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Acknowledgements
The Development and Optimization of Low-Cost Micro-Wind Turbines for Off-Grid Application in Developing Regions
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Automated Shading System: Reducing Home Energy Usage
Matthew A. Jungclaus & Quinn S. Weber
Dear Readers,

I am excited and honored to present the third issue of *The Spectra: The Virginia Engineering and Science Research Journal*. Founded in 2009 by a group of students with a vision to promote undergraduate research, *The Spectra* continues to highlight student creativity as well as the opportunities facilitated by the University of Virginia. *The Spectra* is a two-way bridge, providing a way for student researchers to communicate their achievements as well as for students without experience to cross into the research community. I hope students will realize that not everyone is born doing research. In fact, each author featured in this journal is a testimony to the hard work and perseverance necessary to break into and succeed in the research community. From personal experience, a simple email expressing interest in a professor’s work will open so many doors.

There is no better time than college to explore as many research areas as possible. This year’s issue does a fabulous job in representing the immensely diverse array of research opportunities available to U.Va. students. Undergraduate thesis projects are a great way for students to conduct research and design projects. This year, *The Spectra* features theses ranging from optimizing nanoparticles for diffusion in muscle to creating a model that enables a more energy efficient control of heating, ventilation, and air-conditioning systems in residential buildings. Other students become involved in research and design through university programs, such as ecoMOD, a program that aims to create sustainable, yet affordable, housing units. We are excited to publish an ecoMOD design paper for an automated drape system that reduces energy consumption in the home. A non-traditional engineering research experience can be found with U.Va.’s Policy Internship Program, which gives engineers hands-on experience with science and technology policy. In this issue, policy interns propose how to retain more women in engineering fields and analyze how to advance science in America. Many students choose to participate in summer programs at other universities to expand their U.Va. experiences. One author spent last summer at Illinois Institute of Technology developing a way to improve the body’s ability to regulate blood glucose levels. Undergraduate research at U.Va. does not have to be through an established lab or program. One of our authors conducted an independent research project on low-cost micro wind turbines. Needless to say, there are many research and funding opportunities available for U.Va. students!

Established as a self-governed organization, *The Spectra* owes its success to its student editors who select and peer-review the papers, design the journal, and solicit funding. I have been involved with *The Spectra* since its inception in 2009, and have seen the level of interest and support increase each year. This is an indication not only of the student involvement, but also of the dedication of our faculty and graduate students who help undergraduates pursue research and encourage participation in *The Spectra*. I cannot thank you all enough. The support of several other members from the University community should be recognized as well. Aid from the engineering alumnus Linwood A. “Chip” Lacy Jr., the Office of the Vice President for Research, and the Jefferson Trust, an initiative of the U.Va Alumni Association, has provided *The Spectra* with the means necessary to operate this year and for years to come.

*The Spectra’s* mission is to provide publication opportunities for undergraduates catering to the engineering sciences, promote a community of research, and serve as an educational tool for its readers. We hope that *The Spectra* will impress upon you what U.Va. undergraduate researchers can accomplish as well as inspire you to pursue research of your own.

All the best,

Hannah Meredith

Editor-in-Chief

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Hannah Meredith is a fourth year biomedical engineering student from Richmond, Virginia. She has been involved with *The Spectra* since its inception in 2009, serving as a primary editor, Associate-Editor-in-Chief, and now Editor-in-Chief. In the spirit of undergraduate research, Hannah has explored multiple research opportunities. Going a bit outside the realm of biomedical engineering, Hannah has spent some time researching molecular gastronomy, a non-traditional cooking style that enhances the eating experience by altering the appearance, texture and flavor combinations of food. She also took the opportunity to explore the relationship between engineering and the government one summer through U.Va.’s Policy Internship Program. During her third year, Hannah joined a lab in the biomedical engineering department and started developing a clinical diagnostic test that could be used to detect an infectious strain of amoeba. She is currently finishing up this project as her undergraduate thesis. Hannah also had the opportunity to intern at the Oak Ridge National Laboratory, where she designed synthetic gene circuits to control basic cell functions. This experience sparked her interest in synthetic biology, which Hannah is excited to be continuing after graduation as she pursues her Ph.D. at Duke University. In addition to research and working with *The Spectra*, Hannah has served as Vice President of the U.Va. Biomedical Engineering Society and class representative for the Rodman Council, and enjoys backpacking, cooking and listening to jazz.
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Acknowledgements
Reliable access to electrical power is an essential element in overcoming the stranglehold of poverty in developing countries. Despite well-intentioned efforts, most electrification projects initiated by the developing world end in failure, largely due to high costs, inadequate maintenance, and cultural resistance. This research explores power generation by small wind turbines that are basic enough for an individual in a developing area to build and maintain, using only simple tools and materials. Electrical power can then be produced with both high autonomy and low cost.
Abstract

Nearly two billion people worldwide have no reliable access to electricity, a vital part of the path to development. Micro wind power is one promising solution. Micro wind installations offer environmental sustainability, low capital costs, and excellent adaptability to diverse environmental and cultural situations. Yet, electrification projects in the developing world, including small-scale wind power, have struggled to reach the level of success needed to significantly close the developmental gap. Current studies suggest that this disappointment is largely due to issues with the local stakeholder, including a lack of experience, technical assistance, and funding. This research explores a different approach to technical design as a way to address the economic difficulties of implementing micro wind power installations. The approach taken is unique: the target wind turbine in this study is one that can be both built and repaired using tools and experience available in a developing community. Several different configurations of a battery-charging micro wind turbine were built and tested in both a controlled environment and in real-world situations. Factors analyzed include generator type, blade design, and cost. It is concluded that not only can a micro wind turbine can be built with methods available to developing communities, but such a turbine costs only 40% as much as the best commercial version on a per-watt basis and is far easier to maintain.

Introduction

Centralized electrical power generation and distribution is meager, if not absent, in the developing world. The reasons range from a lack of technology to geographical and economic factors. Yet, electricity is essential. A reliable supply of electrical energy is a necessary element of poverty reduction and economic development (Cecelski, 2000), and it also carries a litany of added economic and social benefits. Among these are improved living standards, higher levels of health, reduced negative environmental impacts, and increased employment (Reiche et al, 2000). A further synergetic benefit is better education. Of the solar-powered households in Kenya with high school-aged children, 47% use solar-powered lighting to study, and the larger the solar installation, the more likely children were to study (Jacobson, 2006). Another benefit is enhanced economics. One study found that for small and micro businesses, electricity can increase worker productivity up to 200% and gross revenues up to 125% (Kirubi et al, 2008).

The most popular and publicized proposed sources of electrical power, especially in rural developing regions, are renewable supplies, usually photovoltaic (PV) or wind systems. These sources of power have perhaps two prominent advantages. They can be easily distributed, easing the infrastructure requirements of delivering energy, and they are also environmentally sustainable, requiring no fuel to run and giving off zero emissions (Sauter & Watson, 2007). The combination of these two factors produces an interesting result: for small (less than 5 kW) applications, renewable energy is actually more economical than conventional forms of energy in an off-grid situation (ESMAP, 2007).

Despite the interest in the electrification of developing areas, actual sustainable progress is far more difficult—electrification projects fall victim to a host of problems. One such problem is the easier availability of traditional alternatives. Some 400,000 people in Africa alone are burning biomass for heat and cooking; it is convenient and an embedded part of their culture, but it is considerably less efficient than modern energy sources and is a cause of numerous health issues (Barnes, Van Der Plas, & Floor, 1997). Other problems involve a lack of financial and technical resources. As a study on solar installations in Fiji concluded, the two biggest problems with successfully installing the solar panels on the island were the high initial cost of the panels and the lack of maintenance to repair frequent technical problems with the systems. In communities surveyed, technical problems were responsible for 236 combined days of power outages from 2008 through 2009 (Dorman, 2011). This is far from an isolated incident. Those working on electrification projects in developing areas often install equipment successfully but then fail to provide adequate maintenance. As a result, approximately half of installed equipment fails in the first year of operation (Vaccaro, et al., 2008) — a staggering figure. Failure is also partially due to ignorance towards local conditions. With an overriding objective to Americanize developing communities, local factors such as geographic conditions or purchasing power have been overlooked. A few projects, however, have managed to avoid some of these difficulties. A 1996 UN-led micro-hydro electrification project in rural Nepal still had 98% of the installations functioning by 2007. Unsurprisingly, the project placed a heavy emphasis on community buy-in and bottom-up participation, including training community members to act as technicians (Yadoo, Gormally, & Cruickshank, 2011). This approach, unfortunately, is altogether too rare.

Small-scale wind power is an emerging field in wind power generation, largely driven by individuals who find the prospect of lower energy bills or no grid connection to be appealing. The small wind industry, however, is not brand new; it has been around for nearly forty years. There is no precise
definition of what “micro” indicates in terms of size or power production, but the range is generally from less than 1 kW up to 5 kW per turbine with a blade length of less than 2 m. Companies such as Southwest Windpower, Bergey, Marlec, Proven (now Kingspan), and Ampair have developed commercial models of this size that are meant for grid tie-in or battery-charging use. Countries around the world, the United Kingdom in particular have made efforts to encourage individuals to use distributed micro wind power, in both urban and rural areas. These efforts have had mixed overall success. In general, the more urban the installation environment, the more problems encountered in installation and operation, including low wind yields, irritating noise, and unexpected turbulence (Peacock, et al., 2007). Simple pole-mounted micro turbines in open areas, especially farms, experienced far more success (Sissons, et al., 2011).

It is worth noting that significant work in wind energy has been produced through non-academic online sources. In Scotland, Hugh Piggott has pioneered extensive do-it-yourself small-scale wind energy projects—designs that have been tested thoroughly and copied extensively. Other prominent individuals in the online community include Dan Fink and Dan Bartmann, (otherpower.com). Most current designs are meant for battery charging with windswept areas of 3-12 m² on farmland in the United States. The majority of home-built wind turbines utilize the Piggott model, which is well designed but requires machining and welding to construct.

There has been little investigation of the use of small wind turbines in a large distributed network to power a community, but such a setup is not unachievable. Several years ago, utilities on the island of Barbados compared several wind-based alternatives as a means to provide a sizeable portion of the island’s power. While traditional large wind turbines were more economical, the study concluded that a significant network of micro (500 W) turbines had the potential to achieve large-scale generation (Bishop & Amaratunga, 2008). Overall, the performance, reliability, and payoff of a micro wind turbine depend largely on the setup and wind conditions. Small wind turbines generally do best when not connected via inverters to a larger grid and when placed in an area that is free of serious turbulence (Glass & Levermore, 2011). Thus, the ideal use of a micro wind turbine is in a battery-charging, off-grid application that is located in a fairly unobstructed rural area.

The goal of this research is to use low-tech design and appropriate technology to overcome some of the obstacles of cost, maintenance, and community resistance that plague current electrification schemes. Instead of relying upon technology filtering down from the developed world and eventually taking hold in the developing one, appropriate technology seeks technical advances that can be immediately applied at a grassroots level in the hands of the people who need it. The goal is to create products that are an order of magnitude more productive than indigenous technology, yet also an order of magnitude cheaper than sophisticated first-world technology—somewhere in between a hand hoe and tractor (Akubue, 2000). Ideal appropriate technology includes products that are constructed at the site of use, are built by locals, use materials found nearby, and are affordable without significant external assistance.

Design

Each component of the wind turbine used in this research was designed to be built with only hand tools. While a table saw, welder, hand saw, and lathe would have significantly shortened construction time, just a handheld electric drill, a jigsaw, a circular saw, and a few other hand tools were used. It would be possible to build either version of the turbine (described below) without the use of any powered tool other than a drill, but much more effort would be required. Every element used—except the magnets, magnet wire, and one commercial DC generator—was either purchased at a standard hardware store or found in scrap bins. Special attention was given to materials that would be available even in developing areas. Therefore, about 90% of the finished turbine was built using wood and pipe (PVC or steel).

Tower

The tower consisted of a 10 ft (3 m) long 1” diameter galvanized steel pipe that was connected to a square base, 3 ft (1 m) on each side, constructed out of the same diameter steel pipe (Figure 1). Several 3/16” steel wires, threaded...
through drilled holes, connected the base and top of the tower, acting as guy wires to stabilize the structure. A lubricated pipe junction with a connected pipe flange provided a bearing platform for the turbine body, and two holes drilled at the top and bottom of the tower allowed power wires to run securely down the inside of the tower pipe. The tower was anchored by sandbags placed at the base. Any convenient heavy object would work for anchoring, including buckets of water, bags of dirt, or concrete.

**Generator**

Two types of generators were used. The first, Generator #1 (Figure 2), was a commercially-available DC generator specifically designed for small wind implementation. The second, Generator #2 (Figure 2), was a hand-built permanent magnet alternator designed specifically for this research. Generator #2 was completely designed and built from the ground-up to be as easy to construct as possible, using a wheel hub from a bicycle as the primary bearing. A rotor was created from this hub with a pipe flange, a length of PVC pipe, and some high-quality glue. Next, a squirrel-cage type stator was constructed around the rotor using pieces of plywood with holes drilled for loops of magnet wire (Figure 3). Generator #2 was then wired in a three-phase configuration and rectified to DC current using 25 A bridge rectifiers (Figure 4). Remarkably, this generator was built with nothing more advanced than a handheld drill.

**Turbine Casing and Tail**

Each generator was encased in a frame made entirely of 1/4" and 1/2" plywood, held together with wood screws. The two-tail design consisted of two 2 ft (60 cm) long tail fins made of 1/4" plywood that attached directly to the frame. For mechanical simplicity, no furling mechanism—a system to protect the turbine in very high winds—was included.

**Blades**

Sets of blades were created from both wood and PVC, allowing for performance comparison. Wood blades were crafted from 4 ft (1.2 m) pieces of 2x6 lumber, and PVC blades were cut out of 8" diameter PVC scrap pipe. Each blade was 3 ft (1 m) long, giving every configuration a blade swept area of 28.3 ft² (3.14 m²). The blades were bolted to a 1/2" thick round plywood hub (Figure 5), which was then connected to the generator (Figure 6). Once the blades were attached, the wind turbine design was complete: two or three blades rotating around a horizontal axis assembly, which then rotated around the vertical axis of the tall tower.

**Battery and Wiring**

To store the power produced from the turbine, each generator was connected to a 12 V 100 Ah deep-cycle Werker brand battery, using 15 AWG wires. A 50 A power diode was added to prevent current from traveling from the battery back to the turbine, which would have caused the turbine to spin backwards and act like a motor.
Methods / Results

Once the turbine components were designed, constructed, and assembled, testing began. Two primary variables were analyzed: the blade construction and the type of generator.

Wood blades were compared with PVC ones, and Generator #1 (purchased) was judged against Generator #2 (hand-built). Trials occurred both in a controlled testing environment and in real-world outdoor use. Outdoor tests were conducted at the Oregon Coast and also at Hood River, Oregon, in the summer of 2011, and controlled tests took place during the summer of 2011 and in early 2012. The outdoor data showed a significant amount of variation, typical when testing wind turbines. Computer models were developed for the turbine, generator, electronics, and battery; model coefficients were determined such that the end-to-end computer simulations provided a good fit for the measured data. SystemVision, a mechatronic systems modeling tool, was used to implement the VHDL-AMS models of the system. This allowed the system to be tested with a high level of accuracy under conditions that could not easily be reproduced without a wind tunnel.

**Blades**

Four different blade configurations were tested: 3-blade wood, 2-blade wood, 3-blade PVC, and 2-blade PVC (Figure 9). Two-blade and three-blade configurations are most common in the wind turbine industry. For consistency, Generator #1 was used with the different blade sets for the real-world tests. Two performance characteristics of the blades were calculated: the tip-speed ratio (also called TSR or $\lambda$) and the pitch factor. The tip-speed ratio measures the aggressiveness of each individual blade. It is defined as:

$$\text{Tip-speed ratio} = \frac{\text{Blade Tip Speed (m/s)}}{\text{Wind Speed (m/s)}}$$

Tip-speed ratio is mainly used in analyzing the blade configuration. The higher the TSR, the more wind that is converted into blade motion. Blades with higher tip-speed ratios also encounter greater difficulties with noise, stress, and air resistance, however. Generally, turbines with fewer
blades use higher tip-speed ratios. Since the tip-speed ratio is calculated per blade and depends primarily on the geometry of the blade, increasing the number of blades used does not change TSR. Also calculated was the pitch factor, which indicates how efficient the blades are without load. Pitch factor is defined as:

\[
Pitch \ Factor = \frac{Rotations \ per \ Minute}{Unit \ of \ Wind \ Speed \ (m/s)}
\]

Note that pitch factor is only calculated when the blades are not driving a load—in this case calculated without the generator connected to the battery.

Blade weight, blade swept area (area circumscribed by the rotating blades), and cut-in wind speed (wind speed that is needed to start the blades spinning from a standstill) were also provided for each configuration (Figure 7). The cut-in wind speed is meant only for relative comparison, since the cut-in wind speed will vary according to the resistance of the generator.

**Generators**

The performance of both Generator #1 (purchased) and Generator #2 (hand-built) was compared using a variety of tests. Experimentally, each generator was spun at various rotations per minute (rpm) under different circumstances to determine its performance characteristics in a controlled manner (Figure 8). These characteristics included voltage per rpm, the torque constant, and the winding resistance. Voltage per rpm is simply the open circuit voltage produced by a generator per rpm, which yielded an almost perfect linear relationship. The torque constant (Kt) defines the relationship between the torque given by the blades and the current (I) produced by the generator. It also is an important characteristic in the modeled voltage output of the generator. Winding resistance (R) is the internal impedance of a generator, which can have a large effect on the generator’s voltage output, and the rotational velocity (\(\omega\)) gives the speed of the rotor, measured in radians per second. The relationships between these variables are generally described by the equations below, ignoring wind resistance.
Besides controlled-environment testing, both generators also underwent real-world testing to measure structural integrity and performance. These results, however, were unsatisfactory for fully characterizing the generator due to large data variations and error factors introduced through turbulence. To compensate for these issues, controlled-environment data was largely used to characterize the generators. This data was then fed into a VHDL-AMS schematic implemented by SystemVision, which performed the complicated calculations needed to accurately describe the situation, and provided expected performance graphs that corresponded very well with the collected real-world data (Figure 10).

**Cost**

The cost of the turbine components was calculated on a per-item basis using prices local to Portland, Oregon (Figure 14). These prices are fairly standard in the continental United States but are likely lower than those found in much of the world. Shipping costs were not included in any of the calculations. The cost of the turbine is defined as the aggregate cost of the blades, generator, casing, and wiring/general costs, while the cost of the whole system is defined as the cost of the turbine plus the cost of the tower and battery (Figure 15).

Six leading commercial small wind turbines of varying size and cost were compared to the best two versions of the turbine developed in this research (Figure 16). It is difficult to accurately compare the power produced by different turbines since power curves are exponential, but 20mph (9m/s) was chosen as a reference wind speed, modeling a strong breeze. This wind speed is generally in the middle of most performance curves, but in the case of the smallest turbines, the power produced may be limited by the turbine automatically furling out of the wind. The overall cost per watt for the different turbines was calculated using the commercial wholesale price as a basis. Tower prices were not included in comparing costs of turbines because costs vary drastically depending on the height of the tower and surrounding geography.

On a per-watt basis, the version of the turbine using Generator #1 was the cheapest option by far, at a cost of only $1.92 per watt. The version with Generator #2 was the next best option, at $5.17 per watt. The best commercial turbine...
was the Bergey Excel 1, with a per watt cost of $5.23. The average per watt cost of all the commercial turbines surveyed was $10.21. Therefore, the Generator #1 turbine cost a full 63% less per watt than the most cost-effective of turbines available for sale, and while the Generator #2 turbine was only 1% more cost-effective, it still was cheaper than anything else for sale.

Discussion

Testing the wind turbine configurations in a real-world environment led to a few design changes. Especially in high winds, it was surprising how much force acted on the turbine. Stabilization problems were largely solved by adding several hundred pounds of sandbags to the base of the tower. Still, at times the wind was strong enough to temporarily bend the 10 ft (3 m) pole that formed the main part of the tower. If used in permanent installations, the tower should likely be constructed out of pipe that is larger than the 1” pipe used in this research. The tower should also be higher than 10 ft (3 m), not only for better wind speeds, but also because a 10 ft height places the blades of the turbine close to eye level, which is extremely unnerving. In real-world implementation, safety precautions need to be made unquestionably paramount. Another unexpected concern was the presence of mechanical vibration. The addition of a furling mechanism, which would turn the turbine out of the wind at higher wind speeds, would reduce this problem. The overall structural integrity of the wind turbine appears to be suitable for extended use outdoors, but longer-term testing is needed to ascertain its enduring durability.

Blades

Given the minimal cost of the blades, they performed remarkably well. The wood blades were clearly more effective than the PVC blades, which was somewhat surprising: the wood blades had a tip-speed ratio of 8.8, which is considered too high for either a two- or three-blade configuration. The high TSR implies that the wood blades were a little too aggressive, which can be seen in the correspondingly high pitch factor. This is likely because the blades had a constant 5° angle of attack (a constraint of the simplified construction process) where a more efficient blade would be designed with a shallower angle of attack towards the tip of the blade. The PVC blades, by comparison, were flatter towards the tip of the blade and had a much better TSR of 4.6. The PVC blades, however, did not perform nearly as well, likely because of two factors: area and weight. These blades were tapered more than the wood blades, which slightly reduced the area exposed to the wind, and they weighed 208% more than the wood blades. This greatly hurt performance, especially in turbulent winds caused by natural gusts. While the wood blades had the larger area and lower inertia needed to catch these gusts of wind, the PVC blades simply had a harder time gaining speed. Furthermore, heavier blades exacerbated any problems with the balance of the blades, leading to unwanted vibration. It is likely that the PVC blades would perform nearly as well as the wood blades under ideal conditions—namely non-turbulent winds. Unfortunately, rapidly varying wind speed is a factor at nearly any potential site.

Generators

While neither Generator #1 nor Generator #2 was perfect for wind application, they both performed ably. Most importantly, both generators produced enough voltage to charge a 12 V battery within reasonable rpm rates (Figure 23), which is far superior to the car alternators, treadmill motors, and other small industrial motors commonly used in non-commercial off-grid applications. Generator #1 was clearly better than the hand-built Generator #2 (Figure 26), but the difference was less than expected considering that Generator #2 was constructed with such minimal tools—basically just a saw, drill, and some glue. Overall, it appears that Generator #2 was approximately two-thirds as effective as the purchased Generator #1 at the reference wind speed, 20 mph (9 m/s). This was largely due to lower effectiveness at turning torque into current. These results are unsurprising, given that Generator #1 was precision engineered so that the flux through the windings would be maximized. Overall, however, both generators remain viable means of generating power.

Cost

The wind turbine designs researched here stand out when compared with other alternatives. At a total full-system cost of $577 (using Generator #1) or $648 (using Generator #2), the cost of the complete setup was incredibly low. Furthermore, the economic advantages of the researched designs compound when looking at the life cycle of a small wind turbine. It is all but assured that a turbine will need repair work and replacement parts. With lower per-component costs, it is likely that the inevitable repairs will cost only a fraction of what they would for turbines from mainstream manufacturers. For instance, a set of replacement blades for the popular Air X micro wind turbine costs approximately $100, while a set of blades for the researched design costs at most $4. It is somewhat surprising that the hand-built version (Generator #2) cost more than the purchased one, but not altogether unexpected. To build a generator with sufficient power output without utilizing modern manufacturing techniques requires more powerful magnets, which are correspondingly more expensive. Interestingly, the overall cost for either version was dominated by the battery, which is relatively irreducible. Also note that the cost estimates assumed every item would need to be purchased. Each component of the turbines, however, was designed to use as many readily available supplies (plywood, pipe, screws, etc.) as possible, so the final cost could easily be reduced.

Social Impact

While it is difficult to estimate the impact of the studied wind turbine designs on a typical community in the developing world, any source of energy—no matter how small—
would be a significant boost to the development process. If implemented correctly, the turbine should generate anywhere from 250 Watt-hours to 1.8 Kilowatt-hours per day in energy, depending on the location and amount of wind. The lower end of this range of energy is ideal for lighting a household or charging cell phones, while the upper end could provide limited refrigeration. It may be optimal for a household or community to utilize multiple turbines, placed in a variety of locations to maximize the wind collection potential. Such an arrangement could provide power for a central application, such as a small school or rural medical clinic. Moreover, such an energy supply would greatly reduce the carbon footprint relative to current energy practices. A further step would be commerce—people in developing countries making these turbines and selling them to others. Locally-owned manufacturing would not only make the turbines cheaper to produce, but maintenance could be provided through the local wind turbine dealer.

Conclusion

Micro wind turbines have the ability to cleanly and efficiently deliver electrical power to off-grid communities in developing areas of the world. Barriers exist, however, in the form of high initial costs and expensive maintenance requirements. The wind turbine designs that were researched demonstrate that such barriers can be overcome by using relatively inexpensive materials and by applying suitable construction methods. Dissimilar blade materials and different generator types were compared. For blades, wood was far more effective, as well as being easier to obtain. For generators, a small commercial generator turned out to be both cheaper and more efficient than the completely hand-built alternative. The generator built by hand, however, allowed the most complicated part of the turbine to be both buildable and repairable on-site, which is of particular importance in developing countries. Overall, each wind turbine design offered lower costs per watt than any mainstream commercial alternative while simultaneously needing only simple materials and tools to build. These are major benefits for developing communities seeking alternative means to reliable electrical power.

Acknowledgements

I would like to thank the Rodman Council, Engineering Student Council, and Dr. Dana Elzey for the funding and support of this research. I would also like to thank my friends who risked life and limb helping test the turbine in fierce winds.

Works Cited


Social Impact

Peripheral artery disease (PAD), despite affecting 8 to 12 million Americans annually with total healthcare costs exceeding $21 billion each year, is considered to be under-recognized by physicians and remains one of the least visible diseases in the public realm. Currently, the status of PAD is marked by misguided research funding yielding ineffective and non-specific treatment options. The purpose of this research is to attempt to create a PAD-specific treatment option using highly-customizable nanoparticle design.
Abstract

The application of nanoparticles (NPs) for the delivery of therapeutic small-particles in skeletal muscle is a promising method of targeted pharmacological therapy. However, the dispersion properties of NPs in targeted tissues remain unexamined. The purpose of this study is to identify the optimal diameter and surface coating (polyethylene glycol (PEG) versus non-PEG) of polymer NPs for diffusion in skeletal muscle. The authors hypothesize that smaller PEG-coated NPs have greater diffusivity in skeletal muscle. This experiment was an in vivo validation study in the gracilis muscles of living rats, where 40, 100, and 200 nm NPs with and without PEG-coating were delivered by ultrasound-assisted microbubble delivery. Primary outcomes included quantifiable total NP dispersion area and NP colocalization with microvessels. Whole mount analysis showed that larger NPs yielded larger total area coverage throughout the entire muscle. Additionally, PEG-coated NPs diffused over a greater area than uncoated particles, with the exception of uncoated 200 nm NPs that had larger area coverage. PEG-coated NPs colocalized more with microvessels than uncoated particles. PEG-coated 200 nm NPs, however, colocalized with fewer microvessels than uncoated 200 nm NPs. It was concluded that the PEG-coat did not increase NP diffusivity or colocalization with microvasculature in the gracilis muscle with statistical significance. However, the observed increased NP area coverage and percent colocalization for 40 and 100 nm PEG-coated NPs is promising for future investigation. Additionally, the results regarding the 200 nm NPs suggest that there is a size limitation for ultrasound-microbubble mediated NPs delivery to skeletal muscle between 100 and 200 nm.

Introduction

Peripheral arterial disease (PAD), by definition, is characterized by the obstruction of blood flow in an arterial tree primarily caused by atherosclerosis, with the exception of the intracranial and coronary vascular systems (Garcia, 2006). It is estimated that there are 8 to 12 million annual incidences of PAD in the United States (Hirsh et al., 2007). However, this approximation underestimates the true prevalence of PAD as patients typically seek treatment once the disease has become severe rather at the onset of mild pain or initial intermittent claudication (Cimminiello, 2002; Hirsch, 2001). Current therapies for PAD include surgical, medical device, and pharmaceutical intervention. The most common solutions, however, are atherectomy, vascular stents, and hyperlipidemia drug treatments. These treatments involve highly invasive medical procedures with total associated healthcare costs exceeding $21 billion annually (Norgren et al., 2010; Pentecost et al., 2003). Furthermore, each treatment lacks long-term efficacy and subjects patients to significant medical risks, such as myocardial infarction, stroke, and hepatotoxicity (McKenney, 1994; Taylor, 1992). Due to these large associated costs and health risks, there remains a need for a long-term, effective treatment for PAD (Taylor, 1992; Zhou, 1996).

The limitations of current solutions have shifted research surrounding PAD treatment towards targeted drug delivery. The intramuscular delivery of nanoparticles (NPs) carrying arteriogenic agents has shown significant arteriogenesis and angiogenesis in animal models (Oda et al., 2010). Similarly, the ultrasound-assisted destruction of microbubbles (MB) conjugated with drug-bearing NPs also facilitates the targeted deposition of NPs into surrounding skeletal tissue (Chappell et al., 2008; Price, 2002). This effectively disperses arteriogenic factors and induces collateral arterial growth. The success of this therapy is measured by quantifying the arteriogenesis and angiogenesis in the affected muscular systems. Although illuminating, the physical movement, dispersion, and diffusion patterns of the NPs in vivo and upon injection remain unknown. Given these reasons, the central goals of this research are to optimize the surface design of racer NPs and evaluate their efficacy in diffusing throughout skeletal muscle.

As such, the overall objective of this project is to optimize the appropriate design parameters for the application of drug-bearing NPs to maximize targeted drug delivery in skeletal muscle. The selected design parameters for study include NP diameter and PEG-coating (Figure 1). These parameters, in theory, will affect NP penetration and diffusivity within the muscle due to the porous conformation and polar properties of the targeted tissue (Lai, Wang, Hanes, 2009).

Methods and Materials

In this study, the diffusivity of tracer NPs were evaluated upon introduction into the gracilis muscles of the hindlimbs of sprague dawley rats. To evaluate NP movement, excised whole mounts were imaged to quantify total NP area as a function of time. In addition, excised whole mounts were cross-sectioned and imaged using confocal microscopy to evaluate three-dimensional NP movement. To do so, the percent colocalization of NPs with microvessels was calculated.

Nanoparticle Acquisition and Delivery

The tracer NPs were fabricated at the Johns Hopkins University (JHU) and were acquired for this research through...
a partnership between this research team's sponsor and JHU. Approximately 200 μL of each tracer NP were acquired one month before experimentation began. NPs were delivered to the gracilis muscle using the ultrasound-assisted destruction of MBs. A 0.5 mL solution of MBs, saline, and two types of NPs was prepared and injected at a steady rate via tail vein injection (0.05 mL NPs1 + 0.05 mL NPs2 + 0.5 mL diluted MBs/Saline). Upon injection, an unfocused 1 MHz transducer coupled to the gracilis muscle using a water-based ultrasound gel (Aquasonic 100; Parker Laboratories, Inc., Fairfield, NJ). Each acoustic pulse consisted of 100 consecutive 1 MHz sinusoids of 1V peak-to-peak amplitude applied every five seconds for three minutes. Sinusoids were each of 1 V peak-to-peak amplitude from a waveform generator (AFG-310; Tektronix, Inc., Beaverton, OR). The waveform signal was amplified by a 55 dB RF power amplifier (ENI 3100LA; Electronic Navigation Industries, Richardson, TX). Maximum peak negative pressure at the focus of the transducer, as measured with a needle hydrophone (Specialty Engineering Associates, Model PVDF-Z44-0400) was 1.0 MPa. Following injection, vasculature was flushed with 0.3 mL of saline. NPs were allowed to circulate for seven minutes, followed by a 3.0 mL injection of saline. Following euthanization, blood removal with 3.0 mL of 4 % paraformaldehyde in PBS and 0.1 % saponin, followed by a single wash for 20 minutes in a solution of PBS and 0.1 % saponin, was completed. Cross-sectioned samples were then mounted muscles were stored in a 50/50 mixture of PBS and glycerol until cross-sectioned.

Whole Mount Processing and Analysis

Directly upon excision, whole mount gracilis muscles were placed in 3.0 mL of saline until mounted on microscopic slides for viewing. While mounted muscles were observed with a x40 objective on a Nikon TE-300 inverted microscope (Nikon, Melville, NY). Using ImageJ software (NIH, Bethesda, MD), total NP diffusion was evaluated by quantifying the total area covered by each NP type. Whole mounted muscles were stored in a 50/50 mixture of PBS and glycerol until cross-sectioned.

Cross-Section Preparation and Staining

Whole mounted gracilis muscles were bisected about their midlines perpendicular to muscle fiber direction. Cross-sectioned samples were washed for 30 minutes in a solution of phosphate buffered saline (PBS) and 0.1 % saponin. A solution of 1:200 BS-1 lectin+, 2 % bovine serum albumin (BSA), 0.1 % saponin, and 5 % normal goat serum (NGS) was prepared and 0.2 mL was added to each cross-sectioned specimen. The samples were stored for 24 hours at 4°C. The samples were then washed twice for 20 minutes in a solution of PBS and 0.1 % saponin, followed by a single wash for 20 min in PBS. Cross-sectioned samples were then mounted for confocal microscopy.

Quantification Metrics

In summary, there are two main metrics used to quantify the diffusivity of NPs in skeletal muscle. First, the total NP area for each NP design was calculated to evaluate two-dimensional surface diffusion. Second, the percent colocalization of NPs and lectin+ vessel profiles was quantified to evaluate NP penetration into skeletal muscle. Both calculations were statistically analyzed using two-way repeated ANOVA measures. Statistical testing was performed in SigmaStat 2.0 using p<0.05 to evaluate statistical significance.

Results

Characterization of Nanoparticle Design

Prior to applying the variously designed NPs in vivo, the design of each particle type was characterized by the NP provider at JHU. The particle size, surface conjugation, and color were determined by dynamic light scattering and laser Doppler anemometry using a Zetasizer NanoZS (Table 1). The subsequent analysis of each particle design, specifically regarding nanoparticle size, revealed that the 40, 100, and 200 nm NPs were designed appropriately for the desired experimentation. However, fluctuations in size occurred more frequently in small NPs. Additionally, it was found that the PEG-coating applied to the NPs increased the size of the NPs by 60 %, 5 %, and 18 % for 40, 100, and 200 nm NPs, respectively.

Table 1: Nanoparticle design characteristics. Acquired NP were analyzed for actual size using dynamic light scattering and laser Doppler anemometry at IHU. Analysis showed variation in NP size up to 60% as a result of the PEG-coating.

<table>
<thead>
<tr>
<th>Particle Type</th>
<th>Expected Size (nm)</th>
<th>Actual Size (nm)</th>
<th>% Difference in Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncoated</td>
<td>40</td>
<td>52</td>
<td>29</td>
</tr>
<tr>
<td>PEG-Coated</td>
<td>40</td>
<td>64</td>
<td>60</td>
</tr>
<tr>
<td>Uncoated</td>
<td>100</td>
<td>91</td>
<td>9</td>
</tr>
<tr>
<td>PEG-Coated</td>
<td>100</td>
<td>105</td>
<td>5</td>
</tr>
<tr>
<td>Uncoated</td>
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<td>208</td>
<td>4</td>
</tr>
<tr>
<td>PEG-Coated</td>
<td>200</td>
<td>236</td>
<td>18</td>
</tr>
</tbody>
</table>

Two-Dimensional Surface Diffusion Analysis

Harvested gracilis whole mounted muscles excised immediately post-treatment were imaged using fluorescence light microscopy. Using ImageJ software, the total NP area was quantified to evaluate two-dimensional particle diffusivity (Figure 1). Results indicated that the PEG-coated NPs diffused a greater area than uncoated particles by 13.9 and 39.2 % for 40 and 100 nm NPs, respectively. However, the uncoated NPs diffused a 34.6 % greater area than uncoated particles by 34.6 %, 39.2 % for 40 and 100 nm NPs, respectively. Nevertheless, fluctuations in size occurred more frequently in small NPs. Additionally, it was found that the PEG-coating applied to the NPs increased the size of the NPs by 60 %, 5 %, and 18 % for 40, 100, and 200 nm NPs, respectively.

Cross-Sectional Diffusion Analysis

Cross-sectioned whole mount gracilis muscles were imaged using confocal microscopy. Using ImageJ software, the percent colocalization of NPs with lectin+ stained vessel profiles was measured to evaluate NP penetration in skeletal muscle.
muscle (FIG. 2). Results showed that the PEG-coated NPs were more colocalization than uncoated particles by 18.6 and 35.0% for the 40 and 100 nm NPs, respectively. The 200 nm uncoated NPs, however, were more colocalized than PEG-coated NPs by 14.5%. Statistical analysis revealed that these differences between NP surface designs were not significant.

**Conclusion**

As an optimization study, the goal of this research was to investigate the diffusion of NPs in skeletal muscle and identify the limiting characteristics in the selected design parameters: size and PEG-coating. For size, it was hypothesized that larger NP sizes would restrict NP movement and penetration into the skeletal muscle. Additionally, it was hypothesized that the PEG-coating would increase the diffusion of the NPs in skeletal muscle due to its ability to balance the surface charge of NPs, therefore limiting surface interactions and increasing circulation time. No previous study has investigated the limitations of pore size and surface interactions of NPs within skeletal muscle tissue.

The results of this study suggest that size is a limiting design constraint for diffusion. It is believed that the size of the NP is limited by the pore size of the extracellular matrix surrounding the muscle tissue. Considering the cross-section analysis, both 40 and 100 nm NPs displayed increased colocalization with microvessels compared to the 200 nm NPs. Thus, at a certain size, believed to be between 100 and 200 nm, NP penetration within muscle tissue is restricted due to this size limitation. However, this size limitation only exists when NPs are attempting to penetrate into the muscle fiber; upon analysis of the whole mount images, it was observed that 200 nm NPs have a larger area coverage than both the 40 and 100 nm NPs. It is further believed that NPs encounter less path interference while traveling parallel to muscle fiber orientation compared to penetrating within muscle fiber bundles and between individual muscle fibers, where NPs must travel across the extracellular matrix.

Regarding the PEG-coating of NPs, it was unexpected that the PEG-coat did not significantly increase the overall diffusion of NPs in skeletal muscle tissue. Multiple studies have shown that conjugation of PEG increases circulation time and can also aid in the diffusion of NPs in various tissues (Lai, Wang, Hanes, 2009). Although the results were suggestive that the PEG-coating might increase diffusivity
when examining both the whole mount and cross-sectional analysis, there was no statistical significance supporting the original hypothesis. The results of this study imply that the overall extracellular matrix charge of the skeletal muscle tissue is not restrictive on NPs diffusion. As such, the surface charge and interactions of the NPs is an important consideration for therapeutic design, but may not be the critical design element. However, as it is well documented that PEG does increase the circulation time of NPs \textit{in vivo} (Lai, Wang, Hanes, 2009), there are possible implications on potential NP delivery to skeletal muscle that were not considered in this study.

In summary, while the data was not significantly conclusive, data suggests that size has an effect on the diffusive properties of NPs in skeletal muscle. There appears to be a constraint on NP size between 100 and 200 nm where the pore size of the extracellular matrix hinders penetration of NPs through muscle fibers. The PEG-coating did not have a significant effect on NP diffusion in skeletal muscle, and may not be as critical in NP design for skeletal muscle as previously thought.

**Limitations**

The difficulty in collecting significant data can be attributed to multiple limitations in the design and nature of the study. First, the small sample size and need to test six unique design groups led to inconclusive data that could have been skewed by outliers. These outliers would be difficult to notice due to the large variance seen between samples and images. Secondly, the effect of a PEG-coat and circulation time may not have taken full effect due to the small window of time allowed for the NPs to circulate. The purpose of this study was to examine the effect of PEG-coating on NP diffusion; therefore, this aspect was not taken into account when formulating the protocol. However, investigation into circulation time is needed. Lastly, there is a limitation due to the three-dimensional nature of diffusion and two-dimensional nature of microscopy. Experimentation investigated both whole mount and cross-sectional imaging of samples; this evaluates the diffusion both along and within the skeletal muscle, but does not reveal the real-time diffusivity of NPs

**Figure 2:** Three-dimensional nanoparticle diffusion analysis. TOP: Confocal images of (left-right) 200 nm PEG-coated green NP, 200 nm uncoated red NP, lectin+ stained microvessels, and merged image of 200 nm uncoated and PEG-coated NP, and lectin+ microvessels, each at x40 objective. BOTTOM: Bar graph of average percent NP-microvessel colocalization for uncoated and PEG-coated NP. Results indicated that there was no statistically significant difference between PEG-coated and uncoated NP (p>0.050).
Future Research

Further experimentation is needed to verify the findings of this study. Immediate next steps include increasing the sample size for each NP's design and increasing the circulation time of each NP type, upon injection, to evaluate effects of the PEG-coating. Additionally, future research is needed to investigate a wider range of NP sizes, specifically between 100 and 200 nm, as it is believed it is within this range when size becomes a significant constraint on NP diffusion. The therapeutic delivery of arteriogenic and angiogenic drugs should also be measured in an ischemic hind-limb model.

The future of NP technology lies within the optimization and controllability of the diffusive properties of NPs. Through controlling these diffusion patterns, more targeted therapies can be offered for many for other diseases that are vascular in origin such as Cardiovascular disease or the inappropriate use of vasculature seen with cancers. Promising animal studies have confirmed the efficacy of NP therapy for treating PAD (Chappel et al., 2008; Oda et al., 2010; Price, 2002); however, more accurate quantification of NP diffusion and the parameters effecting NP diffusion in skeletal muscle is needed. Furthermore, a need for clinical translational research to investigate this potentially minimally invasive therapy in humans is warranted.

Acknowledgements

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References


A Proposal for a Federal Engineering and Science Initiative for Women
Camrynn Genda
School of Engineering and Applied Science, Department of Systems Engineering

As women are either not attracted to STEM fields or drawn away from STEM fields due to unsupportive climates and other factors, they quickly become a source of untapped human capital that could be crucial to the technological prowess of the United States.

Social Impact
As countries like China, Japan, and India increase their technological workforces, the United States must increase its own technological capabilities to retain its place as a leader in innovation and economic growth. Women represent an underutilized resource as their numbers in science, technology, engineering, and math (STEM) fields remain very low relative to men. This research outlines a policy aimed to increase the retention of women in STEM fields by increasing mentorship of young women by STEM federal employees. Implementation of this policy would increase the quality of women’s engineering environment, increase retention of women in STEM fields, and ultimately increase the economic competitiveness of the United States.
Throughout their undergraduate experience, U.Va. engineers are challenged to solve real-world technical problems, from building energy-efficient housing, starting new businesses, to developing new medical technologies.

But a select group of U.Va. undergrads get the chance to try out their problem-solving skills on a different set of challenges: public policy. The problems that face this country – energy, national security, privacy, health and the environment – are partly technical, but are also deeply embedded in economics, politics, and fairness: the world of policy. And it’s policy that often determines whether any of these innovative technical solutions ever make it to market.

Each year for the last twelve years, about a dozen U.Va. undergraduates have gone to Washington (and sometimes Paris!) to work on a wide range of public policy issues. As participants in the Science and Technology Policy Internship Program (PIP), students take a dedicated spring seminar course that helps prepare them for their 10-week summer internship. In the summer, students live together in George Washington University dorms. Interns are placed with high-level policymakers, such as the Director of the National Science Foundation, and work in key scientific agencies, including the White House Office of Science and Technology Policy, NASA, the Department of Energy, and EPA. Students also work at non-governmental organizations such as the National Academies of Science, the World Bank, and other NGOs working on critical technology and policy topics.

Professor Bio

A lawyer by training, Professor Rodemeyer is no stranger to working with scientists and engineers. In his fifteen years as a counsel to the U.S. House Committee on Science, Space and Technology, Professor Rodemeyer found himself one of the few lawyers on a staff composed mostly of Ph.D. engineers and scientists. “It was an amazing opportunity to learn about cutting-edge science issues from some of the country’s top experts,” said Rodemeyer. “Each day brought a new issue: unraveling the human genome, assessing climate change, developing new crops with biotechnology, sustaining human space exploration. It was an incredible on-the-job education.”

Professor Rodemeyer also spent a year in President Clinton’s Office of Science and Technology Policy, before starting the Pew Initiative on Food and Biotechnology, a non-government research project on agricultural biotechnology funded by the Pew Charitable Trusts.

Professor Rodemeyer moved to Charlottesville in late 2005 and almost immediately became attracted to the Department of Science, Technology and Society in SEAS. “It is a great place to explore the complex interactions of technology and society, and it seemed like a place where my experience in Washington could be really useful to future engineers.” For several years, he taught an STS elective on Food and Biotechnology. In 2009, Professor Rodemeyer became the Director of the Science and Technology Policy Internship Program. It’s a way, he says, to “ensure that there’s a strong pipeline of technically-talented people who can understand the world of policy and appreciate the importance of communicating with non-technical people.” One of the most satisfying experiences he has is watching interns catch “Potomac Fever” – an incurable lifetime malady that no biomedical engineer has yet found a cure for.
Abstract

Prowess in science, technology, engineering, and mathematical (STEM) fields was a transformative driver as the United States emerged from its agrarian past to take on a role as a world power in the 20th Century, and as the only remaining superpower in the 21st. However, as countries like China and Japan increase their technological work force, the United States’ position of scientific and technical preeminence appears to be in jeopardy. The U.S. needs to increase technological capabilities of its labor force to remain competitive in the global economy.

Women represent a source of underutilized human capital, which can be called upon to increase the economic competitiveness of the U.S. economy. Although women represent almost 50% of the overall U.S. labor force, they compose only 10% of the STEM labor force. This under-representation of women in STEM fields is caused not by women’s lack of inherent capacity or skills, but by an atmosphere of competition and individual achievement that has for years been shaped to most effectively meet the needs of men, rather than both men and women.

To ensure that the U.S. retains the best possible workforce, this paper recommends that the Office of Science and Technology Policy (OSTP) establish a Federal Engineering and Science Mentoring Initiative (FESMI) to increase the retention of women in STEM fields. This initiative would increase the number of federal employees serving as STEM mentors, and would help coordinate the disparate mentoring efforts of federal agencies. This option has high political feasibility (based on the presence of the Administration’s support of women and the number of federal mentoring programs), low cost (as measured by the resources required to organize volunteers from within the federal workforce), and high efficacy (based on research that demonstrates how well women respond to mentoring when compared to male counterparts).

Introduction

Importance of Science, Technology, Engineering, and Mathematics (STEM)

Prowess in science, technology, engineering, and mathematical (STEM) fields was a transformative driver as the United States emerged from its agrarian past to take on a role as a world power in the 20th Century, and as the only remaining superpower in the 21st. However, as countries like China and Japan increase their technological work force, the United States’ position of scientific and technical preeminence appears to be in jeopardy. As demonstrated in Figure 1, the percentage of STEM undergraduates in the United States now lags behind countries like Finland, Germany, and Japan (Hodges, 2007). According to the National Science Foundation (NSF), “the United States has one of the lowest rates of STEM to non-STEM degree production in the world” (16%), especially compared to Japan (64%) and China (52%) (as cited in Kuenzi, 2008). One potential solution to this chronic issue lies in the hands of an underutilized and significant component of the workforce: women in STEM. If women’s percentage in the STEM workforce increased to their representation in the overall labor force, the U.S. STEM workforce shortage would disappear (Congressional Commission, 2000).

Lack of Women in STEM Caused by Low Retention

A disparity exists between the percentage of women in the labor force and the percentage of women in the STEM labor force. Figure 2 illustrates how the percentage of women in the labor force has increased from 30% to 47% over 50 years (Department of Labor, 2010). Although the percentage of women in the work force is almost equitable to men, women’s STEM labor force is only 10% (Mohmed, 2010).

Low retention of women in STEM fields causes this dichotomy between women’s presence in the overall labor force and women’s presence in the STEM labor force (Belle, 2011). As Julie Sheridan-Eng, the chair of the Institute for Electrical and Electronics Engineers claims, “the real problem is not to attract, but to retain those women who have entered the [STEM] pipeline” (Koebnick, 1998). Research illustrates gender differences where men’s retention rate at undergraduate institutions is 15% higher than the rate for women (Takahira, Goodings, Byrnes, 1998). An extensive study in Colorado shows that women’s attrition from STEM
Past and Present Mentoring Infrastructures

FESMI is also politically feasible because a number of federal mentoring infrastructures are already in place, illustrating that at least some federal agencies are both capable of implementing mentoring efforts and have the means to do so. Federal agencies that are already implementing successful STEM mentoring programs include the Department of Energy (DOE), NASA, the Department of Defense (DoD), and the Department of Commerce (DOC). Many of the STEM programs which include mentoring are centered on women. The DOE’s mentorship program, for example, has 27 female mentorship pairs. Although all the federal STEM programs may not be centered on women, a large portion of them take conscious efforts to incorporate women both in their general STEM programs and within their mentoring programs. For example, to advance the place of women

Analysis of FESMI Based on Political Feasibility, Cost, and Efficacy

In the effort to increase the retention rate of women in STEM fields, FESMI could be a desirable and viable option for OSTP because of its high political feasibility, low cost, and high efficacy relative to other options such as scholarships, STEM grants, and research opportunities (Chesler and Chesler, 2002). In the current budget environment, low cost and high efficacy will be particularly important. Almost as important is political feasibility.

Political Feasibility of FESMI

FESMI is politically feasible, as measured by two aspects: support for women from within the Obama administration, and the large number of federal agencies with mentoring infrastructures already in place.

Obama Administration’s Support of Women

In 2009, President Obama issued an executive order which established White House Council on Women and Girls. The Council is meant to provide a “coordinated Federal response to issues that particularly impact the lives of women and girls […] and to ensure that Federal programs and policies address and take into account the distinctive concerns of women and girls, including women of color and women with disabilities” [As cited in “Report to the White House Council on Women and Girls”, 2010]. Valerie Jarrett, the chair of the Council and Assistant to the President and Senior Advisor, says that the council requires that each federal agency “analyze their current status and ensure that they are focused internally and externally on women” (White House, 2009). The President, Cabinet Secretaries and relevant agency offices facilitate these national efforts for women and girls (White House, 2009). Federal agencies on the Council now report their STEM efforts in support of women and girls to the White House Council on Women and Girls (U.S. Department of Energy, 2010).

Cost, and Efficacy

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employees and female students, the DOE supports STEM education and works with employee groups like the DOE’s Federal Women Program Managers and DOE’s Council on Women and Girls to “[raise] awareness, [enhance] career opportunities, and [provide] opportunities for professional growth [of women]” (U.S. Department of Energy’s Council on Women and Girls, 2010).

The Department of Education has a mentorship program “for seasoned employees to share their knowledge with less seasoned employees with interest in developing their skills” (Report to the White House Council on Women and Girls, 2010, p. 8). In 2010, this program formed 33 mentor-mentee relationships (p. 8). Although not a program focused specifically on women, it has been successful in the past, and portions could be implemented in FESMI.

The Department of Energy’s STEM mentorship program for women has had 27 successful mentorship pairs (both mentor and mentee are female) since the program’s initiation in March, 2011. DOE’s program runs on a 12-month cycle of mentorship. The mentors for the program are all DOE employees, and mentees are mostly undergraduate students from around the Washington, D.C. area (Office of Economic Impact and Diversity, 2011). Mentorship models like that of the DOE could be applied to communities beyond DC and to federal laboratories and headquarters in other locations.

A recommendation for altering current federal mentorship programs is discussed below in “Recommendation for Decreasing Cost: E-Mentoring.”

**Recommendation to Increase Political Feasibility: OSTP’s Role as Federal Facilitator**

The Obama administration is already supportive of advancement of women. Under FESMI, OSTP could serve as a facilitator for linking current federal mentoring efforts. Federal agencies currently report their general STEM efforts to the White House Council on Women and Girls, but the agencies have little to no communication with one another regarding their internal mentoring efforts, a couple of which were discussed above. However, under FESMI, in addition to reporting mentoring efforts to the Council on Women and Girls, federal agencies would work with OSTP as a cross-federal-agency facilitator to coordinate the mentorship process and share information regarding best practices.

To facilitate cooperation of the agencies in the federal initiative, the federal agencies should maintain their mentoring programs already in place – many agencies have already established successful programs. As such, effective aspects of different mentorship programs could be combined into a mentoring framework recommended to federal agencies with no current mentoring programs or to improve existing mentoring programs. Recommending (rather than requiring) proven successful frameworks will increase federal agencies’ desire to work with OSTP because the agencies would be provided mentoring recommendations and resources (such as mentoring curricula) from other agencies – not being required to organize their mentorship programs in a certain way.

Continued communication by OSTP to all federal agencies on the importance of STEM mentoring is of utmost importance. Common standards have been established by the White House Council on Women and Girls – all member executive departments, agencies, and offices on the Council have been required to “develop and submit…an assessment by each member executive department, agency, or office of the status and scope of its efforts to further the progress and advancement of women and girls”. In addition, the executive order “[included] recommendations for issues, programs, or initiatives that should be further evaluated or studied by the Council” (Obama, 2009, para. 10); however, common standards could be established specifically in regard to women in STEM. This is where funding would be beneficial: greater communication and information sharing between agencies to create common STEM mentoring standards.

An example of a recent successful federal effort to increase communication on women in STEM was an International Dialogue on Women in STEM in June of 2011. The International Dialogue event included 16 female scientists from around the world who discussed with the Obama Administration their efforts and “best practices” on increasing the number of women in STEM fields (Andersen, 2011, para. 3). Actions taken before and during the Dialogue increased the event’s success in dissemination of information regarding women in STEM, but different actions after the Dialogue may have increased its success.

Actions taken before the event that lead to its success in dissemination of information were a blog post about the event on the White House website, live streaming of the event online, the ability to pre-tweet questions to be answered by U.S. officials, and the selection of diverse and influential women who provide an experienced hand in application of engaging women and girls in STEM (para. 3 and 5). An additional action that would improve effectiveness would be to send out commitments and plans to which all participants will agree at the meeting. This would allow follow-up and accountability by agencies and OSTP.

Actions not taken after the International Dialogue on Women, which would have made the Dialogue more effective, include a follow-up blog on the White House website and follow-up by OSTP regarding the mentoring ideas at the meeting. Both of these actions would have ensured that ideas raised at the meeting were later followed up on and hopefully integrated into U.S. mentoring efforts. Successful efforts after the event, however, included posting a video recording of the event online for the public, which can be downloaded as an mp3 and disseminated publicly (U.S. International Women in Science Dialogue, 2011). Though additional follow-up after the event would have been desired, this event was a success in sharing diverse and effective mentoring practices used in many different ways.
Cost of FESMI

FESMI would be very low cost (as measured by the U.S. dollars needed to run the program) relative to other popular federal options such as scholarships, research opportunities, and grants. Besides necessitating an additional part- or full-time federal employee to head-up FESMI, the program would need funds for communication (e.g., recruitment of mentees/mentors, distribution of mentoring resources, etc.) and mentoring events (e.g., mentoring conferences, meetings with mentors, etc.). However, many of the communication and event costs are already part of federal mentoring programs. Mentors volunteering their time are already employed by the government and have no associated costs, and mentees are supported by themselves or their home academic institutions. It should also be acknowledged that to the extent the program inspires agencies without mentoring programs to start new mentoring programs, those agencies will incur costs associated with starting a new program.

Similar to OSTP’s handling of White House events, conferences and events associated with FESMI would be hosted at federal agencies on a rotating basis, resulting in sharing venue costs by federal agencies involved in FESMI and minimizing facility rental costs to OSTP. Due to high costs of meals and travel to conferences and events, large-scale FESMI mentoring conferences would occur only at the beginning or end of a given time frame (e.g., beginning of a FESMI mentoring relationship for mentors and mentees to meet one another) (Event Management, n.d.). Because of its historic success in recruiting women to STEM mentoring, all other mentoring communication would occur via cost-effective options such as teleconferencing, video, and individual travel across small distances (Case, n.d.). A successful implementation of such remote mentorship is outlined below in “Recommendation for Mentorship Expansion: E-Mentoring”.

An indirect cost of FESMI might accrue if federal employees are allowed by their supervisors to mentor while on the job. Volunteering time to mentor on the job provides less hours of productivity for the federal government. In addition, looming cuts in the federal budget may result in a smaller number of federal employees, and a subsequent increase in workload for the federal employees who remain. This leaves less time available for busy federal employees to volunteer their time to mentor young women. However, decreased immediate productivity of federal employees would likely be offset over the long-term by future productivity of mentees who turn into the workforce of America.

Recommendation for Lowering Cost: E-Mentoring

MentorNet is an online resource where students log in and find mentorship opportunities in their communities. According to Carol Muller (2003), the founder and CEO of MentorNet, online services of MentorNet provide a One-on-One e-mentoring program which pairs women studying engineering with professionals in STEM industry, government, and higher education for eight months of a structured relationship. In addition, MentorNet has an e-form for discussion groups, a resume database, an online newsletter, and resources to additional information (p. 3). It is recommended that FESMI incorporate a system similar to MentorNet because of MentorNet’s historical success in mentoring women and the low cost associated with such success.

MentorNet’s non-profit organization has been historically successful, especially in regard to presence of women in STEM. From 1998 to 2003, 20,000 individuals were matched in one-on-one e-mentoring relationships. In 2003, there were more than 10,000 active community members, of which 58% were students and 78% were female. There were 1,140 resumes posted online, more than 1,100 individuals posted in e-forum discussion groups, and 17,000 members received online newsletters. In 2003 alone, 3,421 students applied for mentorship, 80 colleges were involved, and mentors volunteered their time from 950 different employers (Muller, 2003). Mentors were comprised of 65% women, and mentees were comprised of 91% women (Muller, 2003). Optimum MentorNet relationships are formed through online algorithmic pairing processes, online mentorship training, participant surveys, and mentorship “coaching” from MentorNet staff sent every 1–2 weeks (Muller, 2003, p. 4). In 2005, MentorNet released that they were going to partner with Society of Women Engineers (SWE) “to facilitate greater mentoring opportunities for SWE members” (Sheehy, Muller, 2005).

The efficacy of MentorNet decreased in 2002 when the organization started charging for its services (Muller, 2005). As seen in Figure 3, the number of participating campuses dropped from around 110 to 80. After a historically-steady incline in the number of matched mentors and mentees, a majority of them female, the numbers dropped quickly. Thus, the set-up similar to MentorNet recommended to the federal government would be free of charge or very low cost. This is feasible because of the low overhead cost of digital dissemination of information, rather than requiring expensive venues for conferences and printing of mentorship curriculum. The overhead cost would also be low if the e-mentoring set-up was launched from a government website platform already in place. Digital options that might necessitate additional funds would include materials, infrastructure, staff costs of maintaining a website, coordinating e-mentorship relationships, updating online resumes, and sending out digital newsletters.

Efficacy of FESMI

FESMI could have high efficacy (as measured by the ability of the program to increase the number of women in STEM) because STEM mentoring has been shown to be one of the most effective means of increasing the retention of women in STEM fields. A woman in an early stage of her STEM career, where attrition from STEM is generally highest, made the following statement:

“Mentoring is the single most important strategy that
supports the success of women in [Science Engineering and Technology]-related careers and organizations. Through my mentoring relationships I have learned how to understand and characterize my organization, how to determine my own value to the organization and how to discover my own personal values and priorities. Through the encouragement of my mentors I have had the courage and discipline to take-on additional training, education and certification that provide necessary credentials for success in my field.” (Bogue, Comedy, Chubin, 2010)

According to research, STEM mentoring of women is effective because of the nature of women and their response to mentorship, especially in comparison to men. Mildred Dresselhaus, an MIT professor well known for her mentoring efforts and awarded the National Medal of Science in 1990, claims that mentoring is specifically important for women because often they have less self-confidence than their male counterparts (Liskov, 2011). The socialization and collaboration between women is especially important in their success in science and engineering fields, where they have less confidence than males, feel alienated, and emphasis is placed on individual achievement rather than collaboration (Chesler and Cheslter, 2002, p. 49).

Research shows that women respond well to mentorship, collaboration, and encouragement, especially compared to males who respond well to individual competition and achievement. Women “place greater priority on interpersonal satisfaction and integration than do men, potentially resulting in different career (and life) priorities [than STEM fields]” (Chesler and Chesler, 2002, pg 49-50).

**Recommendation to Increase Efficacy: Female Federal Employees**

To increase the efficacy of FESMI, it is recommended that FESMI use women as mentors because research shows additional retention of women mentees in STEM fields when mentored by a female, rather than a male. Many mentorship programs use academic professors, research assistants, or federal employees of any gender. Seymour and Hewitt (1997), however, claim the mentor should be female based on research regarding relationships between women and their mentors. Many female mentors “excel at offering personal support, friendship, acceptance, counseling, and role modeling,” which are all attributes of collaboration and group affiliation (Glaser, 2011, p. 3).

In addition, FESMI mentors should be federal employees, to increase the size of the mentor pool and help fill the mentoring gaps that academic faculty cannot fill (recruitment of federal employees for these purposes is outlined in “Increasing Supply of Mentors: Top-Down Recruitment”). Unfortunately, mentorship relationships with STEM professors and academic staff “often do not have a sufficiently high priority for faculty…to be more than peripheral to the daily life of the students whom they are supposed to serve” (Nagda, 1998). Female STEM faculty members are also hard to recruit because research shows their time is in high demand as mentors or members of committees seeking out diversity (The National Academies, 2006, p. 90). Lotte Bailyn of MIT said that the search for gender diversity in academia has brought in new issues, namely women faculty being overburdened and on too many committees (Liskov, 2011).
Increasing Supply of Mentors: Top-Down Recruitment

A challenge that would decrease the efficacy of FESMI is the small pool of potential STEM mentors, as well as the difficulty of recruiting their time to volunteer when their time is in high demand by the government. FESMI would recommend a presidential memorandum to encourage supervisors at the federal agency-level to create internal memoranda for their federal employees. Responses to these memoranda might include interagency mentoring competitions, federal challenges, or Presidential awards for outstanding federal mentorship.

Some individuals see a bright side with claims of large numbers of federal employees as potential STEM mentors. According to the U.S. Census Bureau, there are approximately 2.8 million U.S. federal employees (Federal Government Civilian Employment, 2009). The Washington Post reported last September that there were 20,000 more federal employees under Obama in 2010 than under President Bush in 2002 (Beutler, 2011).

While the two facts above provide a glimmer of hope, if the House Republicans “succeed in cutting tens of billions of dollars of discretionary spending [in 2011],” then those most impacted could be federal employees “whose jobs will be slashed as their agencies pare back” (Beutler, 2011). Even with Obama’s increase in the number of federal employees, the number of federal employees is at its lowest level on a per capita basis since 1962 (Beutler, 2011).

Narrowing down to women as mentors provides an even smaller pool of candidates. Of the STEM federal employees (employed at agencies like NASA, DOE, etc), women only represent a subset. In 1964, 1 % of NASA’s GS-12 or higher grade employees were women; that figure today is 31 %. Though this is a wonderful increase in women’s representation in STEM, it still removes 69 % of potential mentors if FESMI is going to use as many female mentors as possible. More generally at NASA, 36 % of new hires are women, and 25 % of those new hires are in STEM positions. Although these percentages are below parity with men, they are large improvements from 2006 and 2007 when women were only 20.2 % of new hires (NASA’s Support of Women and Girls, 2009). At DOE, the workforce is almost 38 % female (U.S. Department of Energy’s Council on Women and Girls, 2010).

Because of the limited pool of STEM mentors (especially female mentors), FESMI would need an effective recruitment strategy. Actions taken to recruit STEM mentors might entail a top-down approach. This top down approach is outlined in Figure 5 with three levels: 1) the executive level, 2) the agency level, and 3) the volunteer level.

The executive level would entail a presidential memorandum to address agencies’ mentoring efforts relevant to FESMI, and provide options to agencies that they might undertake. The executive level also includes Presidential awards given to individuals who volunteer their time to mentor. An example of such an award is the Presidential Award for Excellence in Science, Mathematics and Engineering Mentoring (PAESMEM), which allows outstanding mentors to be recognized by President Obama. Because PAESMEM is not currently open to federal employees, a similar award could be created for solely federal employees.

The agency level entails supervisors taking the presidential memorandum, and putting it into action within his or her agency. This might be embodied as a mentorship challenge put in place within the agency, or as an internal memorandum addressing federal employees and encouraging their mentoring efforts. It might mean providing federal employees with time to mentor while on the job. These decisions would be made at the agency level, not at the executive level. The third level, made up of volunteering mentors, is where federal employees put into action all that is hoped to be accomplished by FESMI. Encouragement and opportunities communicated at the executive and agency levels could generate interest among federal employees in the benefits of mentoring and hopefully lead to a decision to participate in the mentoring programs.

Throughout the entire recruitment process, FESMI would necessitate clear portrayal of the benefits of mentoring. The qualitative benefits of mentoring include opportunities to “keep in touch with the interests, vocabulary, and development of the young,” “leaving a legacy for STEM education when retired,” and “[gaining] another family and new friends” (Bosak, n.d.). Other benefits of mentoring are outlined by Sipe in her compilation of ten years of research on mentoring programs. Sipe (1996) indicates that 97 % of mentors report a positive mentoring experience; 84 % of mentors claim they are likely to mentor again in the future, and 91 % say they are likely to recommend mentoring to a friend.

Conclusion

In conclusion, it is recommended that OSTP and the federal agencies work together to implement FESMI to increase the number of federal employees who mentor. Although some federal agencies have successful mentorship programs, OSTP as a federal facilitator would allow the collection and dissemination of best mentorship practices. E-mentoring would allow more women to be impacted at a low cost via an internet platform. FESMI’s top-down recruit-

Figure 5. The top down approach to volunteering.
ment of female federal employees is an effective method of increasing volunteers that relate to fellow women. Should a federal volunteer mentorship initiative occur, and a concurrent increase take place in federal employee volunteer efforts, women's presence in STEM could increase, and the U.S. may retain a place of leadership in the global economy for decades to come.

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American Innovation: Promoting Scientific Advancement through Collaborative R&D

Zachary Levin
School of Engineering and Applied Science, Department of Chemical Engineering

Federal funding alone is not enough to drive technological innovation.

Zachary Levin is a third-year student double majoring in chemical engineering and physics. He is originally from Mount Laurel, New Jersey where he attended Lenape High School. At the University of Virginia, he is a Rodman Scholar and is actively involved with the Washington Literary Society and Debating Union and the Omega Chi Epsilon chemical engineering honor society. He was a participant in the SEAS Policy Internship Program in 2011, where he split his time between the offices of Representative Rush Holt and of Lewis-Burke Associates LLC.

Social Impact
Technological advancement is one of the most significant drivers of economic growth. For the United States to remain a leader in global technological innovation, legislation must be enacted to promote continued investment in basic research and development. In constrained economic times when increases in the Federal budget are unrealistic, industry can provide the resources needed to promote investment in research. The purpose of this study is to perform a policy analysis on possible incentives or potential institutional changes to encourage such investment in research.
Abstract

In Fiscal Year 2010, the federal government directly spent $147.4 billion on research and development (R&D); however, federal funding alone is not enough to drive innovation. Investment in basic R&D yields a significant societal benefit, manifesting both as increased labor productivity and overall economic strength. Technological progress gives the nation's firms an initial advantage in the production and sale of new products. In the mid- to long-term, innovation is positively correlated to job growth. While the United States has made significant advances in promoting innovation through legislation reforming intellectual property law, creating Research and Experimentation Tax Credits and Cooperative Research and Development Agreements, and directly funding research at non-profit organizations and academic institutions, the country continues to slip in the world rankings for global innovation-based competitiveness. In order to maintain the standing of the United States as a leader in global innovation-based competitiveness, new legislation must develop new initiatives to foster an environment conducive to basic scientific research and commercialization of new technologies. In the absence of increased federal funding for basic research due to budgetary constraints, industry can provide the resources needed to spur innovation and economic growth if the government creates an environment in which it is economically advantageous to pursue scientific advancement.

Introduction

Since the industrial revolution, technological innovation has been a major driving force in American economic growth. Investment in basic research and development (R&D) yields a significant societal benefit, manifesting both as increased labor productivity and overall economic strength. After the Cold War, the United States has devoted fewer resources towards driving innovation through basic and applied scientific research, jeopardizing its predominant technological standing. The Information Technology and Innovation Foundation ranked the United States sixth in global innovation-based competitiveness. Of the 40 countries ranked, the United States had the smallest growth in the metric criterion in the past decade (Atkinson & Andes, 2009).

Technological progress gives the nation's firms an initial advantage in the production and sale of new products. In the mid- to long-term, this technological progress and innovation is positively correlated with job growth (Atkinson & Stewart, 2011). From the period 1909-1949, the cumulative upward shift in Gross National Product was about 80%. 87.5% of this growth can be attributed to increased productivity due to technological progress (Solow, 1957). Higher productivity leads to increased wages and lower prices, boosting domestic economic activity and creating new jobs. Each new job in manufacturing supports on average 2.91 jobs in other sectors, primarily material supply, capital services, and state and local government oversight (Bivens, 2003).

Because of the extent of the societal rate of return on basic scientific research, private sector firms performing the research cannot fully capture the benefits of the scientific advances accrued. Shareholders and industry competition require short-term payoffs for support and continued success. By collaborating with other firms and non-profits, businesses can increase return on investment and mitigate risk (Stepp & Atkinson, 2011). Of the fastest growing U.S. firms, 56% have partnered in the past three years with universities, federal agencies, or other firms, “resulting in more innovative products, more profit opportunities – and significantly higher growth rates.” Professor Edwin Mansfield demonstrated that “over 10% of new products and processes introduced could not have been developed in the absence of recent academic research,” (Schacht, 2011).

In the past, research ventures were subjected to a “pipeline model” of innovation in which there were a series of distinct steps from development of an idea to commercialization of a product. In the rapidly changing technological environment, this model is no longer considered valid. Innovation is not linear; increased emphasis on research will not necessarily lead to a corresponding increase in product commercialization (Schacht, 2010). Because of this incongruity and the difficulty in privately capitalizing on the benefits of performing basic scientific research, conventional efforts to promote collaborative R&D may no longer prove effective. To maintain the position of the United States as a global leader in innovation, new policy needs to be enacted to create an environment more conducive to collaborative research.

Legislative Background

In the past several decades, the federal government has implemented a number of policies and initiatives providing both direct and indirect support for collaborative R&D ventures. While doing so, there are a number of roles the government can take to strengthen the “social contract” between science and the public interest. The government can invest in basic research and infrastructure for innovation too broadly focused or expensive for private sector firms or academic institutions to viably invest in. The government can create an
open and competitive environment for innovation, allowing venture capitalists and established businesses to experiment and grow. Lastly, the government can, through legislation, provide catalysts to jumpstart innovation in sectors of public interest and national importance (Chopra, 2010).

In Fiscal Year 2010, the federal government directly spent $147.4 billion on R&D (Schacht, 2011). However, federal funding alone is not enough to drive innovation. Without private sector participation and support, new technologies cannot be implemented and commercialized. In an effort to facilitate the commercialization of government funded R&D by encouraging government-industry-university cooperation, the United States Government has enacted tax credits for research spending, reformed intellectual property law to be more favorable to collaborative research, and created Cooperative Research and Development Agreements to aid in technology transfer.

The Economic Recovery Tax Act of 1981 provided for a 20% Research and Experimentation Tax Credit for qualified research expenses (“P.L. 97-34”, 1981). This credit allows firms to deduct in-house expenditures such as wages, materials, and equipment, and also receive credit for corporate grants for basic research at universities and non-profit institutions (Schacht, 2000). A similar 20% flat-tax credit has been enacted for expenditures made to energy research consortia by the Energy Policy Act of 2005 (P.L. 109-58).

To facilitate the private commercialization of technologies arising from government sponsored research, the Bayh-Dole Act (P.L. 96-517, 1980) allows a small business, university, or non-profit institution performing research sponsored by the federal government to retain title to any “subject inventions” resulting from the work (Schacht, 2010). To promote the public interest and to protect the public against “nonuse or unreasonable use of inventions,” (35 U.S.C. 200, 2010) certain licenses and rights are reserved for the government. At the time the Bayh-Dole Act was signed into law in 1980, only 5% of federally-owned patents were being used. By enacting this legislation, Congress recognized that vesting title in a private contractor will encourage commercialization, fostering future innovation in target segments of the economy (Schacht, 2010). According to a study completed by the Government Accountability Office in 1987, this legislation had “been significant in stimulating business sponsorship of university research, which had grown 74%...” between Fiscal Year 1980 and Fiscal Year 1985 (RCED-87-44, 1987). Industry support for university R&D expanded from 3.9% of total funding in 1980 to 7.2% in 2000 (InfoBrief, 2002).

Another study of the technology transfer and patenting activities of the University of California, Stanford University, and Columbia University indicates that factors besides the Bayh-Dole Act may have played a role in this success. According to Professor David Mowery and his colleagues, increased federal funding for biomedical research, expanded research in biotechnology, specific court rulings, and government policies changing augmenting what can be patented all contributed to the increase in university patenting activities. It was the changing nature of biomedical and biotechnology R&D and not the Bayh-Dole Act itself that caused the shift in university intellectual property activity (Mowery, Nelson, Sampat, & Ziedonis, 2001).

The Stevenson-Wydler Technology Innovation Act of 1980 established an Office of Industrial Technology to promote technological development through affiliation with universities and non-profits. This is done through technology transfer, achieved using Cooperative Research and Development Agreements (CRADAs). These agreements define a collaborative venture, developed at the laboratory level at the discretion of the director with little agency oversight. Under a CRADA, title to or licenses for inventions made by laboratory personnel may be granted in advance to the participating for-profit company or organization. At the director’s discretion, the government can waive any right of ownership to inventions resulting from the joint effort; however the government is prohibited by law from providing direct funding to the industrial partner (P.L. 96-480, 1980). While CRADAs extend benefits to both parties engaging in a collaborative R&D venture, there are other effective, non-CRADA forms of cooperative activity. These include personnel exchanges and visits, licensing of patents, contracting work to others, educational initiatives, information dissemination, use of special laboratory facilities, cooperative assistance to state and local programs, and spinoff of new firms from existing corporations to pursue the potential of new, innovative technologies.

Issues and Opportunities

In September of 2009, President Barack Obama outlined his Strategy for American Innovation, designed to bolster America’s future economic growth and international competitiveness through a series of programs and initiatives aimed at promoting innovation. A central tenant of the President’s strategy is to promote market-based innovation by promoting a national environment supportive of innovation, entrepreneurship, and commercialization of technology. While current legislation and reform shows the government’s willingness to support collaborative R&D ventures, it has neither done enough to strengthen the social contract between science and the public interest nor to facilitate the commercialization of technologies resulting from basic scientific research.

Critics of existing legislation supporting collaborative R&D have three primary arguments:

- The laws promoting collaborative R&D have the potential of creating conflicts of interest between involved parties, possibly leading to the failure and dissolution of a joint venture.
- In a difficult economic climate, appropriating funding
to collaborative ventures involving private firms is always a point of political contention, especially when a specified private firm, and not the federal government, will be given title to inventions resulting from the venture.

Specific aspects of the Research and Experimentation Tax Credit fail in incentivizing expenditures in basic research by private companies.

In a study conducted by Dr. David Blumenthal of Massachusetts General Hospital (1996), company representatives were surveyed to determine if there were any problems in their relationships with academic organizations hindering negotiations for a cooperative R&D agreement. Dr. Blumenthal found that the most common obstacles, ranked by frequency, were: university bureaucracies making it too complicated to conclude an agreement; university regulations that interfered with the negotiations or contract; disputes over intellectual property; changes in the direction of academic research resulting in diminished usefulness to the sponsoring company; conflicts of interest; and misconduct on the part of academic scientists. The study also found that a great majority of participating private firms require academic researchers to keep information confidential to allow for the filing of a patent application. Researchers with private industrial funding are more than twice as likely to engage in trade secrecy and withhold research results from colleagues compared to researchers without such support. Researchers who received over two-thirds of their funding from industrial sources were less academically productive and the articles they produced were less significant (Schacht, 2000). Such secrecy can prevent the return on investment to the public beyond that which is captured by the private company, eliminating one of the main government goals in implementing cooperative R&D.

As addressed by the Bayh-Dole Act and the Stevenson-Wydler Technology Innovation Act, companies that do not control the benefits of their investments in R&D are less likely to invest in such activities. While Congress has accepted that there is an anticipated payback to the country in funding research leading to the commercialization of new innovations, there are those who reject on principle any government funding being used to support private firms seeking to commercialize inventions stemming from scientific research. It is argued that commercialization of these products benefits the government and the public good, bringing increased revenues from taxes on profits, job creation, improved productivity in future ventures, and broad economic growth. Many consider these benefits more important than the initial research cost to the government or a potential unfair advantage of one company over another in a cooperative R&D venture.

In the implementation of the aforementioned legislation, the federal government has not successfully created an atmosphere conducive to developing collaborative ventures at an economically viable rate. Much of the blame for this falls on the Research and Experimentation Tax Credit, initially established in 1981 and subsequently renewed fourteen times. The Information Technology and Innovation Foundation argues that the definition of basic research in the tax code as projects “not having a specific commercial objective” fails to incentivize collaborative R&D, one of the most significant sources of innovation in the United States (Stepp & Atkinson, 2011). The Foundation also argues that the tax credit for energy research consortia needs to be more generous to have a significant effect, as would any implemented collaborative R&D tax credit. The National Academy of Sciences offered a similar critique of the Research and Experimentation Tax Credit, as the tax credit goes only to companies that increase their R&D spending over a base amount calculated from prior spending. To be properly effective, the credit must be extended to companies that have consistently expended large amounts of resources on R&D to encourage them to continue to do so (National Academy of Sciences, 2005).

In their report, Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future, the National Academy of Sciences laid out a series of deficiencies in the United States’ commitment to basic scientific research and innovation and gave recommendations to correct them and advance the United States to a standard of excellence among competing nations. The United States Government answered these criticisms with the America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science Act of 2007 (America COMPETES Act) which implemented new initiatives, revised existing legislation, and restructured existing government agencies to better facilitate innovation (P.L. 110-69). The National Academy of Sciences subsequently revised its initial assessment, publishing Rising Above the Gathering Storm, Revisited: Rapidly Approaching Category 5 in 2010, the year many provisions of the America COMPETES Act were due to expire. While they found that the legislation took strides towards fulfilling many recommendations, many more were not acted on or relevant legislation was due to expire in the short-term. Predominant among the shortcomings was direct funding for research projects in various executive branch agencies. The Academy recognized the difficulty of procuring funding for research during times of budgetary constraints and economic difficulty, but said of the shortfall: “A non-solution to making an over-weight aircraft flight worthy is to remove an engine,” (National Academy of Sciences, 2010).

Policy Analysis

In order to maintain the standing of the United States as a leader in global innovation-based competitiveness, new legislation must develop initiatives to foster an environment conducive to basic scientific research and commercialization of new technologies. For a legislative initiative to effectively
promote innovation through collaborative R&D, it must:

- Facilitate the creation of an intellectual property agreement between a private firm and non-profit organization or academic institution;
- Establish a system to govern the patenting, licensing, and disclosure of technologies developed by government, non-profit, or academic institutions;
- Create an environment in which a sponsoring private firm can quickly and effectively commercialize technology stemming from research activities in a collaborative venture;
- Ensure initiating a collaborative venture is economically viable to provide maximum incentive to funding basic scientific research.

Any solution must also be politically feasible, as legislation that cannot be passed and signed into law will not be able to promote innovation as it was designed to do. Due to current federal budgetary constraints, increases in funding for basic R&D are nearly politically impossible. While extremely effective for fostering innovation, increases in funding are omitted for the purposes of this analysis; presented solutions will be procedural or organizational in nature.

Establish Policies to Reduce University–Faculty Conflict

As noted earlier, a conflict of interest can arise as the result of research under a CRADA. Carnegie Mellon University, one of the country’s leading research institutions, recognized that this problem was significantly hindering both commercialization and start-up creation. As a response, the provost instituted a “5 % go in peace” approach, creating a streamlined, common template for faculty based start-ups. This program limits university equity to 5 % or $2 million, and establishes clear royalty guidelines with a three year delay in payments and virtually no university interference (Kamel, 2010). Carnegie Mellon also collaborates with regional economic development organizations to ensure start-ups have the best possible environment for growth after leaving the university.

These policies allow for university faculty to incubate their companies in university laboratories for a short period of time and to hold leadership positions within them. The pro-commercialization atmosphere Carnegie Mellon has created has attracted some of the country’s largest corporations to sponsor collaborative research ventures, including General Motors, Microsoft, Apple, Google, and Intel (Davidson, n.d.). The rousing success of Carnegie Mellon’s Collaborative Innovation Center indicates that this system should be expanded. A policy being put in place to encourage innovation should include a provision that all universities receiving federal research funding must develop a streamlined commercialization strategy similar to Carnegie Mellon’s. This would effectively create a large number of research, development, and commercialization centers across the country, giving rise to an environment that promotes commercialization as a natural subsequent to innovation.

Strengthen the Research and Experimentation Tax Credit

As it is written, the Research and Experimentation Tax Credit only encourages increasing R&D funding from year to year; companies who maintain high levels of funding are not credited. Research activities aimed at commercializing resulting products are also excluded. Unlike increased spending, tax credits to spur innovation and economic growth are popular in a troubled economic climate; a strengthened tax credit is likely to be politically feasible. In order to have a significant impact on the economic viability of collaborative R&D ventures, the tax credit would need to be larger and broader than the current 20% and be redefined to allow research aimed at commercialization. The credit should be made permanent to encourage companies to invest in long-term research projects without fear of later cancellation. In a corporate world where short-term profits and competitive pressures are the main drivers to collaborative research ventures, a tax credit will raise return on investment and encourage further R&D spending.

Reform Intellectual Property Laws

A legislative initiative looking to facilitate collaborative ventures must address the awarding of patents resulting from the R&D work. As research funding accounts for only approximately 25 % of the cost of bringing a new product to market, patent protection can provide a means to incentivize a corporation to make the sizable investment required to commercialize a new technology (Schacht, 2000).

While the effectiveness of patents varies among industrial sectors depending on the ease of “inventing around” a patent, in many areas holding a patent is critical to market success. At the same time, patent protection of a product can stymie further research in a particular area by a non-profit organization or academic institution unaffiliated with the owner of the original patent. To create a competitive innovation environment and further technologies that may have otherwise not be investigated, non-profit organizations and academic institutions should be shielded from intellectual property infringement legislation when using patented inventions for research purposes. Due to the substantial public return on investment resulting from conducting basic research, benefit to society as a whole will greatly outweigh any loss sustained by the patent-holding corporation.

Conclusion

While the United States has made significant advances in promoting innovation through legislation reforming intellectual property law, creating Research and Experimentation Tax Credits and Cooperative Research and Development Agreements, and directly funding research at non-profit organizations and academic institutions, the country continues to slip in the world rankings for global innovation-based competitiveness. To correct this trend, the federal government must further the programs and initiatives provided for in the America COMPETES Act and continue pursuing

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the goals set forth by the National Academy of Sciences. The government should model reforms after organizations like Carnegie Mellon University, which has been enormously successful in attracting industry sponsors to fund collaborative R&D ventures, commercializing the results of those ventures, and contributing to the innovative strength of the surrounding communities. In the absence of increased federal funding for basic research, industry can provide the resources needed to spur innovation and economic growth if the government creates an environment in which it is economically advantageous to do so. If the federal government fails, industry will retreat from opportunities to further technological progress, putting the future economic well-being and global standing of the country in jeopardy.

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The Spectra, May 2012
Improving HVAC Energy Efficiency: A Two-Stage Approach*

Virginia Smith
School of Engineering and Applied Science, Department of Computer Science

“The goal is to develop a model for this system that accurately predicts temperature dynamics within a building.”

Social Impact
Heating, ventilation, and air conditioning (HVAC) systems are the greatest energy consumer in buildings, which account for about three-fourths of all electricity spent within the United States. This makes them an extremely important target for energy efficiency improvements. One area for improvement is in using occupancy sensors to determine which zones within residential buildings need temperature control and which do not. To allow for this type of system, we develop a mathematical model that will predict future temperatures based on current HVAC configurations. This model will enable new, more energy efficient control of the system.

Virginia Smith is a fourth-year student from Blacksburg, Virginia studying Mathematics and Computer Science. She hopes to combine her technical skills with an interest in the environment by pursuing graduate studies in the field of Computational Sustainability. Virginia has conducted this research as part of a senior thesis for her computer science degree at the University of Virginia. She would like to thank her mentors, Professor Kamin Whitehouse and Tamim Sookoor, for all their help on the project.

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Abstract

A significant amount of the world’s energy is used for heating, ventilation, and air conditioning (HVAC) systems. This makes them an important target for energy efficiency improvements. One step toward this goal is to find a mathematical model that accurately predicts the performance of current systems. A common energy-reducing setup in residential buildings is the electrical, dual stage heat pump air conditioner. To study this setup, we collect data from a residential testbed which has been outfitted with sensor networks for the purposes of in situ experimentation. We aim to use this information to develop new, energy-efficient control strategies for the HVAC system at hand. However, these strategies necessitate the use of models which will predict system performance. We develop a two-stage model which, first, learns thermal patterns within the building when the system is OFF due to variable factors such as sunlight, cloud coverage, and wind. This model is then included in the model when the system is ON, allowing us to predict the effect of the system configuration more accurately. Results from this model allow the prediction of temperature within an interval suitable to enable control. This model is scalable to similar systems, and thus can be used to improve the efficiency of HVAC systems by helping to determine more effective control schemes.

Introduction

Buildings account for 75% of the electricity and 43% of the greenhouse gas emissions in the United States (DOE, 2011; McQuade, 2009). Heating, ventilation, and air conditioning (HVAC) is the largest building expenditure, consuming 38% of the energy within buildings (DOE, 2011). This makes HVAC systems an important target for energy efficiency improvements.

Current work in HVAC energy reduction is moving in several directions. One such direction is in the design of new, more efficient equipment. However, buildings and equipment are often replaced slowly (Dawson-Haggerty, et al., 2010). This has made the retrofitting of old HVAC systems an important area of research with regard to energy reduction.

One step toward retrofitting HVAC systems is to identify a mathematical model that enables temperature and energy control. Having an accurate model of the system allows for more effective control schemes. However, large variation in HVAC configurations creates difficulties in developing a universal model. There has been considerable research performed on the modeling and control of different HVAC systems (Henze, et al., 2004; Deng, et al., 2010; Oldewurtel, et al., 2010; Ma, et al., 2011; Nghiem & Pappas, 2011; Aswani, et al., 2011). Our research focuses on the modeling of the dual stage heat pump air conditioner, which is commonly found in residential buildings. The goal is to develop a model for this system that accurately predicts temperature dynamics within a building, while incorporating specific control variables from the system. These variables may then be later utilized when developing a control scheme to seek efficiency improvements.

Though this model may be adapted to similar systems, the immediate objective will be to use the model as part of a control scheme created for room-level zoning HVAC actuation (Sookoor, et al., 2012). This method aims to increase energy efficiency by using sensors to detect activity on a per-room basis and actuate each room in the building accordingly. Efficiency is gained by reducing energy spent in rooms that are empty or in which occupants are inactive.

Prior work has demonstrated that HVAC systems can be retrofitted in order to implement this type of room-level zoning efficiently and inexpensively (Sookoor, et al., 2012). The next step will be to develop and optimize the control schemes used within this type of system.

We begin by describing our residential testbed, an area which has been outfitted with sensor networks for the purpose of in situ experimentation. Sensors deployed to this setting allow for both the collection of data and actuation of the HVAC system itself.

Next, we discuss the physical characteristics of the HVAC system at hand. This is an integral component in the development of an accurate model of temperature dynamics, and it will likely be scalable to many similar systems. Furthermore, it will be important to understand the trends apparent in this data in order to identify areas for efficiency improvements.

Observing trends in the data and understanding the physics behind HVAC systems sheds light on the model that we have chosen. One challenge is that the heat load within the home due to factors such as sunlight, wind, and cloud coverage is highly nonlinear over time. An approach to handling this issue is to include weather data within the model. However, these measurements add complexity to the model, especially when trying to estimate how these factors affect specific rooms or zones within the building. The scalability and computability of the model quickly decreases, which is a potential problem when creating a control scheme for the system.

Our solution is to use a two-stage model approach that
estimates the heat load due to weather patterns when the system is OFF, and incorporates this estimate when the system turns ON. This is advantageous because it does not require extra sensors other than sensors that are already outfitted within the building. It also allows us to more accurately predict the effect of the HVAC configuration itself.

After developing this model, we discuss our results and compare our predictions to actual data from the building. We conclude by analyzing these results and describing the role the model will play in future research.

**Resedential Testbed**

The room-level zoning system described has been deployed in a single-story, 8-room, 1,200-square-foot residential building. A model of the home is shown in Figure 1. The hallway and porch are depicted, but not included within our analysis because of the inability to actuate temperature within these regions. The HVAC system setup is overlaid in order to show the position of vents, ducts, and the central air handler.

Preliminary studies have split the building into two zones, shown in Figure 1 as red and blue, in order to enable room-level zoning. The two zones were conditioned at specific times of the day, rather than providing air to both simultaneously. This simple zoning mechanism was implemented and compared against a traditional, off-the-shelf thermostat manufactured by BAYweb. Results from this study indicated that zoning reduced energy consumption by 20.5 % within a 20-day period while maintaining the same level of comfort via setpoint actuation (Sookoor, et al., 2012).

We expect energy reduction to be even larger when including the occupancy information and predictive control that will be enabled by this model. This prediction is based on results such as those shown in Figure 2, which illustrates empirical occupancy data describing the frequency at which specific rooms within the household are utilized. The findings indicate that there are primarily only 1-2 rooms being used at any given time throughout the day. Reducing energy usage at the other times could greatly improve efficiency.

**Temperature Detection**

Sensors deployed throughout the building allow us to monitor the temperature and HVAC status within each room/zone. We collect temperature data at a fine granularity using temperature sensors placed at various points along the walls. In order to ensure the scalability of this system, we use 21 standard, off-the-shelf temperature sensors (Sookoor, et al., 2012).

One challenge with sensing temperature in this way is that temperatures are not uniform throughout the rooms/zones and along the walls. This can present problems when trying to determine the true temperature of each room. As shown in Figure 3, the placement of wall sensors has a large impact on the variability of the temperatures detected. While the sensors on the internal wall vary within the temperature range similar to the return duct, the sensors on the external wall are subject to large temperature swings. This is because the external wall sensors pick up temperatures from outside of the building through windows, doors, and the wall itself. This is also compounded by the fact that most vents are placed on external walls, making these sensors subject to direct air from the duct (Sookoor, et al., 2012).

Thus, we use two methods to ensure accuracy within our temperature data collection. The first is to only place sensors...
along the interior walls of the rooms. The second is to record the temperature as an average of these sensors, helping to detect the temperature more uniformly throughout the room.

**System Characteristics**

Heating, Ventilation, and Air Conditioning control systems are devised in order to maintain comfort within an enclosed space. In addition to meeting a desired temperature, this comfort is maintained by achieving a certain level of humidity, pressure, radiant energy, air motion, and air quality within a building (Ben-Aissa, 2009).

The testbed in this study utilizes a two-stage heat pump air conditioner. This is becoming an increasingly popular setup because of the efficiency and comfort that it provides. Within residential buildings, the single-stage heat pump air conditioner has historically been the most common configuration, and can still be found in a wide variety of locations. These systems work simply by turning on at 100% when the temperature reaches above/below a certain preset temperature.

In contrast, the two-stage configuration improves upon this model by allowing the system to run either at 67% or 100%. This allows the system to run consistently at a lower rate, which helps to improve temperature stability and comfort. By avoiding the costly power-up cycles, it also improves the efficiency of the system (Lekov, et al., 2006).

Therefore, though the model we have developed is scalable to a single-stage configuration, we show that improvements can be made to the two-stage system, which is at the forefront in terms of comfort and efficiency.

**Two-Stage HVAC System**

The framework for the HVAC system is the air handling unit. This unit delivers conditioned air throughout the building while removing exhaust air and carbon dioxide (CO₂). Most of the equipment is hidden from occupants, being located outside and in ducts within the building.

As shown in Figure 4, this may include fans, compressors, heating/cooling coils, and ducts, in addition to system controllers. The air handling process works in the following way: First, outdoor air is mixed with the return air of the system. The air is then heated/cooled to a preset temperature, and is released into specific spaces through the dampers. The exhaust air from the room is sent into the ducts according to the exhaust fan speed, and it is returned to begin the process again.

The damper is a mechanical device that allows for a variable amount of supply air to be released into a room. It consists of a thin metal sheet, rotated on an axis by an actuator. If the damper is set at 90°, or 0% open, the damper is fully shut and no air is supplied to the room. When the damper is set to 0° or 100% open, the maximum amount of air is released (Ben-Aissa, 2009). The amount of air flow versus damper position is shown in Fig. 5.

![Figure 3. The variation of temperature sensors placed on an external wall (red), internal wall (blue), and near the return duct (green) (Sookoor, et al., 2012).](image1)

![Figure 4. An example air handling system used to supply air throughout a building (HVAC, 2011).](image2)

![Figure 5. The air supplied to a room (air flow) versus the damper position (angle) (Ben-Aissa, 2009).](image3)
The two-stage HVAC system can run in four possible states when heating/cooling: Float; Hold; Heat/Cool 1; and, Heat/Cool 2. Float causes the HVAC system to turn off, and Hold tells the system to remain at the same temperature. Heat/Cool 1 corresponds to running the system at 67%, which provides a lower level of heating/cooling that can supply a base level of conditioned air throughout the day. Heat/Cool 2 turns on when temperature needs to be changed by a significant amount, and the system runs at 100%. The system in our testbed runs stage 2 conditioning if the current temperature is more than 2° above/below the current setpoint (Sookoor, et al., 2012).

Model of the Temperature Dynamics

There are many challenges associated with creating a model for the system described. One is that HVAC systems themselves are large and highly variable. The parameters are complex, and the model is often non-linear with respect to the temperature dynamics. The particular application of this model presents another challenge, in that there is a trade-off between the complexity of the model and its computability. While we aim to create a robust model of the system, it cannot be too complex, or it may ultimately risk the effectiveness of using the model within a control scheme.

These challenges are compounded by the fact that we have created a predictive model using experimental data. This is difficult because the raw data is not always rich enough to allow for robust model development. Furthermore, the data itself presents difficulties from limitations and errors inherent within the sensor networks.

The model that we have developed for this system is a dynamic, linear model. We develop the model in two stages. First, we estimate the effects of heating/cooling due to external factors such as solar radiation, wind, and cloud coverage. This effect is calculated when the system is turned off, and the values are added into our model immediately after the system turns on again. This two-stage approach allows us to compensate for these external factors without having to measure them directly. The results provide us with a more accurate prediction of how the HVAC configuration will predict temperature, which is beneficial in developing a new control scheme.

Model Characteristics

The parameters of the model include the position of the damper, temperature, system status, and time. These values are recorded through the wireless sensor networks deployed in the testbed and stored in a database. The temperature values are measured in degrees Fahrenheit, and the damper positions fluctuate between 0 (closed) and 1 (open 100%). The system status allows us to see whether the system is in off, heat/cool 1, or heat/cool 2 mode. An example of the damper, temperature, and system status for one room is shown in Figure 6.

The model we have chosen is a dynamic, linear model which predicts the change in temperature in one room ($T_k$) over time ($t$) based on the current temperature ($T_k$) and HVAC damper configuration ($D$). The terms $\alpha$ and $\beta$ are coefficients for temperature ($T_k$) and damper position ($D$), respectively. The following model is a form of this deterministic model.

$$\frac{dT_k}{dt} = \alpha T_k + \beta D$$

<table>
<thead>
<tr>
<th>Room</th>
<th>RMS Error (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living Room</td>
<td>0.0370</td>
</tr>
<tr>
<td>Kitchen</td>
<td>0.0285</td>
</tr>
<tr>
<td>Dining Room</td>
<td>0.0308</td>
</tr>
<tr>
<td>Bathroom</td>
<td>0.0402</td>
</tr>
<tr>
<td>Mudroom</td>
<td>0.0222</td>
</tr>
<tr>
<td>Nursery</td>
<td>0.0498</td>
</tr>
<tr>
<td>Bedroom</td>
<td>0.0399</td>
</tr>
</tbody>
</table>

![Figure 6. The system status (on/off), temperature (°F), and damper position (open/closed) for one room in our testbed over the period 11/30/2011-12/04/2011.](image)

![Figure 7. A plot of the predicted (solid) and measured (dashed) temperatures when the system turns on for a one-step time prediction from 11/30/2011-12/04/2011. Associated root mean square errors are shown at right.](image)
Here the change in temperature over time is calculated by finding temperature and time differences. The dampers, D, correspond to a vector on/off position for the dampers in all n rooms. In contrast, the temperature, $T_k$, corresponds to the temperature in the $k^{th}$ room.

**Two Stage Approach**

In order to estimate the effects of weather patterns on the temperature dynamics, we begin by modeling the change in temperature over time as a result of the current temperature when the system is off. This model (shown below) allows us to calculate a value, $\alpha$, which constantly changes in order to compensate for changing weather patterns.

$$\frac{dT_k}{dt} = \alpha T_k$$

Next, when the system turns on, we use the previously calculated $\alpha$ values to predict the effect of the damper configuration. We calculate the $\beta$ values of this full model through linear regression. Using the previously calculated $\alpha$ values allows us to predict the direct effect of the damper configuration more accurately, under the assumption the effect of weather does not change dramatically within a short period of time.

**Analysis**

Visually examining the measured and predicted temperatures (Figure 7) highlights a few modeling errors. One is that the predicted temperatures fail to predict periods of rapidly changing temperature. However, because the temperatures within this region are acting within a narrow range, this rapid change is likely to appear as noise to the system, and is reasonably captured by the predictive model.

Another visible error is that the predicted temperatures fail to capture the temperature magnitude in some cases throughout the week. The largest error is about 2°F, a value which may be due in part to noisy sensor data. Although this may appear large, it still lies within an interval that would ensure comfortable temperatures to occupants when creating a control scheme. Furthermore, the average error is 0.0192°F, which is quite low and would certainly ensure comfort and precision within the system. Another indication of a good fit is that the root-mean-square error (Figure 7) for this prediction is very low.

One difficulty in analyzing the effectiveness of this model is that we aim to use it to predict temperatures more than one step in advance. We visualize this analysis by showing the distribution (within two standard deviations) of the model errors aggregated over each prediction, x minutes into the future.

Both plots indicate that the error rates are worse for some rooms than for others. Figure 8 shows that the absolute value of the error can get quite large over time. However it is important to remember that these predictions are up to 20 hours in the future.

Predictions within a reasonable interval are shown in Figure 9. This shows the prediction error up to 30 minutes in the future. As can be expected, the average errors tend to increase as we predict further into the future. The variance of these errors also tends to increase as we look further into the future. However, the predictions remain within a realm of 1 degree Fahrenheit over this time period, which is within a suitable range to enable control.

**Conclusion**

We have presented our residential testbed, studied the characteristics of the dual stage HVAC, identified a mathematical model of the system, and discussed the impact of our results. The two-stage, dynamic model that we have developed provides an accurate way to predict the temperature in a zone based on a few, accessible parameters in the system. It also allows the calculation of highly variable terms, such as the heat load due to solar radiation, wind, and cloud coverage, without the need to explicitly measure these terms.

These results will be used in future work in order to develop a control scheme for the HVAC system that will enable room-level zoning and take into account occupancy measurements. The model gives us better insight into the dynamics of the control scheme, and allows for a more efficient design. This control scheme may then be used to create a more energy efficient design for similar HVAC units. This type of work is a crucial step in the developing the
type of energy-agile systems that can ultimately be used to quell our dependency on fossil fuels.

**Acknowledgements**

I would like to thank Kamin Whitehouse for his mentorship and guidance throughout this research experience. I would also like to thank Tamim Sookoor for his support in conducting this research. This research is based on work supported by the National Science Foundation under Grant No. 1038271.

**References**


Social Impact

Type I diabetes, resulting from the body’s destruction of its own insulin-producing beta cells of the pancreas, affects approximately 5% of all diabetes patients worldwide. The disease is typically diagnosed in juvenile patients, but dealing with the condition is a life-long process. Islet-cell transplantation, a therapy for Type I patients, is the encapsulation and transplantation of new insulin-producing cells via a 3D polymer scaffold “bead”. The scaffold’s material properties studied in this paper have implications for increasing survival rate of transplanted cells, thereby increasing the viability of islet-cell transplantation as a realistic future therapy for diabetic patients.

It is hoped that a solution implementing predictably degradable alginate can be eventually utilized in islet cell transplantation and drug delivery as a treatment for Type I diabetes.

Jessica Ungerleider is from Vienna, Virginia. She is a third-year studying biomedical engineering. Her research was conducted at the Illinois Institute of Technology in Chicago, IL as a part of a Research Experience for Undergraduates Summer Diabetes Institute under the mentorship of Dr. Eric Brey. Although this research was completed only during a ten-week period over the summer, Jessica’s passion for diabetes research has extended to her work in a tissue engineering lab here at the University of Virginia. Her research on alginate microbeads at IIT and diabetic retinopathy at U.Va. has encouraged her to attend graduate school to pursue a Ph.D. in biomedical engineering. In addition to research, Jessica is involved with the Society of Women Engineers, the Rodman Scholars program, Biomedical Engineering Society, and Alternative Spring Break. This summer, she will be researching microfluidics chips at the Naval Research Laboratory in Washington, DC.
Abstract

Alginate microbeads have been investigated for cell and drug delivery. However, it is difficult to control the degradation of alginate. Oxidation of the polymer can allow for controlled degradation of alginate via hydrolysis. In this study, we investigate the influence of oxidation on the formation and degradation of alginate microbeads. Sodium alginate was oxidized by reaction with sodium periodate (NaIO4). The level of oxidation was evaluated by Fourier Transform Infrared Spectroscopy (FTIR) and spectrophotometry at 486 nm using a thyodene indicator. This partially-oxidized alginate was used to synthesize alginate microbeads using a 2-channel air-droplet micro-encapsulator. The physical properties of the resultant microbeads were evaluated over time. Alginate samples were oxidized at levels ranging from 2.5 to 49.5 % proportional to NaIO4 concentration, and the degree of oxidation was corroborated using FTIR. The reaction yield was 68±6.4%. Oxidation altered the microbead properties relative to controls. Spherical beads were able to be formed using alginate at 0-2.5% oxidation. Beads made with 5% oxidation formed but had an altered morphology, while oxidation levels above 5 % beads did not form. In conclusion, we have oxidized alginate and generated microbeads. The oxidation of alginate alters the ability of microbeads to form and their resultant structure. Degradation time of the microbeads is hypothesized to increase with degree of oxidation. Current studies are investigating microbead degradation as a function of oxidation. It is hoped that a solution implementing predictably degradable alginate can be eventually utilized in islet cell transplantation and drug delivery as a treatment for Type I diabetes.

Introduction

Type I diabetes mellitus, resulting from the autoimmune destruction of insulin—producing β-cells of the pancreas, affects approximately 5 % of all diabetes patients worldwide. The disease is typically diagnosed in juvenile patients, but treatment of this condition is a life-long process. One current treatment involves continuous monitoring and adjusting of insulin and blood glucose levels with insulin pumps or intravenous injections, while another involves transplantation of islets, the hormone-producing cell aggregates of the pancreas. Monitoring insulin levels can be very time intensive, whereas islet cell transplantation is a one-time procedure. However, islet cell transplantation is not without its own problems. First, the host risks immune rejection of transplanted cells and thus must take immunosuppressants. Second, the survival rate of islet cells following transplantation is low, resulting in the need for a large number of islets to treat a single patient.

To combat these problems, our laboratory has devised a procedure to fabricate multilayer alginate microbeads that addresses both major issues. First, a poly-L-ornithine (PLO) coating is added to the inner alginate bead to act as a barrier to reduce the immune response. Next, an outer layer of alginate is cross-linked after formation of the PLO layer. This layer can be embedded with therapeutic proteins, such as fibroblast growth factor, in order to increase local neovascularization at the transplant site, thereby increasing viability of the islet cells1,2 (Figure 1).

Although the therapeutic proteins are initially embedded in the outer alginate layer, our group has shown that after a period of 30 days, most of the protein has been released from the outer layer3. After it has released its protein, the outer layer poses a transport barrier for nutrients needing to get to and from the islet cells. A proposed solution to this problem would be to synthesize an outer alginate layer that degrades over time, after releasing therapeutic proteins from its network. By oxidizing the alginate, we can expect that degradation times will be faster and more predictable than non-oxidized alginate.

Oxidized alginate has been used in many applications as a...
degradable polymer or scaffold. Chemically, oxidation causes the carbon ring to be broken, forming two aldehyde groups. The open-chain ether bond then becomes susceptible to hydrolytic scission, thus breaking the long polymer chain down into smaller, less homogenous chains (Figure 2). As these chains form the building blocks of polymer scaffolds, breaking them down into smaller fragments would accelerate the degradation of the bulk scaffold. The degree of oxidation can be varied by changing the amount of oxidizing agent, pH, temperature, or molecular weight distribution.

Although many groups have studied the degradation of oxidized alginate in hydrogels, our group is unique in examining the degradation properties of oxidized alginate in microbeads. We will examine the degradation of oxidized alginate microbeads with the eventual purpose of studying protein release kinetics and degradation kinetics from an oxidized alginate outer layer. The goal of this study is to synthesize oxidized alginate, quantify the level of oxidation, make microbeads using oxidized alginate, and study the degradation kinetics of these beads over time. It is hoped that an oxidized outer alginate layer with predictable degradation properties can be implemented in an islet cell transplantation model. It could optimize survival of the islet cells by releasing growth factors that initiate blood vessel growth and by minimizing the transport barrier for nutrients to and from the cells.

Methods

The oxidation of sodium alginate was conducted as previously described. Briefly, solutions of sodium alginate and sodium periodate were combined and stirred for 24 hours. The reaction was quenched with an equimolar addition of ethylene glycol and stirred for 30 minutes. The sample was dialyzed against deionized water for three days using membranes with a 3500 molecular weight cut-off, with water being changed at least three times per day. The resulting solution was freeze-dried using a lyophilizer and samples were verified by observation of a 1730 cm$^{-1}$ peak on FTIR spectroscopy, corresponding to the aldehyde group formed by oxidation via hydrolysis of the alginate chain.

The degree of oxidation was determined by measuring unreacted periodate using an adapted procedure described by Gomez et al. Briefly, an indicator solution was prepared by combining equal volumes of 10 % weight-by-volume thyodene and 20 % w/v potassium iodide solutions. After the 24h oxidation period, but before quenching with ethylene glycol, 3 ml of sample solution was combined with 1.5 ml indicator solution, and the absorbance reading was compared against a standard curve of periodate (0.8 – 2.0 x 10$^{-5}$ M). The amount in moles of periodate reacted was then calculated and compared to the amount of alginate in solution.

Microbeads were formed using a 2-way air-jacket microencapsulator with an air jacket pressure of 22.5 psi and an alginate syringe pressure of 20 psi. The beads were expelled into a 100 mM solution of CaCl$_2$ and allowed to cross-link for 15 minutes before being washed and stored in normal saline to remove excess Ca$^{2+}$ and alginate.

Beads undergoing degradation analysis were stored in an incubator at 37°C and monitored frequently using a Zeiss inverted microscope. Pictures were taken and analyzed using AxioVision software.

The swelling ratio was analyzed by measuring wet weight of beads immediately after their formation using a 100 μm cell strainer to remove excess water and then measuring dry weight after a three day incubation period in a 37°C lab oven. Swelling was determined by taking the ratio of the difference between wet weight and dry weight to the wet weight.

Results

Oxidation was confirmed based on the presence of the characteristic aldehyde peak at 1730 cm$^{-1}$ on FTIR spectroscopy images (Figure 3). Oxidized alginate was
synthesized at levels ranging from 2.5 % to 49.5 %. The level of oxidation was successfully quantified using UV/Vis Spectroscopy, and was linearly correlated to the level of NaIO₄ (Figure 4).

Beads were synthesized using oxidized alginate from 2.5 % to 10 % oxidized. Spherically shaped beads were not seen in 7.5 % or 10 % oxidized samples. Immediately after formation, beads were imaged on an Axiovision microscope. While control beads and 2.5 % oxidized beads look similar, 5 % oxidized beads seem to have a more tortuous border (Figure 5).

Swelling ratio was calculated for beads at day 0. It was observed that the swelling ratio in 2.5 % oxidized beads was significantly lower than the swelling ratio for control beads (p < 0.05, Figure 6).

Although quantitative analysis was not able to be performed, beads were observed qualitatively over a period of two weeks, and over that time 5 % oxidized beads had completely degraded. Images comparing control beads and 5 % oxidized beads can be seen immediately after synthesis and again at the two week time point (Figure 7).

**Discussion**

We were able to synthesize oxidized alginate and quantify this oxidation by FTIR and UV/Vis spectroscopy (Figures 3,4), and found that there is a linear correlation between the ratio of NaIO₄ /alginate and level of oxidation.

In the future, alginate can be oxidized at a predictable level using this relation.

In forming beads using a microencapsulator, it was observed that samples with oxidation levels over 5 % did not form into spherical beads. Even beads formed from 5 % oxidized alginate had an obvious initial qualitative difference in morphology from the control and even 2.5 % oxidized beads (Figure 5). This suggests that increasing oxidation leads to significant differences in chain length and charge, preventing the polymer from ionically cross-linking into a stable enough conformation to form into spheres.

Other groups have used covalent cross-linking to combat this stability problem⁸,¹², so it is possible that covalent cross-linking would help beads to maintain their spherical...
shape. However, the relative expense of reagents and added procedural steps of covalent cross-linking makes ionic cross-linking a more ideal solution.

Furthermore, this difference in initial physical properties was confirmed by a significantly decreased swelling ratio in oxidized beads over non-oxidized beads (p < 0.05, Figure 6). The decreased swelling ratio means that the oxidized beads contain less water. It would be useful to study the swelling ratio of oxidized vs. control beads over time to see if this difference in physical properties grows over time, indicating degradation.

Lastly, it was shown that 5% oxidized beads degrade over a two week time period under in vivo calcium levels. This study was performed only qualitatively as quantitative methods were not used at the beginning of the trial and thus consistency in data analysis was not achievable. However, future trials should elucidate a consistent quantitative timeline for different levels of oxidized alginate microbeads. Shape factor, volume fraction, and swelling ratio can all be employed as quantitative measures of degradation. Degradation of oxidized outer layers should also be measured to determine if this is a feasible model for multilayered alginate microbeads (Figure 1). Last, it is important to determine the compatibility of protein encapsulation in oxidized outer layers and seeing if this is also compatible with the degradation of the outer layer. Eventually, it is hoped that these design constraints can be optimized to create an efficient islet cell transplantation model as a treatment for Type I diabetes.

Conclusion

In this study, we have synthesized oxidized alginate and quantified the level of oxidation using FTIR and UV/Vis spectroscopy. We have shown the ability of oxidized alginate to ionically cross-link and form into spherical microbeads, observing more severe morphological changes at higher levels of oxidation. We have quantified this difference by measuring a significant decrease in swelling ratio of oxidized samples over the control.

Future studies should be aimed at elucidating the exact degradation timeline and its structural characteristics in oxidized alginate microbeads. Eventually, the oxidized alginate should be incorporated into the outer layer of multilayer alginate microbeads in order to study the degradation and protein release kinetics from this outer layer specifically. A degradable outer layer could have important implications for islet cell survival and viability upon transplantation into Type I diabetic patients.

Acknowledgements

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References

Automated Shading System: Reducing Home Energy Usage

Matthew A. Jungclaus and Quinn S. Weber
School of Engineering and Applied Science, Department of Mechanical Engineering

The team anticipates that household energy consumption will decrease as the shading system optimizes heat flow.

Social Impact

The residential sector will consume 29% of the baseline energy in the U.S. by the year 2020 and half of that energy will have been used for heating and cooling (McKinsey 29). This demand will largely be met by fossil fuels which emit harmful gases into the atmosphere and whose supply is finite. One of the most effective methods of reducing greenhouse gas emissions, a known contributor to global warming, is by decreasing residential energy usage, and increasing the efficiency of existing home energy systems. Windows are one of the most consistent and significant breaches in a home’s thermal barrier. Additional insulation over windows in times of significant heating or cooling could decrease demand on a home’s heating and cooling systems and decrease the home’s overall energy demand (Krigger and Dorsi). The completed system will provide a tangible example of the various sustainability technologies available to residents and visitors of Charlottesville.

Matthew Aaron Jungclaus (left), originally from Moorestown, New Jersey, is a fourth-year mechanical engineering major at the University of Virginia. Matt is heavily involved in the ecoMOD program, an interdisciplinary initiative for affordable, sustainable housing at U.Va.. He has worked with ecoMOD and its related projects in energy efficiency since his first year. The research surrounding this article is based on the work that Matt, Quinn, and other students have carried out on the ecoREMOD project over the past few years under a number of research grants. Outside of his research, Matt enjoys performing with the U.Va. Jazz Ensemble and participating in community service. After graduation, Matt will continue to work in building energy performance with Clark Energy Group in Arlington, Virginia.

Quinn Weber (right) is a fourth-year mechanical engineering and economics double major from Doylestown, Pennsylvania. His interest in solving energy related problems led him to join the ecoMOD program as a second year and he has been involved in many capacities since. Some roles include being a member of the HVAC team, producing educational videos for the Local Energy Alliance Program, and working on two Jefferson Public Citizens grants. Recognizing the need for more innovative methods for decreasing residential energy consumption, Quinn, Matt, and other members of ecoMOD began researching this project in early 2011 in Charlottesville. While not working on this project, Quinn enjoys spending early mornings on the Rivanna Reservoir as a member of the Virginia Men’s Rowing Team. After graduating in May of 2012, Quinn will begin looking at the energy problem from a different perspective as an analyst at DC Energy in Vienna, Virginia.
The Spectra, May 2012

coMOD is a collaborative design/build/evaluate project of the Schools of Architecture and Engineering and Applied Science at U.Va., striving to create sustainable, prefabricated housing units in partnership with affordable housing organizations. Since 2004, the project has worked with Habitat for Humanity and Piedmont Housing Alliance to build prototypes, and has also developed prototype designs for the non-profits People Incorporated of Virginia, Jefferson Area Board for Aging and Building a Bridge. Graduate and undergraduate students in a variety of disciplines manage projects and participate in all aspects of ecoMOD. The project is engaged in two types of design efforts: ecoMOD projects are newly constructed housing units deploying prefabricated construction strategies and ecoREMOD projects are focused on regenerating and adapting historic buildings. Each ecoMOD unit engages the intersection of sustainable design, affordable housing, and prefabricated construction, while ecoREMOD units do so in historic contexts. ecoMOD XS units are small scale accessory dwelling units to be placed behind or attached to existing homes in urban contexts. Technology and environmentally thoughtful design are strategies woven throughout the ecoMOD projects. There is no one right solution for many of these issues, rather, the various strategies play to particular strengths, weaknesses, and preferences. Technologies implemented in the houses include solar photovoltaic (electric), solar thermal (water heating), ground source (geothermal) heat pump. The engineering team has developed monitoring systems that record energy usage, temperature, humidity, CO₂, and other energy performance variables. We also do modeling and simulation to improve our ability to design for superior energy efficiency. For more information, please visit, http://ecomod.virginia.edu/

Professor Bio

P. Paxton Marshall, Professor of Electrical and Computer Engineering is active in energy and sustainability research and experiential learning incorporating community engagement. He was engineering director for the U.Va. solar house project, an energy independent house designed and built by students. The house placed second overall, and first in the Design and Livability and Energy Balance categories, in the 2002 DOE Solar Decathlon. Marshall works with the U.Va. School of Architecture on ecoMOD, a research and design / build / evaluate project that has created four ecological, modular and affordable house prototypes and three deep renovations. Marshall was engineering director of the Learning Barge project, which created a floating environmental classroom for the Elizabeth River. The barge is powered by photovoltaic and wind generators and heated by a solar thermal system. Marshall is the former Chair of the Energy Conversion and Conservation Division and the Engineering and Public Policy Division of the American Society for Engineering Education. Marshall’s classes have worked with U.Va. Facilities Management on energy assessment and design projects which resulted in U.Va. being designated as EPA Green Lights and Energy Star Partners of the Year in 1999 and 2001 respectively. Marshall has participated in the development of the Global Sustainability minor, the Jefferson Public Citizen Program, the Engineering Business minor, the Science and Technology Policy minor and Washington summer internship program. He has developed and taught classes on “Global Sustainability”, “Engineering in Community Settings”, “Developing Community-based Projects” and Commercial Building Energy Systems. Marshall has an Affiliated Faculty appointment with the School of Architecture.
Abstract

The team proposes an automated shading system that has been designed and assessed for use in ecoREMOD, a showcase for energy efficiency in Charlottesville, Virginia. The goal of the system is to reduce energy consumption in the home by optimizing heat transfer through windows in residential buildings. Homeowners are seldom aware of the summed effects of radiation and conduction through windows that often lead to excessive energy consumption. Even if homeowners are aware of this, they may not be able to ameliorate this issue effectively. The team designed a mechatronic system, featuring a microcontroller, sensors, and an actuator, that uses light and temperature data to continuously optimize this heat transfer by advantageously moving an insulated shade. A past ecoMOD team began work on this project and purchased a prefabricated motorized shade. This shade was incorporated into the current team's project, but the method of automation was significantly improved. The design was developed to include the original shading system in addition to direct control of the shade's motor by way of the Parallax Propeller microcontroller chip and a number of integrated circuit chips. These digital components allow for custom control of the shading system's motor. A number of sensors communicate directly with the Propeller chip, which processes the information and orients the shading system as 'up' or 'down.' Since the ecoMOD project relies on sensor data to evaluate its homes, the team also included a data transmission system, which will allow live data to be transmitted to ecoMOD's preexisting data storage hub in the ecoREMOD house. The team will rely on both data and user reviews to ensure that the system meets expectations. The current apparatus is a fully functioning prototype with a functioning data transmission system, but has not yet been integrated into the ecoREMOD home.

Introduction

Buildings account for a large amount of energy consumption in the United States. According to McKinsey and Company, the residential sector alone will consume 29%, or 11.4 quadrillion BTUs, of the baseline energy in the country by the year 2020 (McKinsey, 2009). Energy star claims that half of this energy is used for heating and cooling (Energy Star, 2009).

The need to heat and cool one's home stems from the difference between the desired indoor temperature and the outside temperature. Energy must be used to close this gap, and in climates such as Virginia's, this is especially difficult due to the large temperature variations between seasons. This gap is demonstrated in Figure 1, which shows the summed weekly temperature difference throughout the year.

It is apparent that Charlottesville experiences a large heating and cooling load throughout the year. Due to insulation issues within homes, this high load results in wasted energy. For example, the Green Building Advisor found that as much as one third of the energy paid for in a home leaks through small holes in the walls.

Inefficiency in the thermal envelope of the building is due to various types of heat transfer, such as conduction and radiation. Conductive heat transfer is the result of a temperature gradient across an object and is represented by the following equation:

\[ q = -k \Delta T \]

In this equation, \( q \) represents the heat flux through the thermal envelope, \( k \) represents the thermal conductivity of the material at hand, and \( \Delta T \) represents the difference in temperature between each side of the wall. The thermal conductivity constant, \( k \), is completely dependent on the material through which the heat is transferring. Materials with a high conductivity allow more heat flow for the same temperature gradient. Window glass has one of the highest thermal conductivities among the materials used to build homes, with conductivity over four times that of wood, and over ten times that of standard insulation materials (“Thermal Conductivity”, 2012).

In addition to conduction, windows are subject to solar radiation. Energy from the sun passes through the atmosphere and is radiated into the home through windows. This quantity, solar insolation, varies based on the time of year.

Figure 1: This graph shows the weekly degree-days in Charlottesville in 2011. Each data point is calculated by summing the daily difference between the desired indoor temperature (66 while heating and 72 while cooling) and the outside temperature over a week.
have shown that the shading system will save approximately 105 kWh of heating and cooling energy during one week of peak winter heating, and approximately 28 kWh during one week of peak summer cooling in the ecoREMOD house (Kobayashi and Khazdozian, 2010). These estimates and the conservative assumptions included in the simulation provided preliminary justification for moving forward with the system design. The system prototype will serve as a proof of concept that can be physically tested for its effectiveness.

A secondary goal of the project is to address the dearth of information and education available to homeowners about sustainability. While many people may be aware of the need to limit the use of energy in the home, they may be unaware of the ways to accomplish this (Zografakis, Menegaki and Tsagarakis, 2008). Through a grant from the Southeast Energy Efficiency Alliance, the Local Energy Alliance Program (LEAP) was established in Charlottesville in 2009 to “lead the effort in our local community to conserve energy in buildings” (LEAP, 2011). This system will be given to LEAP to use in their headquarters, ecoREMOD, as a tool for accomplishing that goal.

The overall purpose of the project is to increase awareness of home sustainability and provide a means by which it can be achieved. The next section of the article outlines the method by which the automated window blind system was developed and implemented.

Method

Developing a Mechatronic System

Mechatronic systems can readily benefit any iterative process because humans are unable to continuously measure environmental signals and adjust a system accordingly. The purpose of a mechatronic system is to use a microcontroller to gather sensor data, process that data, engage an actuator as necessary, and continuously repeat that process. In the proposed system, the microcontroller would choose to move an insulated shade up or down based on data from indoor and outdoor temperature sensors and an exterior solar radiation sensor. The first step in developing this system was to acquire the core structure: a microcontroller, sensors, and an actuator.

The microcontroller chosen for this project is the Parallax Propeller Chip, as shown in Figure 3. The primary advantages of this chip over others are its parallel processing and multiple input/output capabilities. Furthermore, algorithms can be programmed on a computer using the SPIN programming language and uploaded to the chip via a USB cable. For the purposes of the project, this simplicity and customizability are essential, as the prototype will undergo a process of continuous development.

The sensors used are the LM34 temperature sensor and a standard photoresistor. Both sensors operate by varying electrical resistance through each in response to changes in the environment. Each device is supplied with +5 V and connected to ground, or 0 V, and each acts as a voltage di-
vider. Figure 4 describes the operation of a voltage divider. Changes in the environment, such as an increase in temperature, cause the internal resistance of the sensor to change. As the supply passes through the sensor, the changing resistance causes a change in the output voltage. This signal can then be translated to a temperature reading or light reading by the microcontroller. Advantages to using the LM34 and the photoresistor are their low cost and high sensitivity to environmental stimuli.

After interpreting the sensor data, the microcontroller sends a signal to the actuator, which in this case is a DC Brush motor that moves the shade up or down. In 2009, an ecoMOD team working on a similar project invested in a motorized shading system that was not automated. In the interest of following ecoMOD’s principles of conservation and reuse, materials from that project were incorporated into our design. The system consisted of a remote control that sent infrared signals to the circuitry, which controlled the movement of the motor. This movement was tracked with an encoder, which determined the number of motor rotations by counting digital pulses. A signal was then sent back to the circuitry and the process was repeated. This flow of information is depicted in Figure 5.

Various options for modification were considered, such as overriding the signal sent from the remote, using a proximity sensor or mechanical stop button instead of the encoder, and modifying the internal circuitry. The advantages and disadvantages of each were weighed, and the final decision was to remove everything from the system except the motor and encoder. This would allow for the most customization, simplicity, and repeatability in other applications.

The thermal properties of the existing shade were appealing. The double cell technology adds an estimated thermal resistance of 2.8 ft² °F h/Btu as compared to the expected 1.6 ft² °F h/Btu of single cell (“Cellular Insulating Shades”, 2012). Figure 6 features a cross section of the shade and window and shows the ability of the shade to trap air, which decreases the rate of heat transfer.

**Developing a Circuit**

After developing the core components of the mechatronic system, the specifics of the circuit had to be determined. The team decided to use an H-Bridge circuit to control the motor, use an analog-to-digital converter to collect the data, and connect an LCD display to the circuit to display live data.

The H-Bridge circuit is a circuit that can allow a motor to spin in two directions based on one input pulse from the microcontroller (as opposed to other circuits that would require multiple inputs or multiple motors). An H-Bridge operates by opening or closing specific switches to control the direction that the electricity flows through the leads of the motor. Figure 7 shows this functionality.

The specific H-Bridge used in this project is the Texas Instruments SN754410 Quadruple Half-H Driver. One of the primary advantages is its ability to control two motors, which will be necessary later in the project when two side-by-side shades need to be controlled simultaneously. The H-bridge chip takes in a supply of +12 V and, depending on the state of the pin connected to the Propeller Chip, sends the output voltage in a specific direction to move the motor accordingly. The original circuitry of the motor was removed,
and the motor was attached directly to the H-Bridge.

Before the analog voltage signals from the sensors could be sent to the Propeller Chip, they needed to be converted to digital signals. To accomplish this, a TLC2543 integrated circuit (IC) Analog to Digital Converter (ADC) was used. This chip takes in the analog signals from up to 11 sources, and converts each signal into a binary number that identifies a specific voltage. Because the ADC is a 12-bit chip, it identifies each input voltage with a binary number between 0 and 4095 (a total of 4096 positions) based on set upper and lower boundaries. Since the team calibrated the chip’s upper and lower boundaries to 0 V and 4.095 V, respectively, the chip’s binary output correlates easily to the voltage output of each sensor. Each binary unit correlates to an additional 0.001 V, so a reading of 3000 would correlate to 3 V. This provides a very fine resolution when compared with a more common 8-bit ADC. The sensor signals are sent to the microcontroller as binary digital signals for processing.

Though the microprocessor primarily uses the signals to control the automated shade, the team intends to use the signals for data collection and educational displays. The team is in the process of developing a wireless circuit that will transmit the sensor data to a central hub for data analysis by the ecoMOD team. The team is in the process of integrating an LCD (liquid crystal display) screen that will show the user what the sensors are reading and why the shade is reacting accordingly.

The final circuit diagram was developed using CAD-Soft EAGLE software and can be found in the appendix at the end of this report. The voltage regulators at the top of the page signify a voltage decrease, from the +12 V of direct current needed to operate the motorized shade (which will come from a wall transformer) to +5 V and +3 V, which are necessary for operation of the Propeller Chip and the associated IC chips. The Propeller Chip, EEPROM chip, Propeller Plug, and Crystal are the necessary components for the operation of the microcontroller. The other components on the diagram are described in more detail earlier in the report.

In addition to the original circuit, the team has decided to use a pre-packaged, wireless data transmission technology called XBee. This chip, shown in Figure 8, can wirelessly transfer data from a microcontroller, like the Propeller Chip, to a computer that is separate from the system. The team applied the XBee chip to the automated shading system in order to transmit data to ecoREMOD’s data storage hub. This data will be useful for determining the effectiveness of the system and for supplying additional evaluation data for the house in general.

The full circuit, excluding external motor connections, can be seen in Figure 9. The figure features the circuit on an experimental breadboard. The circuit will eventually be moved to a more permanent prototyping board for more compact and more permanent mounting in the ecoREMOD house.
Developing an Algorithm

In order for the circuit to function properly, the microcontroller requires proper programming with an algorithm that will appropriately open and close the blind. The microcontroller was programmed to implement this algorithm using the SPIN language. SPIN is an easy-to-use, yet incredibly versatile and functional programming language that was specifically developed for use with the Propeller Chip. Since the team will not be present for calibration of the system in future years, it is important that the chip is programmed in a functional, yet simple manner. Though writing in SPIN may take processing power from the chip, which must convert SPIN instructions to binary pulses, the chip can still readily execute over 640,000 SPIN code instructions per second.

The goal of the algorithm is to provide instructions to the Propeller chip about how to interpret the data received from the sensors. The simplified decision making process is represented by a flowchart in Figure 9. The first step is to receive data from the sensors and then convert that binary data into an appropriate unit system, which in this case is wattage. The next step is to combine the wattages from the different sensors to determine the total heat flow through the window. This total heat flow is then used to make a decision about how to move the drape. For example, if the home is in heating mode and the total heat flow through the window is positive, meaning heat is entering the home through the window, then the Propeller chip sends a signal to the motor to open the drape. A time when this may be the case is on a sunny, autumn day. The outside air may be slightly colder than the inside air, but the heat provided by the sun outweighs that conductive loss and makes it optimal to keep the drape open and allow that sunlight to warm the house.

The team encountered several issues when coding and applying algorithms for the circuit. First, there were issues with identifying appropriate light calibrations for the photoreistor. After installing the LCD display, which can be seen in Figure 10, the team was able to use it as a diagnostic tool to display raw and processed light data values from the...
Propeller Chip. This allowed for calibration of the system by using resistors to change the sensitivity of the photoresistor’s voltage output in response to changes in lighting. The team also had issues with determining appropriate stopping points for the drape. Initially, the upper and lower limits were set by moving the motor for a specific amount of time. However this method is insufficient, as it does not account for potential changes in the internal resistance of the motor that over time would cause the limits to drift. After experimentation with the internal encoder, the team was able to use the data it provided to very accurately move the motor to a specific location. This method is a much more sustainable and repeatable way to move a motor and will minimize the need to calibrate the system in the future.

Results and Conclusion

The outcome of this project is a working system that responds to light and temperature data and moves a shade up or down to optimize energy flows through the window. The final design can be seen in Figure 12.

Currently the system is a fully functioning prototype, but more work is required before permanent installation in the ecoREMOD home. Largely, the team needs to calibrate the system for the physical, experimental conditions that it will face in ecoREMOD. Some minor adjustments also need to be made physically to the system so that the electronic components have more permanent fixtures that allow easy access for future teams.

The team anticipates that household energy consumption will decrease as the shading system optimizes heat flow. As a result the residents can expect lower energy bills throughout the year. In addition, the feedback provided by the LCD display will educate the residents and visitors about both the motivating problem and the proposed solution. The team hopes that this technology will make a lasting impact on the field of sustainability and contribute an effective solution that inspires homeowners to make the needed change.

Acknowledgements

The team would like to thank their faculty advisor, Professor P. Paxton Marshall, for his continued support of their work and other energy efficiency initiatives at the University of Virginia. The team would also like to thank the Local Energy Alliance Program for allowing research to be conducted in ecoREMOD and for eventually showcasing the final product.

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Figure 12: The XBee wireless transmission chip allows a user to transfer data from one remote source to another. In this case, data is being transferred from a microcontroller to a computer in a separate location.
Appendix A:
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