Electrical Power Generation From Electrostrictive Polymers For Autonomous Distributed Systems

(Annual Report Submitted October 29, 1999)

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Contract Number: N00014-98-C-0274
Start Date: 31 July 1998
ftp.onr.navy.mil/dept/32/322om

LONG-TERM GOALS

There is an ever-growing military, scientific and commercial need to establish Autonomous Distributed Systems (ADS) for studying and measuring oceanographic, atmospheric and other data in the littoral regions of the world. The long-term goal of this program is to develop an electrical power supply for these applications that is reliable and easy to operate, has a long maintenance-free operating life, and is as low cost as possible. An ideal system for meeting these goals is to have a power generation system that directly converts the mechanical energy in waves and currents into electricity. This electrical energy, scavenged from the ocean environment, can then be used to directly power or to recharge the batteries of the components in the ADS.

The successful completion of the program will provide remote electric power generating equipment for water based military and civilian applications having capacities of a few watts to hundreds of kW. Based on unique piezoelectric and electrostrictive polymers, the generators require no fuel and produce no emissions. Battery recharging stations for autonomous underwater vehicles and undersea sensor networks will have their mission duration capability extended for years. Long lived oceanographic data collection systems will be possible for weather prediction and environmental monitoring.

OBJECTIVES

The program will focus in detail on electrostrictive device fabrication techniques for high reliability operation under large mechanical stress in high voltage, high power electronic circuits. It is expected that the electrostrictive polymers will have low mechanical and electrical losses and that this will result in the electrostrictive generator having a mechanical to electrical energy conversion efficiency in the range 50% to 75%, i.e., two to three times greater than that presently achievable with a piezoelectric PVDF generator. The new electrostrictive generator is expected to be physically smaller and less expensive to manufacture.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **29 OCT 1999**	2. REPORT TYPE	3. DATES COVERED **00-00-1999 to 00-00-1999**

4. TITLE AND SUBTITLE **Electrical Power Generation From Electrostrictive Polymers For Autonomous Distributed Systems**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Ocean Power Technologies, Inc.,1590 Reed Road,Pennington,NJ,08534**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**5**	

The Program's technical objectives will be to continue polymer materials development, demonstrate the power capabilities of the selected polymers and power conversion electronics, and demonstrate a complete generator in laboratory operation:

- Demonstrate a two to three fold performance gain with irradiated PVDF:TrFE polymers, operated as electric field induced piezoelectrics (electrostrictives), over PVDF in an OPT AUV recharging generator operating in the laboratory.
- Work will be continued in parallel to develop electrostrictive Silicone as a higher performance replacement for PVDF:TrFE. The material has a very high resistivity and breakdown field, facilitating extrodinary values for k^2 (electromechanical conversion efficiency). Silicone is very fragile and will be evaluated against PVDF:TrFE as a practical generating element.

The Phase II Option's technical objective will be to demonstrate an OPT AUV laboratory generator operating in a mission power profile selected by the Navy Program Manager.

APPROACH

Ocean Power Technologies, Inc. (OPT), expert in ocean power extraction, and the Materials Research Laboratory (MRL) of Pennsylvania State University, expert in piezoelectric materials, have teamed in this program to investigate the use of the electrostrictive polymer Silicone and PVDF:TrFE copolymer as a superior alternative to commercial piezoelectric PVDF for use in OPT's wave power generation systems.

The proposed program is planned to flow from development and demonstration of the technology for each component of an OPT generator to the demonstration of a fully functional generator operating in the electrical load profile of a Navy selected AUV application.

The OPT and MRL team began the program with a design review of the small laboratory generator test section concept that was developed in Phase I.

OPT fabricated the small test generator mechanical structure and power conversion electronics. MRL aided by Measurement Specialties Inc. (MSI) has fabricated several PVDF:TrFE elements required for testing and are currently annealing larger samples for the larger generator. OPT has found the help of SRI International in supplying a number of small silicone samples for comparison against PVDF:TrFE. MSI had been utilized to provide polymer electroding services with carbon based materials and the electrical connection system, that can withstand high strain levels. Future PVDF:TrFE samples will be electroded by MRL with a non-solvent based electrode as the solvent has been found to attck the irradiated PVDF:TrFE samples. The test unit was assembled and put into operation at OPT.

The small test generator system has been operated through a range of frequencies and strains. Tests have shown in both PVDF:TrFE and Silicone that the DC leakage through the material is negligible as both materials have high resistivities. Polyurethane was previously eliminated as an immediate option due to its relatively low level of resistivity. The generating elements have been limited to single layers in order to correlate the results with those obtained in the Phase I Option. PVDF:TrFE and Silicone elements are being evaluated to allow a choice to be made as to the best overall material for this application. Multi-layer elements will be used shortly. They will have higher capacitance which is preferable for the switched resonant circuit operation. The multi-layer elements will provide the opportunity to address issues that arise from higher power output levels, electrical lead attachment, heat transfer, and reliability. A key result of this testing will be quantifying the amount of electrical and mechanical losses in the material. The tests will be conducted at OPT, and will use OPT's resonant electronics approach as well as matched resistive loads. Based on the results, the larger generating system will be employed with the optimal material. The laboratory prototype generator will be tested and demonstrated, and its performance and reliability recorded. Problems will be addressed immediately to obtain the best performance.

WORK COMPLETED

Testing has characterized the transverse strain as a function of electric field for the irradiated 50:50 and 70:30 molecular ratio PVDF:TrFE copolymer. Results reveal the copolymer has a high field capability, resisting breakdown through 175 MV/m (breakdown of dry air occurs at 3 MV/m). The result is very encouraging as the efficiency of the material, k^2, goes as the bias field squared.

In the 70:30 copolymer d_{31}, the coefficient associated with electro-mechanical coupling, was found to be 200 pC/N by plotting the induced strain vs. bias field over the wide range of bias field. The magnitude of d_{31} is determined by computing the slope of the quasi-linear section of the strain vs. bias field curve, where the magnitude is assumed to go linearly with bias field. The value of d_{31} is slightly lower than expected in a copolymer completely transformed into the Relaxor phase.

The dielectric hysteresis is not fully eliminated by irradiation as evidenced by the experimental irradiation treatments. The best experimental irradiation treatment occurs at 60 Mrads at 105°C. Although the dielectric hysteresis loop narrows quite significantly from its pre-irradiation state, some dielectric hysteresis remains. The results reveal that the Relaxor phase is still not optimally induced. Although the 70:30 copolymer is the most commercially readily available, the composition is currently difficult to induce into the Relaxor phase.

More recent testing at PSU has concentrated on the 50:50 copolymer to see how easily the relaxor response could be induced. The tests were conducted on the SOLVAY (Belgium) material that was recently irradiated at PSU after extrusion and stretching by MSI. The results indicate, as expected, that the 50:50 copolymer does not require as high of a radiation dosage or temperature as the 70:30 copolymer to begin transformation into the relaxor phase.

It has been recognized that the efforts to increase d_{31} also weaken the material in the crosswise (2) direction due to the high orientation in the lengthwise (1) direction. To alleviate the crosswise brittleness while still maintaining the high level of crystallinity MSI conducted a test consisting of various annealing conditions. The results reveal that annealing at higher temperatures results in higher percentages of crystalline growth, similarly increasing the exposure time increases both the size and percentage of the crystals. Large crystal sizes correspond to brittle materials. In an attempt at producing the optimum several different temperatures were examined against exposure time. Free annealing was also examined vs. annealing under tension.

RESULTS

The summary conclusions of work performed to date are:

For the studied samples of 50:50 PVDF:TrFE at fields above 60 MV/m where the slope of the strain vs. bias field is quasi-linear the d_{31} values are encouraging,187 pC/N at a bias field of 80 MV/m, reaching almost the same value of d_{31} for a lower bias field than in the 70:30. d_{31} increases linearly with bias field. Although the level of the d_{31} is still slightly lower than optimal, it is significantly closer to a complete transformation into the Relaxor phase.

To achieve optimal electromechanical coupling in the copolymer the material must be stretched and annealed to orient the crystalline chain and increase crystallinty respectively prior to irradiation. Due to the high orientation of the crystalline structure is in the lengthwise (1) direction the structure is fairly weak in the crosswise (2) direction. The optimal crystal growth, structurally, of the 50:50 copolymer coincides with an annealing temperature of 110 °C for 60 minutes under light tension. It is expected that samples irradiated under this annealing condition will be the most mechanically feasible.

The irradiated copolymer appears to be particularly sensitive to the solvents in the Carbon electrodes currently used by MSI. Future testing will be confined to non-solvent electrodes to avoid the resulting failures.

Silicone samples have been supplied by SRI International to be tested alongside the irradiated coplymer. The samples appear extremely promising in achieving high values of k^2, although they will have a lower energy density (J/m^3). Initial testing was conducted using a copper wire as a connection to the electrodes. The wire, rubbing along the top surface of the electrodes, quickly wore a hole through the material. The alternative is to bring a portion of the electrode to the edge of the material and connecting directly. This method of connecting to the electrodes is mechanically sound, but the power must travel through a higher resistance to extraction. Future testing will be carried out this way until a lower resistance, mechanically sound alternative is formed.

Polyurethane's resistivity has been revealed as too low for practical operation as an electrostrictive generator. The power required to maintain a bias field would be of the same order as power generated. Tests have been conducted to construct a silicone/polyurethane composite to achieve higher values of resistivity than polyurethane and structurally stronger than silicone. The composite has high values for electromechanical coupling, as do both materials alone, but current compositions do not have practical levels for resistivity.

IMPACT/APPLICATIONS

Upon successful completion of this program, OPT will be positioned to sell its electric power generating equipment for water-based government and private sector applications having capacities of a few watts to many kilowatts. That breadth of power capacity, coupled with the following key advantages of OPT's power system, presents a significant opportunity:

- The "solid state" nature of the electrostrictive materials is highly resistant to salt-air and other corrosive effects, and can withstand a wide range of temperature.
- The generators require no fuel and produce no emissions.
- Significantly higher duty cycle than wind and solar (photovoltaic).
- OPT's systems will operate at high efficiency, with small size, and are efficient at low and variable speed.

- If the technical goals of the Program are achieved, OPT estimates that electrical power for small, secondary power applications (1 watt to 1 kilowatt) will be in the range of 7¢ - 10¢ per kilowatt hour, including capital, operating and maintenance costs. This compares very favorably to diesel power (25¢ - 100¢ per kWh, depending on location), solar/photovoltaic power (25¢ - 75¢ per kWh), and wind power (10¢ - 30¢ per kWh).

The successful development of generators utilizing electric field induced piezoelectric polymers has important applications including the following:

(a) For overt surface deployed and covert sub-surface deployed power generation:
- Tether points for local recharging of underwater equipment such as AUV's for application within the Autonomous Oceanographic Sampling Network.
- Visual, radio, radar interactive channel markers for follow-up landings where harbor infrastructure facilities are unavailable or destroyed.
- Long-live hydrophone arrays or other data acquisition sensors, including undersea sensor networks, sonar buoys and weather reporting buoys.
- Power for coastal defense networks, islands or remote coastal locations.

(b) For high current flow situations, the generator can be re-configured to generate power under the surface for similar functions as above.
(c) 10 to 200 watts generators for powering lights and horns for aids to navigation for the U.S. Coast Guard.
(d) Power for oceanographic research sensor and data communication.
(e) Power for aquaculture (fish farming) installations.

TRANSITIONS

MRL is the leading research institute in the U.S. on piezoelectric and electrostrictive materials. This research covers single crystals, ceramics, thin films and polymers. Significant in terms of related work to this program is that MRL is investigating the properties of the electrostrictive PVDF:TrFE for use in actuators, i.e., the reciprocal application to generators.

RELATED PROJECTS

Under its current development program, OPT has worked on the construction of prototype power generating systems based on both electromagnetic technology and the piezoelectric polymer PVDF. OPT has also had (i) a Phase I and Phase II SBIR Contract from Office of Naval Research to investigate the feasibility of an OPT Generator located either at or below the surface to provide up to 1 kW of power to recharge the batteries of Autonomous Underwater Vehicles; (ii) OPT has received the Phase II option contract for the AUV program to deploy and test a 1 kW surface system in the ocean; (iii) OPT, with Princeton University, Pennsylvania State University and Autonomous Underwater Systems, Inc., and Cambridge Advanced Technologies and Simulations, is working on a contract for the generation of electrical power from the flow energy of water (rather than ocean waves), using eel-like generating system structures made from piezoelectric polymers.