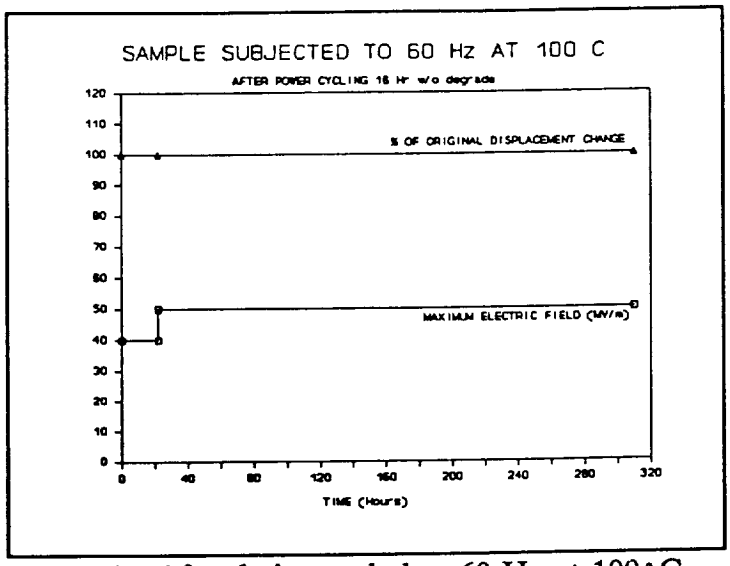

Figure 8. After being cycled at 60 Hz at 100 °C for more than 300 hours, Sample B exhibited undiminished pyroelectric properties.

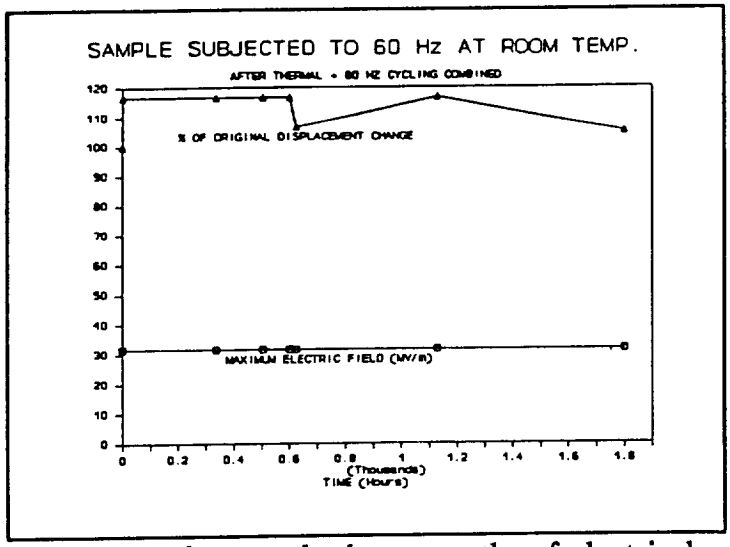

Figure 9. After nearly three months of electrical cycling, sample C exhibited very little degradation in performance.

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