Evaluation of Solar Cells as a Potential Power Source for Shallow Subtidal Instrumentation

A Capstone Project Presented to the Faculty of Earth Systems Science and Policy in the
Center for Science, Technology, and Information Resources at California State
University, Monterey Bay in Partial Fulfillment of the Requirements for the Degree of
Bachelor of Science

By
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To the ESSP Faculty,

This capstone project is designed to determine whether solar cells can provide an effective alternative to batteries as a power source for shallow underwater scientific instrumentation. If so, solar cells may replace batteries, lowering research costs, and saving time by not having to replace batteries. These benefits might also have a positive impact upon the policy implications of that research. The results of this project should give an indication of the success of underwater testing of solar cells, and then relate the various impacts (economic, mobility, maintenance, etc.) related to using solar cells instead of batteries as a power source in underwater instrumentation.

My target audience is the researchers that would benefit by using this technology in their research. To estimate the cost of underwater research with dataloggers, using solar cells vs. batteries, I contacted two outside researchers to receive current costs of diving and research travel, as well as costs of batteries and non monetary expenses. I asked the researchers if they would have interest in my research, and if they would foresee using this technology within their instrumentation in the near future.

I contacted Dr. Brian Helmuth (University of South Carolina), and Dr. Jim Leichter (Woods Hole Oceanographic Institute). Dr. Helmuth replied with responses that were honest and helpful, stating that the use of the solar cells would also prove to be solid and secure. They would have to be able to withstand the rough physical environment and still be effective in powering their instrumentation. Though unstudied, I feel that these cells would have to be well protected from damage because the cells themselves are glass-like and probably much more fragile than batteries. This would add to the cost of using solar cells to replace batteries. Dr. Helmuth also provided data, which is reflected in the following paper, within the discussion of cost and feasibility of using the solar cell design.

I chose to do this project because cheap and effective ways of collecting environmental information are essential for the agencies and researchers that have an influence on public policy. The researchers want their data to be as accurate and cost effective as possible. The data retrieved from dataloggers using solar cells might have the ability to be more precise than the data collected from instruments which run on batteries, due to a possible decrease in human impact upon the studied area (because of battery replacement, maintenance, etc.). They also might have the ability to be more cost effective because of the ability of solar cells to provide energy from a continuous source.

There is some light available at shallow depths within some of these studied habitats. If the use of solar energy for this instrumentation is possible, then the amounts of time and money saved by converting may be significant to the researcher. This conversion also has the capacity for being "greener" due to the reduction of use of typical (and toxic) throw away batteries.

Please assess my project within the following foci:

- Application of Knowledge in the Physical and/or Life Sciences (MLO#3)
  I chose this focus because of the physical limitations studied in this report that determine the success or failure of the solar cells to provide a usable amount of energy for underwater instrumentation.
- Acquisition, Display, and Analysis of Quantitative Data (MLO#5)
  I chose this focus because I will show through experimentation the ability or inability of solar cells to provide a usable amount of energy for underwater instrumentation.

There are many assumptions included in the process of this report. I assume that there is a need for improving research techniques. I assume that this would prove to be useful to someone. I also believe that there are benefits (cost, reliability, etc.) from using solar power underwater. Also, I make the assumption that solar cells are better for the environment than everyday "throw away" batteries. Understand that these biases are my motivation for completing this project, but they should not contaminate the findings of this report.

Thank you for your interest and time.
Sincerely,
Nathaniel Atherstone

Abstract

Solar power has the potential to provide a limitless and cleaner form of energy than everyday "throw away" (alkaline, lithium, Nickel Cadmium, etc.) batteries. The goal of this project was to determine whether or not solar cells could provide an effective alternative to batteries as a power source for shallow underwater scientific instrumentation. This was achieved by researching the most appropriate types of solar cells available, and then testing their capabilities both on land and below the ocean. The solar cells used seem to be an expensive and highly limited option. The 37mmx33mm solar cells I used can provide 5.5V with 0.275mA current at a depth no greater than 10 feet, midday. The circuits using solar cells in conjunction with capacitors do not seem economical when comparing with batteries to power the same small dataloggers. Pros and cons of solar power are discussed along with further research ideas aligned with this topic.

Introduction

The goal of this project was to determine whether or not solar cells could provide an effective alternative to batteries as a power source for shallow underwater scientific instrumentation.

Researchers use instrumentation to study the specific properties of habitat and ecological development, both before and after human interaction. Data collected from underwater instrumentation can influence decisions about how those habitats are studied, used and protected. The accuracy and viability of that instrumentation is important when decisions are made.

There are researchers studying the properties of shallow water ecological habitats, these studies have potential policy implications. The following are just a few of the people who are doing research that has an effect on policy and decisions that are made about their studied habitats.

Dr. Bob Richmond, a researcher at the University of Guam, is interested in spatiotemporal patterns of sedimentation. Excess sedimentation kills off corals and has been on the increase near river mouths with the development of golf courses, hotels, and other tourist industries. His research has major policy implications for the development of the tourist industry within Guam, and development worldwide. (Moore personal comm., 2000)

Dr. Jim Leichter, a researcher at the Woods Hole Oceanographic Institute, is looking at internal waves of cold deep water that "splash" up onto reefs by cross-shelf upwelling. His research studies "the influences of physical forcing and environmental variability on the dynamics of near-shore benthic communities." (Leichter, 2001) The data collected and studied helps to determine the physical and ecological aspects of coral reefs, and the implications of global climate change.

Dr. Brian Helmuth, a researcher at the University of South Carolina, is looking at small-scale (sub-meter to several meter) light, heat, and flow patterns and their effects on coral growth. His research focuses on "quantifying the mechanisms by which organisms interact with their physical environment, the effects of these processes on the physiological performance of individuals, and the subsequent consequences of organism/environment interactions to population and community ecology." (Helmuth, 2001) The data collected and studied helps to determine the physical and ecological aspects of coral reefs, and the implications of global climate change.

Dr. Steve Moore, a researcher at the California State University Monterey Bay, is studying flow microhabitats and their effect on distribution of marine organisms in Monterey Bay, CA. The management of the ecological systems involved is dependent upon understanding the various physical and ecological interactions within that ecosystem. His current research involves improving spatiotemporal research techniques using relatively small, inexpensive, yet effective instrumentation. (Moore personal comm., 2000)

The usefulness of the spatiotemporal data collected with underwater instrumentation in the above research is dependent on the reliability of the data collected. Spatial precision, resolution, and area covered can increase with more instruments, so many instruments are needed to determine the relationships accurately (Moore, 1999). But the costs of the instrumentation and the budget of the research typically limit the number of instruments available to the researcher. So, if instrumentation can become cheaper, more instruments can become available for the research.

These instruments currently rely upon batteries for an independent energy source, allowing for placement in remote areas. But the batteries hold a heavy cost. Budgets are limited, and research is limited upon the amount of batteries that can be bought, because batteries are a primary cost of this type of research. Also, the life span of those batteries is limited, requiring dive and travel costs associated with battery replacement.

Aside from monetary costs, continued diving within the research site takes time. The time could be used doing other forms of research in the area. Also, continued intrusion within the studied site causes more human interaction within the data set, causing possible errors in the data.

When looking at the problems attributed to the use of batteries I questioned if there is a better way. If solar power could allow for a self-sustaining energy source for the instrumentation, then there is a possibility to decrease the costs of research (costs of batteries, diving and travel) and increase the accuracy of the data, due to fewer human interactions with the research site. But is there enough light underwater to make solar power viable?

Light intensity decreases with depth in water, and the attenuation is greater for red light than for blue light.
According to Denny (1993) the attenuation of the light can be determined by Lambert's Law:
$I_{(x)} = I_{(o)}e^{-\alpha(\lambda)x}$ where $I_{(o)}$ is the original intensity at the surface, $I_{(x)}$ is the intensity after traveling distance x through the saltwater, $\alpha(\lambda)$ is the attenuation coefficient, which varies with wavelength (λ). For red light ($\lambda = 700$nm) the attenuation coefficient is about $10^{-0.5}$, and for blue light ($\lambda = 460$nm) the attenuation coefficient is about $10^{-2.5}$. Using this equation we can determine that only 3% of surface levels of red light ($\lambda = 700$nm) is available at a depth of 10 m, whereas 95% of blue light ($\lambda = 460$nm) is available at that depth (Denny, 1993). The attenuation of infrared light is even stronger, with essentially none of it reaching 10m depth. This presents a potential problem with regard to solar power, as most of the commonly available solar cells respond primarily to red or infrared light (Shah et al, 1999). The problem becomes even more serious when one considers turbidity. Turbidity can further reduce the amount of light reaching an underwater solar cell by absorbing UV and visible light (Gonzalez and Carroll, 1994).

Monterey Bay ocean waters are turbid waters. They have high levels of nutrients, which allow for high levels of life. High levels of algae and phytoplankton on the ocean surface are a direct result of coastal upwelling, which results from the approaching currents into the bay. At times the visibility of the waters is no greater than a few feet. (MBNMS, 2000) This limitation to light penetration is a fundamental factor for this project. If the cells are effective here, under some of the worst conditions for light absorption, then they can be effective in places where the conditions are better, such as tropical seas, where waters are typically much clearer.

The properties of electricity are important to understand in order to get the full idea of what is happening in this project. The following is a quick review of the electrical properties commonly discussed throughout this paper. All entries are obtained from Wolfson and Pasachoff, 1995.

- Electric charge is the total amount of charged atomic particles (protons, or more commonly electrons) that are moving around in the circuit. Electric charge is commonly measured in Coulombs. A Coulomb (C) is the SI unit of charge equal to 6.25×10^{18} elementary charged particles.
- Electric current (I) is a net flow of a specific amount of electric charge per a specified amount of time. The unit of electrical current is the Ampere (A) (commonly abbreviated as an Amp. 1Amp = 1 Coulomb per Second.(1A=1C/s)
- The Volt is the potential difference of a charge, or the "electrical pressure" it would take to move that charge through a circuit. The units of a Volt (V) are Joules per Coulomb. (1V = 1J/C)
- Energy is the amount of work that it would take to move that charge at a specific current with the voltage involved. That work is dependent on the voltage multiplied by the current. A Joule (J) is the SI unit of energy, or work. (1J = 1VC).
- The electrical Power (P) of the system is the rate at which the work is done within the circuit. The power is the amount of charge per second times the "electrical pressure" placed upon that charge as it is moving (P = V(C/s) = VI). The SI unit of Power is the Watt (W) (1W = 1J/s)
- When a voltage causes current to flow there is generally some "electrical resistance" that limits the current flow. Resistance is defined as the voltage required to produce a unit current. (R= V/I) This is known as Ohm's law, and is later used to measure the Current of the solar cell system with the known Voltage and Resistance. An Ohm (Ω) is the SI unit of resistance.

These are electrical properties that are associated within all circuits, including a solar powered system. The solar cells turn the available light that is absorbed by the cells into electricity by inducing a charge across semi-conducting metals, creating a potential across that charge (voltage).

To convert light into electricity, all photovoltaic cells rely on different bands of semi-conducting materials (Service, 1996). Most photovoltaic solar panels are typically made with silicon, which is capable of producing an electrical current when exposed to most of the visible spectrum, and near-infrared light (Shah et al, 1999). A gallium-arsenide band can be used within a photovoltaic solar panel. Gallium Arsenide (GaAs) is more sensitive to wavelengths from the ultra-violet through the visible portion of the spectrum (Unal and Bayliss, 2000). When these two layers are "stacked" within a photovoltaic cell, the efficiency (ability to convert light into electrical current), and spectrum of absorption are increased. Using a GaAs layer nearly doubles the efficiency of a standard silicon-based solar cell (Burggraaf, 2000).

Shallow marine habitats offer a fair amount of visible light. This light can be absorbed by sensitive photovoltaic solar panels at shallow depths, but light availability will decrease as you increase depth. If the solar cells are efficient and reliable sources of energy for dataloggers within the shallow depths of the ocean, then research processes and data collection techniques in shallow water research can benefit from this. With usage of small and simple integrated circuit (IC) design, one can build dataloggers that can be used to sense simple, yet fundamental properties of shallow water environments (Moore, 1999). If these simple circuit designs have a small power draw, then there would be a higher potential to power these dataloggers with a solar cell design. Also, if the datalogger IC is designed to work with a solar cell design, then the limits of the data collection timeline might be influenced by the ability to replenish a store of energy instead of relying upon a completely exhaustible source (battery). For example, a simple datalogger, which would take data for 2 months at a time with a 9V battery, could potentially be able to retrieve data indefinitely with a solar cell design.

This understanding can be further developed into economic cost analysis. If the dataloggers are placed in a remote area and if battery replacement increased the total amount of visits, then the costs of travel and research could be drastically reduced. Travel costs alone can be a major element if data collection can be reduced from monthly to yearly intervals due to the ability of the datalogger to gather its own energy for use via the solar cells.

The limiting factor for retrieval intervals of the dataloggers would be placed from the energy availability (diving to replace batteries) to the amount of data that can be collected (diving to retrieve data). With the recent technological advancements over the last 20 years, we now have the capability to collect large amounts of data at a time. Utilizing this advancement, combined with a solar cell design, a simple IC datalogger has the potential for being left alone for years at a time to collect data. Also, if the data is retrieved remotely by satellites (clearing the collected memory storage), then the datalogger could be left within the testing spot indefinitely, without any disturbance to the testing environment while allowing for "up to date" data collection.

Methods

I first determined the amount of available radiation to determine what types of solar cells would be most effective in absorbing these wavelengths. The amount of available radiation both above and below ocean waters was calculated from information provided by Denny, 1993 (Chapter 11 [Pages 226, 232-233]).

In consultation with Dr. Moore, I determined that 2 different **Panasonic** *Sunceram* photocells would be appropriate for the project. They are gallium arsenide and silicon based, which allows them to absorb a greater spectrum of light than basic silicon cells. The bigger the spectrum available for absorption, the more likely the cell can absorb the levels of light available within the ocean. The largest cell measures 37x33mm. The smaller cell measures 24x22mm.

I then recorded and plotted the current and voltage outputs of the cells, testing daily on dry land (using a voltmeter). I tested each of the two cells under different light conditions. Each day I used a wide range of resistors to help determine which condition provided the most power out of the cell. I then plotted the information as voltage vs. current. This plot showed the power output of the solar cells on land to use as comparative data, and as a control. After acquiring this data, my advisor and I determined if we could use these cells for this project.

After land testing, I arranged for a single underwater test dive at different depths by Dr. Moore. We configured a simple circuit, which measured the voltage outputs of the solar cells with a 20k-resistor load. This circuit was placed within an underwater flashlight housing with the solar cells facing up against the clear face of the flashlight. The dive determined if there was any potential of the cells to work underwater, and gave further motivation for the project. By comparing this data with the dry land data, we calculated a crude estimate of how much current and voltage we would have available to us for use within a datalogger.

I also researched up to date information on rechargeable battery pack developments. I used this information to determine that using a rechargeable energy storage unit was currently improbable, knowing the underwater outputs of voltage and current underwater by the cells. I then compared the use of rechargeable batteries with the use of a capacitor. A large capacitor would be able to store relatively small amounts of energy at different rates/levels of recharge. We determined that a 5.5V 1-Farad super capacitor was appropriate based upon a solar kit designed by Parallax, Inc. for a BASIC stamp. Thus a capacitor shall be considered the energy storage unit from now on.

I tested the hypothesis that a capacitor would discharge back through the solar cells when dark. I charged the capacitor up to a known voltage and left the capacitor attached to the 24mmx22mm solar cell for a period greater than 24 hours. I measured the rate of the voltage drop, and then incorporated the collected information from this test into the construction of the circuit.

In collaboration with Dr. Moore, I designed a circuit (Fig1) that would measure the output of the solar cells at a particular depth for an extended period of time. I used a voltage divider to decrease the voltage output of the solar cells (by ~ 1/3), because the cells can generate a voltage greater than the maximum level of imput into the datalogger (~ 5v) when in series, in bright sunlight. Then I attached the datalogger measuring the voltage output from the solar cells. It also measures the voltage of the capacitor. The voltage of the solar cells and the capacitor were measured in 5-minute intervals for a full 48 hours.

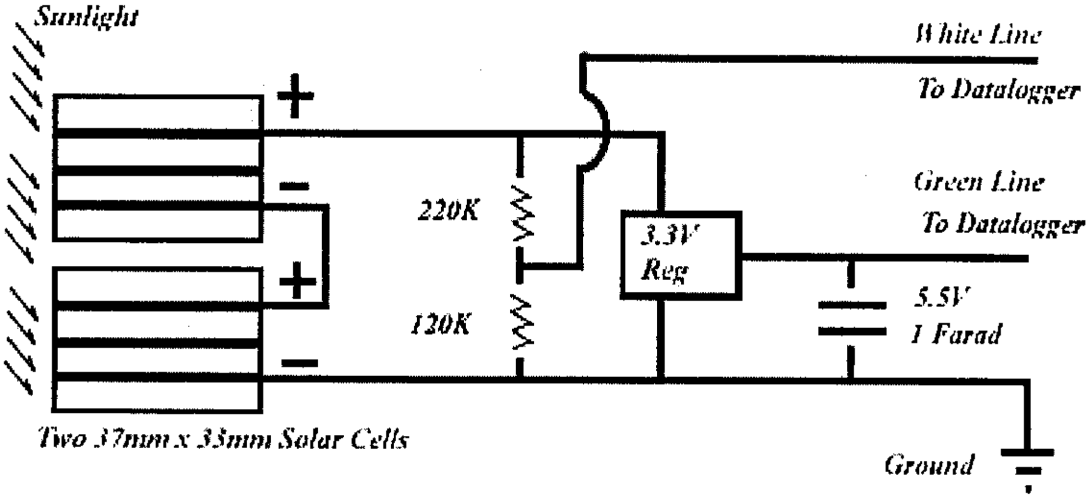

Figure 1: Circuit design to the datalogger which will record a known fraction of the voltage output of the solar cells over time along the white line, and the voltage of the capacitor over time along the green line.

This circuit is planned to be placed in an underwater dive light housing with the solar cells placed face up through the clear face of the flashlight. The flashlight will be placed at a 20ft depth in the Pacific Ocean at McAbee Beach, Monterey, CA for a full 48 hours. (This test is planned but will not be completed before this report is submitted)

While the datalogger is underwater, information on the weather, tide, and solar patterns will be recorded. This data will be used later for understanding why the data might be different from day to day, and will help in understanding what can and might have happened during the test. It is also important to understand the sunrise/sunset patterns during the testing period, as well as the tidal variation during the test.

After retrieving the datalogger, I will be able to determine the power output of the cells underwater and estimate the ability to use the solar cell for simple, shallow water, datalogger power, with the information within the datalogger. From this information determine if the test needs to be run again, and compare the daily activity of the cells and the capacitor over time.

If the testing proves to be successful, we can then determine what it would take to incorporate the cells and capacitor within a datalogger, which will draw no more current than the solar cell proved to provide. I will then be able to determine the output of the solar cells as a function of depth, allowing for a judgement of the depth where a datalogger can effectively use solar power based upon the amount of voltage and current needed to run that instrument effectively.

Results

Dry Land Testing:

Data on the current and voltage outputs of the cells were recorded and plotted, testing daily on dry land (using a voltmeter). The testing was held within Frederick Park, at CSU Monterey Bay. The conditions of each day are as follows:

- Day 1 – Clear skies with no clouds. ~ 70°F 12/07/00 From 1:30pm to 3:00pm.
- Day 2 – Partly cloudy skies, 25% cloud cover. ~ 70°F 12/06/00 From 1:30pm to 3:00pm.
- Day 3 – Cloudy skies (80%) high winds with small gaps in clouds. ~65°F 12/11/00From 12:30pm to 2:00pm.
- Day 4 – Overcast skies, full clouds. ~60°F 12/09/00 From 11:45am to 1:30pm.

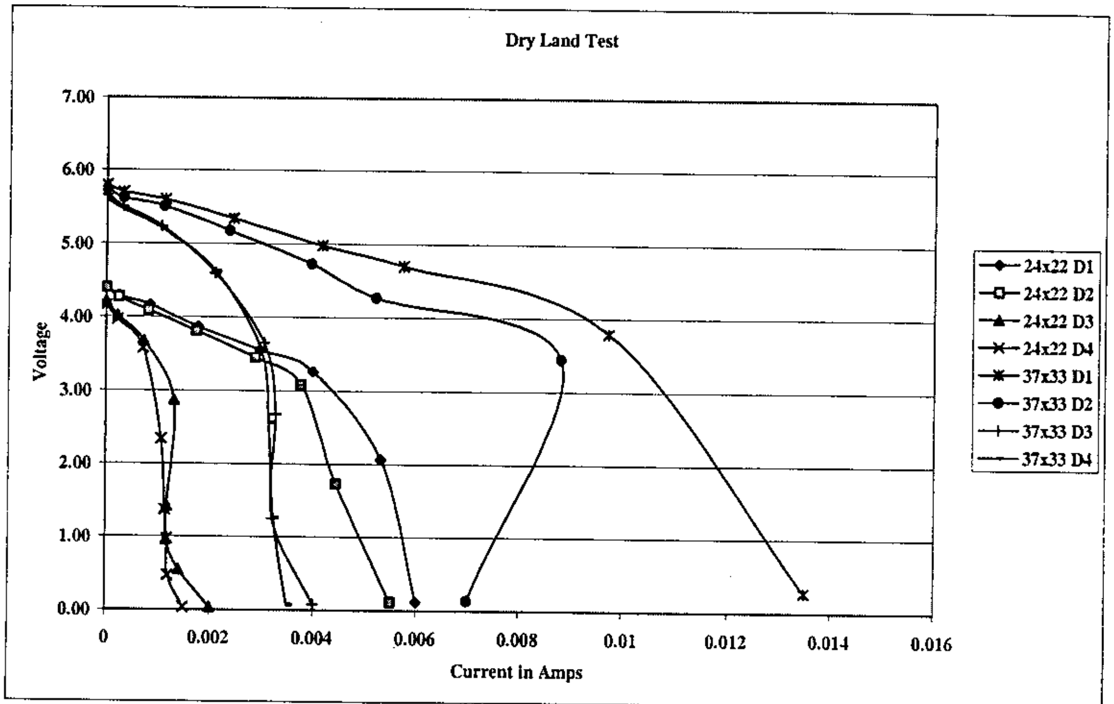

Figure 2: Data Graph illustrating relationship between Voltage and Current output of cell for each day, for both the larger (37mmx33mm) and smaller (24mmx22mm) solar cells.

Single underwater test dive voltage and current outputs of the solar cells recorded by Dr. Moore:

The following are data in the form "depth" = "voltage" obtained during a dive over the Hopkins shallow reef just offshore of Hopkins Marine Station in Pacific Grove, CA. Data were taken on a clear winter day with bright sun, about 11:00 am, in surgy water with poor visibility (about 20' near surface, falling to about 10' near bottom due to stirred up sediment and debris). The circuit measured the voltage outputs of the solar cells with a 20k-resistor load. Readings were made with the photocell pointed up toward surface through the clear plastic lens of a flashlight housing, but not always directly at the sun. Each point was taken for a minimum of 20 seconds.

At surface = 5.5-6 volts
10 feet underwater = 4-5 V
20 feet underwater = 3-4 V
30 feet underwater = 1-3 V
40 feet underwater = about 1 V or less

The wide variations in readings with depth apparently were due to orientation of panel with respect to sun, kelp shadows, and/or variations in local water clarity. These will, of course, be factors in any real deployment. (Moore personal comm., 2000)

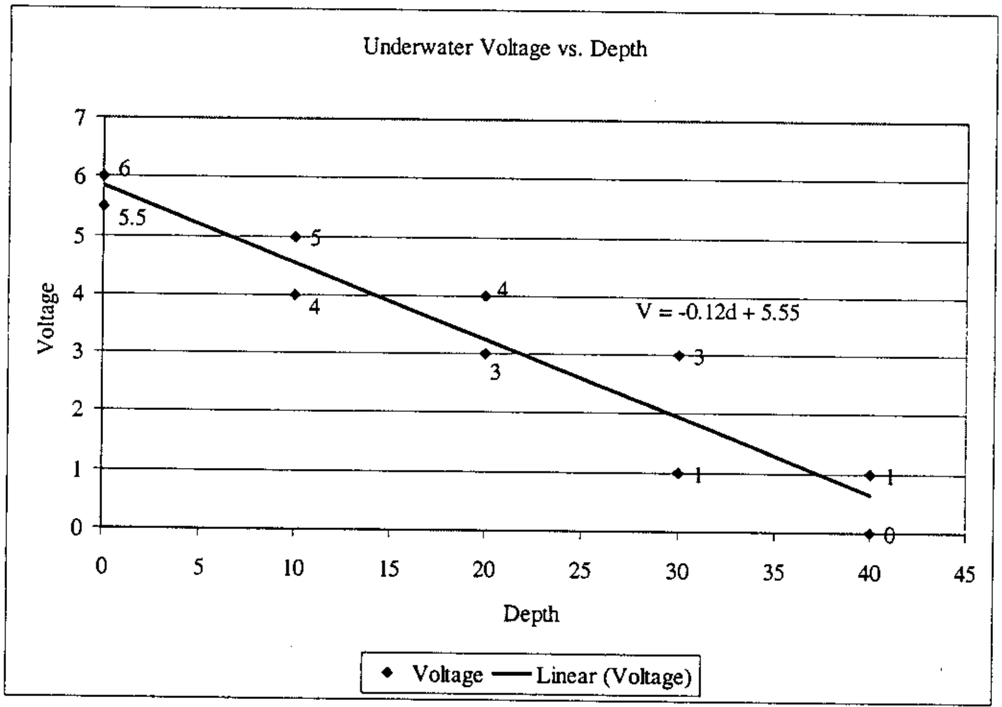

Figure 3: Underwater test dive data relating Voltage to depth, with added trend-line to estimate function of voltage and current to depth for 37mmx33mm solar cell. This data was taken using a 20k resistor.

The maximum voltage was 5.5V at the surface. The maximum current was 0.275mA at the surface as well. This was calculated using Ohm's law knowing the value of resistance as 20kOhm and the voltage being 5.5V

Charge Rate of Capacitor in Full Sunlight

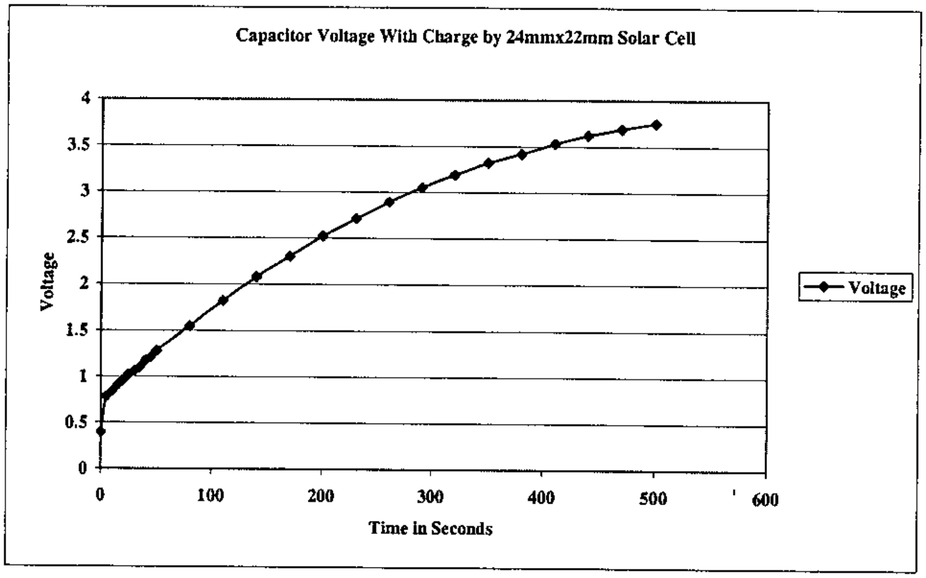

Figure 4: Rate of charge over time of 5.5v 1-Farad Super-capacitor receiving amount of light which would provide a potential 4.4V from the small (24mmx22mm) solar cell. Data taken on 3/11/01 at 9:20am with clear skies.

Capacitor Drain in Darkness

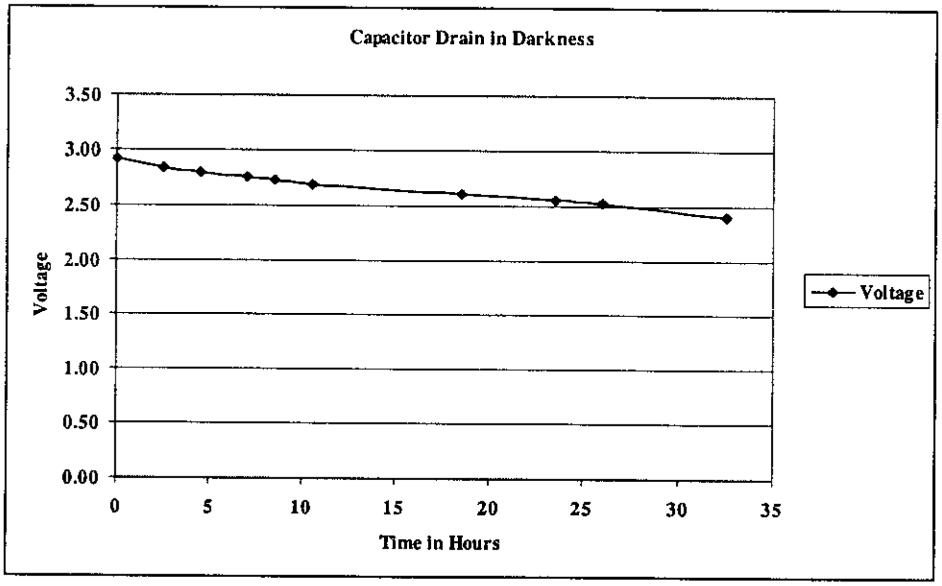

Figure 5: Data set of draw of voltage over time of a 5.5v Super-capacitor receiving a 0v potential from the small (24mmx22mm) solar cell. Data taken within a "dark box" containing the capacitor and solar cell circuit, allowing for the circuit to be in the dark for the duration of the test.

Discussion and Analysis

We designed the final test circuit to measure the ability of the solar cells to collect and store energy underwater. For an efficient circuit design we tested the abilities and relationships between the solar cells and the capacitors we wanted to use. Each of these tests had an influence upon our circuit design through their conclusions.

The results from the dry land testing (See table 1, fig. 2) indicate that the highest output from the 37mmx33mm solar cell is no more than 6v and the largest available current was 13.5 mA. The highest output from the 24mmx22mm solar cell is no more than 4.5V and the largest available current was 6 mA. This information was vital to determine the range of available voltage output we could have with the solar cells chosen. This would then be used to determine how we would recharge the capacitor, and how we should regulate that charge within the circuitry. This was determined under optimal conditions, on land, not underwater.

The charge rate of the capacitor, in full sunlight, determines the capability of the solar cells to charge the capacitor during a clear day at the surface. Knowing the rate of the cells in charging the capacitor is important because the cells might be subject to variability in light. The charge rate lets us know how efficient the capacitor is when there is a good source of light. This data shows that the cells charge the capacitor relatively quickly in full sunlight, to a rate of about 3v/5min when approaching the maximum voltage available by the solar cell. (See fig. 4)

The "Capacitor Drain in Darkness" test (See fig. 5) shows that there is a loss of energy by the capacitor when the solar cells are placed in the dark (0V). This means that we need to use diodes in our circuit to prevent the loss of voltage held within the capacitor when the cells are in the dark. This was determined because unnecessary diodes would increase the amount of energy needed to run the circuit as a whole. Diodes create a small loss of total voltage to use, but they prevent a loss of voltage within the capacitor to the solar cells when the cells are subject to little light.

Due to unforeseen problems with dive scheduling and the datalogger, which would have measured the voltage output underwater over a 48 hour period of time, the designed circuit has not been tested underwater. Instead, we will use the preliminary test dive taken earlier to help determine the feasibility of underwater solar cells. This is currently the only underwater data that we will be able to use due to this unfortunate problem.

The underwater test dive voltage and current outputs of the solar cells (recorded by Dr. Moore) gives us an indication of about how much light is going to be available on a "typical" dive day (see fig. 3). This information provides a basic understanding of what we could expect from further testing with the final circuit design.

With this data we can determine an estimate of the voltage and current with respect to depth for the 37mmx33mm solar cell. The trend-line function for voltage is $V= -0.12d+ 5.55$ (where $V=$ volts, and $d=$ Depth). The trend-line function for current (using a 20k resistor) is $I = -0.006d + 0.2775$ (where I = current and d = Depth) calculated using Ohm's law.

These functions can be used to determine how much voltage or current you can get at the studied depth. Or they can be used to determine the maximum depth you can study, with a known voltage or current draw from your datalogger. We will use these trend-lines to determine if solar cells can power a datalogger at a 10' depth. The available estimated maximum Voltage at 10' is -0.12

(10)+5.5= 4.3V. The available Current (in mA) with 4.3V at 10' is –0.006(10) + 0.2775 = 0.2175mA. These numbers are the peak amount average.

This amount of light is only available during a clear day for approximately 4 hours, not 24 hours. This is important to understand when designing the solar cell circuit. In order to maintain the necessary voltage for 24 hours you would need to compile excess charge (~ 6x the necessary amount) and store it within your capacitors in order to reserve that energy for the times when there is insufficient light. By storing excess charge within your capacitors, you will have a greater voltage for that charge as it moves within the circuit.

By producing 4.3v with one 37mmx33mm solar cell underwater at 10', we can then estimate how many solar cells it would take to run a datalogger at various voltages at 10'. For example, Dr. Helmuth uses an Onset datalogger that measures water temperature. The datalogger uses a 3.6V lithium battery, and draws a current of 0.206mA and can take measurements for up to one year. Assuming that the datalogger is receiving no less light availability than received during the test and runs with a resistance of 20k, then we could, in theory, effectively run the datalogger with 6 37mmx33mm solar cells, with 2 sets of three linked in series (maximum voltage of 12.9V) and those pairs in parallel (maximum current of 0.435mA). This should provide a sufficient amount of both voltage and current to last the datalogger for the whole day. This circuit would then be connected to two 1Farad 5.5V Super-capacitors each with a voltage regulator. The voltage regulators would limit the amount of desired imput to the capacitor without destroying it.

The costs of the capacitors and solar cells could compare to the costs of battery use within these dataloggers. Dr. Helmuth uses a 3.6V lithium battery for 1 year and one battery costs about $5. The solar cells cost $6.25 each (or 2 for $10) and the capacitors cost $7 each. The total estimated cost to run one datalogger with the solar cells would then be 3x$10 (solar cells) + 2x$7 (capacitors) + 2x$1 (voltage regulators) = $46. By dividing the costs of batteries per year by the cost of the solar cell setup we find that the return cost interval is 10 years.

Travel costs have the potential to be reduced, but it would take a lot of planning. If the design of the datalogger and solar cells were effective and reliable, then the use of independent solar cells could reduce the travel costs for the researcher. Instead of diving every year to replace the batteries Dr. Helmuth could dive every other year to retrieve the data from the dataloggers. Let's assume the dive time was cut in half, thus reducing his annual cost of diving, and travel to his research site. This would save Dr. Helmuth money every other year. This money would contribute to the return cost of using the solar cells as a power source, but that return interval would be dependent on the number of solar cell dataloggers at the research site.

The costs of the batteries and diving time saved can be compared to the costs of the solar cells, capacitors and circuitry needed to run the dataloggers effectively. It is easy to see that there is a potential for reducing long-term costs by using solar cells, but it would require a hefty start-up price. The 10-year interval is a long time for a return on investment, making this use questionable because most research is completed within a few years. However, these dataloggers could be reused and adapted for each research site before and after that 10-year interval.

Another factor to consider is the costs of loss and damage of the dataloggers over time. There is a loss factor in underwater research due to the harsh physical conditions involved in these environments. The costs of loss are greater when using solar cells as a power source. All of the money put into powering the datalogger can be washed away during a storm, and the researcher might not know about it for years because they were saving money by not having to visit their studied site as often. Then all of that time is lost. Before deciding to power a datalogger with a solar cell circuit design the researcher must consider the potential for loss, this is the "gambling factor" in choosing this style of research.

There is also the option for remote transmission of the data. If the solar powered dataloggers were able to transmit their data, by satellite, to the researcher at home, then the weight of costs would be altered. Information from the dataloggers would be up to date, which has many benefits for the researcher. Data can be analyzed and presented without travel. A broken or lost datalogger would be immediately identified. The researcher would save money by only having to travel to the site to replace lost dataloggers. They would never have to travel to the site to retrieve data or replace batteries. This would increase the return cost of the solar cell circuit, but the datalogger would cost a lot more because of the added necessity of power for transmittance (i.e. more solar cells and capacitors), along with the cost of the transmitter.

Conclusions

There is little research covering the use of solar cells for underwater instrumentation. This is unfortunate, but exciting. There is some potential for the use of solar cells to power shallow water instrumentation, shown with the data collected from this project. But it is an expensive and very limited alternative, and seems too risky for most underwater applications. Hopefully this will be a "first step" guide that others can use to advance the possibility for using solar cells for power sources in underwater instrumentation.

I would like to see more research in the use of different prototypes of cells used in various combinations to allow for absorption of a greater wavelength spectrum underwater. Is GaAs the most appropriate solar cell type, or are there better/more economic solar cells, which can be used more widely? Do integrated circuit combinations, of the solar cells and super-capacitors, vary in efficiency?

I would also like to see a more developed cost/benefit analysis between the use of batteries and solar cells. What are the average travel costs and opportunity costs that would be saved by designing a datalogger that would run off of solar cells? Is it truly worth it? I have only one example with average costs, I would like to see someone take this further.

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