MORE

Micro Ocean Renewable Energy

Harvesting ocean kinetic energy to power sonobuoys, navigational aids, weather buoys, emergency rescue devices, domain awareness sensors and fishery devices

a Small Business Innovative Research proposal

submitted to:

The Naval Air Systems Command
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submitted by:

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Table of Contents

Figures and Tables

Background

The U.S. Navy spends over $100 million annually on sonobuoys to increase our undersea domain awareness. The AN/SSQ-101 Air Deployable Active Receiver is the most capable sonobuoy the Navy has ever deployed, yet it costs over $5k per unit and has a maximum operating life of only 8 hours. The Naval Air Systems Command (NAVAIR) has issued a Small Business Innovative Research (SBIR) solicitation for energy harvesting devices that could be fitted to the AN/SSQ-101. Mark Krawczewicz of Tocreo Labs and Eric Greene of Eric Greene Associates, Inc. have teamed to develop novel ocean kinetic energy harvesting techniques for sonobuoys and other floating electronic systems. Mr. Krawczewicz has over 25 of experience developing advanced electronic systems for the National Security Agency and private industry. Eric Greene Associates has conducted R & D for the U.S. Navy and commercial clients since 1988. We view this SBIR project as an opportunity to utilize a variety of emerging U.S. technologies to pioneer the field of Micro Ocean Renewable Energy.

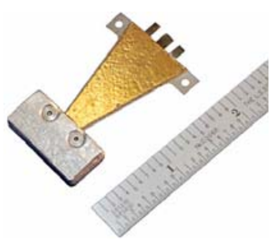
Abstract

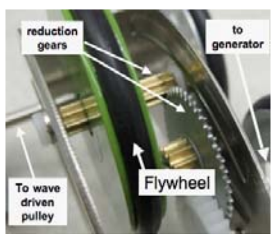
The AN/SSQ-101 Air Deployable Active Receiver (ADAR) sonobuoy has evolved as a vital Anti-Submarine Warfare (ASW) tool, with the ability to deploy a sophisticated hydrophone array from a single A-size canister. We are proposing the evaluation, modeling, simulation, and characterization of three kinetic energy harvesting technologies:

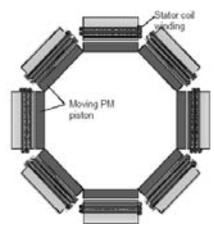
1. Piezo-Ceramic Device – utilizes a newly-developed ruggedized laminated piezo (RLP) device as the “micro-power” solution to convert relative wave motion to electrical energy. RLP is a mechanically simple design accommodated into a small volume.

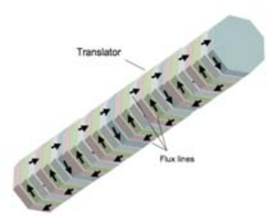
2. Rotary Magnetic Generator – a traditional rotary geometry micro-generator with an innovative mechanism to continually spin the generator from the low frequency waves.

3. Linear Magnetic Generator – a novel magnet/coil device that can be deployed from the AN/SSQ-101.









Anticipated Benefits

There is significant opportunity to utilize emerging micro-energy harvesting, battery & power management and advanced manufacturing technologies developed in the U.S. for extended mission sonobuoys.

The current AN/SSQ-101 seawater battery system makes it prohibitive for consideration of any uses beyond anti-submarine warfare. However, if we could drastically reduce the cost of the battery system and significantly extend mission endurance, this or a sonobuoy of similar design would be viable to monitor marine mammal migration, port security and seismic activity. Micro Ocean Energy (MOE) harvesting could also be attractive for lighted navigational buoys, weather buoys, as well as fish trap, lobster & crab pot markers. As our waterways become more populated, there is an increased need to illuminate and send data from anchored systems.

We also see the potential to drastically extend the operational life of emergency position indicating radiobeacons (EPIRBs), which are designed to save the lives of seafarers who get into trouble by alerting rescue authorities and indicating their location. MOE may also be adaptable to “black boxes” on ships and airplanes, allowing for longer recovery windows.

Keywords

sonobuoys, ocean energy harvesting, kinetic wave energy, ruggedized laminated piezo devices, rotary magnetic generator, linear magnetic generator

Identification and Significance of the Problem or Opportunity

The AN/SSQ-101 Air Deployable Active Receiver (ADAR) sonobuoy has been systematically refined and re-engineered over 65 years to become a mainstay and exemplary performing component of the U.S. Navy.

"With the proliferation of advanced diesel-electric technology, open access to submarines on the free market, and continued advances in other navies' forces [ref. 1]", ADAR sonobuoys have evolved as a vital Anti-Submarine Warfare (ASW) tool, with the ability to deploy a sophisticated hydrophone array from a single "A-size" canister. However, the state-of-the-art battery technology and power requirements of the AN/SSQ-101 results in an upper operational limit of 8 hours, after which aircraft need to "reseed" the area with replacement sonobuoys. Developing a renewable energy extraction device that could exploit the sonobuoy's environment will dramatically increase its operational endurance and reduce the payload weight and environmental issues associated with the current power supply.

The challenge presented by the "A-size" sonobuoy energy harvesting requirements are the limited volume available in the deployment canister; power requirements of the sonobuoy electronics, especially the transmitter; and the need to develop a device that is reliable over a range of environmental conditions. The satellite industry has developed clever solar panel arrays that are very lightweight and deploy from small packages. However, an ocean-based deployment of such a system would not be viable over a range of sea state conditions and the system would only be effective under ideal sunlight conditions.

OTEC power plants and autonomous underwater vehicles (AUVs) that traverse ocean thermoclines utilize temperature differences to generate power, but there is no "compact" way to deploy such a system from the "A-size" envelope. The same is true for thermoelectric arrays designed to make use of the difference between air and sea temperature. Extracting kinetic energy from environmental wave action appears to be the most viable form of energy harvesting for sonobuoys. Figure 1 shows the average global significant wave height, illustrating the potential for kinetic wave energy harvesting [ref. 2]. Note that the vast majority of the world's oceans experience conditions between Sea State 2 and 4.

Wind Speed (Kts)	Sea State	Significant Wave Height (Ft)	Significant Range of Periods (Sec)	Average Period (Sec)	Avg Wave Freq (Hz)	Average Length of Waves (FT)
3	0	<.5	<.5 - 1	0.5	2.000	1.5
4	0	<.5	.5 - 1	1	1.000	2
5	1	0.5	1 - 2.5	1.5	0.667	9.5
7	1	1	1 - 3.5	2	0.500	13
8	1	1	1 - 4	2	0.500	16
9	2	1.5	1.5 - 4	2.5	0.400	20
10	2	2	1.5 - 5	3	0.333	26
11	2.5	2.5	1.5 - 5.5	3	0.333	33
13	2.5	3	2 - 6	3.5	0.286	39.5
14	3	3.5	2 - 6.5	3.5	0.286	46
15	3	4	2 - 7	4	0.250	52.5
16	3.5	4.5	2.5 - 7	4	0.250	59
17	3.5	5	2.5 - 7.5	4.5	0.222	65.5
18	4	6	2.5 - 8.5	5	0.200	79
19	4	7	3 - 9	5	0.200	92
20	4	7.5	3 - 9.5	5.5	0.182	99
21	5	8	3 - 10	5.5	0.182	105
22	5	9	3.5 - 10.5	6	0.167	118
23	5	10	3.5 - 11	6	0.167	131.5
25	5	12	4 - 12	7	0.143	157.5
27	6	14	4 - 13	7.5	0.133	184
29	6	16	4.5 - 13.5	8	0.125	210
31	6	18	4.5 - 14.5	8.5	0.118	236.5

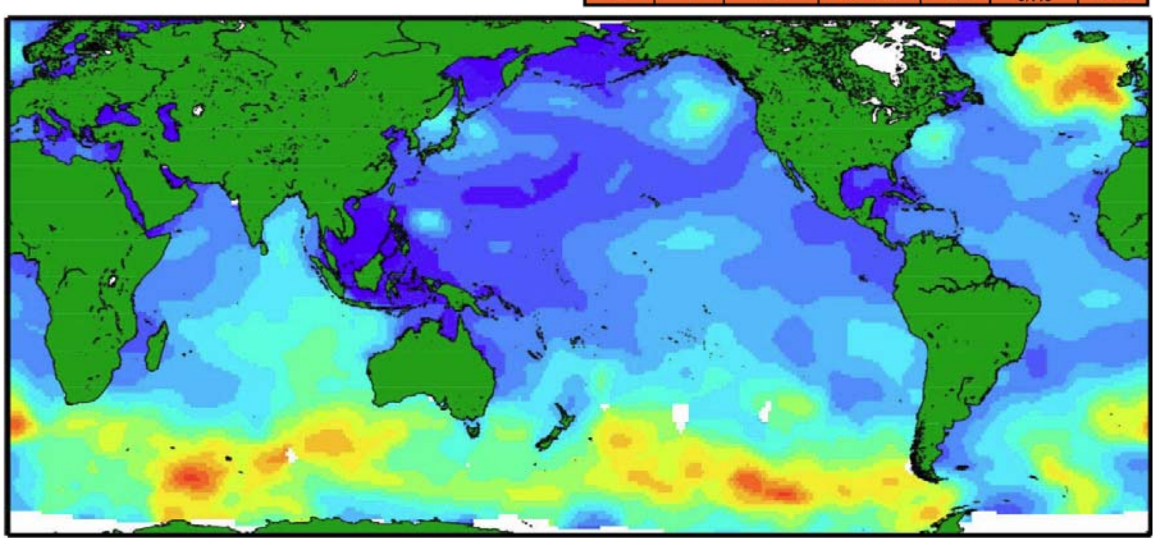


Figure 1. Sea State Wave Characteristics and Average Global Distribution

The renewable energy community is beginning to realize the potential of ocean wave energy to make a significant electrical energy contribution. Indeed, it has been estimated that the territorial waters of the U.S. have the potential to generate 260 tetra watt-hours per year (6.5% of the total annual U.S. requirement) if energy capture devices can be economically developed and deployed [ref. 3]. Viable wave energy harvesting for the AN/SSQ-101 will require devices demonstrated to have very high “power densities” that are cleverly engineered to “blossom” from an “A-size” canister for maximum wave energy extraction.

For Phase I, we are proposing the evaluation, modeling, simulation, and characterization of three kinetic energy harvesting technologies, which are shown in Figure 2.

1. **Piezo-Ceramic Device** – utilizes a newly-developed ruggedized laminated piezo (RLP) device as the “micro-power” solution to convert relative wave motion to electrical energy. RLP is a mechanically simple design accommodated into a small volume.

2. **Rotary Magnetic Generator** – a traditional rotary geometry micro-generator with an innovative mechanism to continually spin the generator from the low frequency waves.

3. **Linear Magnetic Generator** – a novel magnet/coil device that can be deployed from the AN/SSQ-101.

During our Phase I Option period, we will validate our modeled and simulated data from all three proposed options with scaled prototypes and testing using the U.S. Naval Academy Hydromechanics Wave Laboratory.

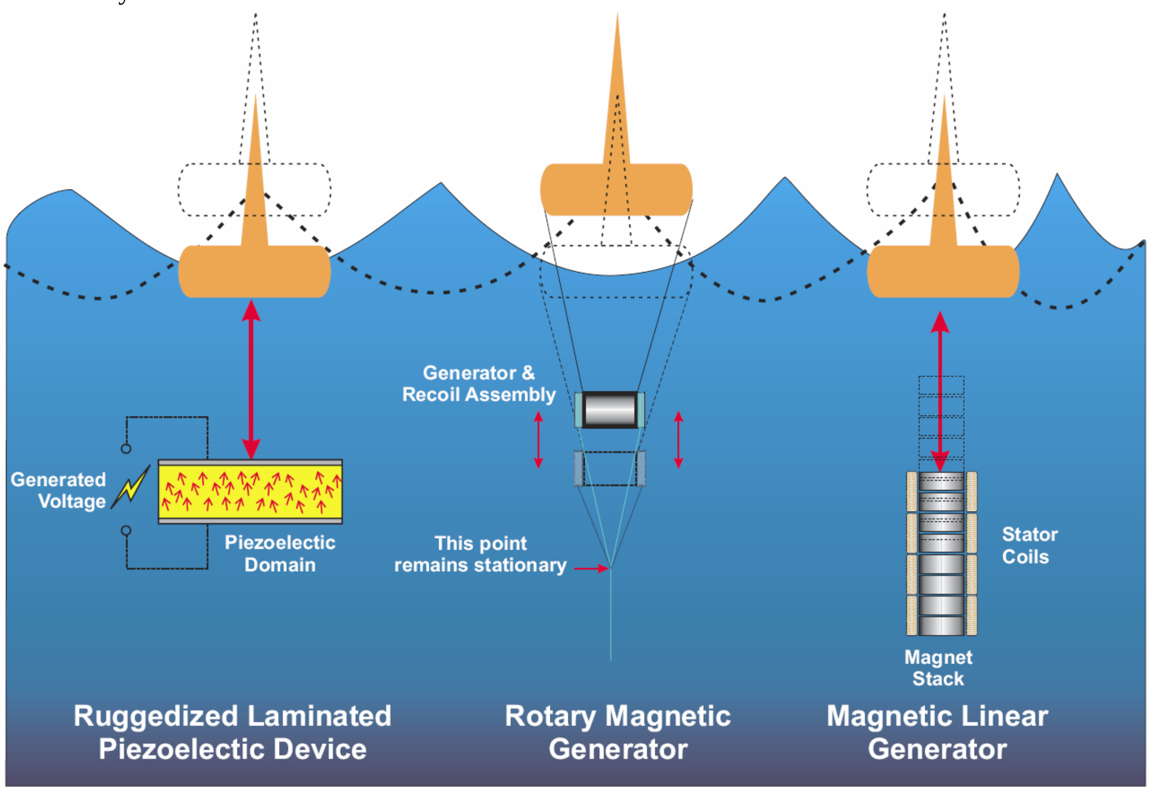


Figure 2. Schematic Representation of Proposed Wave Energy Harvesting Systems to be Investigated

Due to the level of challenge to generate the required power given the compact volume and weight restrictions, we have strategically partnered with a leading-edge piezo-cermanic company and solid state thin film battery companies. All of these strategic partners have U.S.-based development and production facilities and provide unique capabilities that lower the risk for all three design approaches.

Efficiency of coupling wave motion and the energy harvester is a key challenge. Wave power is available in low-speed (frequency of wave), high force, and the motion is not in a single direction. Most readily available electric generators, like turbines and piezoelectric devices, operate at high speeds with steady flow or higher frequency input vibrations.

The current sonobuoy suspension system to isolate the hydrophone array from induced noise by wave or flow motion minimizes the relative motion between the array and surface transponder section - all within an extremely compact, smoothly deployable container - has been widely successful. In addition, this flexible suspension cable incorporates electrical signaling interface between the floatation unit and the hydrophone array. However, kinetic energy is not captured with the current configuration.

Phase I Technical Objectives

The goal of the proposed Phase I project is to determine the viability of three possible energy harvesting methodologies to augment the power supply on the AN/SSQ-101 sonobuoy. This effort will include various simulations of wave energy over a range of sea states and the design of stowed and deployed energy harvesting systems, including method of deployment. The developed energy storage unit will combine solid state secondary micro energy cells (ultra capacitors) to store the ocean harvested energy in parallel with primary power cells in a package optimized to accommodate the energy harvesting apparatus.

There is significant opportunity to utilize emerging micro-energy harvesting, battery & power management and advanced manufacturing technologies developed in the U.S. for extended mission sonobuoys. Phase I work will focus on developing an integrated ocean power harvesting solution for the AN/SSQ-101 by developing leading edge technologies from other industries for this unique application.
Phase I work will address the following issues:

1. The energy requirements of AN/SSQ-101 electronics will need to be characterized to determine potential emerging miniaturized battery technology and associated electronics required to optimize the sonobuoy power supply for renewable energy utilization.

2. Is there enough environmental kinetic energy to efficiently couple into a piezo-ceramic laminated thin film power harvesting option using surface ocean waves and is there a viable way to deploy an extraction system?

3. What is the optimal geometric shape, size and lamination thickness of the piezoelectric film and overall system deployment configuration to optimize power output?

4. Is there enough kinetic wave energy to efficiently drive an energy harvesting system using a customized direct-drive linear magnetic or rotary magnetic generator within the given weight and size constraints? We shall also ensure that the power harvesting option will not denigrate the performance of the AN/SSQ-101 hydrophones and digital compass.

5. How will an integrated system (power harvester, primary & secondary batteries, and power conditional circuitry) fit inside and be deployed from an “A size” canister?

6. What is the projected manufacturing cost of the proposed energy harvesting system?

7. Are there any environmental considerations for at-sea disposal of the expendable sonobuoy?

Phase I Work Plan

Task 1. Determine Mechanical Wave Energy Extraction Potential

Wave Energy Potential

Surface waves are generally characterized by the parameters shown in Figure 3, with λ being the wavelength, H the wave height, c the wave velocity, and η denoting the displacement of the free surface as a function of x coordinate and time [ref. 4]. Observations of deep water waves have shown that surface particles move in a circular motion, as shown in Figure 4. If we consider T to be the wave time period (inverse of λ), then the surface particle travels a distance πH with an average velocity of $\pi H T$.

Germaine to our consideration of ocean wave energy harvesting potential is the Trochoidal wave traditionally used by naval architects to perform "static" analysis of wave loads on long, slender ships. Trochoidal or "breaking" waves are characterized by the relationship $2/\boldsymbol{k} = \boldsymbol{\lambda}/\boldsymbol{\pi}$, where $\boldsymbol{k}$ is the inverse of the particle's path radius. Equally important, Figure 4 shows that the particle velocity decreases ***exponentially*** with depth, making it critical that our kinetic energy harvesting devices be located near the sonobuoy float.

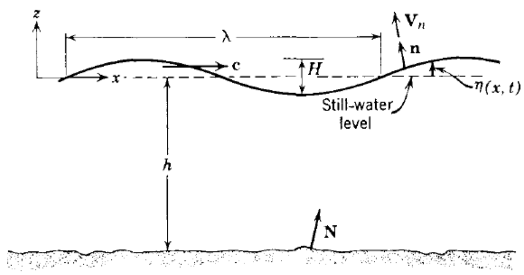


Figure 3. Schematic of a Traveling Surface Wave [ref. 4]

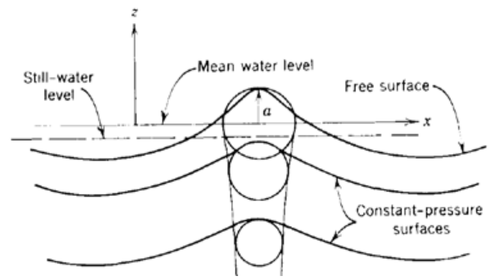


Figure 4. Constant-pressure Surface and Particle Orbits in a Trochoidal Wave [ref. 4]

If we rely only on the sonobuoy float and assume that the hydrophone array remains stationary, then the maximum wave energy force possible is predicted by McCormick as:

$$F_{zc} = \frac{\rho g H \pi R^2}{4}\left(1 - \frac{\pi^2 R^2}{2\lambda^2}\right)\left(e^{-2\pi d/\lambda} + 1\right)\cos(\omega t)$$

where $\boldsymbol{R}$ is the radius of the float (approximately 9 inches), $\boldsymbol{\rho}$ is the mass density of seawater (2.00 slugs/ft^3), $\boldsymbol{d}$ is the depth of the float and $\boldsymbol{\omega t}$ is the circular wave frequency * time

For a body of width $\boldsymbol{B}$ (1 foot), the ***total*** energy available is equal to $\boldsymbol{\rho g H^2}\,\lambda/8$, which for a Sea State 4 wave (H = 7.5 ft, λ = 99 ft) is about 45,000 ft-lbs. In Sea State 2 this value is closer to 360 ft-lbs. McCormick has shown that the heaving efficiency of a floating body is around 40%, so there may be as little as 145 ft-lbs (about 200 joules or ½ watt-hr) available if kinetic energy is optimally extracted from the float. Under Task 2 a parametric study will be conducted to determine available wave energy potential over a range of sea states, depths and "capture" areas. Figure 5 shows the maximum amount of energy that can be extracted for a heaving body the size of the sonobuoy float as a function of wind speed [ref. 5]. Under Task 2 we will refine this prediction to take into account the specific characteristics of the float.

Compliance Cable Modeling

In order to effectively harvest kinetic wave energy, we want to duplicate the compliance cable spring characteristics with our energy harvesting device to ensure that the hydrophone assembly does not experience any heave motion. Therefore, we need to estimate the force exerted by the existing compliance cable in order to design a coil spring system with similar characteristics. The overall length of the compliance cable is 21 feet un-stretched, which doubles in length when fully loaded (estimated to be 1/2 breaking strength). Based on available cable stowage area, the compliance cable appears to resemble 7/32 inch MIL-C-43701 Type I shock cord, with a spring constant of around 8 pounds/foot. If this data is correct, the expected cable force for various operating conditions is shown in Table 1.

Table 1. Estimated Compliance Cable Forces

Compliance Cable Length	Force	Condition
21.00 feet	0.0 lbs	no load
22.75 feet	13.8 lbs	Sea State 2
23.75 feet	21.6 lbs	Sea State 3
24.13 feet	24.6 lbs	buoy at 1/2 w.l.
28.00 feet	55.0 lbs	Sea State 4
27.26 feet	49.2 lbs	buoy submerged
42.00 feet	165.0 lbs	1/2 breaking strength

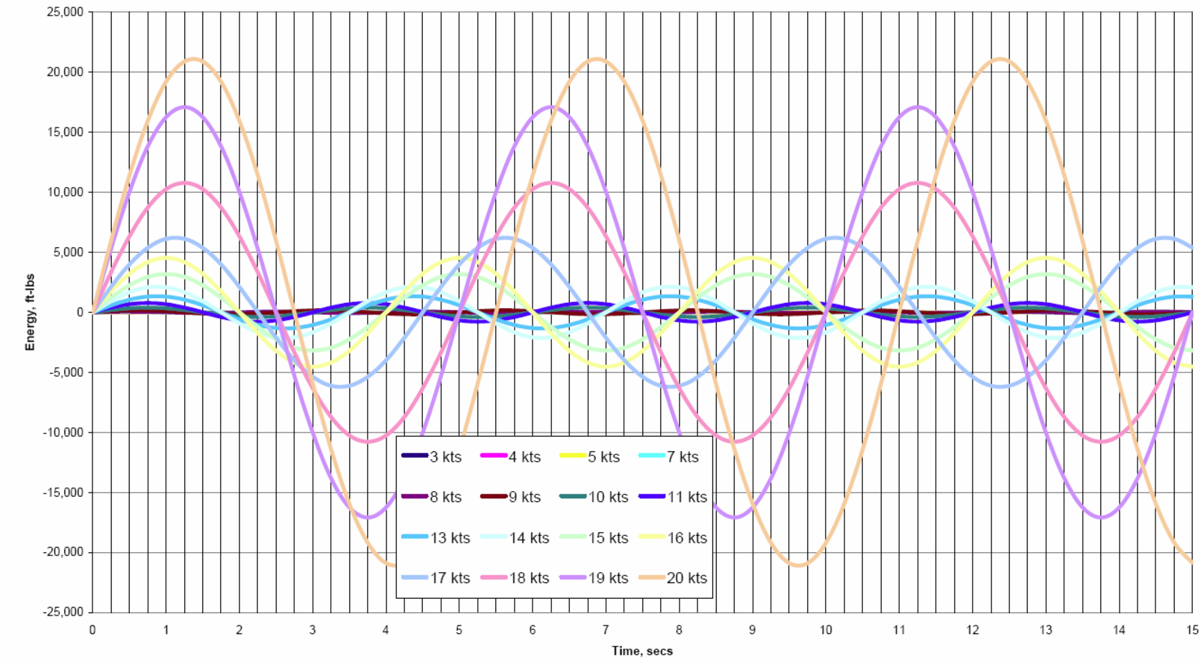


Figure 5. Maximum Available Kinetic Energy from Heaving Buoy as a Function of Wind Speed

Novel Kinetic Energy Extraction Geometries
The parameters that will be considered when designing a kinetic wave energy harvesting arrangement for the AN/SSQ-101 sonobuoy are: 1. Ability to be deployed from available sonobuoy volume; 2. Relative motion between anchor point and wave particles; 3. Area of energy harvesting mechanism; 4. Natural frequency of energy harvesting mechanism; and 5. Energy harvesting systems must be quiet enough not to affect hydrophone performance.

Task 2. Investigate Piezoelectric Energy Harvesting
Piezoelectric generators employ active materials that generate a charge when mechanically stressed. The proposed piezoelectric configuration will maintain the damping characteristics of the existing compliance cable yet capture the energy currently stored as potential energy in the elastometric properties within the suspension cable.

The potential energy that is currently stored and released in the elastomeric suspension material can be harvested rather than stored with the addition of a ruggedized laminated piezo (RPL) material. The custom engineered ceramic material possesses an innate molecular construct where small distortions of the cells mechanically amplify distortions in neighboring cells.

When the piezo-ceramic is strained by an external applied force, like wave energy, the cells in the ceramic are deformed slightly. This shifts the central atom and leads to a tiny polarization of the ceramic. The sum of the polarizations of many cells leads to a net polarization of the ceramic. By placing an electrode on each side of the piezoelectric laminated device, the net polarizations produces a flow of electrons, a D.C. electric current.

During Phase I we plan on investigating custom made high quality piezo-ceramic material manufactured by AdaptivEnergy in Hampton VA. AdaptivEnergy has engineered a piezo-ceramic with a power density 50% greater than competing piezoelectric devices and ten times greater than piezo fiber composites [ref. 6].

The proprietary fabrication process utilized by AdaptivEnergy produces a rugged device that can survive high impulse and shock inputs (to >60 G without failure), reliability that has been tested to >150,000 hr. MTBF, and performance at extreme temperatures (minimal operating range of –20°C to 100°C).

In our initial meeting with AdaptivEnergy we determined that a “stacked” RLP arrangement operating in the 0-compression mode would be optimal for wave energy harvesting. Figure 6 shows a proposed arrangement that would use two stacks of piezo devices acting in compression.

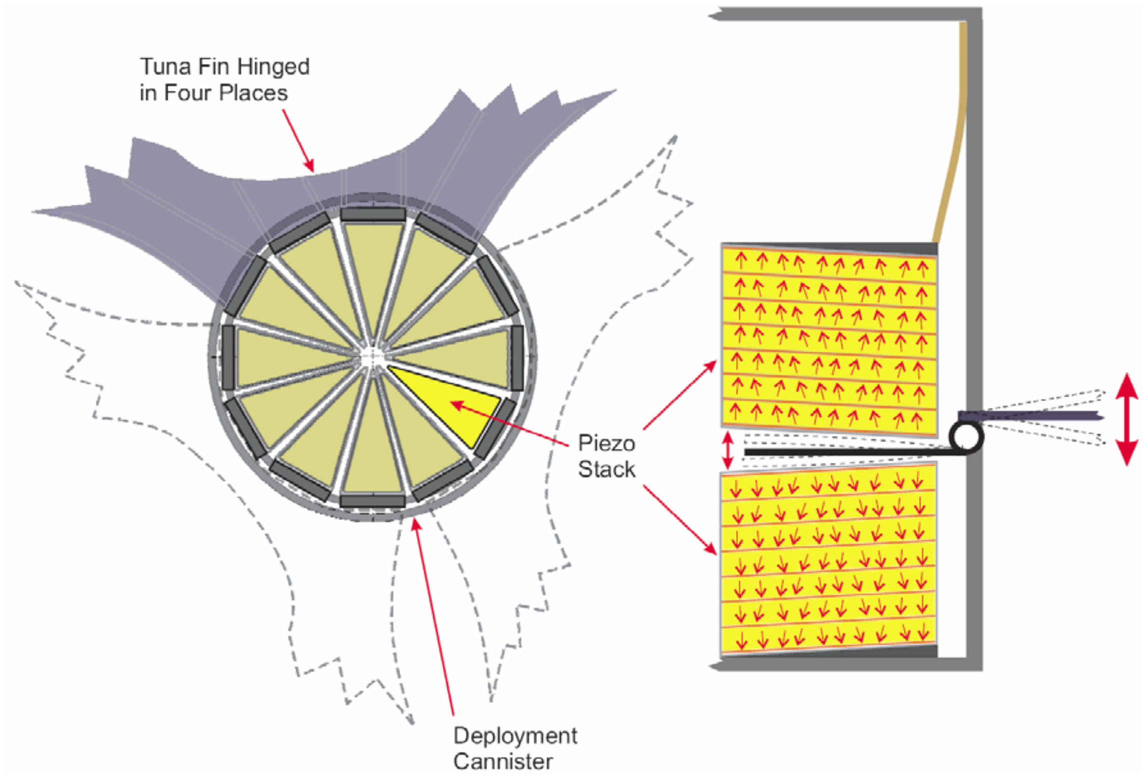


Figure 6. Piezo Stack Arrangement

Piezoelectric Power Conditioning Circuitry

A series of piezo transformer (PZT) devices act like an AC current generator in parallel with a complex output impedance. When the PZT devices are mechanically vibrating at the resonate or harmonic frequency, the PZT thin film experiences a time-varying change in mechanical stress, alternating between tensile and compressive stress. This results in a time-varying generated charge within the PZT layer, which is the source of AC current.

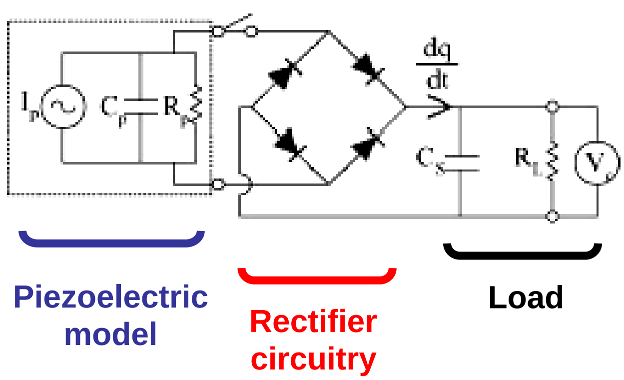


Figure 7. Equivalent Electrical Model of the Piezo Power System

A rectifying circuit and electrical storage capacitor are required for harvesting the electrical energy from each PZT device. Figure 7 shows the simplified condition circuitry needed to harvest the energy.

The rectifying bridge circuit consists of four small-signal Schottky diodes (i.e. STMicor-electronics 1N5711). These diodes are chosen specifically for their very small forward voltage drop of around 0.2V. This allows for the largest possible DC voltage to develop across the capacitance or load.

Task 3. Investigate Rotary Magnetic Generator

Presently, the most efficient way to convert kinetic energy to electrical energy is with rotary magnetic generators, as used in engine-driven generator sets and alternators. To utilize a rotary magnetic generator, the heave wave motion of the sonobuoy float must first be converted into a radial torque motion. This is particularly challenging since the entire system must be stowed into the very tight area of an "A-size" buoy. We propose that the three main components of an effective rotary magnet energy harvester are a Recoil Unit, a Flywheel & Gearing Unit, and a Generator Unit, shown in Figure 8.

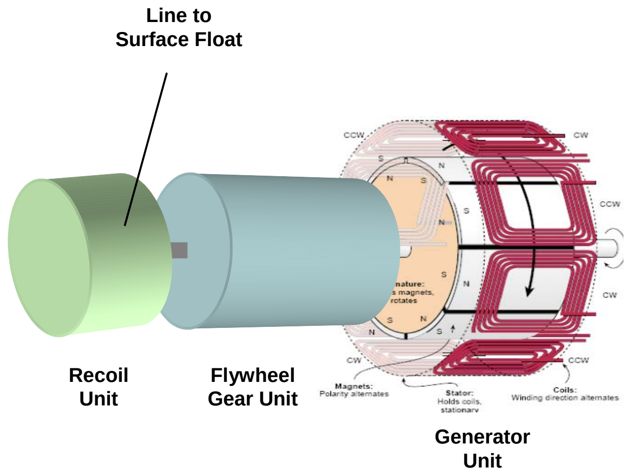


Figure 8. Rotary Magnetic Generator Components

The Recoil Unit

The recoil unit converts the up and down motion of the waves into a radial circular motion. When the surface float is at the lowest point of the wave, the coil spring is "relaxed" and the pull line connecting the surface float to the radial generator unit is fully coiled around a pulley.

Using a slip clutch mechanism shown in Figure 9, when the wave height rises, the surface float exerts a pulling force turning the pulley. Via a geared assembly, the flywheel is energized to convert some of the kinetic energy to potential energy while the magnetic generator harvests electrical energy. As the wave reaches its maximal vertical height and begins to fall, the pull line is wrapped around the pulley by the spring tension in the coil spring. The critical feature of the recoil unit is that it has a clutch to ensure shaft connection to the flywheel. The gearing unit and generator are only turned in one rotary direction and momentum is maintained by the flywheel. This arrangement allows the unit to be extremely compact by not requiring a counter weight to extract downward wave energy. This recoil mechanism is comparable to a retractable dog leash, a tape measure, or a lawnmower starting pull cord.

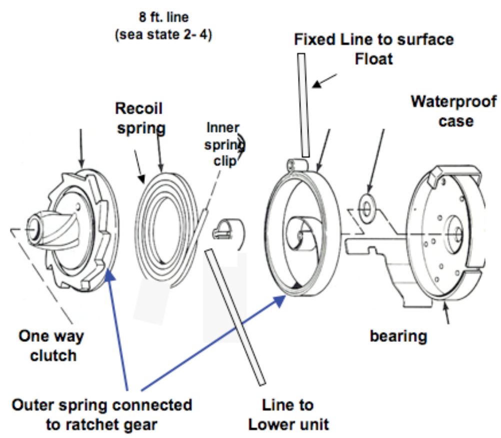


Figure 9. Recoil Mechanism

The Flywheel and Gearing Unit

In order to create a compact ocean wave energy harvester it is essential to avoid various energy-sapping transformations from one form of energy to another. Therefore, we propose using a small, low-speed flywheel with the goal of continually powering the generator from a surface wave with a period of 1-4 seconds. The flywheel allows the generator to spin continuously instead of stopping and starting with the sinusoidal wave action. The losses through friction of the entire system will be simulated and prototyped to determine the exact power that can be produced by the generator.

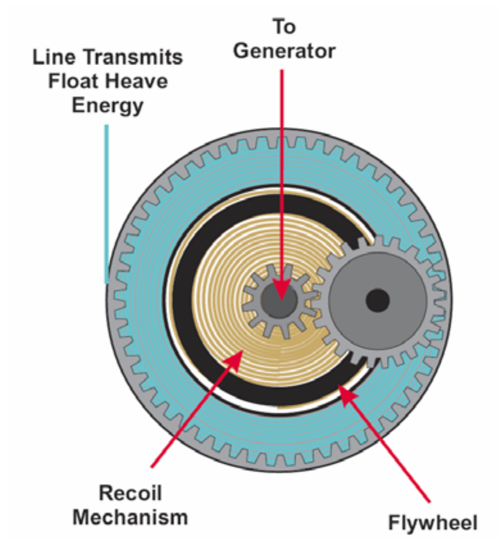


Figure 10. Configuration of Gearing System for Rotary Magnetic Generator

In general, resistance from starting the flywheel and the induced magnetic field within the generator are the largest components of friction. Typically, mechanically-driven flywheels designed to match wave forces and pulleys have been highly efficient in other systems like spacecraft, computer backup power systems, and hybrid automobiles. We will employ a similar geared flywheel system shown in Figure 10 to optimally couple the kinetic wave energy to the generator.

<u>Generator</u>
In general, the larger the generator, the more it will weigh and the more energy it will produce. However, these characteristics do not scale linearly as the generator becomes smaller due to the characteristics of the magnetic flux field and edge effects. The two main parts of a rotating type generator are the armature and stator. Permanent magnets are mounted to the armature, which is the part that spins. There are no electrical connections to the armature - it simply moves the magnets. The magnets are oriented in the armature so that the poles alternate N-S-N-S., as shown in Figure 11.

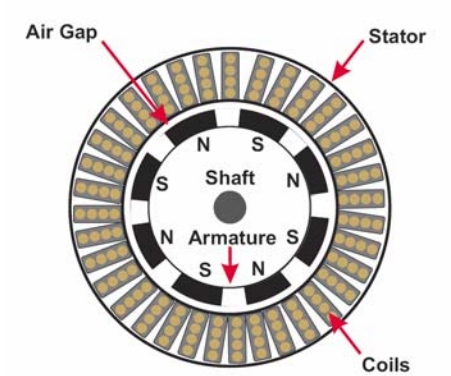


Figure 11. Rotary Generator

The stator does not move. It consists of an array of wire coils connected together that alternate in the direction that they are wound. The coils and magnets are spaced evenly with each other. The cores must be of magnetic material, but also must be electrically non-conductive to avoid power-wasting eddy currents. The air gap is the distance between the spinning magnets and the stationary coils (between the armature and the stator) and must be kept as small as possible.

We do not intend to design the magnetic rotary generator but rather will leverage the work of one of several National Labs and U.S. based companies that specialize in micro-generator modeling and design. Dr. Aleksandr S. Nagorny at NASA's Glenn Research Center has focused on generator/ flywheel modules for satellite energy storage that mimics many of the constraints of our proposed research [ref. 7]. We will strongly leverage this and other leading edge research and manufacturing to optimize the energy density given our weight and volume constraints.

Task 4. Investigate Linear Magnetic Generators
One of the first ideas for use of linear magnetic generators was filed as a US patent in 1980 [ref. 8] but it was ruled out due to excessive weight and inefficiency. However, progress in permanent magnet materials along with lower powered sensor and RF electronics now make this idea conceivable for the AN/SSQ-101.

The basic principle of operation of a linear generator is shown in Figure 12. The only moving part is the translator where magnets are mounted with alternating polarity. The translator moves linearly next to a stationary stator that contains windings of conductors, called the armature windings. A voltage is induced in the windings as the magnetic field changes, which is caused by wave motion.

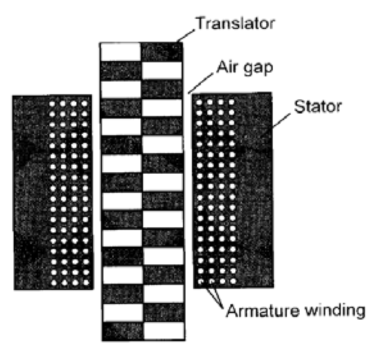


Figure 12. Cross-Sectional View of a Linear Generator

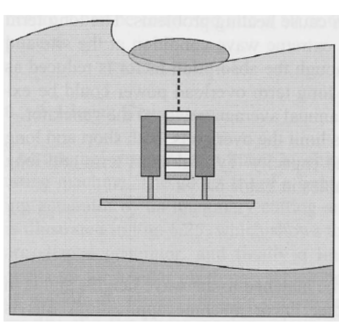


Figure 13. Floating Point Absorber with Submerged Damper Plate

Linear generators all require a point absorber and a reference system. The relative linear motion between the two drives the generator. Since the AN/SSQ-101 sonobuoy does not utilize a bottom anchor, the reference system in the configuration is the hydrophone array and compliant suspension cable. The AN/SSQ-101 array and cable will act as a damper plate, as shown in Figure 13. A key challenge of this configuration is maintaining the hydrophone array at a precise depth while maximizing the *z* axis motion at the generator and preventing overload in higher sea states. The float (point absorber) and reference system (hydrophone array) form an oscillating system where the waves are the driving force and the generator acts as a damper. Performance and power extracted from the linear generator is optimized by addressing these five key challenges: 1. Translator design; 2. Stroke Frequency; 3. End Seals; 4. End Magnetic Fields; and 5. Rectifying Circuitry

To maximize the energy conversion, the translator throw length must match the wave height. Since the AN/SSQ-101 sonobuoy's entire length is 39 inches, the translator length will be significantly less then the specified sea state 2 to 4 operational range. The Ohmic losses will increase as the conductor wire coil length increases if the stator is made longer. Maximizing the length of the fixed magnet translator core relative to the stator will optimize power output, weight, and lower costs. Also, the translator can't "bottom out" in high sea states, as this would create excessive noise.

The relatively slow speed of the vertical (*z*-axis) motion of the surface waves that drive the linear generator is our primary concern. We anticipate designing a customized linear generator based upon recent work at the Uppsala University in Sweden [refs. 9 & 10].

The most obvious challenge of the linear generator option is the slow speed. The speed of the moving part of the generator, the translator, will be determined by the vertical speed of the sea surface, which is on the order of 1-2 m/s. This is about 10-80 times slower then conventional rotational generators and consequently the reaction force required is 15-50 times larger to give the same output.

The point of fixation and seals must maintain a precise air gap between the translator and the stator. The seals must also remain watertight at the system's design depth. Linear Generators have open magnetic flux fields on each end which may affect the sonobuoy electronics. As with the piezo energy harvester investigated in Task 2, the linear magnetic requires a rectifying circuit to extract power from wave energy. Circuitry will be optimized to match the expected wave frequency.

Task 5. Design Power Storage Architecture

The Navy's need for efficient advanced battery technology ranges from AUV systems, such as air, sea, surface, undersea, and ground vehicles to embedded and deployable power systems, such as vehicles, artillery, radios, beacons, and sonobuoys [ref. 11]. Efficient energy storage as well as energy harvesting is vital to these applications. We propose to place the primary battery in parallel with a secondary battery along with conditioning circuitry to power and extend the lifetime of the AN/SSQ-101 buoy, as shown in Figure 14. We feel that advanced sonobuoy battery technology can leverage other Navy research and result in solutions for other Navy applications.

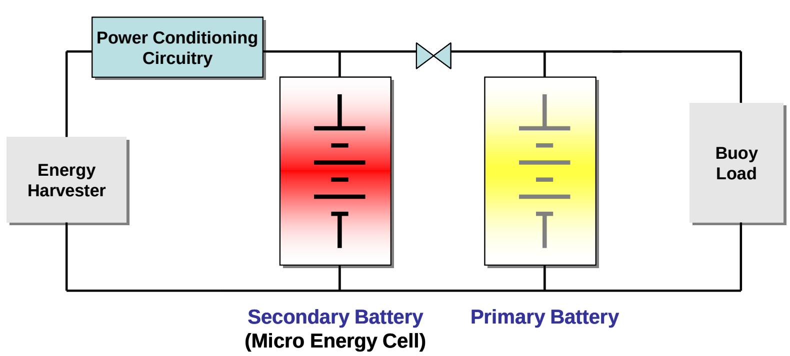


Figure 14. Power Storage Architecture

We recognize that the AN/SSQ-101 primary battery needs to be either the existing silver chloride magnesium "saltwater" battery or a comparable performing battery with higher power density and equivalent shelf life.

The secondary battery to capture and store the energy harvested will be a novel solid state device termed a micro-energy cell. The micro energy cell will load share with the primary battery to extend the buoy power lifetime. Sometimes called a super or ultra capacitor, the Micro Energy Cell we are proposing has high energy density and novel device chemistry.

The micro-energy cell is very attractive in that they can trickle charge energy generated from the kinetic harvesters many times more efficiently then the primary battery [ref. 12]. However, the rechargeability comes at a cost. Existing rechargeable technology is not capable of delivering as much energy in a single use as the incumbent primary battery technology. Therefore, it will be critical to understand the charging capabilities from the wave energy and validate the energy conversion efficiencies to evaluate the expected performance of the total power solution.

The micro-energy cell will store all the energy generated by the piezoelectric and magnetic energy harvesting devices. The peak load on the primary battery will be reduced with parallel battery architecture. Unlike digital circuitry in the lower sensor section that draws a steady current, a VHF transmitter loads the battery with short, heavy current spikes during it's transmit mode. The micro-energy cell added to the system can take over the task of providing the intermittent pulse power allowing the primary battery to function only as a supplier of steady current.

Figure 15 shows a micro energy cell manufactured by Infinite Power Solutions Inc. (IPS) Littleton, CO, which employs chemistry that has both super capacitor and rechargeable battery characteristics. IPS has completed the build-out of the first volume manufacturing facility dedicated to the production of thin-film micro-energy cell products. We have met with the Chief Technology Officer of IPS on related applications and feel their approach is very promising.

The total cell thickness is only 180um.   This unique device represents a new class of electronic component that bridges the performance gap between batteries and super capacitor. The graph in Figure 15 compares the energy density of micro-energy cells with other devices.

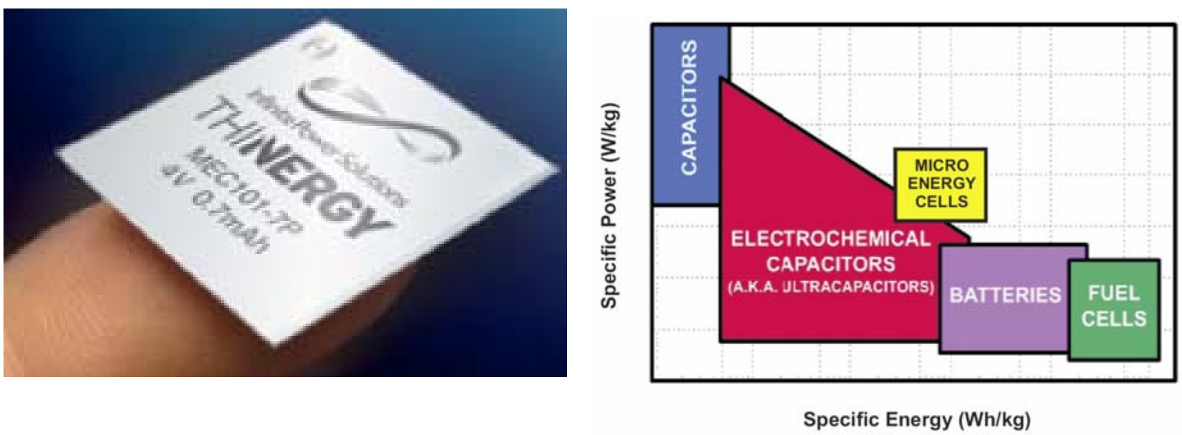


Figure 15. Infinite Power Solutions Micro-Energy Cell (left) and Characteristics (right)

We propose custom-sized micro-energy cells to optimally fit within the diameter AN/SSQ-101 "A-size" container. To store enough energy to double the sonobuoy lifetime, the micro-energy cells will be stacked and the estimated total size is shown in Figure 16.

Micro-energy cells are fabricated using vacuum deposition process to deposit the thin layers of inorganic materials. The cathode material is lithium cobalt oxide ($LiCoO_2$) and the anode material is lithium (Li) metal. Together they form a 4.2V cell. A solid-state electrolyte known as LiPON (lithium phosphorus oxy-nitride) is used as the separator between the negative anode and positive cathode.

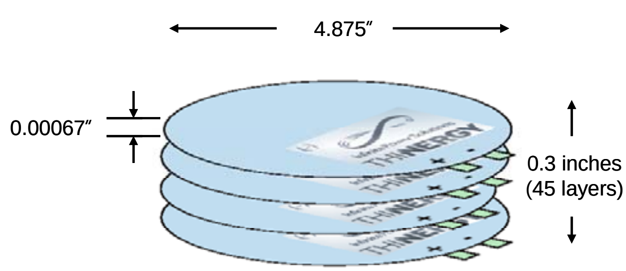


Figure 16. Estimated Size of the Micro Energy Cell

Key attributes of the Micro Energy Cell are:

- High-power discharge eliminates need for external boost capacitors for high-pulse currents;
- Stackable for increased energy and power without increasing footprint;
- Can be deeply embedded and laminated within printed circuit boards or other materials;
- Lasts the lifetime of the system for zero maintenance or replacement cost;
- Superior charge acceptance, even at charge currents of a few hundred nano-Amps;
- Supports more recharge cycles than any other rechargeable battery;
- Rapid recharge in seconds to minutes, depending on the state of charge;
- All solid-state chemistry with no liquid or polymer (organic) electrolyte used;
- Ultra-low electrical current leakage, with less than 1% reversible charge loss per year;
- Extremely broad operating temperature range; and
- Safe (can't overheat) and restriction of hazardous substances (RoHS)-compliant; contains no heavy metal or toxic chemicals.

Redesign Primary Battery System

Part of this effort will evaluate the primary battery to determine if volume can be reduced to accommodate the energy harvester. The current AN/SSQ-101 uses a silver chloride magnesium or "saltwater" battery.

The battery delivers between 6-8 hours of operation. The working voltage of a cell is normally 1.6-2.5 volts but is affected considerably by density, type of magnesium alloy, static or forced flow electrolyte, temperature and salinity. Individual cells must be put in series and parallel to generate the desired voltage & power, respectively.

A compelling feature of the saltwater battery is prolonged storage life (over five years) with no deterioration in performance, since seawater acts as the electrolyte and all components are in solid form.

We will compare the saltwater battery to a new "printed" solid state battery by Solicore (Lakeland, FL). The battery chemistry has very high energy density; is safe; and should have a comparable shelf life to the silver chloride magnesium battery. Similar to the micro-energy cell using thin film layers for construction, for the same capacity the Solicore battery would result in a 67% reduction in volume. The estimated stacked design to generate 18V is shown in Figure 17.

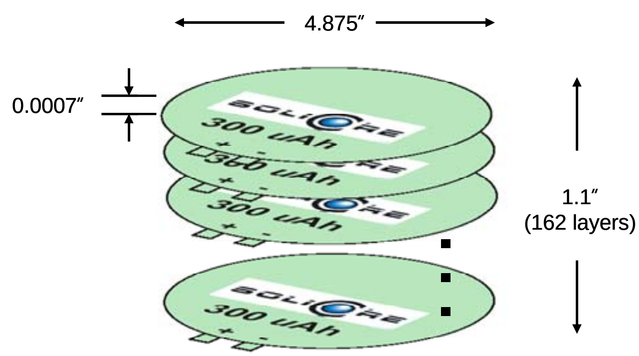


Figure 17. Estimated Size of Optional Primary Battery for Evaluation

Task 6. Design Deployable Energy Harvesting Systems

Harvesting Device Stowage Loacation

One challenge of this effort is to make an energy harvester that stows into a very compact space yet when deployed generates sufficient power. Figure 18 is a cross sectional view of the AN/SSQ-101 sonobuoy showing the three major regions and the relative volumes that they occupy (**A** houses the hydrophone array and compass; **B** houses the battery and deployment cables; and **C** houses the float and electronics).

To minimize our impact on the AN/SSQ-101 design, all three of our energy harvesting solutions will fit into the volume denoted as **B**. This will require redesign and modification of this area. This volume includes the seawater battery (3″); signal cabling pack (2″); and compliance cable pack (3″) – all of standard "A-size" 4 7/8 inch diameter. Future research will investigate the redesign of the Surface Unit Electronics Region **C**) to reduce power consumption and provide additional volume for energy harvesting devices.

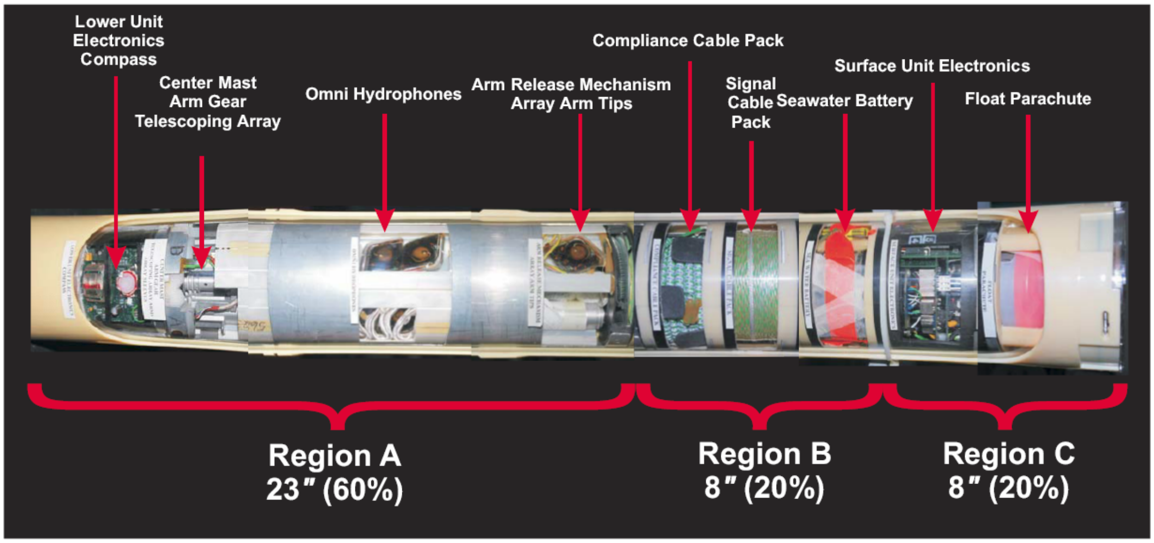


Figure 18. Cross Sectional view of AN/SSQ-101 Showing Relative Volumes [ref. 13]

<u>Wave Energy Extraction</u>

The design of the mechanical elements of an energy harvesting system for the AN/SQ-101 sonobuoy is a two-part challenge. First, mechanical energy needs to be extracted from the environment and second, this energy must be efficiently converted to electrical energy. To accomplish the first task, we look to the emerging science of biomimicry.

> "Those who are inspired by a model other than Nature, a mistress above all masters, are laboring in vain." - Leonardo Da Vinci

Some ocean-dwelling fish, including tuna, mackerel and sharks, have a form of swimming called thunniform. In thunniform swimming, most of the lateral movement occurs in the tail and adjacent area of the body with very little bending of the fish's body. The tail or caudal fin is usually large and crescent shaped to increase the power of each sweeping motion. This form of swimming is ideal for species that cover long distances and swim fast because it conserves energy [ref. 14].

Indeed, when researchers at MIT set out to develop a long-range propulsion system for autonomous underwater vehicles (AUVs), they developed the "RoboTuna" shown in Figure 19 alongside our inspiration for a wave energy extraction fin. MIT professor Triantafyllou realized that the vortices produced by a tuna's tail fin reduce rather than add drag, which is the opposite of what is observed in non-articulating bodies moving through water. The goal of the RoboTuna was to develop the maximum amount of long-range propulsive energy using a minimal amount of battery power (which can often account for up to 70%

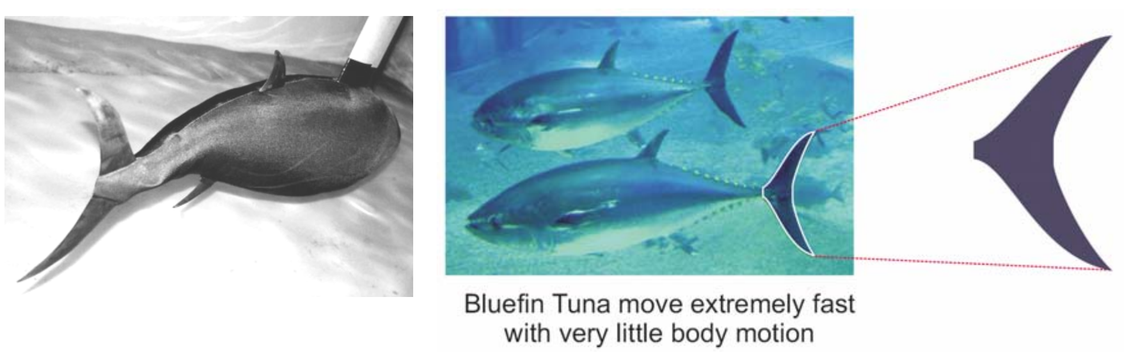


Figure 19. MIT's RoboTuna (left) and Our Inspiration for A Wave Energy Extraction Fin (right)

of an AUV's volume) [ref. 15]. We would like to "reverse" this equation and extract the maximum amount of energy from oscillating fins to power our proposed piezo energy converter, as shown in Figure 20. The fins are hinged to transmit compressive loads to stacks of piezo devices. Recognizing that fishtail fins have evolved for optimal forward propulsion and operate at frequencies of 1.2 Hz to 3.5 Hz [ref. 16], we expect to optimize our energy harvesting foils during Phase II. Figure 21 shows how the upper piezo stack will fall into place during deployment and lock the hinged tuna fin in a horizontal position.

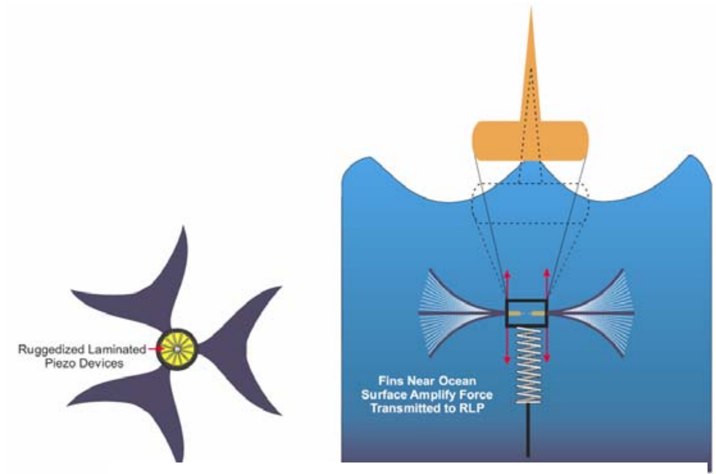


Figure 20. Tuna Fins for Ruggedized Laminated Piezo Energy Harvesting Concept

Linear Magnetic Generator
For the linear magnetic generator we will utilize the fins to stabilize the stator assembly at deeper depths while the translator is excited by the heave motion of the float. For this application the fins will be fixed rather than hinged and act as dampers, as shown in Figure 22.

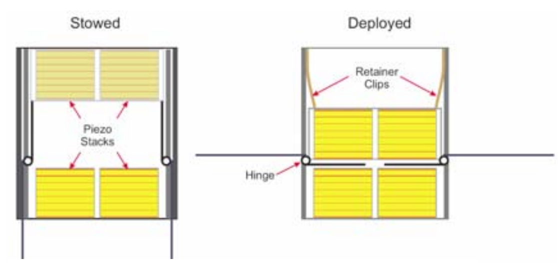


Figure 21. Piezo Stack Deployment Sequence

Fin Deployment
One of the most appealing aspects of mimicking the tuna's tailfin for energy harvesting is the relatively small planar area it uses to generate a lot of force. Figure 23 shows our vision of how an array of three fins could be hinged and wrapped inside the sonobuoy's outer casing for rapid deployment. The fins will incorporate Mylar film technology with very small diameter integral fiberglass rods to guarantee deployment to the desired shape. State-of-the-art sailmaking technology will be investigated to determine if Mylar film "molding" is appropriate for the sonobuoy fins. Mylar is attractive because it will help reduce friction to facilitate canister deployment.

All of these design assumptions will be verified and refined during Task 6 in consultation with the incumbent USSI/Sparton AN/SSQ-101 ADAR sonobuoy manufacturing team.

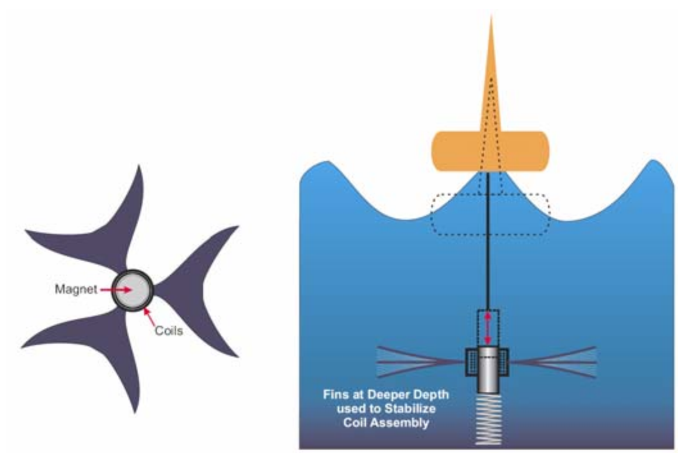


Figure 22. Tuna Fins for Wave Linear Magnetic Generator Concept

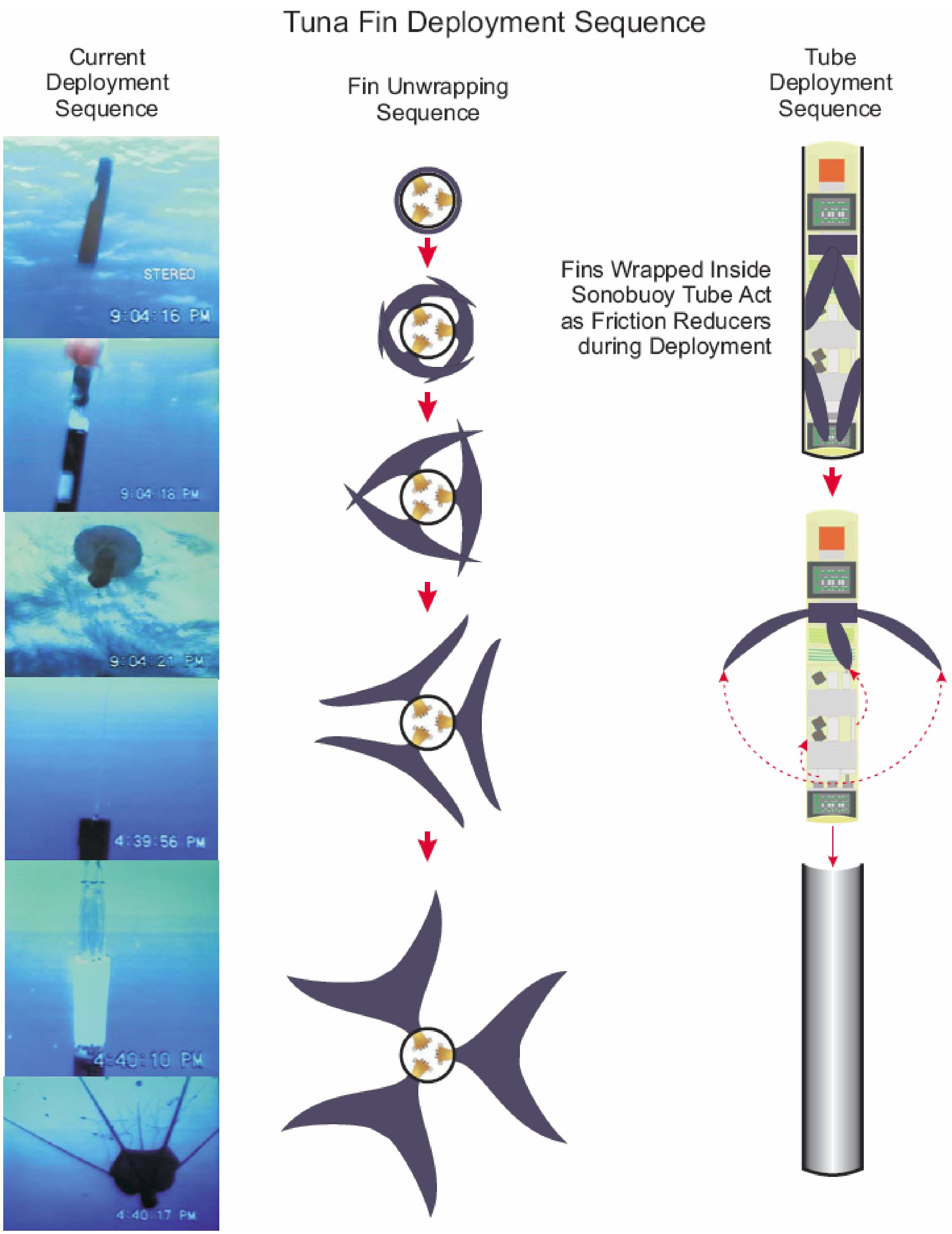


Figure 23. Proposed Tuna Fin Deployment Sequence

Phase I Option Work Plan

1. Build Small Demonstrator Element and Test in Wave Tank

A minimal amount of testing in the USNA's small towing tank is proposed for the summer of 2010. The goals will be to test several variations of fin geometry and to verify the viability of RLP energy conversion in a wave environment. We have had preliminary discussions with Mr. John Zseleczky and Professor Greg White on the logistics of working at the USNA Towing Tank facility.

A major goal of the limited testing will be to determine the viability of converting mechanical wave energy to electrical energy with stacked piezo devices excited in compression. We would also like to determine the effectiveness of the proposed tuna fin actuators at various distances from the wave surface.

2. Develop Custom RLP Design for Ocean Energy Harvesting

To date, ruggedized laminated piezos (RLPs) have been developed to operate at high frequencies and in low strain regimes. During the Phase I Option period, we will continue to work with AdaptivEnergy, the RPL technology developer to optimize the geometry for ocean energy harvesting.

During Phase I, piezo stack development will be accomplished at the design level based on prototypes built to date by AdaptivEnergy. During the Option period, we expect to commit to a specific geometry and pursue limited production for performance validation.

Schedule

We are able to propose an aggressive Phase I schedule because we plan on using two Co-Investigators who will focus on unique aspects of the design problem. This allows for scheduling "overlap" of tasking. Mr. Greene will focus on the mechanics of wave energy and the mechanical design of extraction devices. Mr. Krawczewicz will concentrate on the electricity generation problem with input on mechanical design. Both investigators have a strong background in prototype manufacturing and close collaboration will ensure that the best ideas are applied to wave energy harvesting for the AN/SSQ-101 sonobuoy.

We also plan to proactively seek out leading edge U.S. companies to partner with. We have found that by leveraging state-of-the-art research done by other researchers, ideas germinate faster and technology insertion can be accomplished in a shorter time frame. Figure 24 is the proposed schedule for Phase I and Phase I Option work.

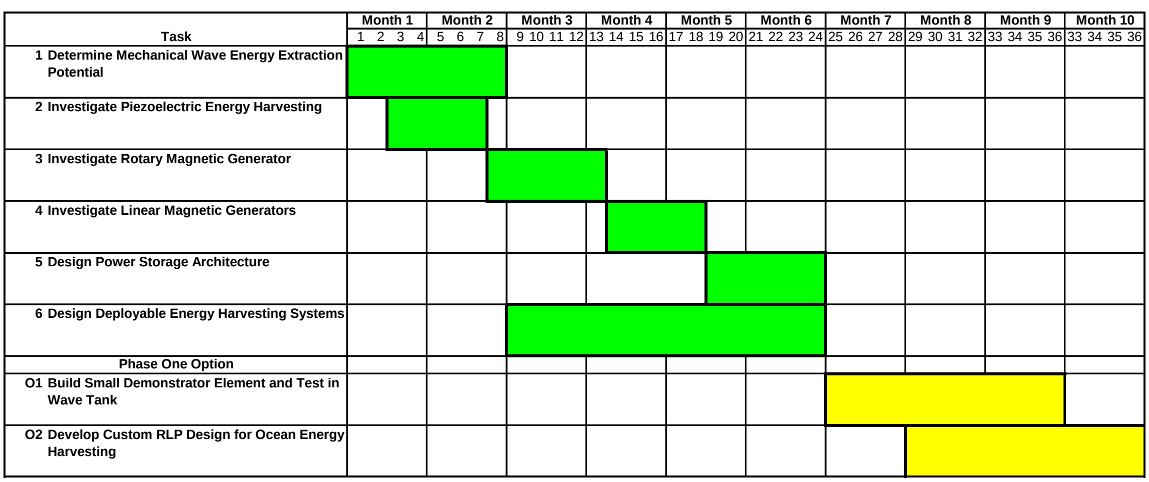


Figure 24. Proposed Work Plan Schedule

Related Work

Project Team Related Research

Mr. Greene is a member of the U.S. delegation to the International Electrotechnical Commission (IEC) TC 114 committee on Marine Energy Devices and works to develop design and safety standards for ocean energy converters. For the U.S. Navy, Mr. Greene has developed material specification guidelines, roadmaps for composite material research and numerous novel uses for composite materials, including an AUV thruster system and a DDG-51 rudder. As an avid offshore sailor, Mr. Greene recognizes both the energy potential and destructive power of ocean waves.

Mr. Krawczewicz spent 22 years at the National Security Agency as an integrated circuit designer, senior cryptographic research engineer, and manager. During his design career, Mr. Krawczewicz developed new technologies, including a 10Gbit high speed encryptor, the first CMOS monolithic randomizer, a low powered CMOS fingerprint sensor array, a patented integrated zeroizable RAM with active tamper sensors, a novel smartcard with cryptographic co-processor, and the first secure key processor IC for Type 1 mobile devices.

Mr. Krawczewicz successful patented, developed and piloted an ID badge for airline and airport employees using an integrated novel thin film flexible windowing display. Upon authentication into the secure part of the airport, the employee’s badge switches from an obfuscated state to transparent state, visually displaying their photo, name, and other biographical data.

As a 10-time finisher of The Great Chesapeake Bay Swim and barefoot water skier, Mr. Krawczewicz is acutely aware of wave energy potential on a “personal” level.

Related Research of Other Investigators

Surface Wave Piezoelectric Generator

In 1983 George Taylor (Ocean Power Technologies (OPT), Pennington, NJ) and Joseph Burns patented a concept that utilized flexible sheets of piezoelectric material on the surface of the ocean to generate electricity [ref. 17]. Unlike our approach, the Taylor invention covered a relatively large area of the ocean’s surface, with assemblies on the order of 50 meters to develop resonant conditions with wavelengths of 100 meters. To the best of our knowledge, this patent was never commercialized, with OPT choosing to focus on traditional wave buoy point absorber technology. We have met with a member of the Board of Directors of OPT who advises them on piezo devices and expect to discuss micro ocean energy harvesting with OPT during our Phase I research.

AUV Battery Development

Research is ongoing to develop optimal battery solutions for autonomous underwater vehicles (AUVs), which must support propulsion systems as well as sensor suites [ref. 18]. Many of the same power constraints, such as primary versus secondary battery; limited space; undersea operation; and long shelf life come to play with AUV batteries as with sonobuoy powering requirements. Therefore, we look to leverage AUV battery research at specialty R & D companies.

Relationship with Future Research or Research and Development

Repacking the VHF Radio Circuitry

Tocreo Labs has extensive experience with micro-manufacturing and component population of small flexible circuits. With over 25 years of experience specializing in Government, military and avionics platforms, thin film chip packaging, powered smart cards, and next generation direct printing of using nano-silver, Tocreo has pushed the current flexible printed circuit board (PCB) technology to perform with high reliability and low cost.

Figure 25 shows the same circuit on two types of thin film PCB materials. Both technologies allow for minimum signal trace widths of

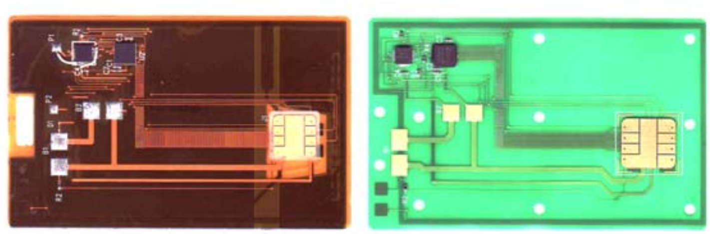


Figure 25. ~50um Thick Thin Film PCB Examples

150um, permitting direct attachment the integrated circuits (IC's) using flip chip, Microflange™ or direct wirebond. The circuit to the right uses screen printing signal traces on an flame retardant substrate, which is a low cost, highly robust technology that is then encapsulated with a water and chemical proof urethane elastomer. The circuit to the right uses lithographic processing on polyimide (Kapton™ by 3M) which is more expensive, but is stable in much larger temperature ranges.

The existing AN/SSQ-101 VHF radio module PCB and design could be optimized to significantly reduce the size, power, weight and cost by utilizing thin film PCBs and components. The design approach for the module would integrate low profile components on a flexible PCB, encapsulated in a robust urethane elastomer polymer. The module will be sufficient to withstand all the operational stresses and harsh environmental conditions of the AN/SSQ-101.

Tocreo Labs also has expertise in new direct printed nano-silver PCBs. Using ink jet printing, "direct write" small silver particles (2-10 nm) suspended in solvents and with low processing temperatures (<150 C), silver nano-crystal inks are ideal for ultra thin printing electronic devices on plastics, as shown in Figure 26.

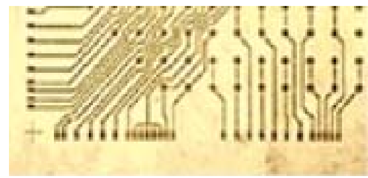
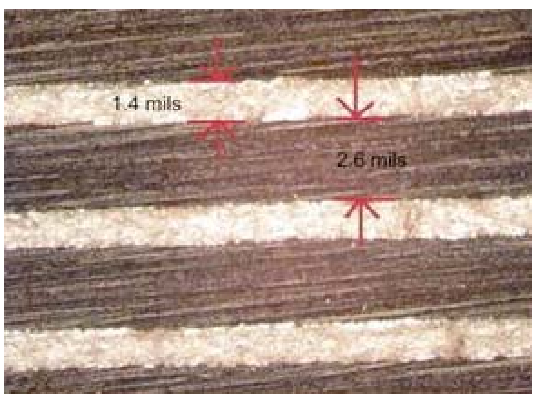


Figure 26. Direct Silver Printed PCB

A 200% trace density reduction can be attributed to the micro electrical mechanical systems (MEMS) aerosol jet devices developed originally for the ink jet printers that have been adapted to precisely deposit circuit traces. Figure 27 shows a sample board from top and cross-sectional view showing the resolution possible with this technology.

Applying this PCB manufacturing technology would reduce the size (thickness & area) of the electronic radio-frequency system to allow for more volume for power harvesting.



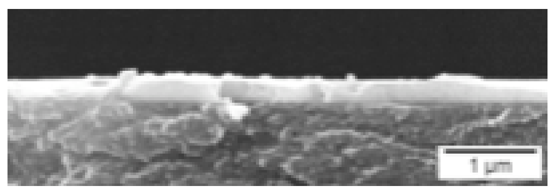


Figure 27. Top view of Line & Space Widths using Nano-Silver Traces (left) and Conductive Silver Film on PET Cured from Nanoparticles Precursor (above)

<u>Thermoelectric Energy Harvesting</u>

Hybrid 3cm square thermoelectric modules (i.e. ThermoLife™, Riverside, CA and SII - Seiko, Japan) could generate approximately 30-40mW with a 5 degree C temperature gradient. For our proposed research, this option was ruled out since it would require a large surface area within the float, thermal absorption material to generate big temperature differentials, and the thermoelectric modules are too thick (1.27mm) to compactly stow integrated into the floatation device. However, as advances in this technology mature it may become attractive for calm water sonobuoy operations.

<u>Commercialization Strategy</u>

Our primary goal is to develop an energy harvesting system for the AN/SSQ-101 sonobuoy that meets the needs of the U.S. Navy. Therefore, it is essential that we coordinate our research plan with the current manufacturer and the end-users. The AN/SSQ-101 executes a finely-choreographed deployment sequence shown in Figure 28, which can not be adversely impacted by our proposed wave energy harvesting system.

We recognize that the AN/SSQ-101 sonobuoy is manufactured by Sonobuoy Tech Systems, which is a joint venture between Undersea Sensor Systems Incorporated and Sparton Electronics Florida, Inc. [ref. 19]. Upon notification of a Phase I award, we would expect to meet with Bill King, Sparton project manager in Deleon Springs, FL to coordinate our Phase I research with the current AN/SSQ-101 design. Paramount will be guidance provided by the SBIR Technical Points of Contact at the Patuxent River Naval Air Station, Peter Woodside and Jason Payne, as they represent the customer's perspective on any proposed product improvement. We expect to continue to receive technical insight from Mr. Ronnie Batman at Pax River and Dale Hoit at NSWC, Crane.

The current AN/SSQ-101 seawater battery system accounts for almost 10% of the sonobuoy cost. The unit cost of the AN/SSQ-101 currently makes it prohibitive for consideration of any uses beyond anti-submarine warfare. However, if we could drastically reduce the cost of the battery system and significantly extend mission endurance, this or a sonobuoy of similar design would be viable to monitor marine mammal migration, port security and seismic activity. Indeed, the Navy is very concerned with the migratory activity of marine mammals to minimize harassment during sonar training exercises [ref. 20].

Micro Ocean Energy (MOE) harvesting could also be attractive for lighted navigational buoys, weather buoys, as well as fish trap, lobster & crab pot markers, especially as the need to collect sensor data grows. As our waterways become more populated, there is an increased need to illuminate and send data from anchored systems.

We also see the potential to drastically extend the operational life of emergency position indicating radiobeacons (EPIRBs), which are designed to save the lives of seafarers who get into trouble by alerting rescue authorities and indicating their location. MOE may also be adaptable to "black boxes" on ships and airplanes, allowing for longer recovery windows.

During our Phase I research period we plan on meeting with the Chief Technology Officer of Ocean Power Technologies (OPT), the world leader in wave buoy power. We will explore the viability of scaling up MOE technology as an effective way to deliver power to coastal cities. OPT has over 10 years of experience testing their PowerBuoy design and have partnered with the U.S. Navy, USDOE, Lockheed Martin, PNGC Power, Leighton Contractors, Iberdrola, and the Scottish Government [ref. 21].

Based on the opportunity, design methodology and proposed approach developed for this SBIR proposal, we have piqued the interest of at least two sources of venture capital. We expect to formally pursue these funding sources during the Phase I Option period after successful completion of Phase I. This will help us leverage Government resources during Phase II and ensure rapid insertion of developed wave energy harvesting technology with the AN/SSQ-101 and other powered buoy systems.

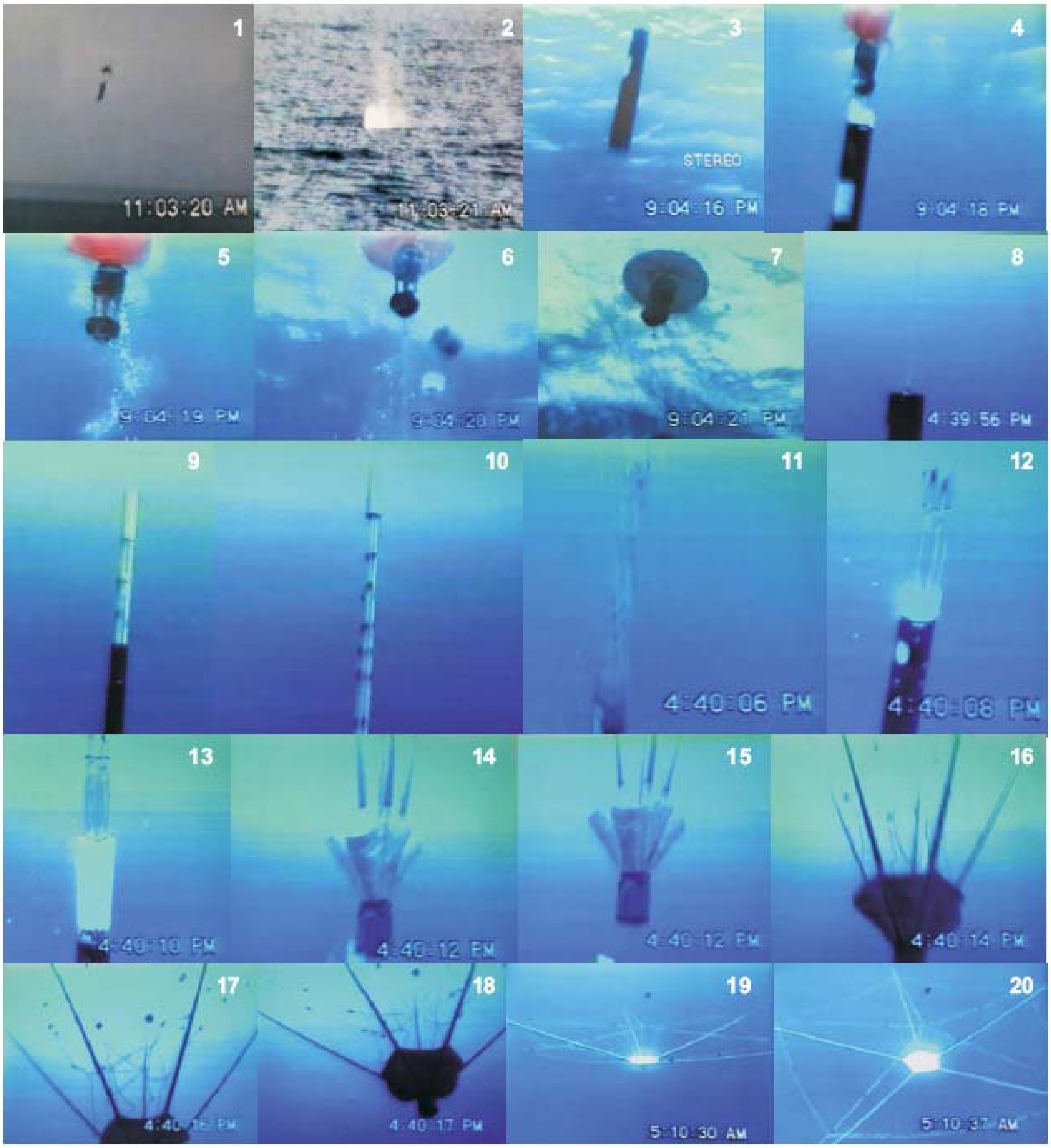


Figure 28. AN/SSQ-101 Deployment Sequence [ref. 13]

Key Personnel
Eric Greene, Naval Architect/Marine Engineer
EDUCATION
S.B. in Naval Architecture and Marine Engineering, Massachusetts Institute of Technology, 1979

EXPERIENCE
Eric Greene Associates, Inc., President, 1987-Present
Mr. Greene founded Eric Greene Associates, Inc. to advance our understanding of composite materials for marine structures. Engineering advanced materials for marine structures, understanding the performance of composites in fires, composites education, instrumentation of marine equipment and ocean renewable energy are the primary areas of corporate expertise. Some recent projects include:

- Technology transfer assistance for major Norwegian shipbuilder supporting the U.S. Office of Naval Research (ONR)
- Lecture series in the Netherlands on marine composite construction for the megayacht industry
- Cost modeling of next generation Navy hovercraft for ONR ManTech program
- Development of a "stowable" megayacht helicopter landing platform
- Riser load calculations for a floating transit offloading & storage platform
- Revision of NAVSEA Technical Publication T9074-AX-GIB-010/100, "Material Selection Requirements," to include updated guidelines for composites
- Fire workshops for the National Association of Marine Surveyors and NASA

Structural Composites, Inc., Naval Projects Program Manager, 1990-Present
Mr. Greene served as the Program Manager for the Composite Twisted Rudder project. In this capacity, Mr. Greene was responsible for securing $7 million in funding from various Government resources and managing all technical and programmatic aspects of the project.
Giannotti and Associates, Inc., Naval Architect, 1985-1987
Mr. Greene's responsibilities with this firm started at the level of Project Engineer and graduated to Program Manager, overseeing an omnibus NAVSEA contract.
Severn Companies, Inc., Manager, Marine Systems, 1984-1985
Mr. Greene was responsible for marketing and product development of a microprocessor-based fuel management system for diesel propulsion plants.
DLI Engineering Corporation, Marine Engineer, 1981-1982
Mr. Greene was involved in test plan preparation, data acquisition and analysis of machinery condition monitoring and hull structural response on U.S. Navy ships.

MEMBERSHIP
Society of Naval Architects and Marine Engineers, member since 1979.
International Electrotechnical Commission (IEC) TC 114, Marine Energy Devices, U.S. delegation

SELECT REPORTS, PRESENTATIONS and PUBLICATIONS
1. "Composites for Renewable Energy, 2008, http://change.gov/open_government/entry/composites_for_renewable_energy/
2. "Labor-Saving Passive Fire Protection Systems for Aluminum and Composite Construction," Ship Structure Committee Report Number SSC-442, NTIS#: PB2005-108998, Publish date: 09/15/2005.
3. "Composite Twisted Rudder," presented at ShipTech 2005, Biloxi, MS, March 2005.
4. MARINE COMPOSITES Overview Course presented at the 6th Annual Multi-Agency Craft Conference at the Naval Amphibious Base, Little Creek, Norfolk, Virginia 18 June 2003
5. "Thermo-Mechanical Testing of Marine Laminates" invited presentation at the Office of Naval Research
6. "Closed Molded Integral Shock Mitigation for Special Operations Craft," presented at the 5th Annual Multi-Agency Craft Conference at the Naval Amphibious Base, Little Creek, Norfolk, Virginia 18 June 2002.
7. "Consideration of Composite Materials for Moderate-Sized Warships," with Loc Nguyen, U.S. Navy, 8th International Conference on Marine Applications of Composite Materials, Melbourne, FL, March, 2000.
8. *MARINE COMPOSITES*, Second Edition, 377 pages, 1998, Annapolis MD.
9. "The Development of a Standard Shipboard Strain Recorder," 1987. SSC-344, Final Report for the SSC.

Mark S. Krawczewicz, Electrical Engineer

EDUCATION

B.S. Electrical Engineering, University of Maryland, College of Engineering, 1984
Graduate Program, Johns Hopkins University, Applied Physics Lab
Graduate Studies, George Mason University, Computer Engineering
Part time Adjunct Professor, Loyola College, College of Engineering, 2000- present

SECURITY CLEARANCE

TSSI Security Clearance

EXPERIENCE

Tocreo Labs, Chief Executive Officer, July 2009 - present
Tocreo Labs is developing several products including, thin film power harvesting, medical, security, authentication, and security smart cards integrating displays, sensors, and actuators.

Priva Technologies Inc., Executive VP of Travel Division & Product Development, April 2007 – July 2009
Patented novel authentication technology (Patent pending no. 61025088). Successfully launched a smart card integrating a plastic display from concept to prototypes for live pilot for secure airport authentication of employees and flyers. Patented display obfuscates user's photo & biographic data until authentication, then switches display states inside secured area. These prototypes were then designed into high volume / cost efficient products. Other duties included hiring, strategic planning & forecasting, sales & marketing, management, program review and partner agreements & program development.

National Security Agency, Cryptographic Product Development Technical Director, Feb 1984 – April 2007
Crypto Modules Product Group INFOSEC
Mr. Krawczewicz designed & developed the Secure Key Storage IC, novel active tamper for crypto modules. He was part of Senior Technical team working with leading US security companies to evaluate & enhance their security products.

NSA – Chairman, The Secure Mobility Forum
Mr. Krawczewicz started and ran this National Conference to bring Government Labs, Academia, and small innovative companies together to solve the problem of securing mobile devices. He also led an internal NSA integrated process team to tackle the same challenge.

As a Senior Electrical Engineer at NSA for INFOSEC, Mr. Krawczewicz managed security for Bluetooth, Land Warrior, Risk Adaptable Security Policy, LPI / LPD/ AJ, and software defined radio. As a Research & Engineering Hiring Executive, he was responsible for hiring for R2, M1, and R5 personnel.

With responsibility as Secure Token Technology Team Leader, Mr. Krawczewicz initiated and led the Smartcard research effort for NSA. As a Biometric Analog Sensor IC Designer, he designed numerous CMOS imaging sensors. He started his career at NSA as a High Speed Key Generator Designer working with integrating circuits, including Key Generators, Analog Sensors, Randomizer, biometric sensors, and secured memory.

Kraz Publishing, Chief Executive Officer, Aug. 1987 – June 2001
Mr. Krawczewicz managed production and sales operations for a monthly periodical that supported the real estate industry. Kraz Publishing was named one of the top 10 of 400 franchises in the U.S. for 8 years

Facilities/Equipment

For our Phase I option we are proposing to test elements of the candidate wave energy harvesting system in the U.S. Naval Academy's 120-foot towing tank in Annapolis, shown in Figure 29. The 120-foot towing tank is the workhorse of the laboratory and is in use almost every day when classes are in session, so we propose to do our experiments from June until August. This tank has a dual flap wavemaker and is used extensively for wave measurements, resistance and seakeeping experiments. Waves from .4 – 1.6 Hz can be generated at amplitudes of up to 0.75 feet, which will be suitable for doing ¼- to full-scale experiments. Because the overhead costs of the Towing Tank facility are covered year-round, we expect to fund our modest requirements for Phase I Option work using a MPIR arrangement between NAVAIR and the USNA. Phase II testing will require a more formal contracting arrangement to include full-time summer involvement of a USNA professor.

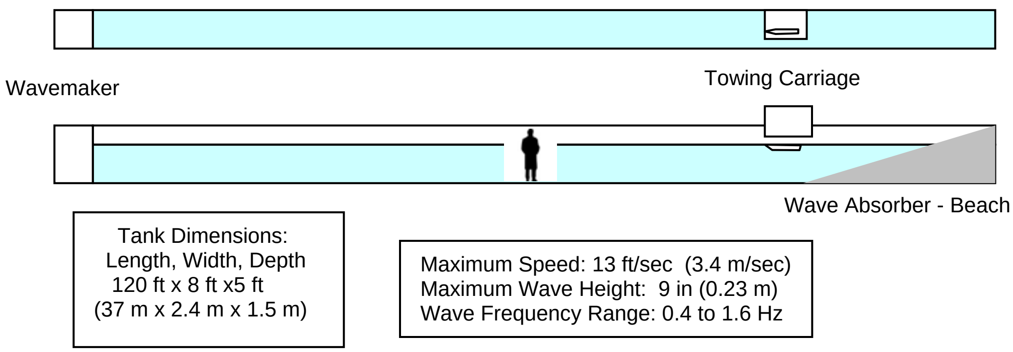
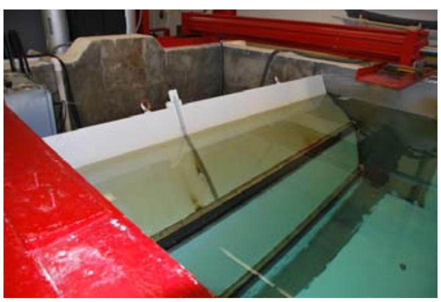
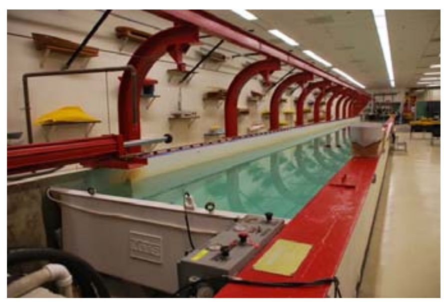


Figure 29. Above is A Schematic of the U.S. Naval Academy's 120-foot Wave Tank. At Right is Co-Investigator Mark Krawczewicz alongside the Tank. Below are Photos of the Tank's Wave-making Mechanism





Subcontractors/Consultants

Eric Greene Associates, Inc. will subcontract to AdaptivEnergy for the Phase I Option portion of this project.

Prior, Current, or Pending Support of Similar Proposals or Awards

Eric Greene Associates, Inc. does not have any prior, current, or pending support of similar proposals or contract awards.

References

1. Flaherty, C., “Patrolling the Front Lines of History,” *Proceedings*, U.S. Naval Institute Press, Annapolis, MD, September, 2009.
2. Naeije, M., Scharroo, R., and Doornbos, E., “The Next Generation Altimeter Service Challenges and Achievements,” Proceedings of ‘Envisat Symposium 2007,’ Montreux, Switzerland, April 2007.
3. Musial, W., “Ocean Energy Activities in the United States,” International Symposium on Water & Energy, Instituto De Ingenieria, Mexico City, Mexico, March 22, 2007.
4. McCormick, M.E., ***Ocean Wave Energy Conversion***, Alternate Energy, A Wiley Series, 2007.
5. Cruz, J. (ed.), ***Ocean Wave Energy, - Current Status and Future Perspectives***, Springer Series in Green Energy and Technology ISSN 1865-3529, 2008.
6. Tanner, T. “Energy Harvesting—The Next Evolution for Wireless Sensors,” http://wireless.sensorsmag.com, Oct 1, 2008.
7. Aleksandr S. Nagorny, A.S., Jansen, R.H. and Kankam, M.D, “Experimental Performance Evaluation of a High Speed Permanent Magnet Synchronous Motor and Drive for a Flywheel Application at Different Frequencies,” NASA/TM—2007-214428, December 2007.
8. Neueschwander, V. U.S. Patent 4539485, “Buoy Coupled with Piston to Linear Generator,” 1985-09-03.
9. Danielsson, O. “Design of a Linear Generator for Wave Energy Plant”, masters project, Uppsala University, Sweden, Jan. 2003.
10. Ivanova, I. “Simulation of a 100 kW Permanent Magnet Octagonal Linear Generator for Ocean Wave Conversion”, Uppsala University, Sweden, 2007.
11. Smith, P., “Navy/Marine Corps Power Needs and Initiatives,” NSWCCD, 10th Electrochemical Power Sources Symposium, Williamsburg VA, August, 2007.
12. Percival, R., “New Device Class Stores Harvested Ambient Energy,” Infinite Power Solutions, Electronic Products Power Supplement, A Hearst Business Publication, August, 2009.
13. Patuxent River Naval Air Museum, Sonobuoy display funding provided by NAVAIR and Navmar Applied Sciences Corporation, Lexington Park, MD.
14. Tolkoff, S.W., “Robotics and Power Measurement of the RoboTuna,” Masters Thesis, MIT 1999.
15. Triantafyllou. M.S. “Origins of the MIT RoboTuna, MIT Ocean Engineering Department, http://web.mit.edu/towtank/www/Tuna/Tuna1/origins.html
16. Shinjo, N. “Investigation into the uses of Shape Memory Alloy of Biometric Propulsion of Underwater Vehicles,” PhD. Dissertation, Florida Institute of Technology, August, 2005.
17. Taylor, G. U.S. Patent 4404490, “Piezoelectric Element Under surface – Power Generation from Waves Near Surface of Bodies of Water,” 1983-09-13.
18. Johnson, A.P., “Battery Systems for Maritime AUVs,” Electrochem Commercial Power, OCEANS 2007 Conference, Vancouver, BC, CAN, Oct. 2007.
19. AN/SSQ-101 ADAR Sonobuoy Specification Sheet, Sonobuoy Tech Systems, NSN: 5845-01-453-8699.
20. Commander, U.S. Pacific Fleet & Commander, Third Fleet, U.S. Navy, “Request for a Letter of Authorization for the Incidental Harassment of Marine Mammals Resulting from Navy Training Operations Conducted within the Hawaii Range Complex,” submitted to Office of Protected Resources, National Marine Fisheries Service, NOAA, July 2007.
21. Taylor, G., “Ocean Power Technologies,” presentation at the Global Marine Renewable Energy Conference, OREC, Washington, DC, April, 2009.