Public Interest Energy Research (PIER) Program
FINAL PROJECT REPORT

ENERGY INNOVATIONS SMALL GRANT PROGRAM: 2003 INDEPENDENT ASSESSMENT REPORTS

Prepared for: California Energy Commission
Prepared by: San Diego State Research Foundation

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PREFACE

The California Energy Commission Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Energy Innovations Small Grant Program: 2003 Independent Assessment Reports is the interim report for the Energy Innovations Small Grant Program (contract number 500-98-014) conducted by San Diego State University Research Foundation. The information from this project contributes to all of PIER's RD&D Programs.

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For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

The California Energy Commission has been conducting the Public Interest Energy Research (PIER) program through competitive solicitations to advance science or technology in each of the seven PIER program areas to benefit California ratepayers since 1997. In addition, the Energy Commission has also funded and managed the Energy Innovations Small Grant (EISG) Program since 1998. The role of the EISG program is to advance research into new and innovative energy concepts and technologies whose feasibility is not yet sufficiently established to meet traditional research and development (R&D) funding requirements.

The Energy Innovations Small Grant (EISG) program supports early-phase development of promising new energy technology concept. This category of projects is not covered by PIER general solicitations that focus primarily on development of established concepts. Qualifying EISG projects address one of the defined PIER RD&D areas. If the feasibility of an innovative energy concept is proven through the EISG project work, then traditional R&D funding may become available to further develop the project.

Independent Assessment Reports (IARs) are written at the completion of every EISG grant project. These reports outline the objectives of the project, discuss the successes and failures, and offer recommendations for potential future work. This report presents a collection of twenty four independent assessment reports for EISG grant projects awarded during 2003.

Keywords: Ratepayer, California Energy Commission, Energy Innovations Small Grant, EISG, Independent Assessment Report, IAR, Public Interest Energy Research, PIER RD&D, electricity, natural gas, transportation, research, energy technology concepts, project, market, outcomes, conclusions, benefits

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EXECUTIVE SUMMARY

The Energy Innovations Small Grant (EISG) program is a component of the Public Interest Energy Research (PIER) Program managed by the California Energy Commission. The PIER Program benefits California electric and gas ratepayers by funding energy research, development, and demonstration (RD&D) projects that are not adequately provided for by the competitive and regulated energy markets.

The Energy Commission recognizes the need for a program to support the early development of promising new energy technology concepts that are not mature enough to be covered by PIER general solicitations. The Energy Commission has established the EISG program to meet this need.

This report is a compilation of the Individual Assessment Reports (IARs) for grant projects that were awarded in 2003 and that have not been previously published.

All data sources for tables and figures are from the author unless otherwise noted.

CHAPTER 1: Introduction

Table 1.1: 2003 EISG Projects with Published IARs

Project	Researcher	EISG Funding
Development of Magnesium Diboride-based Superconductor/Metal Matrix Composite Wire for use in Superconducting Transformers	NOVE Technologies, Inc.	$72,060.00

Table 1.2: 2003 EISG Projects with IARs Included in this Section

Project	Researcher	EISG Funding
Application of Stochastic Filtering and Control Methodology to the Optimization of Wind Turbine Control Design	University of California, Los Angeles	$74,993.00
Flywheel System for Bulk Energy Storage	Cobalt Energy, LLC	$75,000.00
End-Use Efficient, Environmentally Friendly Water Softening Device	Material Methods, LLC	$75,000.00
Construction and Testing of a High Efficiency Solar Water Still	The Starburst Foundation	$74,998.00
Pressure Reducing Valve Turbine	SOAR Technologies, Inc.	$75,000.00
Covell Village: A Model for Sustainable Communities	Davis Energy Group, Inc.	$74,965.00
The Day Switch	Lighting Research Center, Rensselaer Polytechnic Institute	$75,000.00
High Efficiency Lanthanide Doped Ceria-Zirconia Layered Hybrid Electrode for SOFC Generators	Intertec Advanced Materials, Inc.	$74,936.00
Innovative Wheel Concept to Increase Gas Turbine Efficiency	Markron Technologies, LLC	$75,000.00
Innovative Injection-Molded Plastic Package for High-Concentration PV Cells	Amonix, Inc.	$75,000.00

Biomass-to-Syngas, Novel Low-Cost Counter-Current Process	Taylor Energy LLC	$74,908.00
New Membranes Based on Ionic Liquids for High Temperature PEM Fuel Cells	Rutgers, State University of New Jersey Materials Science and Engineering	$75,000.00
Pulsed Ultrasound Water Treatment	Sonipulse, Inc.	$74,610.00
Test and Evaluation of Heat Transfer Parameters for CAES Tank System	Lieberman Research Associates	$75,000.00
Wind Turbine for Low Speed Regimes: Hi-Q Rotor	Hi-Q Products, Inc.	$75,000.00
A Unique Dielectric Light Injector for Ultra Efficient Cavity Converters: A Novel Approach for Advanced Solar Concentrator and Directed Laser Beam Applications	United innovations, Inc.	$75,000.00
High Performance, Nanostructured Cathode for Lithium-Ion Rechargeable Battery	University of California, Davis	$75,000.00
Development of Magnesium Diboride-based Superconductor/Metal Matrix Composite Wire for use in Superconducting Transformers	NOVE Technologies, Inc.	$72,060
A New Physical Water Treatment Technology for Energy Efficient Chillers	Choson Research Corp.	$74,290
A Zero Current Ripple, Energy Efficient, and Reliable Low Cost Residential and Commercial Zero Emission Direct Power-Conversion System	University of Illinois	$74,999
Development of a Wireless Lighting Control Network	UC Berkeley	$74,915
Phase-Changing Frame Walls for Peak Demand Reduction, Load Shifting, and Energy Conservation in California	University of Kansas Center for Research, Inc.	$74,596
Bio-Solar Conversion of Carbon Dioxide into Hydrogen via Bacteria Embedded in Colloidal Gas Aphrons	UC Los Angeles	$74,948
Efficient Lighting by Sensing and Actuating with Mems "Smart Dust" Motes: A Feasibility Study	UC Berkeley	$74,009

CHAPTER 2:
2003 Independent Assessment Reports

The Energy Innovations Small Grant (EISG) program awards numerous grants for innovative energy research projects every year. Independent Assessment Reports (IARs) highlight the project outcomes for each of the EISG projects. This chapter includes the IARs from grant projects that were awarded in 2003 that have not previously been published.

2.1 Application of Stochastic Filtering and Control Methodology to the Optimization of Wind Turbine control Design

Awardee: University of California, Los Angeles

Principal Investigator: A. V. Balakrishnan

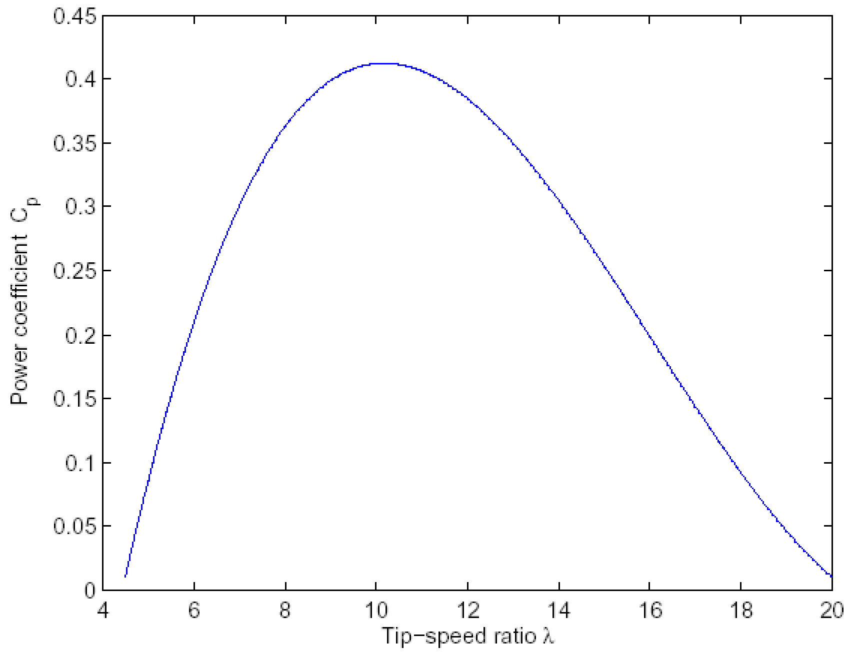
2.1.1 Introduction

Wind energy is currently the fastest growing energy worldwide. It is expected that a large number of wind turbines will be installed in the next 10-15 years. There is a critical need for research on further reduction of the cost of energy (COE) of electricity generated from wind energy. California wind power plants could increase their efficiency by optimizing the rotor speed in relation to the wind speed. Figure 1 illustrates the relationship between power coefficient and the tip-speed ratio(a function of wind speed and angular velocity) for a 600 –kW turbine. The goal of this project was to apply stochastic filtering and control theories to the optimal controller design for wind turbines.

Electricity from wind turbines in California amounted to over 3200 million kWh in 2001, at a cost of $192,000,000. This project, if implemented on the California wind turbines could result in a 3 percent saving in COE (cost of electricity), or more than $6,000,000 annually for residents and businesses in this state

The major result of this report was an algorithm to estimate the power coefficient of variable speed wind turbines from commonly available observation data, namely the rotor angular velocity as derived by angular displacement and the generator output power. A generic Newton-Raphson algorithm was applied to the estimation problem to identify the power coefficient in the presence of observation noise in combination with a stochastic wind estimation algorithm. The final innovation developed was a control algorithm for enhancing energy capture of a wind turbine that accelerates or decelerates the angular velocity of the rotor toward the optimal value as quickly as possible based on the estimated wind speed.

Figure 1: Power coefficient of a 600-kW turbine.



2.1.2 Objectives

The goal of this project was to determine the feasibility of applying stochastic filtering and control theories to the optimal controller design for wind turbines. The researchers established the following project objectives:

1. Achieve a comprehensive nonlinear dynamical system model for the stochastic control problem of large-scale wind turbines.
2. Enhance the performance of controls by utilizing accurate measurement of wind speed.
3. Derive optimal control algorithms for the nonlinear stochastic control problem, and develop systematic procedures for wind turbine control design.
4. Achieve an accurate model by comparing simulation result with NREL existing wind turbine data.
5. Demonstrate 3-5 percent reduction in COE(cost of energy).

2.1.3Outcomes

1. An algorithm to estimate the power coefficient of variable speed wind turbines from commonly available observation data, namely the rotor angular velocity and the generator output power was presented in this report. This algorithm was in the form of a third order polynomial:)

$C_p(\lambda(t)) = a_3\lambda^3(t) + a_2\lambda^2(t) + a_1\lambda(t) + a_0$, where $C_p(\lambda(t))$ = the power coefficient and $\lambda(t)$ = tip speed ratio

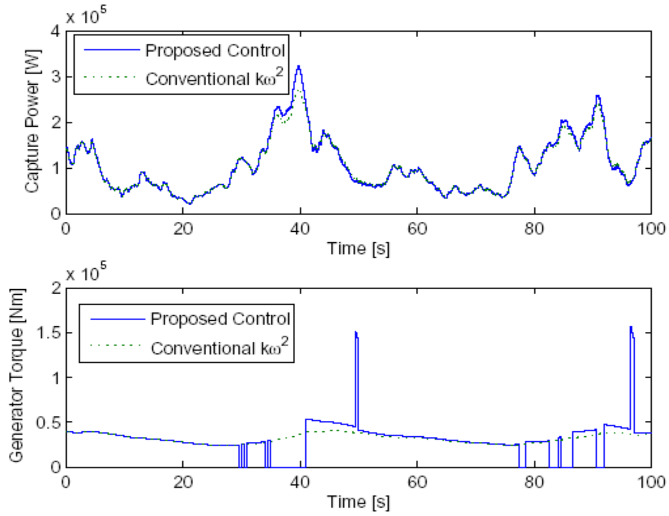
This function is shown graphically in Figure 1. The algorithm provides the means to obtain a more faithful model of wind turbines which is crucial to the design of advanced control algorithms.

2. As a specialization of the power coefficient estimation algorithm, a stochastic wind speed estimation algorithm which requires only the rotor angular velocity measurement (as derived by angle data) was proposed. The algorithm was derived from the rigid body model of wind turbines, which was condensed to this equation: $\dot{\omega}(t) = g(\omega(t), v_0)$, where $\omega(t)$ is the angular velocity and v_0 is the wind velocity. The actual relationship is developed from observational data of wind velocity versus angular velocity.

3. A control algorithm for enhancing energy capture of wind turbines was also proposed. The idea was to accelerate or decelerate the angular velocity of the rotor toward the optimal value as quickly as possible based on the estimated wind speed.

4. Extensive numerical simulations were carried out on Matlab to analyze and to verify the performance of the algorithms. The effects of the initial guess, the noise variance, and the time history were studied in detail. The results of one of these simulations, Figure 2, showed that when the variations in the wind speed were high during the period 30 to 40s the controller was able to detect a large difference in the captured power and the available power. The bang-bang operation mode is engaged to resume optimal-tip speed ratio as soon as possible. Particularly, the generator torque was reduced to zero in response to the wind gust during 35s to 40s. During the period of 35s to 42s, the average captured power increases from 21.9kW to 24.2 kW -- a 10.7 percent improvement. When the whole 100 s interval is considered, the average captured power increases from 10.41 kW to 10.59kW -- a 1.7 percent improvement.

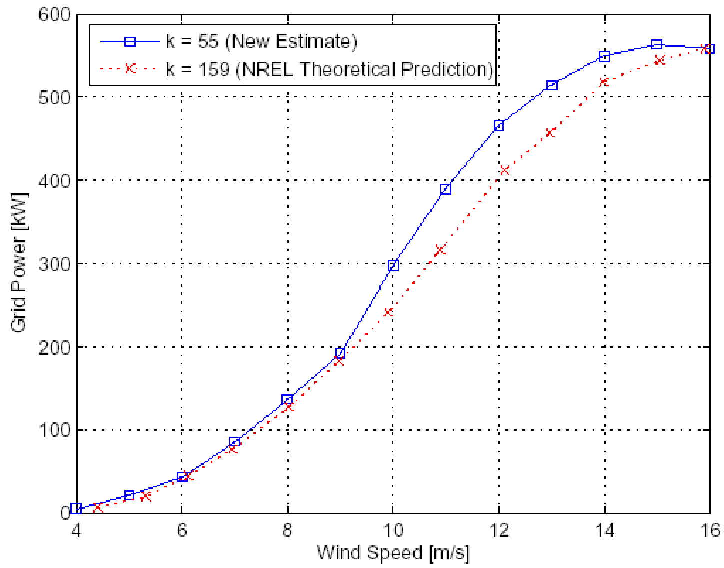
Figure 2: Comparison of the Capture Power with the Proposed Control Algorithm, and the Conventional Standard Region II Control



Experiments were also conducted on a 600 kW full-scale research wind turbine to evaluate the performance of the algorithms on real data. It was verified that the power coefficient estimation algorithm was able to reduce the uncertainties in the power coefficient of the wind turbine in that the output power increases as a result of having a more accurate control gain in the standard Region II control law. It was also demonstrated that a real-time implementation of the wind speed estimation algorithm could be performed on the experimental test bed. This simulation is shown in Figure 3.

5. It was demonstrated through the use of the experimental data that the energy capture of the experimental wind turbine could be increased by more than 10 percent when the wind speed was between 10-14 m/s. Since 10-14m/s lies within the range where the experimental turbine operates about 50 percent of the time, it is it is felt that the proposed 3-5 percent improvement in COE could be achieved.

Figure 3: Experimental Measured Increase in Turbine Efficiency



2.1.4 Conclusions

The IAR should/will contain enumerated conclusions that singularly address each respective outcome and that result from an objective analysis of the research results. This structure will be used when it provides a clear and meaningful conclusion.

1. An algorithm to estimate the power coefficient of variable speed wind turbines from commonly available observation data, namely the rotor angular velocity and the generator output power was presented in this report.

2. As a specialization of the power coefficient estimation algorithm, a stochastic wind speed estimation algorithm which requires only the rotor angular velocity measurement (as derived by angle data) was presented.

3. A control algorithm for enhancing energy capture of a wind turbine was developed and described.

4. The estimation and control algorithms as presented in 1,2 and 3 above were evaluated and validated by extensive simulations in Matlab and experiments conducted on a 600 kW full-scale research wind turbines.

5. The 3-5 percent reduction in COE was demonstrated and supported by simulation and experimental results.

Based on the above conclusions and data presented in the final report, it is concluded that concept feasibility was demonstrated. The wind speed, power factor and control algorithms that were presented were subjected to simulations utilizing data from a real-world wind turbine, and the resulting 3-5 percent improvement in efficiency was documented.

2.1.5 Recommendations

This study showed that the power factor algorithm was not sufficiently general to be used in varying wind speed conditions. Therefore a more general algorithm should be developed that takes into account this situation.

Also needed is more testing in controlled wind tunnel situations for further verification of the algorithms.

The most important recommendation is in the writing of this report. The technical complexity is too much for the typical reviewer, and effort is needed in making the description of the algorithms and the application of the algorithms more understandable and clear.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for follow on funding within the PIER program.

Receiving follow on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

However, the researchers did not indicate any interest in receiving follow-on funding, so some other entity would be needed to apply for this funding.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is in the potential for reduced cost of electricity to the ratepayer due to more efficient use of wind turbine electrical generation. In year 2001, California wind industry generated more than 3200 million kWh of electricity, costing Californian about $192M. The 3 percent reduction in the COE reported in this project could lead to more than $6M savings for residents and business of the State each year.

2.2 Flywheel System for Bulk Energy Storage

Awardee: Cobalt Energy, LLC

Principal Investigator: Dr. Christopher Gabrys

2.2.1 Introduction

Renewable energy sources have tremendous potential to provide, environmentally friendly solutions to California's increasing energy demands. The use of renewables is limited by cost and, in some cases, intermittency of power production. Regardless of the source of electric power, it must be used precisely when it is produced. However, some renewable sources generate power at times that do not necessarily coincide with demand. The ability to transform unscheduled power into schedulable power is one of the greatest challenges that faces the electric power industry as it taps into the enormous potential provided by renewable energy sources.

California presently spends approximately $26B on electricity annually, with only 11 percent of generation coming from renewables (CEC, 2003). The DOE projects that wind-turbines will produce power at the lowest cost over the next few years, with a target of 2.5 cents/kWh. This would reduce generation costs by 40 percent compared with natural gas, at 4 cents/kWh, the most economical fossil fuel. At the currently achievable 4 cents/kWh, wind-turbine power is nearly equal in cost to power fueled by natural gas. California ratepayers could have more renewable energy in the mix of supply if the energy produced by intermittent resources could be stored for use at periods of peak demand.

Coupling energy generation with low-cost, bulk energy storage is one means by which renewable sources can become more competitive and reliable. Currently available methods used for bulk energy storage include pumped hydro, compressed air, flow batteries, superconducting magnetic energy storage, and conventional batteries. Hydro storage is not a practical option in most cases, and the remaining methods except conventional batteries are cost prohibitive. Conventional batteries are not desirable because of the high costs associated with their short life cycle. Factoring in replacement costs due to a relatively short life cycle, conventional batteries can achieve an energy storage cost of approximately $9/Wh over a 20-year period, as calculated by the researcher. Current flywheel systems typically are used for short durations in uninterruptible power supply (UPS) systems, but are too costly to use for bulk energy storage. The researcher has developed a new bulk-energy-storage flywheel based on a patented High Performance Steel Flywheel (HPSF) technology. The researcher claimed HPSF technology allows safe operation of low cost steel flywheels at roughly twice the speed of current steel flywheels, storing nearly four times the amount of energy per unit cost. Using the HPSF technology, a flywheel is constructed to a thickness less than the critical diameter for the alloy steel to achieve full hardening as shown in Figure 4. Ultrasonic testing of the flywheel discs ensures that there are no flaws larger than a threshold size. The approach is scalable by stacking multiple discs that are joined by a thermally assembled interference fit as shown in Figure 5. The researcher proposed to construct a 1/100-scale, bulk-energy-storage system based on the HSPF technology and validate a projected cost of less than $2/Wh and 30,000-cycle life for the system.

Figure 4: 1.2 kWh Flywheel (1/100 Scale)

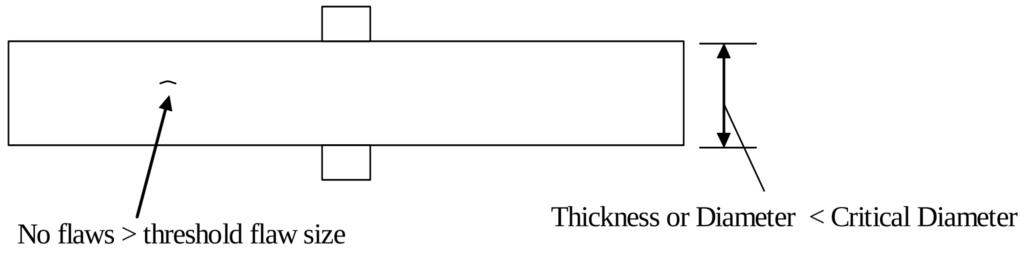
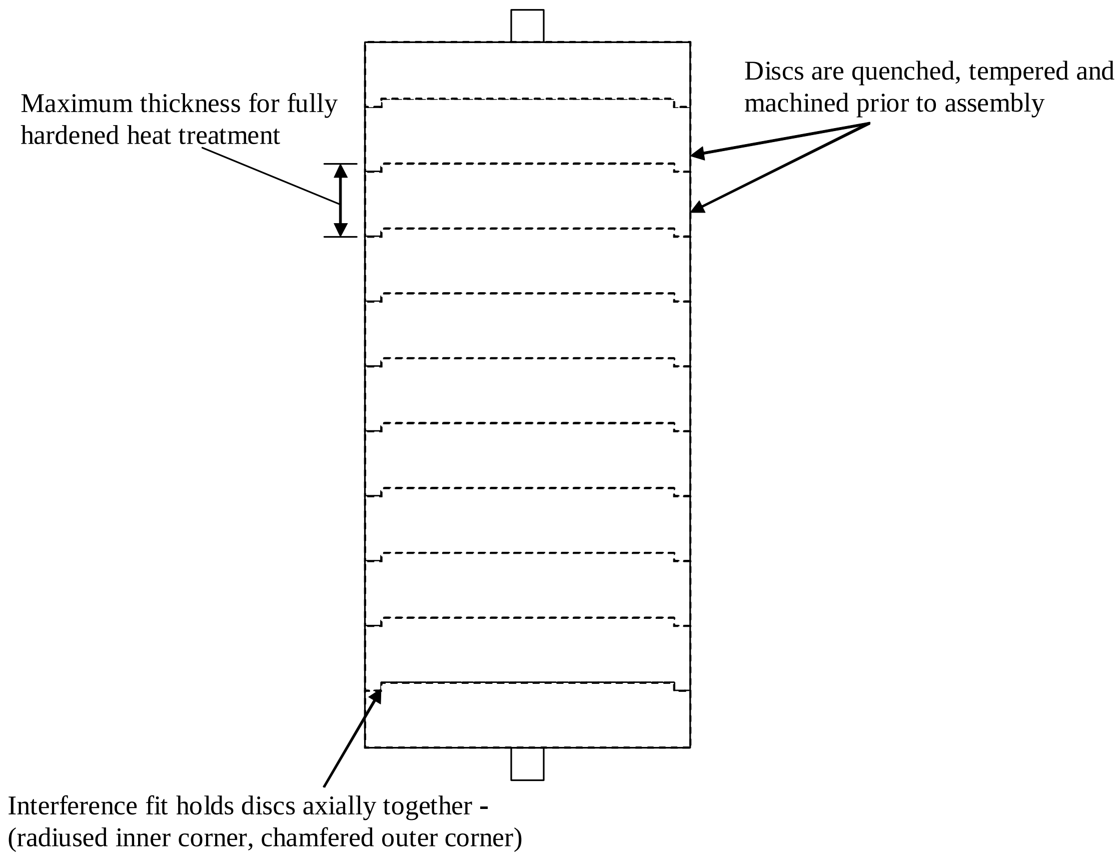


Figure 5: 12 kWh Flywheel (Full Scale)



2.2.2 Objectives

The goal of this project was to determine the feasibility of using a new system of flywheel technology to provide low-cost, bulk energy storage . The proposed flywheel was an assembly of interference-joined, ultrasonically tested discs. The researcher established the following project objectives:

1. Obtain flywheel system components
2. Assemble a subscale prototype that will have a capacity of 1.2 kWh.

3. Demonstrate that the magnetic-bearing system is capable of achieving complete magnetic levitation of the flywheel.
4. Demonstrate that the flywheel can be charged to 400 m/sec (31,700 rpm).
5. Demonstrate that the flywheel will operate for 10 hours at 400 m/sec without failure.
6. Demonstrate a motor-generator efficiency of no less than 95 percent.
7. Demonstrate that total operating losses are less than 40 watts.
8. Demonstrate a round-trip efficiency of no less than 80 percent, assuming 2 cycles per day.
9. Show that data generated in this project continue to support a projected cost of $2/Wh and a life greater than 30,000 cycles.

2.2.3 Outcomes

Actual flywheel construction, as shown in Figure 6, deviated significantly from the proposed design with no explanation for the deviation.

The flywheel is capable of storing 1.7 kWh, with 1.5 kWh usable when discharged to a minimum speed.

The magnetic bearing system successfully operated with full magnetic levitation of the flywheel.

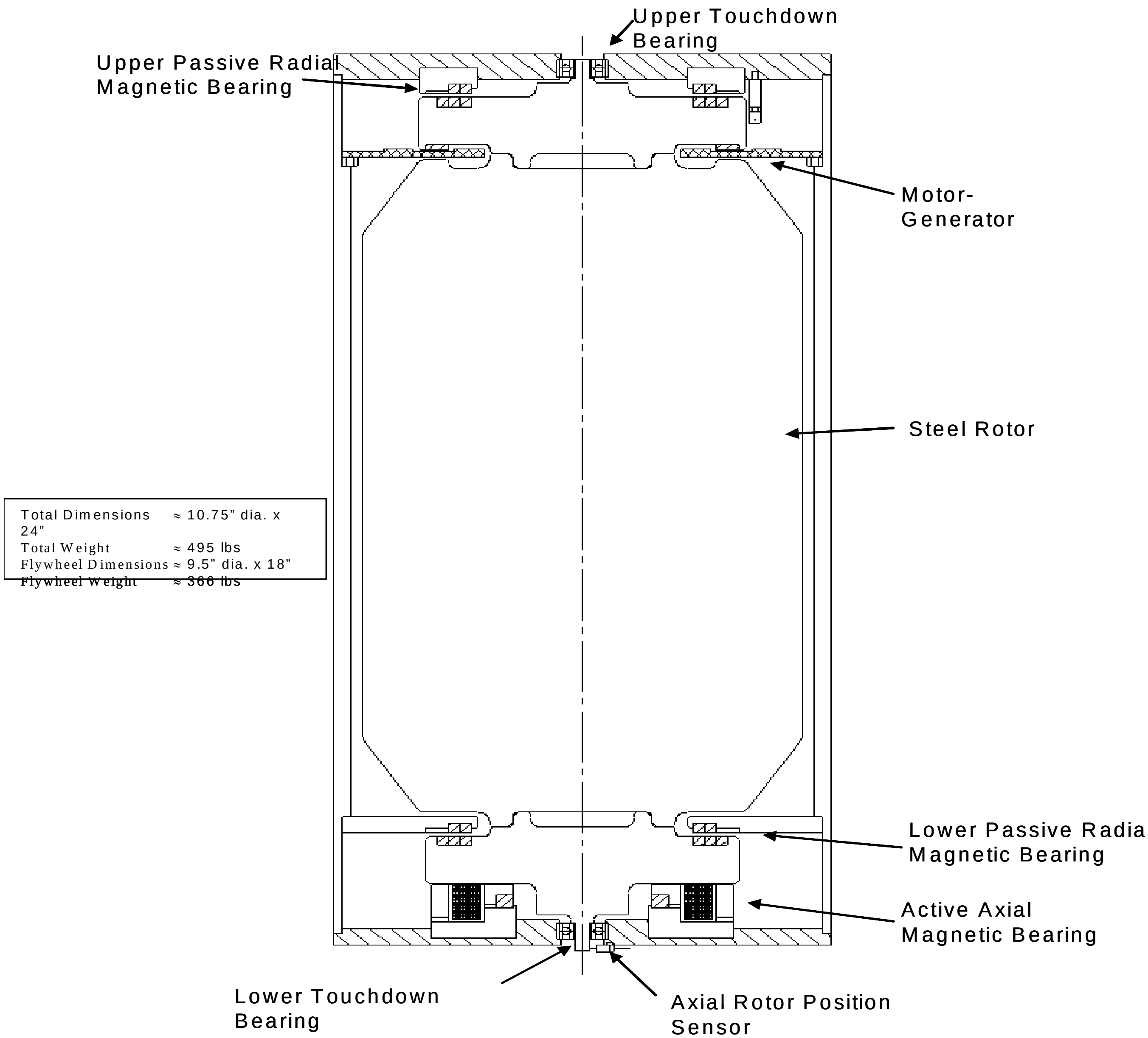
Incorrect placement of magnets on the motor-generator assembly prevented charging of the flywheel to 400 m/sec (31,700 rpm). The flywheel system was disassembled to correct the magnet placement by drilling holes through the motor generator. Although all other portions of the flywheel system were unaffected by the correction of the assembly error, stress concentrations caused by the holes drilled in the motor generator limited the safe operating speed to 63 m/sec, rather than the originally proposed 400 m/sec. Replacement of the defective part would have required a 12-week lead time and could not have been obtained within the project timeline. Therefore, testing proceeded with the flywheel operating at 63 m/sec.

Flywheel operation at 400 m/sec for 10 hours was not possible due to the assembly error. The flywheel operated successfully at 63 m/sec for 10 hours.

The motor-generator efficiency tested at 63 m/sec demonstrated an efficiency of 97.8 percent with a load of 4.09 A (1 light bulb) and 98.7 percent with a load of 2.26 A (4 bulbs wired in series). The higher efficiency of 98.7 percent was used in calculations of round-trip, energy-storage efficiency.

Losses were calculated from the no-load spin-down test starting at 63 m/sec. Magnetic bearing consumption and drag losses were calculated at 3.6 and 4.3 watts, respectively, for a total of 7.9 watts. Operating loss for a 400-m/sec flywheel was estimated to be 50 percent greater than that for the 63-m/sec flywheel, for a total of 12 watts.

Figure 6: Constructed 1.2 kWh Flywheel (1/100 Scale)



A round-trip efficiency of 84.7 percent was calculated assuming a 98.7 percent motor-generator efficiency and 12-watt loss for the 400-m/sec flywheel system.

A cost estimate for mass-production of 1,000 units of the 1/100-scale flywheel systems capable of producing 1.5 kWh resulted in a unit cost of $1.62/Wh. No cost analysis was presented for a full-scale system. The cycle life was determined using a finite-element model that has been validated for rotating, isotropic-material cylinders. Results of this model plotted cycle life as a function of stress and flywheel discharge. The maximum flywheel stress using another finite-element model was determined to be 84 ksi, resulting in a cycle life of 34,600 for a discharge to 10,000 rpm and 32,500 for full spin down. Both of these values exceed the hypothesized 30,000-cycle life.

2.2.4 Conclusions

In evaluating achievement of goals and objectives for this project, it is important to note that objectives 4 through 9 were dependent upon operation of the flywheel at 400 m/sec.

1. The objective of constructing the originally proposed flywheel system was not met. Flywheel design deviations call into question the scalability of the 1/100 model to full-scale production. Furthermore, the investigator did not address the relevance of data for the prototype tested to the proposed stacked configuration.
2. The objective of constructing a subscale prototype with a capacity of 1.2 kWh was met. Storage capacity of the flywheel system exceeded the original design requirement with a capacity of 1.5 kWh.
3. The objective to achieve full magnetic levitation was met. It is reasonable to assume that the originally proposed "stacking" configuration would be levitated similarly to the flywheel constructed.
4. The objective of demonstrating that the flywheel could be charged to 400 m/sec was not met. The proposed flywheel operational speed is largely what set it apart from conventional steel flywheels. The researcher claimed the HPSF technology allows for safe operation of the flywheel at roughly twice the speed of conventional flywheels, resulting in significant cost reduction for energy storage. Assembly errors resulted in a flywheel operating speed of 63 m/sec. This falls below not only the typical operating speed of a conventional flywheel, but also below flywheels that have been tested by others nearly 15 years ago. Conclusions based upon testing at 63 m/sec cannot be projected or estimated for a system operating at 400 m/sec.
5. The objective to operate the flywheel safely at 400 m/sec for 10 hours was not met. As speed increases, a variety of problems arise that are not evident at low speeds.
6. The objective to demonstrate a motor-charge efficiency of no less than 95 percent was not met for the originally proposed 400 m/sec flywheel. The investigator noted that "efficiency at higher speeds would not be significantly impacted because the motor-generator voltage also increases with speed, thereby reducing the current for the given power level and the incurred resistive losses." In a typical motor, efficiency decreases exponentially as speed increases. Motor efficiency also varies exponentially with load. Although the load was varied using two tests, additional testing would be needed to define the efficiency-load curve. Similarly, data obtained for a motor speed of 63 m/sec is not representative of that for 400 m/sec.

7. The objective to demonstrate total operating losses of less than 40 watts for a 400-m/sec flywheel was not met. An operating loss for the system spinning at 63 m/sec of 7.9 watts achieved the objective to fall below a maximum of 40 watts, but at a lower operating speed. Therefore, there is a need to estimate or extrapolate what would have happened at the higher speed. However, there is no scientific or experimental basis presented for the estimated operational loss of 12 watts for a system spinning at 400 m/sec. Drag loss is a function of speed squared. Thus, a full-speed flywheel would experience approximately 40 times the drag loss of a flywheel operating at 63 m/sec. Losses due to magnetic bearing consumption at the higher speed cannot be determined given the data presented. However, the exponentially increased drag loss alone would result in a total operating loss in excess of the project objective.

8. The objective to demonstrate a round-trip efficiency of no less than 80 percent assuming two cycles per day was not met. Round-trip-storage efficiency was based on erroneous assumptions, rather than experimental evidence (see items 6 and 7 above).

9. The objective to show, from data generated in this project, a projected cost of $2/kWh, and greater than 30,000-cycle life was not met. The original objective and project description suggests that full-scale HPSF flywheels could be produced for less than $2/kWh, particularly in a cost comparison of the HPSF flywheel with other conventional methods of bulk energy storage. The estimates presented for the 1/100-scale system cannot be assumed to be the same as those for a full-scale system.
   Accuracy or relevance of the finite-element models cannot be determined given the data presented. The 84 ksi stress at the flywheel center was theoretically determined using a single element of the originally proposed "stackable" flywheel, without experimental validation. Calculations determining cycles as a function of stress and discharge do not include a description of the configuration analyzed (one "stackable" flywheel element, the taller cylinder as constructed, or a full-scale system), nor do they elaborate upon any mesh refinement or model calibration. Further, there is no discussion regarding relevance of the finite-element results to a full-scale flywheel.

The original goal of the project was to determine the feasibility of the HPSF flywheel system for providing low-cost, bulk energy storage that can improve the dispatch ability of renewable electricity generation. Outcomes and conclusions of this research were hindered by an assembly error that prevented full-speed operation of the 1/100-scale flywheel system, as well as a modified configuration for the flywheel rotor. As the "stackable" configuration and high-speed operation are critical to the technology being investigated, few of the objectives were met as originally stated or intended. Although the investigator attempted to relate the 63 m/sec system to a full-speed system, reported results for a full-speed system are not validated experimentally, and are based on assumptions that are often unrealistic. Had the constructed system been correctly assembled and able to operate safely at 400 m/sec, it is unclear how results for the system as built would relate to the originally proposed "stackable" configuration. There is no explanation for the design modification from the originally proposed system.

2.2.5 Recommendations

The researcher should consider the following recommendations upon commencement of additional work in this area:

1. Replace the defective motor-generator to allow for testing of the flywheel at 400 m/sec.
2. Consider design requirements to allow for cost-effective disassembly of the interference-fitted components for possible maintenance and repair purposes.
3. Complete a 1/4 scale system (30 kWh) tests using the "stackable" flywheels as originally proposed in preparation for full-scale field testing.
4. Prepare a cost estimate for a full-scale flywheel system (120 kWh).

In theory, the HPSF technology appears promising. However, this technology will require additional review and investigation prior to seeking additional funding.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research, if successful, is reduced environmental impact of the California electricity supply or transmission or distribution system. It would accomplish this by improving the dispatch ability and competitiveness of renewable-energy generation, reduction in power-generation costs, and reduction in pollution. California presently spends approximately $26B on electricity annually, with only 11 percent of generation coming from renewables (CEC, 2003). Under use of these sources is largely due to their energy intermittency. HPSF flywheel systems for bulk energy storage could enable electric power delivery to coincide with consumer demand and result in even greater utilization of renewables.

Unlike bulk energy storage using conventional batteries, HPSF systems are environmentally friendly. The cycle life of HPSF systems is more than 10 times greater than conventional batteries. Bulk-energy-storage flywheel systems provide an 82 percent reduction in cost compared with conventional batteries when factoring in maintenance, disposal, and replacement costs over a 20-year period. HPSF systems are also recyclable and contain no toxic materials.

2.3 End-Use Efficient, Environmentally Friendly Water Softening Device

Awardee: Cobalt Energy, LLC

Principal Investigator: Dr. Christopher Gabrys

2.3.1 Introduction

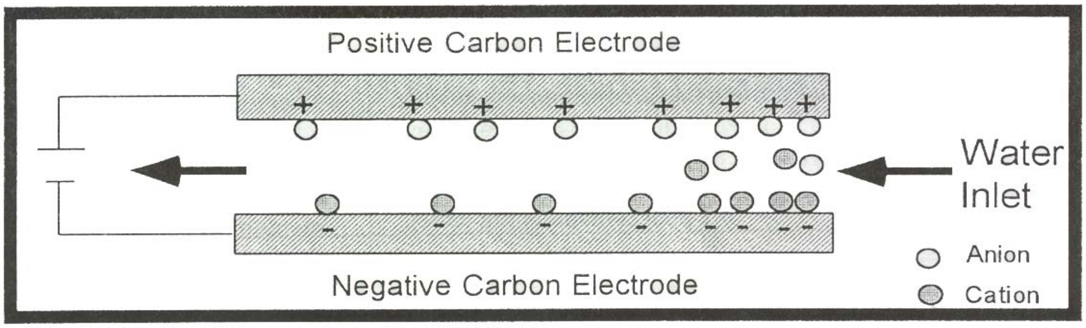
Future environmental considerations in California may require alternatives to the currently prevalent point-of-entry (POE) water softening technology. Today, 13 percent of California's urban water (approximately 1 billion gallons per day) is softened by an ion exchange (IE) process. Ion exchange discharges excess salt (sodium chloride) into the sewage system during its regeneration cycle. This conflicts with a trend in California toward restricting brine discharge into municipal sewers. A new, environmentally friendly, water- and energy-efficient technology will be needed for end use if new regulations mandate IE phase-out or replacement. Today's alternatives do not fully meet these criteria. Environmentally friendly reverse osmosis/ nanofiltration (RO/NF) technology presently is available, but it is not end-use efficient.

IE technology sets the benchmark for system cost and end-use efficiency[1] with a recovery percentage between 95 percent and 98 percent. Since the largest energy cost in water softening processes is the energy associated with the wasted water, highly efficient replacement technologies are preferable. RO/NF has a water end-use efficiency of 40 percent. An alternative technology with a 90 percent recovery rate could save Californians 1,730 million kWh/yr, worth about $173 million/year. In a state with perennial water shortages and increasing demand, any improvement in efficiency would be a welcome conservation tool.

The researcher proposed the development and evaluation of an advanced, Flow-Through-Capacitor-based (FTC) reactor with new Ionic Charge Barriers (ICBs) in a prototype device that would efficiently soften up to 140 Gal/day of tap water (Figure 7). The research sought to modify small devices now on the market to improve both recovery and rejection to >90 percent through new electrode technology, advanced reactor design, and improved techniques of process control. A proprietary, nano-structured carbon electrode was incorporated into the FTC reactor to enhance performance by significantly increasing the active surface areas for ion adsorption and removal. The flow-through reactor was designed to minimize flow resistance and reduce power consumption. Improved process-control techniques for modulation of the applied DC voltage were incorporated in an effort to ensure smooth functioning of the FTC reactor with a long service life and reduced maintenance. The device consisted mainly of two carbon electrodes, two ion-exchange membranes, and a DC power source. As water flowed through the narrow gap, an applied electric field removed salts and other species through adsorption onto the electrodes.

[1] The terms "water end use efficiency" and "recovery" are used interchangeably in this report.

Figure 7: Illustrative Diagram of FTC with Charge Barriers



2.3.2 Objectives

The goal of this project was to determine the feasibility of using an advanced, flow-through-capacitor-based (FTC) reactor with new ionic charge barriers (ICBs) to soften water while maintaining low energy usage and 100 percent compliance with mandated levels of salt discharge. The researchers established the following project objectives:

1. Design and Fabricate System Prototypes
   - Design high-recovery FTC prototypes
   - Build high-recovery FTC prototypes
2. Evaluate Rejection Efficiency
   - Measure hardness rejection for tap water of > 90 percent using fabricated prototypes
   - Measure repeatability and reproducibility to demonstrate >80 percent confidence
3. Evaluate energy usage
   - Measure water use efficiency of > 90 percent using fabricated prototypes
   - Measure device energy input of <3 Wh/gallon of purified water
4. Assess Competitiveness
   - Determine life-cycle cost of ownership for POE softening, from the perspective of the homeowner, and compare against both NF and RO
   - Calculate energy costs and compare against NF and RO

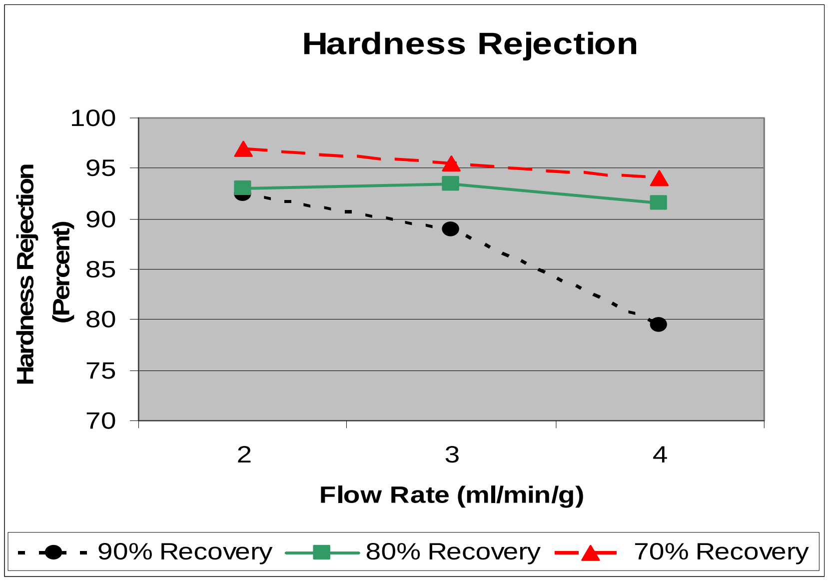
2.3.3 Outcomes

1. The researcher designed and built a prototype FTC incorporating a plate-and-frame electrochemical concept. This prototype softener contained power electronics, a controller, pre- and post-filters, and the flow-through capacitor. The researcher sized the prototype at 140 gpd.

2. The researcher identified a range of operating conditions that satisfy the criterion of > 90 percent hardness rejection. High recovery is possible with high rejection, as shown in

Figure 8. These data were repeated with both short and long intervals between repeats. This performance came at a cost in terms of limited life for the device. It operated less than a week at 90 percent recovery before performance dropped significantly. Reducing recovery well below the target criterion to 60 percent extended device life to roughly six months.

Figure 8: Hardness Rejection for the FTC



3. Water use efficiencies of > 90 percent were measured over a range of flow rates, as shown in Figure 8. Measured cell energy was 2.92 Wh/gallon. Total device energy utilized for purification was 5.7 Wh/gallon purified, measured at the wall plug. This figure includes the FTC cell energy consumption, plus energy to run the solenoid valves, controller, and power supply. These ancillary components use approximately the same amount of energy as purification.

4 The life-cycle and total energy cost (including energy to deliver water) of the prototype FTC was similar to NF/RO.[2] The life-cycle cost of the FTC, based on actual performance, is $9.49/1000 gallon purified[3], while NF/RO life-cycle cost is $10.52/1000 gallon purified.

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[2] Here we consider NF/RO systems suitable for POE water softening. POE systems have lower salt rejection and higher water use efficiency (recovery) than the popular, 30 gpd, under-the-counter RO systems.

[3] This figure depends on achieving a fivefold reduction from the prototype's $10,000/gpm production cost to $2000/gpm for a commercial unit through volume production and additional engineering of $2 Million over 2 years.

While the FTC has higher maintenance costs, NF/RO has higher water costs due to lower water-use efficiency.

The total energy use of the FTC, based on actual performance, is 13.0 Wh/Gal purified, while NF/RO is 14.4 Wh/Gal purified. While the FTC has higher purification energy at the plug than NF/RO, its more efficient use of water reduces the energy required for delivery.

2.3.4 Conclusions

1. The goal of designing and building a high-recovery FTC prototype was met.
2. The prototype device met the hardness-rejection goal over a range of operating conditions, demonstrating that high rejection is possible with high recovery. However, the prototype experienced a very short life at 90 percent recovery before performance declined significantly. Reducing operation to 60 percent efficiency increased life to roughly six months, but it compromised the project goal of high efficiency in exchange for a short lifetime.
3. When device life was not used as a controlling factor, the prototype displayed high rejection at high efficiencies. Energy efficiency of the cell was within the project's goal of < 3 Whr/Gal, but the ancillary load of the remaining hardware (solenoid valves, controller, and power supply) added nearly an identical amount, resulting in a total wall plug usage of almost double the project goal. This result does not necessarily suggest that a production-scale unit would not meet the design goal. The ratio of ancillary load to cell load is unusually high in the small prototype because it was not designed to minimize ancillary loads. In contrast, these loads would not increase much in a larger-size production unit, and the design for such a unit would include optimizing its power consumption. Taking these factors into consideration, the PI estimated that a unit of commercial size could be built with a 3.3 Wh/Gal rating.
4. The FTC device with the operating parameters of the prototype would not be commercially viable in competition with NF/RO technology for POE softening. Although it has similar life cycle costs and lower total energy consumption and water usage, its very short lifetime would hinder customer acceptance. A service interval of six months at a cost approaching $1000 would not be acceptable.

The most likely improvement with commercialization would be reduced energy consumption for the device, as described in Conclusion 3 above. The path to solving the tradeoff between device life and efficiency is not as clear; it would depend on future engineering advances that allowed substantially longer life at high efficiencies. The researcher indicates that only limited lifetime studies have been performed. Preliminary indications are that the charge barriers (ion-exchange membranes) are the weak link.

The FTC device developed could meet (or come close to meeting) the original goals set for rejection, water-use efficiency, plug-energy consumption (at commercial scale), and life-cycle costs (at commercial scale, assuming a 5-fold reduction in production cost from prototype). However, the study discovered a potential "fatal flaw" in the extremely limited life of the prototype when operated in continuous purification service. Until a significantly longer life (5 years compared to the prototype's 6 months at reduced recovery) is obtained, without offsetting compromises in the other performance parameters, the technology is not commercially viable in competition with available NF/RO technologies for POE softening.

2.3.5 Recommendations

Although today's ion exchange technology is a current winner in terms of cost and performance, at some point it may be prohibited or heavily restricted due to the environmental impact of its brine regeneration process. California needs replacement technologies available to fill the gap as old technology is phased out. The limited life of the prototype device poses a significant barrier to its commercialization at this point, and the researcher indicates that there are no plans to continue FTC development. However, the following additional research would help determine whether solutions can be developed that would allow FTC technology to become a viable IE replacement candidate for POE softening:

1. Conduct in-depth studies of FTC lifetime to better understand causes of performance degradation.
2. Conduct analysis and engineering to mitigate the causes of FTC performance degradation with a target of 5-year service life, while preserving a 90 percent rejection at 90 percent efficiency.
3. Conduct engineering to identify a path to a commercial device with energy usage of <3.5 Wh/Gal.
4. Confirm that production costs can be reduced by four-fifths from a prototype to a commercial unit.
5. Identify cost-reduction strategies for charge barriers with a target of a 10-fold reduction.

Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefits to the ratepayer from this research are increased affordability of electricity in California. Energy-cost savings occur only if California mandates a phase-out of the current ion exchange water softeners due to their brine-regeneration process. Once this takes place, the only known alternative technologies are NF/RO and, potentially, FTC. Assuming successful commercialization of an FTC device for POE softening, its superior water usage efficiency (90 percent) as compared with RO (40 percent) would provide energy savings through reduced water pumping and wastewater services, as well as conserving California's limited water resources.

Available figures for California's per capita water usage and percentage of electricity consumption used for water pumping and wastewater services yield an electricity consumption of 4.4 Wh/gal. Available estimates show that about 30 percent of residential water customers use softening at a per capita rate of 75 gallons per day, or an estimated total urban water softening usage of 1×10^9 gallons per day. A comparison of water usage between the prototype FTC device and current NF/RO technology shows that the replacement of existing IE with FTC, vs. replacement with NF/RO devices could result in a saving of about 380[4] to 1,730[5] million kWh/yr electricity (up to 1 percent of urban electricity consumption), with a retail value of $38[6] to $173[7] million per year for California.

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[4] Savings at 60% efficiency required to extend prototype life to six months

[5] Savings assuming further research leads to operation at >90% efficiency with 5 year life

[6] Corresponds to 60% efficiency

[7] Corresponds to 90% efficiency

2.4 Construction and Testing of a High Efficiency Solar Water Still

Awardee: The Starburst Foundation

Principal Investigator: Paul LaViolette, Ph.D

2.4.1 Introduction

In certain arid agricultural regions such as the western San Joaquin Valley, there is a strong need to desalinate and recycle irrigation drainage water to lower the water table of saline ground water[8] and to do this in an economical manner not requiring large amounts of energy

In the past, solar distillation technologies have been considered economically impractical because their produced water cost has been high compared to municipal drinking water at ~$460 per acre-foot (AF). The economics for solar water desalination may be more favorable in the San Joaquin Valley for drainage water desalinization since drainage water reuse is a necessity independent of the price of municipal water, and solar energy levels are higher than most coastal regions of the state. In the San Joaquin Valley soil salinity has become excessive because of failure to reclaim and recycle agricultural drainage water. The long-time practice of importing irrigation water has raised the water table due to the presence of an impermeable clay layer which prevents downward percolation of the water. Fertilizer salts have leached into the ground water and the resulting salty ground water has risen to root-level killing crops. About 2.5 million acres of productive farmland there are threatened by saline shallow ground water, of which about 750,000 acres have already been lost due to elevated soil salinity. The California Department of Water Resources (DWR) has implemented a program to address this problem, promoting solar evaporation ponds as a way of dispensing of this water. However, these ponds require excessive acreage, about10 percent of the arable land area, for evaporating once-used irrigation water. Moreover in many regions these ponds pose a threat to bird wildlife due to their high concentration of toxic metals such as selenium. Consequently, California is interested in exploring drainage water desalination and reuse as a way of reducing solar evaporation pond acreage. Furthermore, the California Dept. of Water Resources is interested in exploring alternatives to reverse osmosis (RO) desalination since RO by itself does not provide a complete brine disposal solution. At 10,000 TDS, RO desalination must discharge 25 percent of the input stream volume as high-salinity water. Also RO consumes large amounts of electricity per acre-foot (AF) of processed water. Hence if an alternative technology can be found that consumes less energy per acre-foot of water produced, benefits would flow to the California ratepayers.

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[8] www.sjd.water.ca.gov/drainage/purpose_history/index.cfm

The purpose of this project was to determine the feasibility, performance, and operating characteristics of a multi-effect solar water still invented in the mid 1970's by the principle investigator Paul LaViolette. When fully inflated, the still has the shape of an arching tube (Figure 9.) The solar distillation test bay that was constructed for this project measured about 1.17 meters in width, about 8.8 meters in length, with a height of about 0.5 m when inflated. In a commercial installation distillation bays could measure up to 30 meters in length and would be arrayed side by side to form a solar distillation "farm". The solar still used solar energy to evaporate water into a ducted airstream and subsequently condensed water from this airstream to produce fresh water. Initially, it was theorized that this solar still would function as a multi-effect still, recycling its released heat of condensation to assist evaporation (Figure 10.) By comparison, a conventional[9] greenhouse solar still is a single effect still, meaning that it uses its acquired solar heat only once to distill a given amount of feedstock water. The project focused on the potential use of this still to the application of desalinating high-salinity agricultural drainage water for reuse in crop irrigation. Purification of substandard and saline water relies heavily on electric power. So if the proposed technology were to prove superior to existing desalination technologies it could result in substantial savings to California in terms of reduced kilowatt hour consumption used in the desalination of irrigation drainage water, or in the production of desalinated water for residential or industry use.

[9] In a greenhouse still, solar radiation is absorbed by a light-absorbing floor panel and heats an overlying layer of water (see Appendix A, Figure A-2). The heated water evaporates and its vapor condenses in droplets on an overlying, cool, inclined window pane. The condensed water droplets run down this pane and collect in a trough at the side of the still. Such stills are designed to lose heat through their window pane to the environment so as to encourage vapor condensation. Thus all of the solar energy they absorb to evaporate water is lost to the environment upon condensation.

Figure 9: The Dune Solar Still: a) Side View, b) End Section View, and c) Edge Detail

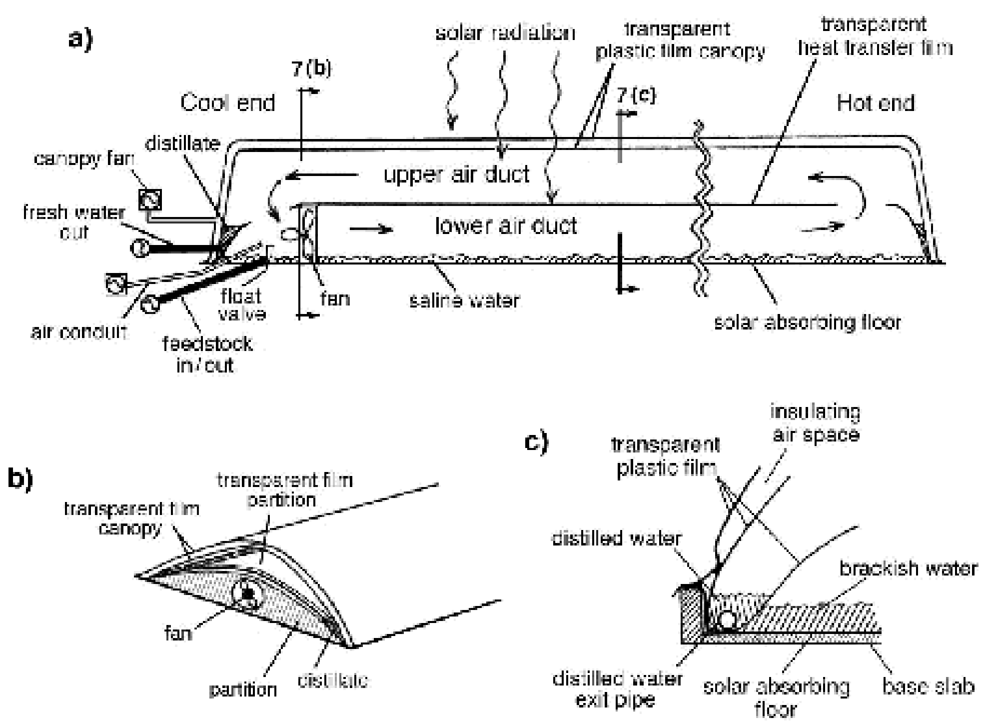
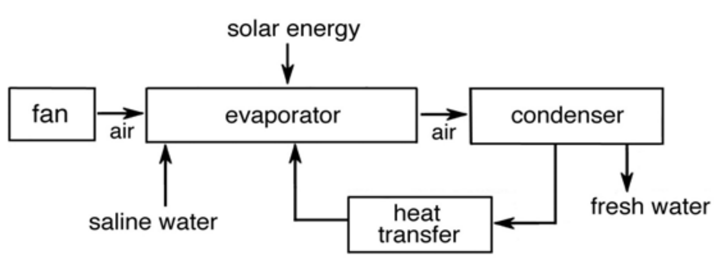


Figure 10: Heat Recycling in a Multi-Effect Solar Still



2.4.2 Objectives

The goal of this project was to determine the feasibility of a multi-effect solar still design to reduce the salinity of brackish agricultural drainage water with a minimum use of electricity. The researcher established the following project objectives:

1. Demonstrate a polyethylene solar still output of 2.5 gallons of distilled water per m^2 of still area per day while consuming less than 4 watt-hours of electricity per gallon of distillate. Agricultural drainage water will be the input water source and contain less than 10,000

TDS salinity. This objective to be met during winter season conditions of cloudless sky and 75° F ambient air temperature.

2. Demonstrate a polyethylene solar still output of 3.5 gallons of distilled water per m^2 of still area per day while consuming less than 2.5 watt-hours per gallon of distillate. Agricultural drainage water will be the input water source and contain less than 10,000 TDS salinity. This objective to be met during summer season conditions of cloudless sky and 100° F and higher ambient air temperature.
3. Demonstrate a FPA Teflon solar still output of 3.5 gallons of distilled water per m^2 of still area per day while consuming less than 2.5 watt-hours per gallon of distillate. Agricultural drainage water will be the input water source and contain less than 10,000 TDS salinity. This objective to be met during winter season conditions of cloudless sky and 75° F ambient air temperature.
4. Demonstrate a FPA Teflon solar still output of 5.0 gallons of distilled water per m^2 of still area per day while consuming less than 1.53 watt-hours per gallon of distillate. Agricultural drainage water will be the input water source and contain less than 10,000 TDS salinity. This objective to be met during summer season conditions of cloudless sky and 100° F and higher ambient air temperature.
5. From the data, demonstrate projected cost of $113/$m^2$ for building a 173 m^2 still module.
6. Demonstrate, from the data, a projected cost of $490 per acre-foot of distilled water when using agricultural drainage water of less than 10,000 TDS.

2.4.3 Outcomes

1. The polyethylene still produced 0.5 gallons/m^2/day during the September-October test period. It demonstrated an efficiency of ~25 percent. This still consumed 47 watt-hours of electricity per gallon of produced distillate. These data came from tests performed on fresh input water rather than the planned brackish agricultural drainage water. The researcher cancelled the brackish water tests after receiving the data from the fresh water tests. No tests were conducted in the winter months.
2. No data was taken during summer months.
3. The researcher did not construct a still with PFA Teflon. No data were acquired. The researcher performed a computer simulation of this still and found the efficiency would improve to 30 percent, but production would still not meet the production goals. The researcher estimated power consumption of 39 watt-hours per gallon when the still is constructed with PFA Teflon.
4. The researcher did not construct a still with PFA Teflon. No data were acquired. See Outcome #3 above.
5. The researcher continued to use his estimate of $113/$m^2$ for construction costs.
6. The researcher calculated the cost of the distilled water to be $16,400 per acre-foot using a solar still constructed of FPA Teflon material.

2.4.4 Conclusions

1. The polyethylene still produced one-fifth the water and used about 11 times the energy predicted. The tests were accomplished in the fall, rather than the winter. Therefore the data should have been better than winter projections. While the use of fresh water, rather than brackish water, may have had an effect on the data it probably was not significant. Clearly feasibility was not proven. The test results did prove the researcher’s claim that these systems are difficult to model.
2. No data were taken during summer months. Preliminary data taken in the fall were so far off prediction that additional tests were deemed unnecessary.
3. Because of the poor initial data and the amount of funding available the researcher did not build a still with PFA Teflon. The computer simulations of a still built of this material indicated improved performance, but still less than originally predicted.
4. Because no PFA Teflon still was constructed it could not be tested in the summer season.
5. Any estimate of construction costs should be considered as very rough estimates until a still design is proven to work. Materials costs vary greatly.
6. The cost of produced water is considerably higher than water produced by greenhouse stills and reverse osmosis. Clearly the tested design is not economically viable.

Feasibility was not proven in this project.

2.4.5 Recommendations

The PA and the researcher recommend that no further R&D funds be allocated to improving the design tested in this project. However, if the researcher decides to continue research in this area, the PA recommends that he consult with heat transfer experts regarding the heat transfer in this unique design. The data suggest that this still design is not operating in a multi-effect mode. This recommendation is specific to this particular design. Because of the need to increase water re-use in agricultural areas and the need to reduce energy use while purifying the brackish water, this area of research should be vigorously pursued.

Benefits to California

Public benefits derived from PIER research and development is assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research will be increased affordability of electricity in California. Low energy use water purification could have a significant impact on electricity demand in the agricultural regions of central California. Since the testing in this projects revealed that the design under test used more energy than conventional designs there would be no incentive to pursue this particular design further. Nor is it possible to estimate any potential benefit.

2.5 Pressure Reducing Valve Turbine

Awardee: SOAR Technologies, Inc.

Principal Investigator: Michael A. Maloney, P.E.

2.5.1 Introduction

Drinking water and irrigation water systems throughout the State of California utilize hundreds of pressure reducing valves (PRV) to reduce pressure between system zones, and to reduce pressure to appropriate pressure for local use. In each case energy previously used to increase the pressure of the water is dissipated during the pressure reduction process. There is a potential to recover that energy in the form of electricity. While reaction turbines in the water stream could reduce water pressure while producing electricity, water authorities insist that the pressure reduction function not be directly linked with the energy recovery function. The reason for this rule is to prevent large swings in downstream water pressure if the energy production hardware were to fail. One example of failure is a total loss of electrical load on a pressure reduction turbine generator. This would cause the turbine to increase speed and the downstream water pressure to increase. Prior to this project there was no proven method to achieve pressure reduction with indirect power generation.

Outfitting 800 PRVs with indirect power generators could result in the production of 116 GWh of energy annually in California. This has a potential value of $13.9 million at $0.12/kWh. All energy produced in this manner would create no additional NO_x, CO or CO_2. In addition, the energy produced could be classified as renewable for the purposes of meeting the state renewable portfolio standard.

The researcher proposed a method to provide reliable pressure reducing functionality as required by PRV users, with indirect power generation as a byproduct. This project involved development of a full-scale power generating pressure reducing valve with an integrated impulse turbine. The impulse turbine operates in a high pressure air chamber. The air chamber allows the water to strike the impulse turbine buckets to generate power without impeding water flow. The air chamber is pressurized to the same level as the output water pressure. This arrangement could cause increased levels of entrained air that could be detrimental to water system operations. (Entrained air consists of free air bubbles flowing in the water stream and is easily separated by mechanical means. Dissolved air is chemically dissolved in the water.)

Other issues associated with this design were pressure regulation and turbine efficiency. The purpose of this project was to investigate these issues using a full-scale prototype.

This proposed methodology for the PRV turbine uses an impulse-type turbine to capture the energy in the water. This type of turbine allows the pressure regulation to be independent of the energy output of the turbine. Flow through the turbine is controlled through a needle nozzle on the device. Disconnecting the turbine from the load has no effect on the output water pressure of the PRV.

The goal of this project was to develop a small, full-scale generating pressure reducing valve model to determine the significance of air entrapment at 800 GPM with an input operation pressure of 150 PSI with and output pressure ranges of 20 to 100 PSI.

2.5.2 Objectives

The purpose of this project was to prove the feasibility of a full-scale power generating pressure reducing valve. The resulting valve had to meet water department regulations and needs. The researcher established the following objectives:

1. Design, build and fabricate a full-scale prototype valve.
2. Conduct testing of the pressure reducing valve (PRV) turbine
   - Demonstrate the turbine generates power over the design operating range, up to 800 GPM at 150 PSI pressure input with 100 PSI reduction.
   - Verify the device operates at standard pressure reducing valve specifications (1 percent output pressure regulation)..
   - Verify the turbine efficiency is greater than 80 percent when the pressure reduction is 70 to 140 PSI. Measure any reduction in turbine efficiency due to operation in a pressure chamber.
   - Measure the air entrained in standard water sources.
   - Verify the air dissolved by the turbine is equal or less than the theoretical maximum at 100 percent air saturation or the water, since this reduces the amount of added air required to maintain the air pocket in the turbine enclosure. (This objective was added after the start of the project.)
     - Measure air usage (air entrapment in outflow) by the device. Calculate and measure amount the air dissolved into the water during operation of the turbine. Demonstrate entrapped air can be removed with standard air bleeding devices to less than 1 percent.
3. Verify that the projected manufacturing cost of $350/kW can be supported.
4. Verify that the projected cost of power generated from the proposed device is $.03/kWh over the life of the product.

2.5.3 Outcomes

1. The turbine model operated properly up to one-half of the design flow. Significant air entrainment in the outflow prevented operation for flows greater than 400 GPM. As the amount of air entrainment increases the air pocket around the impulse turbine is reduced and eventually eliminated. Without the air pocket the power and efficiency of the turbine are reduced markedly.
2. Test results
   - Regulation of the output flow worked, but not within the 1 percent limits standard for commercial PRV specifications. Measured output pressure regulation was 12 percent.
   - Turbine efficiency of over 80 percent was measured and is the same whether the turbine is operated with or without backpressure from the output water stream.
   - Standard water sources contain less than one percent of entrained air at atmospheric pressure.
   - Since air in the chamber was dissolved into the water during operations, the PRV turbine required a supply of air to maintain the air pressure in the turbine chamber.
   - Measured amounts of the dissolved air were approximately 50 percent to 75 percent of the maximum calculated value. Dissolved air is lost to the system and must be replaced using an air compressor. An air separator was used to remove the entrained air in the output water stream. The captured air was returned to the turbine air pocket. This allowed the researcher to increase the allowable flow up to 550 GPM from 400 GPM.
3. The researcher estimated manufacturing costs of $1000/kW to $1500/kW.
4. The researcher projected cost of the power generated from the PRV turbine at $.06/kWh over the life of the project.

2.5.4 Conclusions

1. The researcher successfully built and operated a power producing PRV that meets most water supplier regulations. He successfully proved the feasibility of his concept. The fact that he was not able to operate at full flow does not detract from the proof of feasibility.
2. Test Results
   - Water pressure regulation remains a significant issue for future development. The measured regulation accuracy does not meet the needs of water suppliers
   - Turbine efficiency was successfully proven.
   - Dissolved air did not reach the 100 percent saturation number because the residence time in the turbine was relatively short. All air dissolved in the water is lost to the system and must be made up and returned to the high pressure chamber using air compressors.
   - Entrained air can be separated from the outlet water and returned to the high pressure chamber without re-pressurization.
3. Capital costs were estimated using RETScreen International software. The software and cost estimates of equipment were supplied to this project by the Canadian Department of Natural Resources. Future cost estimates should be derived from suppliers of equipment.

4. While double the estimate cost of $0.03/kWh, the projected cost of electricity of $0.06/kWh remains an attractive cost for on-site power usage. This is about one half the cost of purchased power. However, the cost of electricity is highly dependent on the capital cost estimate. The PA recommends future estimates be based on estimates from manufacturers.

2.5.5 Recommendations

The PA recommends that the researcher continue his work on power producing PRVs. He should concentrate his work on improving the accuracy of the pressure reduction regulation. In addition he should devote additional activity to reducing air loss from the turbine chamber. The cost, both financially and in energy units, of making up the lost air must be accurately measured. The PA recommends a collaborative effort with a turbine manufacturer to more accurately estimate the cost of the capital equipment. Real world overhead, marketing, maintenance, and profit numbers should be used in all of these estimates.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for follow on funding within the PIER program.

Receiving follow on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research project is reduced environmental impacts of the electricity supply system. Reduced environmental impacts come from recovery of energy now lost in the process of reducing water pressure. Outfitting 800 PRVs with indirect power generators could result in the production of 116 GWh of energy annually in California. This has a potential value of $13.9 million at $0.12/kWh. No fuel is burned to recovery this energy. All energy produced in this manner would create no additional NO_x, CO or CO_2. In addition, the energy produced could be classified as renewable for the purposes of meeting the state renewable portfolio standard.

2.6 Covell Village: a Model for Sustainable communities

Awardee: Davis Energy Group, Inc.

Principal Investigator: Mark Berman

2.6.1 Introduction

In the U.S., a large percentage of electrical energy for buildings is supplied from centralized utilities. Distribution losses and lack of reuse of combustion products results in a relatively low utility delivery efficiency of 31.3 percent[10]. Inefficiencies in the system result in increased unit costs passed on to consumers, and increased pollutant emissions at the generation source.

To combat system inefficiencies, many European countries have begun providing energy to consumers through Combined Heat and Power (CHP) systems, also known as District Heating and Cooling. CHP systems are typically comprised of gas-engine-driven generators for generating electricity, heat recovery equipment for utilizing the waste engine heat, compression chillers and/or absorption chillers for providing chilled water for space cooling, and an underground network of piping to deliver heating and cooling to the customers within the district (Figure 11). Because CHP systems use a co-generation plant that is proximate to the end-users, combustion products including heat and steam can be recycled within the system, and the typical 8-9 percent distribution loss can be minimized, resulting in efficiencies roughly twice that of centralized utilities (~ 80 percent vs. 30 percent - 50 percent)[11]. With a CHP system, total residential energy usage could decrease from approximately11.90 kWh/ft^2 to 10.52 kWh/ft^2, and carbon emissions could reduce by 61 percent for a given demand. Additional benefits of a CHP system include improved system reliability and reduced reliance on the grid during peak usage periods which are typically charged at a premium.

The researcher proposed to assess the feasibility of implementing the CHP model within the Covell Village development in Davis, CA. Covell Village consists of approximately 1,100 single-family homes, 300 multi-family units, and assorted commercial/retail space, totaling 2.78 million square feet of conditioned space. This village is well suited for district heating and cooling due to its relatively high density and large size. The CHP system would be located within Village Center retail/commercial portion of the site. Excess electric generation would be

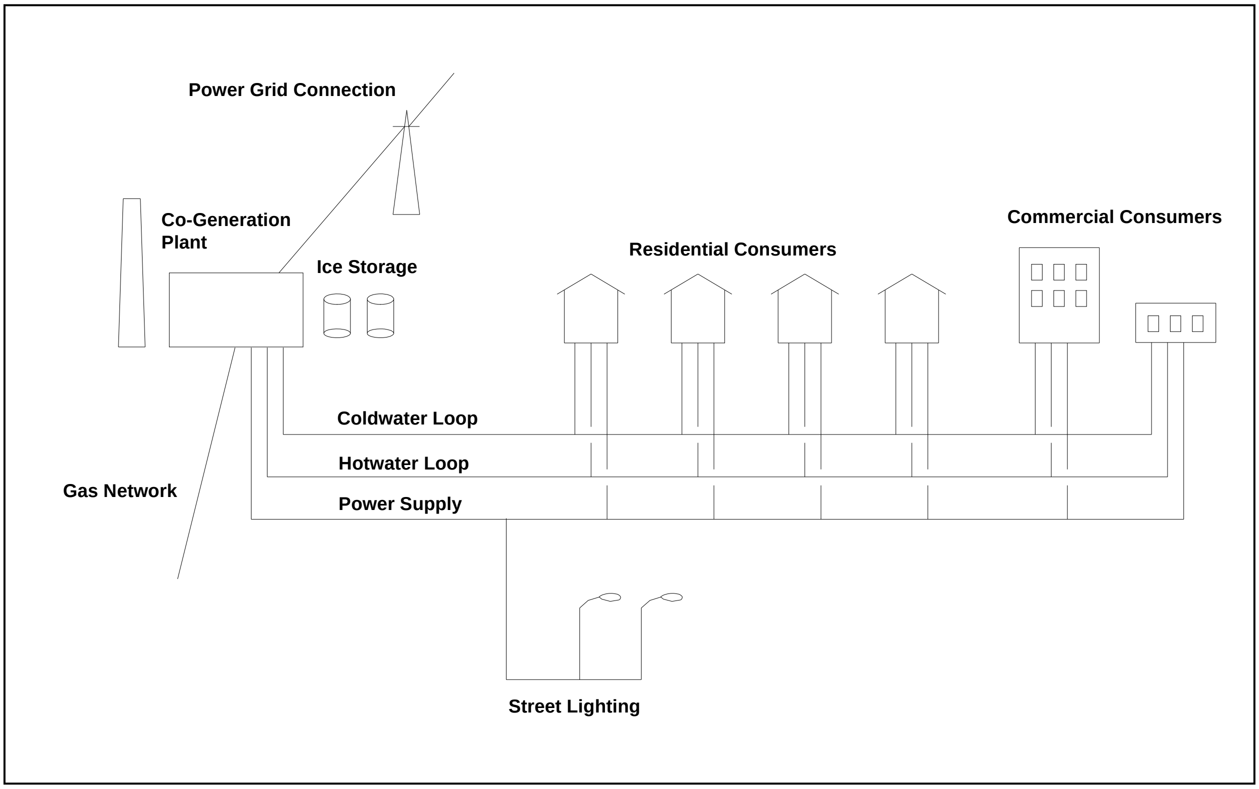
[10] U.S. DOE 2004

[11] Brown & Koomey, 2003

returned to the grid for credit, and deficiencies would be purchased from the grid, operated locally by PG&E. Peak demands are leveled using ice storage units which are charged at night and discharged mid-day. Analysis of the return on investment included the following components:

1. CHP system construction costs, projected at $25 Million. The PI suggested that a $5,000 premium per house would be reasonable to offset the system cost.
2. Substitution of conventional heating, cooling and water heating equipment traditional water heaters with a District Energy service station, estimated at a $3,700 savings per house
3. Energy production unit costs.

Figure 11: Schematic of a District Heating and Cooling System



2.6.2 Objectives

The goal of this project was to perform a preliminary CHP feasibility assessment for the Covell Village project. The researcher established the following project objectives:

1. Total residential energy use less than 10 kWh_{elec}/ft^2 with electrical usage target of 4.5 kWk/ft^2-year (vs. 5.0 for Title 24 compliant house).
2. Home prices within 10 percent of conventional Title 24 homes.
3. Monthly mortgage payments plus monthly energy bill less than conventional Title 24 homes.
4. CO_2 emission reductions of 40 percent or more relative to standard development.
5. Renewable energy sources demonstrate a return on investment (ROI) of > 11 percent.
6. Proposed District Energy system has a projected ROI > 11 percent.
7. Combining the proposed District Energy with super-efficient construction practices result in a projected ROI > 11 percent.

2.6.3 Outcomes

Total base case residential energy use was estimated at11.90 kWh_{elec}/ft^2-year. Projected usage under the District Energy case was estimated at 10.52 kWh_{elec}/ft^2-year, falling short of the goal of 10 kWh_{elec}/ft^2-year. Failure to achieve this objective was attributed to difficulties in cost-effectively incorporating additional energy efficiency in conjunction with the CHP design.

Substitution of conventional heating, cooling and water heating equipment with a District Energy service station was projected to reduce "in house" costs by $3,700 per house. The researcher suggested that a portion of the $25 million District Energy system construction cost be borne by the homeowners, but conceded that the system would be cost prohibitive without public subsidy.

A savings of $3,700 per house translates into a $22 monthly mortgage reduction. A 10 percent reduction per month in thermal energy cost translates to approximately $6 per month, for a total savings of approximately $30 assuming a 30 year loan at 6 percent interest. This savings assumes that the homeowners will bear no portion of the District Energy system construction cost.

At build-out, projected carbon emission reductions will total 5480 metric tons per year, or 61 percent less than for conventional energy supply practice.

Solar water heating is not economically compatible with CHP due to the low marginal cost of utilizing engine waste heat generated by the CHP system. Solar electric similarly proved to be incompatible due to a larger unit cost than energy supplied through the District Energy system once installed. Economics of other sources, such as a biogas facility, were not quantified, but may prove to be synergistic.

Assuming PG&E operated the CHP system, annual costs were 6 percent lower than conventional energy supply with standard building practices. Note that this included a discounted personnel and administration cost which is not explained in the report.

Assuming PG&E operated the CHP system, annual costs were 9 percent lower than conventional energy supply with advanced building practices.

2.6.4 Conclusions

The objective to show total residential energy use less than 10 kWh_{elec}/ft^2-year was not met. The researcher did not specify system improvements that would allow this objective to be met.

Although the base price of the house was not specified, the objective of keeping home prices within 10 percent of conventional Title 24 homes was met. According to the California

Association of Realtors, the median home price in California was $538,770 in October 2005[12]; therefore, the objective would be met if the net system cost were less than $53,877. The PI indicates a unit equipment cost savings per home of $3,700, assuming that the District Energy system would be subsidized in part if not in its entirety. Should public subsidy be unavailable, the cost per home for the District Energy system would be approximately $18,100. Reducing this by the equipment cost savings results in a net cost of $14,400 per home, still within the project objective. While the objective was met as written, the appropriateness of this objective may be questioned. Consumer acceptance of this premium will be a significant marketing challenge. Given the proximity of the co-generation plant to the residences, consumer acceptance will very likely be hindered by the same NIMBY issues that have plagued the utility industry in siting new power plants. These two factors alone may prove fatal to implementation of a CHP project. The concept that there is a market for homes at a premium price sited near a combustion-based power plant will require a very significant marketing effort, and the existence of this market would seem to be part of the feasibility of this concept.

The objective to show a savings in monthly mortgage payments and monthly energy bills relative to conventional Title 24 homes can only be met with the assumption that the homeowner will bear no portion of the District Energy system cost. The likelihood or reasonableness of this assumption is not established in the report. The PI suggests that builders could charge homeowners a $5,000 premium over conventional pricing, with $8,700 per home remaining to offset the District Energy system cost. With this suggested premium, the mortgage payment increase would more than exceed any savings realized in monthly energy bills. Should subsidy be unavailable, the construction premium would need to be raised to $14,400, with a corresponding increase in monthly mortgage far surpassing the $6 monthly savings in utility costs.

The objective to reduce CO_2 emissions by 40 percent or more was met. The PI notes that although emissions would be reduced, they would be discharged to the community in which the end-users live. While it is reasonable to expect the community to be exposed to its energy impacts, it will further add to the marketing challenge and consumer acceptance.

The objective to show a ROI >11 percent for renewable energy sources was not met. Solar thermal and solar electric were either duplicative or detrimental to project cash flow.

The objective to show a ROI >11 percent for the district energy system under standard building practices was not met. The 6 percent ROI is sensitive to interest rates and fuel price escalation. Sensitivity studies in fuel and electricity price escalation indicate that CHP is less attractive with fuel cost increases, and more attractive with electricity cost increase. By assuming that both fuel and electricity would increase at similar rates, effects on the model are neutralized. The PI indicates that higher interest rates would weaken CHP economics and lower interest rates would improve them, however a sensitivity analysis was not presented. The ROI did not

[12] California Association of Realtors, 2005

account for capital outlay for construction of the district energy system. Factoring in the district energy system cost, the simple payback period is in excess of 50 years, making this an unattractive investment.

The objective to show a ROI >11 percent for the district energy system under standard building practices was not met. The 9 percent ROI is sensitive to interest rates and fuel price escalation in a similar manner as described in item 6 above. Also, similar to item 6, this analysis did not include the capital outlay for the system. Incremental costs of implementing advanced energy-efficiency practices surpassed the incremental savings realized when combined with CHP. Therefore, it is not economically advantageous to exceed Title 24 energy-efficient building standards.

The original goal of the project was to perform a preliminary CHP feasibility assessment for the Covell Village project. This project is clearly not economically feasible. Few of the objectives were met as stated. From an economic perspective, the reasonableness of the expectation that the district energy system capital costs can be fully subsidized is critical, but is not established. Even with this assumption though, the return on investment makes the project only marginally attractive. Beyond economic acceptability is social and political acceptability. The researcher showed that CHP systems are incompatible with incorporation of renewable energy sources, or improvements in energy-efficient building practices. While this certainly indicates room for advancement in cost-effectiveness and/or government subsidy for renewable energy sources and energy-efficient construction, the use of CHP as presented is contrary to the current regulatory focus on increasing energy efficiency, decreasing usage and minimizing our impact on the environment. Further, with a lower unit cost (resultant from a higher conversion efficiency), there is a risk that usage would increase as seen historically. Given the risks associated with this investment, a significant ROI premium over standard investment options would seem necessary to attract investment.

CHP is advantageous in terms of load management and grid reliability. Ice storage allows for better management of peak loads, which would provide for significant savings under a demand metering system. Grid reliability is also gained for consumers within the supplied district, as well as for those served only by traditional utilities as electricity can be transferred to and from the grid by the CHP system.

This study leaves some question as to who should own and operate the system. Although several owner and operator scenarios are discussed, the PI suggests that PG&E is the logical choice for system operator in spite of the fact that PG&E has not expressed an interest in serving as the owner. While it is true that PG&E is the prime beneficiary of the conversion efficiency and is capable of doing this task, there may be an opportunity for competitive bidding both in terms of cost of operation and also in terms of performance.

The potential applicability of this technology appears to be relatively low. The district energy approach is only feasible in large master-planned communities with high density. This includes approximately 10 percent of new homes built in California. The marginal project economics seen in Covell Village would be enhanced for projects in areas of extreme climate. This further reduces CHP's applicability as there are few areas within California characterized by extreme climates, and most of those are not likely candidates for high-density, large, master-planned communities. Significant infrastructure requirements for the district energy system appear to make retrofitting cost prohibitive. The low potential applicability for this technology may counteract efforts to secure public subsidy.

At present, there are too many unanswered questions regarding CHP acceptance, plant ownership, operation, and financing to conclude that application of CHP within Covell Village is feasible. Significant market and regulatory analysis will be required to resolve these issues.

2.6.5 Recommendations

The researcher should consider the following recommendations upon commencement of additional work in this area:

Conduct market analyses to identify:

- Consumer acceptance (particularly in regards to NIMBY questions).
- Maximum bearable construction premiums.
- Scope and applicability of District Energy systems to California residents for economically feasible installations.
- Parties interested in project ownership.
- Parties interested in operating the CHP system.
- Conduct a regulatory review to determine:
- Regulatory obstacles.
- Potential for subsidy of the CHP plant.

The CHP technology has significant obstacles to overcome in terms of economic viability and market acceptance. Efforts to overcome these obstacles will be required prior to resubmission for follow-on funding within the PIER program for assistance in full-scale field testing and commercialization.

Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system

- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is an improvement in the efficiency and reliability of the California electricity system. By bringing power generation to the end users, CHP systems can more efficiently use the combustion products and minimize the typically 8 – 9 percent transmission and distribution losses resulting in overall systems efficiencies roughly twice that of current central plant technology (~80 percent vs. 30 percent-50 percent). This conversion efficiency results in lower cost and pollutant emissions for a given demand. Interaction of the components within the co-generation CHP plant allow for better management of peak demand. Although the CHP plant is sized for the target community, it may exchange energy supply with the grid to supplement power in times of shortage/outage, or generate revenue by depositing surplus electricity. This exchange mechanism provides more reliability for customers within the CHP district, as well as those receiving power only from conventional utilities. Reliability for grid users would increase as more CHP plants were brought online.

Application of the high-efficiency CHP system would result in a 61 percent reduction in emitted pollutants with the following annual reduction estimates for Covell Village as shown in Table 1:

Table 1: Reduction Achieved by Application of High-Efficiency CHP System

Pollutant	Annual Reduction (Metric Tons)
CO_2	5,480
SO_2	3,280
NO_X	10,770

These reductions presently have no financial value, but could become a valuable asset in the future. For example, avoided carbon trades in the Kyoto countries trades at up to $10 per metric ton, translating to a yearly value of $54,800 for the Covell Village project[13].

[13] Point Carbon, 2005

2.7 The Day Switch

Awardee: Lighting Research Center, Rensselaer Polytechnic Institute

Principal Investigator: Peter Morante

2.7.1 Introduction:

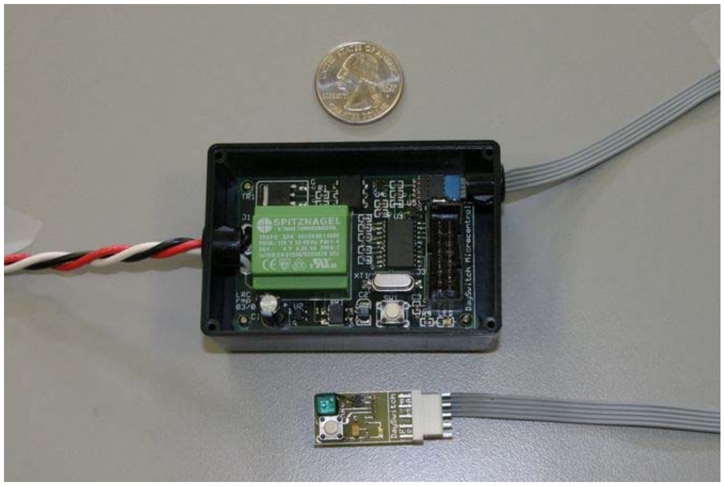
Approximately 25 percent of all electricity use in California is for lighting[14]. This use could be reduced if inexpensive and effective automated controls were available for commercial office environments. Current photo sensor technologies require additional wiring that adds to the initial cost and makes it difficult to install in existing buildings. These existing technologies are also inflexible in that each photo sensor controls a number of lighting fixtures in a space. This causes some areas to be too dark while others are over-lighted because daylight rarely penetrates uniformly into a building's interior.

Current estimates indicate that California's commercial building owners could save 120 million kilowatt hours per year by reducing their lighting energy by 15 percent using a more effective photo sensor switch to control lighting on- and off-times. This assumes use in both in new construction and in retrofit situations. The reduction in peak electric demand is as important as the energy savings. Since peak electric demand usually occurs on sunny days, automated light switches would reduce artificial lighting in areas well lit by daylight. Reduction in peak electric demand related to the use of these light switches could be as high as158 megawatts for California.

The researcher proposed to develop a new automatic light switch technology, called "The Day Switch". His criteria included low cost, ease of installation, and a calibrated photo sensing device. The new switch uses a light-to-frequency photo sensor which converts light illuminance to a digital signal. A micro controller uses the digital signal to calibrate the switch and to determine when to turn on and off the electric lights in response to the amount of daylight. The light level multiplier to turn off the lights and the time delay are programmable. These components were combined into a relatively low-cost package pictured in Figure 12.

[14] www.energy.ca.gov/efficiency/lighting/index.html

Figure 12: Final Day Switch Prototype



2.7.2 Objectives

The goal of this project was to determine the feasibility of a low-cost, easy-to-install and calibrate photo-sensing device for individual lighting fixtures that will turn the fixture on and off based on the lighting contribution of daylight. The researchers established the following project objectives:

1. Develop a detailed schematic design with components costing less than $6.00.
2. Demonstrate the operation of all components and electrical circuitry under a wide range of possible operating conditions, 0-70 degrees C and 10 lux – 10,000 lux.
3. Demonstrate the switch's compatibility with most common types of ballasts.
4. Measure installation and commissioning times of less than 15 minutes and two minutes, respectively.
5. Demonstrate the successful operation of the switch and a connected luminaire in response to a number of different daylight conditions.
6. Discuss commercialization with at least one manufacturer.
7. While not part of the original objectives, an experiment to determine occupant satisfaction and acceptance of switching lights on and off in the presence of daylight was added to the project objectives.

2.7.3 Outcomes

1. The goal of total component costs less than $6.00 was not achieved. Total component cost was $7.25.
2. The researcher measured an effective range of 1 lux to 12,000 lux with an accuracy of +/- 3 percent. The project used components specified to operate in a thermal rating of at least 0 to 70 degrees C. However, no actual thermal stress testing was performed over this temperature range.

3. The switch was wired ahead of any ballasts used in the light fixture and did not interact with the ballast. Using a triac, the switch turned the power to the ballast on and off in the same manner that a wall switch turns power on and off. Therefore, every ballast (instant start, rapid start and dimming) used with the switch worked satisfactorily. The switch also worked effectively with light fixtures that do not require a ballast.
4. Experiments measured the average combined installation and commissioning time at eight minutes and two seconds. The experiments included an installation and commissioning exercise with four male and female participants, whose ages ranged from the 20's to 50's.
5. The researcher connected the switch to a luminaire and subjected it to different daylight levels. At each daylight level, the switch operated properly always turning the lights off close to its programmed setting of two times the lighting level provided by electric lights alone.
6. The researcher discussed commercialization with two lighting control manufacturers. One manufacturer expressed interest in continuing discussions.
7. The following are the results of the human satisfaction experiment:
   - As daylight illuminance increased, switching events became more acceptable by subjects.
   - Switching events were more acceptable when electric lighting was turned on than when electric lighting was turned off.
   - As daylight illuminance increased, the difference in acceptance between when electric lighting was turned on and when electric lighting was turned off was reduced.

2.7.4 Conclusions

1. The researcher estimated the cost of component parts of the switch at $7.25 when purchased in production quantities. Final product cost to the user usually runs three times the cost of components. In this case the researcher estimated total installed costs of $20 for new construction and $35 for retrofits. The higher component cost can still provide viable economic returns for most California businesses in both new construction and retrofit situations. The researcher, using simple payback analysis, found payback times of one to three years depending on the energy saved and the local cost of electricity. The longest payback periods occurred when the switch was retrofitted in buildings in the Sacramento Municipal Utility District service area.

2. There is still some question as to the reliability and durability of the components, especially in extreme temperature ranges, since no long term of temperature testing was done.

3. The switch will work with fluorescent and incandescent light fixtures.

4. Installation and commissioning/calibration times were within the initial objectives of 15 minutes to install the device and two minutes to commission the switch making it a candidate for retrofit situations.

5. The outcome indicated that the switch performed as predicted with varying light levels.

6. There is manufacturing interest in commercializing the Day Switch. However, additional development work is required to improve the prototype especially in the area of commissioning. The LRC, through Rensselaer Polytechnic Institute, is patenting the Day Switch and applying for a trade mark for the name "Day Switch".

7. The preliminary human satisfaction testing was a valuable addition to this project. Additional testing of this type should be accomplished to establish the best set points for on and off operations of the switch.

The switching concept proposed for this project was demonstrated to be feasible. The researcher developed a photo sensor costing less than $8 in parts. The developed switch proved to be easy to install and performed as expected in turning on and off a lighting array in response to varying light levels from 1 to 12,000 lux. The payback times are anticipated to be less than 3 years. Long term reliability is of the components, especially in extreme temperature situations (0 to 70 degrees C) remains unknown.

2.7.5 Recommendations

1. The PA recommends additional assessment of the technology to determine if costs can be further reduced and the calibration process simplified.
2. The PA recommends that a more thorough experiment be conducted to determine occupant acceptance levels of on/off switching at different delighting set points. This study should include the impact on uniformity of light levels with some of the light fixtures on and others off, and occupant acceptance of switching only some of the lights off while others remain on.
3. A review should be conducted of the software that predicts the contribution of light from neighboring light fixtures and test against actual lighting conditions. Testing of this software will identify the possibility of adjacent electric lights affecting the on/off cycling of nearby fixtures.
4. Testing should be done that verifies the actual lifetime of the switch when cycled through numerous switching cycles. This testing should include extreme temperatures and its effect on the life of the switch components.
5. Conduct a full-scale demonstration of the technology and evaluate energy savings and occupant acceptance.

6. A full economic analysis should be performed that includes the time value of money. This study should include time-of-use electricity pricing since all businesses will be on time-of-use meters in a few years.
7. The researcher is encouraged to continue working with a manufacturer to commercialize the product. Working with that manufacturer, the researcher should develop a marketing plan with market penetration rates.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for follow on funding within the PIER program. The researcher reported the receipt of a grant of almost $200,000 from NYSERDA to further the development of this switch. Any additional funds from the PIER program need to be coordinated with the New York funded program.

Receiving follow on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is in the increased affordability of electricity in California. When Day Switches are installed in new construction and in retrofit situations, the electrical savings for an open plan office setting could be as high as 15 percent compared with non-automated lighting systems. Based on 15 percent savings, the square footage of available non-residential building space and new construction estimates, the researcher estimated this technology has the potential to save 120 million kilowatt hours per year within California with full market penetration. Assuming $.10 per kwhr, the economic savings could be as high as $12 million annually. The reduction in peak electric demand is as important as the energy savings. Since peak electric demand usually occurs in on sunny days, the developed switch would limit lighting use during that peak period. The reduction in peak electric demand for California could be as high as 158 megawatts. Market penetration of "add-on" switches can be slow in commercial buildings due to several factors. Many, if not most, commercial buildings are leased. Since the tenants pay the electric bill, the building owner has no incentive to reduce electricity costs. Tenants have limited incentives to make building improvements except during the move-in period. The PA estimates savings due to this switch to grow at the rate of 5 percent of the available floor space per year. Maximum market penetration may be limited to less than 50 percent of available square feet. Realistically energy savings could be as high as 60 million kilowatt hours per year five years after market introduction. The reduction in peak demand could be as high as 79 MW at the end of the same period. The researcher and his manufacturing partner need to develop a market penetration plan to refine these rough estimates.

2.8 High Efficiency Lanthanide Doped Ceriazirconia Layered Hybrid Electrode for SOFC Generators

Awardee: Intertec Advanced Materials, Inc.

Principal Investigator: Juan Sepulveda

2.8.1 Introduction

Distributed electrical resource (DER) can complement central electric power generation by providing incremental capacity to the utility grid and to end users[15]. End users and electric utilities benefit by avoiding or reducing the cost of transmission and distribution system upgrades. Fuel cells are an attractive power source in DER systems. Fuel cell system capacities for residential, commercial, and light industry applications generally run in the range 5 kW to 250 kW, however multi-megawatt sizes are being considered for base-loaded utility applications[16]. The cells operate by combining externally supplied hydrogen and oxygen to generate electricity. The oxygen can be supplied by air while the hydrogen is either created by some other process or stripped from a hydrogen containing fuel such as methane usually by a separate reforming process. The only effluents from cell operation are water vapor and primarily carbon dioxide from the reforming process. Significantly the fuel cell effluent stream is largely free of major atmospheric pollutants. Of the four leading types of fuel cells, the solid oxide electrolyte fuel cell (SOFC) is attractive because of its very high efficiency and tolerance for impurities in the fuel. SOFC electrical efficiency is order 50 percent at atmospheric pressure and overall energy of efficiency 80 percent with waste heat utilization[17]. Even higher electrical efficiencies are possible with pressurized reactants[3]. However the electrolyte of existing SOFC must be operated at high temperatures near 1000 ^{o}C to have sufficient electrical conductivity. This temperature requires that the metallic interconnects be of expensive chromium alloys. If the electrolyte operating temperature could be reduced to 800 ^{o}C then much less expensive interconnects could be used with significantly lower system cost.

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[15] http://energy.ca.gov/distgen/background/background.html.

[16] http://www.energy.ca.gov/distgen/equipment/fuel_cells/applications.html.

[17] http://www.electricity-today.com/et/june00/fuel2.htm.

Currently the cost of commercial competing type of fuel cell (phosphoric acid electrolyte) is $4000/kW uninstalled and, for a 200kW size unit, is $5500/kW installed[18]. SOFC are less well developed but their long term, uninstalled cost is projected to be in the range $1000-1500/kW uninstalled[19]. The ability to reduce the cost of metallic interconnects would certainly aid in the effort to reduce the cost of SOFC to benefit the ratepayer. It would be likely to reduce operating costs and maintenance costs as well. Another benefit to the ratepayer would be a reduction in atmospheric pollutants per unit output over conventional fossil fuel combustion generators. It is estimated that fuel cells release 50 percent of CO_2 emissions but up to 99 percent less NO_x / SO_x than fossil fuel power plants[20].

The key advancement of science needed to permit the use of less expensive interconnects is the development of a solid oxide electrolyte material that will operate below 800°C. The authors identified a high conductivity material, gadolinium doped ceria (G10DC) that would function at this temperature. It is not, however, stable against reduction at 800°C in the presence of hydrogen. Therefore the author proposed the development of a new hybrid layer structure for the planar electrolyte as shown in Figure 13. In this structure the G10DC electrolyte is sandwiched between two thin layers of scandium stabilized zirconia (S10SZ). The S10SZ conducts well enough at 800°C when thin and, importantly, is impermeable to hydrogen. Layering with S10SZ also improves the mechanical strength of the electrolyte. [During performance of the research the author also studied additional electrolytes of S10SZ alone, and scandia and ceria stabilized zirconia S10C1SZ).] The authors proposed that the porous cathode would consist of lanthanum stabilized manganite (LSM) and S10SZ. The porous anode would be a mixture of NiO (nickel oxide) and S10SZ. Operation at the lower temperature of 800°C rather than the 1000°C of existing technology would permit the use of the lower temperature lower cost metallic interconnects.

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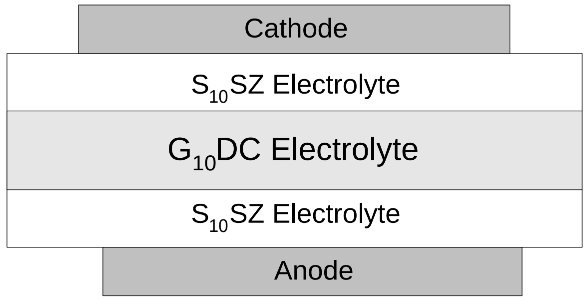
18 http://www.energy.ca.gov/distgen/equipment/fuel_cells/cost.html.

19 http://www.energy.ca.gov/distgen/equipment/fuel_cells/cost.html.

20 http://www.renewables.ca/h.html.

Figure 13: Single-Cell Hybrid Layered Structure



2.8.2 Objectives

The goal of this project was to determine the feasibility of increasing the efficiency of SOFC generators by unique design and application of ceria to zirconia to form an improved solid electrolyte.

The researchers established the following project objectives:

OBJ. 1. Define Workplan.

OBJ. 2. Define formulations and measure properties, analyze microstructure, and define preliminary process.

OBJ. 3. Fabricate Electrolyte

OBJ. 3.1. Develop electrolyte slurry preparation to 5000-7000 cp.

OBJ. 3.2. Develop tape casting and lamination to produce 200 μm thick green electrolyte.

OBJ. 3.3. Develop firing cycle to produce 94 percent dense electrolyte, 140 μm thick fired.

OBJ. 4. Fabricate Electrodes.

OBJ. 4.1. Fabricate anode to 60 percent of theoretical density.

OBJ. 4.2. Fabricate cathode to 60 percent of theoretical density.

OBJ. 4.3. Produce electrode flatness better than 0.003 cm/cm.

OBJ. 5. Manufacture test cells and measure

OBJ. 5.1. Measure ionic conductivity of at least 0.1 S/cm at 800°C.

OBJ. 5.2. Measure *V-I* curves.

OBJ. 5.3. Achieve cell-stack efficiency of better than 35 percent at 800°C (no co-generation).

OBJ. 5.4. Show that the projected 20 percent increase in SOFC life continues to be supported by project data.

OBJ. 6. Analyze Manufacturing Cost.

OBJ. 6.1. Show that the target cost of $85-90/kw for cell stack can be realized**.**

OBJ. 7. Conduct Life Cycle Cost Analysis.

OBJ. 7.1. Show that the projected life cycle cost of $0.039/kWh from a SOFC that incorporated the proposed technology continues to be supported by project data.

2.8.3 Outcomes

OBJ. 1. This objective was met. A project workplan was prepared with a Gantt chart listing timelines and milestones.

OBJ. 2. This objective was met. Formulations of different mixed oxide electrolyte and electrode compositions were defined. Rheology and sinterability of starting slurries and mechanical properties of fired sample were studied. Microstructure was analyzed using the scanning electron microscope (SEM). Mixing, casting, firing, and electrode coating/firing conditions were defined.

OBJ. 3. In most respects **t**his objective was met. The electrolyte fabrication process was developed and defined.

OBJ. 3.1. This objective was met and later modified. Slurry viscosity was intentionally kept in the range 3000 – 5000 cp rather than 5000 – 7000 cp because it was found to work better. Slurry properties were measured and reported.

OBJ. 3.2. This objective was substantially met. Tape casting and lamination techniques were developed which yielded green tapes in the thickness range from 100 – 190 ◎ with one additional tape listed with thickness 1070◎◎. Laminated tapes of overall thickness 268 and 371 ◎ are reported.

OBJ. 3.3. This objective as stated was met in that a firing cycle was developed which produced zirconia based electrolytes of nearly 100 percent theoretical density. It was very significant, however, that a co-fired layered electrolyte showed 2-4 percent porosity and mechanically failed. Fired electrolytes $S_{10}SZ$-$G_{10}DC$-$S_{10}SC$ of thickness 60-85-60 μ or 60-170-60 μ and about 2" diameter were produced for electrochemical testing. Shrinkage, flatness, fired thickness were measured. Microstructure was analyzed through SEM.

OBJ. 4. This objective was met.

OBJ. 4.1. This objective was met. Anode density of 60 percent of theoretical was achieved.

OBJ. 4.2. This objective was met. A cathode density of 60 percent of theoretical was achieved.

OBJ. 4.3. This objective was met. Flatness 0.002-0.003 cm/cm was achieved in a variety of samples.

OBJ. 5. This objective was partly met in that test cells were manufactured but not all proposed measurements were performed.

OBJ. 5.1. This objective was not achieved. An electrolyte conductivity of 0.0763 S/cm was achieved for $S_{10}SZ$ at 850°C, but not 0.1 S/cm at 800°C.

OBJ. 5.2. This objective was met in the sense that *V-I* curves were measured for Y_8SZ and $S_{10}SZ$ samples, but not G10DC as proposed.

OBJ. 5.3. Significantly, this objective was not met. The project did not measure cell-stack efficiencies because of problems of mechanical integrity in the test cells.

OBJ. 5.4. This objective was not met. A lack of project data precluded the determination.

OBJ. 6. This objective was partly met in that manufacturing costs were analyzed**.**

OBJ. 6.1. This objective was not met. The manufacturing cost analysis for the cell stack was done but the target cost of $85-90/kW was not achieved for the type of cell developed in this project. The higher cost of $2,250/kW of cell stack was estimated for the SOFC developed in this project.

OBJ. 7. The objective was partly met. A life cycle cost analysis was conducted.

OBJ. 7.1. It was not possible to meet this objective due to the lack of data on working fuel cells. The life cycle cost analysis that was performed was based on estimates. These considerations resulted in a 20 percent reduction in operating cost resulting and an estimated electricity cost of $0.035/kWh. Similarly it was estimated that operating at 800°C will result in a 100 percent longer life cycle of 40,000 hr.

2.8.4 Conclusions

- Oxide formulations were defined and measured, preliminary process parameters defined
- G10DC based electrolytes were prepared but were found to be not mechanically robust
- Electrode fabrication was successful
- Test cells were manufactured but cell efficiency was not measured
- Only a theoretical manufacturing cost was carried out
- Life cycle cost analysis was performed

It is concluded that a sound, well thought out research program was implemented in the preparation of electrolytes and electrodes. Sound laboratory practices in the execution of the program were carried out and a considerable amount of research was performed. Good use of existing technology for SOFCs employing YSZ electrolytes operating at 1000°C was made, both by analysis of the literature and by actual sample fabrication and measurement. However the chief goal of proving feasibility of a new electrolyte operating at 800°C was not proven.

2.8.5 Recommendations

I have doubts about it being possible to accomplish their fundamental goal of oxide encapsulation of G10DC to isolate it from hydrogen gas at 800°C. I think the large temperature excursions from room temperature to operation temperature will inevitably lead to cracking and the reduction of Ce^{4+} to Ce^{3+} by hydrogen. If some means could be found to produce a self-healing coating, in loose analogy with the self-healing properties of Cr containing alloys in oxidizing atmospheres, then I would be more optimistic. In the absence of that, I think their approach of using a different high conductivity low temperature electrolyte such as S10SZ based alloys has a greater chance of success.

Benefits to California

Required introductory text Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply or transmission or distribution system. The proposed improved fuel cell technology offers many potential advantages such as reduced emissions, higher efficiency, elimination of transmission losses, co-generation capability and enhanced grid reliability. It could provide the additional needed electrical power for a centralized facility or distributed generation facilities as well as providing an alternative energy source for isolated communities or towns, large size industrial facilities, educational facilities as universities and colleges, government facilities, defense facilities, etc.

2.9 Innovative Wheel Concept to Increase Gas Turbine Efficiency

Awardee: Markron Technologies LLC

Principal Investigator: Ron Kincaid

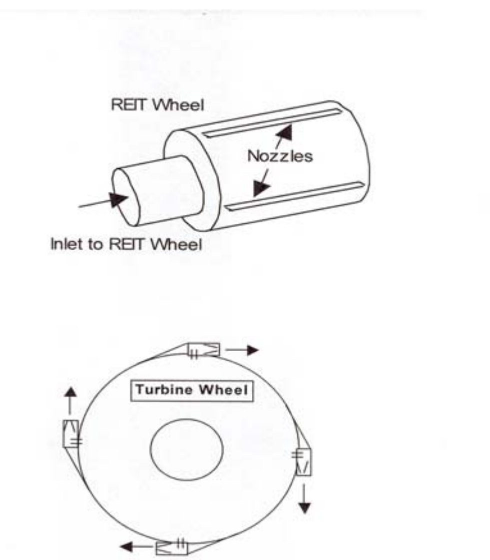
2.9.1 Introduction

Distributed generation is one of the policy priorities at the California Energy Commission. Very low emissions should give small gas turbine engines and microturbines a key role in providing distributed generation. They also have significant advantages in applications that combine heat and power. Unfortunately, the thermal efficiency of most small units is far less than that of central power plants and less than most reciprocating engines. Even with exhaust heat recuperation, microturbines convert only about 30 percent of the energy in fuel to electricity and about 70 percent when hot exhaust gasses are put to use. (By comparison, reciprocating engines convert 33 percent to 40 percent of the fuel to electricity when operating on natural gas.) While heat recovery equipment can exploit the energy in hot exhaust gasses, most applications require more electricity and less thermal energy. In addition, electricity has a higher economic value than thermal energy. Advances in thermal efficiency could increase the use of these engines in applications that require higher ratios of electricity to thermal energy.

More efficient electric conversion would allow greater use of microturbines in California. In many areas of California the requirement for (thermally driven) heating and cooling is low during much of the year. Producing more electricity without increasing the size of the engine would help satisfy customers’ needs and reduce the demands on the electric grid. In this project the researcher proposed a turbine wheel that he predicted would boost overall engine efficiency by 30 percent when compared to engines of similar size operating at similar conditions.   If he had achieved this improvement, microturbine efficiency would have risen to nearly 40 percent. An engine that combined heat recovery with 40 percent thermal efficiency would speed the deployment of distributed microturbines in California.

The researcher proposed to eliminate turbine-wheel losses by replacing the conventional radial turbine expander with an external-impulse turbine wheel (Figure 14). The researcher claimed two advantages to his design. First, it would convert kinetic energy losses associated with a radial or axial turbine expander into usable shaft energy. The researcher suggested that the impulse turbine would extract useful work from the kinetic energy of the nozzle, without significant exit losses and other moving blade losses. Second, the new turbine design could operate at a lower pressure ratio, facilitating higher recuperator effectiveness. The researcher expected both advantages to lead to higher engine efficiency.

Figure 14: Proposed Recuperator External Impulse Turbine (REIT)



2.9.2 Objectives

The goal of this project was to determine the feasibility of a bladeless turbine wheel to increase the efficiency of small gas turbine engines. Nozzles on the periphery of the wheel provide the motive power. The researchers established the following project objectives:

1. Complete design of a nozzle assembly for a turbine wheel with one or more nozzle(s) and an approximate air-flow of 275 lbs/hr.

2. Design wheel to achieve windage loss no greater than 2 percent and internal flow losses no greater than 1.5 percent (with compression factor compensation.)
3. Design and construct test rig for turbine wheel. Rig to sustain operation for 10 hours at full load at 1000° F.
4. Test wheel to ensure mechanical integrity and demonstrate wheel and exit losses <7 percent.
5. Demonstrate overall system efficiency of 40 percent or greater at turbine inlet temperatures of 1700° F for a wheel sized to a 50kW gas turbine engine.
6. Show, from project data, projected life-cycle cost of $0.05/kWh for a 50 kW gas turbine engine incorporating the bladeless turbine wheel.

2.9.3 Outcomes

1. The researcher completed final drawings of the wheel and test rig.
2. The researcher hired Inventive Turbomachinery Consultants to estimate thermodynamic efficiency. The consultants found the researcher's estimate of turbine wheel efficiency to be incorrect by a factor of two. This large error was due to viewing the output of the wheel at rest (laboratory frame of reference) rather than spinning. The proposed wheel displayed no advantage over conventional wheels in a new estimate using the correct efficiency number.
3. The test rig was built.
4. After the researcher received the calculations from Inventive Turbomachinery Consultants he decided not to fabricate a wheel. The project stopped at this point.
5. The wheel was neither built nor demonstrated
6. The researcher collected no data allowing him to project energy costs.

2.9.4 Conclusions

The proposed wheel does not offer the advantages of increased thermodynamic efficiency as proposed by the researcher. This conclusion is based on the work of Inventive Turbomachinery Consultants. This wheel design will not produce additional energy over a conventional turbine wheel. Therefore, feasibility was not demonstrated.

1. The designs of the wheel and rig were completed prior to detailed analysis.
2. The researcher wisely sought outside counsel to validate the design calculations. The outside consultants found the fatal error in the original calculations. After correction of the error, the proposed wheel showed no advantage over conventional wheels.
3. Unfortunately, the researcher built the test rig in parallel with the analytical work to verify the performance of the wheel.
4. The turbine wheel was neither built nor tested. No conclusions can be drawn
5. Since the wheel was not tested, its performance remains unknown.
6. Similarly, no data was gathered regarding the cost of energy produced by such a design.

2.9.5 Recommendations

Based on the calculations performed by the outside consultant, the Program Administrator recommends, as does the researcher of this project, that no further funds be spent advancing the bladeless turbine wheel concept evaluated in this project.

Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research would have been increased affordability of electricity in California. A more efficient turbine wheel for gas turbine engines under 5 MW would have increased efficiency from the low 20 percent range for unrecuperated micro-turbines and the low 30 percent range for small industrial turbines to over 40 percent. Small gas turbine engines with high efficiency and ultra-low emissions could have stimulated the installation of a greater number of distributed resources. The distributed gas turbines would have provided both excellent thermal efficiency and added reliability and security to the electrical distribution system. Unfortunately, this project was not successful. This makes any estimate of future benefits impossible.

2.10 Innovative Injection-Molded Plastic Package for High-Concentration PV Cells

Awardee: Amonix, Inc.

Principal Investigator: Kenneth Stone

2.10.1 Introduction

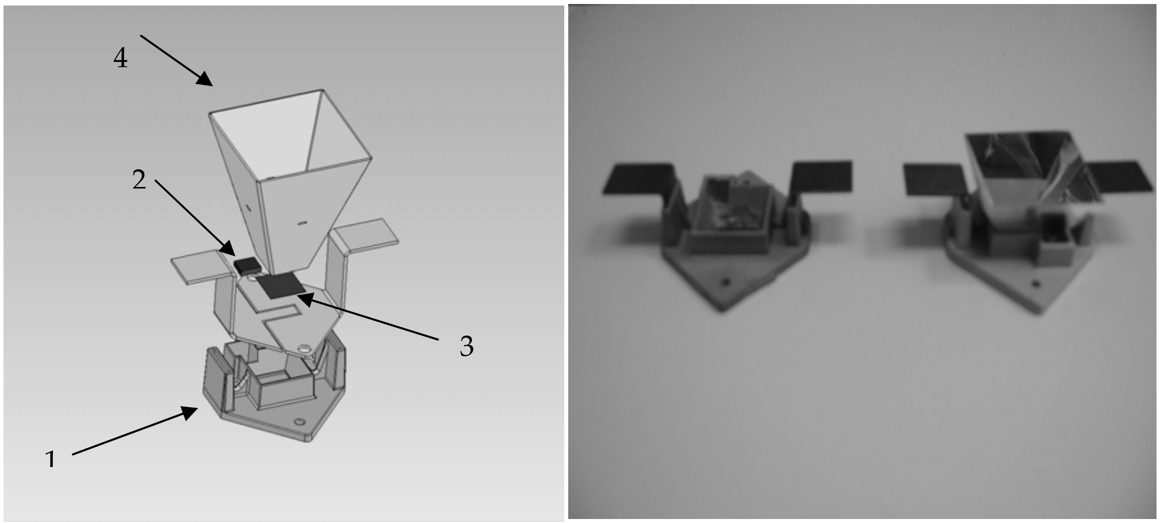
Expanded use of photovoltaics for electricity generation is an important policy goal of the Commission and Governor Schwarzenegger. Photovoltaics provide power consistent with California summer peaking requirements. Photovoltaics produce electricity with no air pollutant emissions during their operation. The California Public Utilities Commission has announced an ambitious program to have 3000 MW of photovoltaics installed by 2017[21]. Unfortunately, photovoltaics remain one of the highest cost generation alternatives. Most of the cost for photovoltaics is in the cost of the cells themselves, with the remainder in the cost of modules and balance of system. Reducing the cost of cells is a primary avenue for reducing the cost of photovoltaics and leading to competitive pricing.

One way to reduce the cost of cells within photovoltaic modules is by using less cell material. Amonix and others have developed several approaches that use less cell material, reducing the area of cells and maintain cell output by concentrating the sun on the cells through a system of lens. These systems are referred to as "high concentration photovoltaics" (HCPV.) Arizona Public Service (APS) has been jointly demonstrating HCPV with Amonix since 2001. Other utilities, including California utilities, have been active in the development and demonstration of HCPV through EPRI. Using HCPV technology can reduce the use of high cost cell material by 500 to 1000 times compared to conventional PV technology.

Amonix has proposed a novel way to manufacture HCPV while ensuring the cells and modules can withstand the high temperatures inherent in HCPV due to the concentration of sunlight. The approach includes use of a new material, CoolPoly™ that serves to transfer heat away from the cell and forms the support substrate for the cell, and provides electric isolation. The approach also promises to reduce overall parts and materials requirements, and simpler design that should lead to reduced system costs while maintaining or improving performance and efficiency. Figure 15 illustrates the concept.

[21] http://www.cpuc.ca.gov/PUBLISHED/NEWS_RELEASE/52745.htm

Figure 15 Simplified HCVP Design



1. Plastic substrate component with the electrical circuit molded into it.
2. Electric diode
3. Solar cell
4. Fresnel lens and secondary optical (focusing) element

2.10.2 Objectives

The goal of this project was to determine the feasibility of using a unique injection molded material to produce a lower cost and higher performance cell package for concentrated PV systems. The researchers established the following project objectives:

1. Design a cell package with fewer parts, lower material cost, and reduced manufacturing processes compared to other HCPV designs.
2. Demonstrate the feasibility of being mass-produced.
3. Fabricate 50 cell packages.
4. Demonstrate the cell package is capable of surviving up to 800X sun concentration.
5. Demonstrate a 20 degree C reduction in cell operating temperature.
6. Demonstrate the package meets the electrical and environmental requirements.
7. Confirm cell package cost reduction.

2.10.3 Outcomes

The project completed the design and testing of two cell package designs that met the manufacturing and operating requirements.

1. The researcher reduced the parts count by 50 percent for one concept and number of required manufacturing process steps by 50 percent for both concepts. The parts count for

concept one was five, compared to the baseline of eleven. Manufacturing process steps were eight for concept 1 and nine for concept 2, compared to the baseline of nineteen.

2. The researcher fabricated cell packages with a belt furnace. A belt furnace is required for mass production. Both concept 1 and 2 also provide mass production advantage compared to the baseline concept, due to the elimination of a UV coating that requires frequent rework. Reduced process steps also facilitate mass production.
3. Fifty cell packages were fabricated. The desired 7 to 10 mil thickness of the bottom of the cell package was not achieved with the initial mold. The mold was modified from a bottom thickness of 10 mils to 50 mils.
4. The cell packages survived sun concentrations of 800X, equivalent to 80 W/cm^2 solar flux.
5. Design concept #1 had a 7.5 degree C reduction in cell temperature and concept #2 achieved a 15.4 degree reduction in the cell operating temperature, relative to the side-by-side comparison to the baseline cell design. All cell temperatures were measured on a relative basis, as actual temperatures vary depending on ambient temperatures and wind speed.
6. The current IEEE standard specifies a breakdown voltage of 2000 V dc and a water submersion test. The cell packages for both concept #1 and concept #2 were tested to confirm they satisfy the breakdown voltage of 2000 V dc, water submersion test, and an electrical isolation test.
7. A 68 percent reduction in the cell package cost per watt was achieved. The cost function (cost/power) for the baseline design of $1.92 per watt was reduced to $0.41 per watt for concept #1 and to $0.48 per watt for concept #2.

The baseline unit in all of the comparisons is the current Amonix commercial, high concentration PV system. The current commercially available system is being field tested at Arizona Public Service and other locations.

2.10.4 Conclusions

The work in this grant confirmed the feasibility of the proposed materials and design concepts. The cell temperature reductions compared to the baseline designs did not meet project objectives. Reduced materials and simplicity of manufacture confirmed expected system cost reduction. Material cost estimates for one concept is 68 percent less than the cost for the baseline design and 64 percent less for the second concept. The overall cost function, as measured by $/W increased by a factor of 4.24 (or the cost was reduced by that amount.) Because of the lower operating temperature, the power performance would increase for both design concepts compared to the baseline design, but this should be verified in actual performance testing.

2.10.5 Recommendations

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for follow on funding within the PIER program.

Receiving follow on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Actual cell performance, as measured by electrical output should be verified in actual field-testing. Further work should attempt to increase the cell temperature reduction, and to determine thermal cycling behavior of the electrical connections and structural system. Further reduction in cell temperature should be investigated by increasing the heat sink area, different design of the heat sink, and/or the use of thermal grease or thermal film material. In addition, the PA recommends that additional mold design efforts be undertaken to fabricate a cell package base with a thinner bottom and mold multiple cell package components at the same time. Manufacturing replicability should be verified by the manufacture of 200-300 cell packages and verification of the manufacturing process with performance verification by in-situ testing.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply and transmission system at lower cost. Secondary benefits include enhanced public safety and supply security. Public safety would be enhanced due to the reduced amount of cell materials needed for a given amount of photovoltaic generation capacity.[22] Supply security would be enhanced for similar reasons because the supply of

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[22] As described in *Potential Health and Environmental Impacts Associated With the Manufacture and Use of Photovoltaic Cells,* November 2003, EPRI, Palo Alto, CA, and California Energy Commission, Sacramento, CA: 1000095, the manufacture of PV cells has potential public safety risks.

photovoltaic cells has been constrained, in part, because of the shortage of necessary cell material.[23]

The further development and deployment of this technology could benefit California rate-payers by reducing the cost to meet peaking power requirements. On a typical hot summer California day, the amount of energy supplied on peak is approximately 9,000 MWh per day or approximately 337,500 MWh annually. The cost of on- peak energy in 2005 is an average of 29.1 cents per kWh. With the cost reduction provided by the new HCPV cell package, an estimated levelized energy cost for the Amonix system is approximately 13 cents per kWh. Using an avoided cost of $0.29/kWh and an annual demand of 337,500 MWh, the HCPV system could save the California rate-payer $57 million per year, if used to satisfy all peak demand.

2.11 Biomass-to-Syngas, Novel Low-Cost Counter-Current Process

Awardee: Taylor Energy LLC

Principal Investigator: Donald Taylor

2.11.1 Introduction

More than 31 million tons of organic material, including paper, wood, and urban green waste, were disposed of in California landfills in 2003.[24] Thermal conversion of organic waste is an attractive alternative to disposal in landfills and could generate electricity and/or renewable fuels for transportation, while avoiding the equivalent use of oil, coal, and natural gas. The 85,000 tons/day of organic feedstock are enough to produce approximately 4,000 MW of electricity. The dollar-value of these California feedstocks, if converted into electricity valued at $0.05/kWh, would equal $200,000 dollars per hour, or $1.6 billion dollars per year. Five cents per kWh is the value of generation portion of the retail price of electricity of approximately $0.13/kWh. At the present time there are few cost effective thermo-chemical conversion technologies available to fill this California market need.

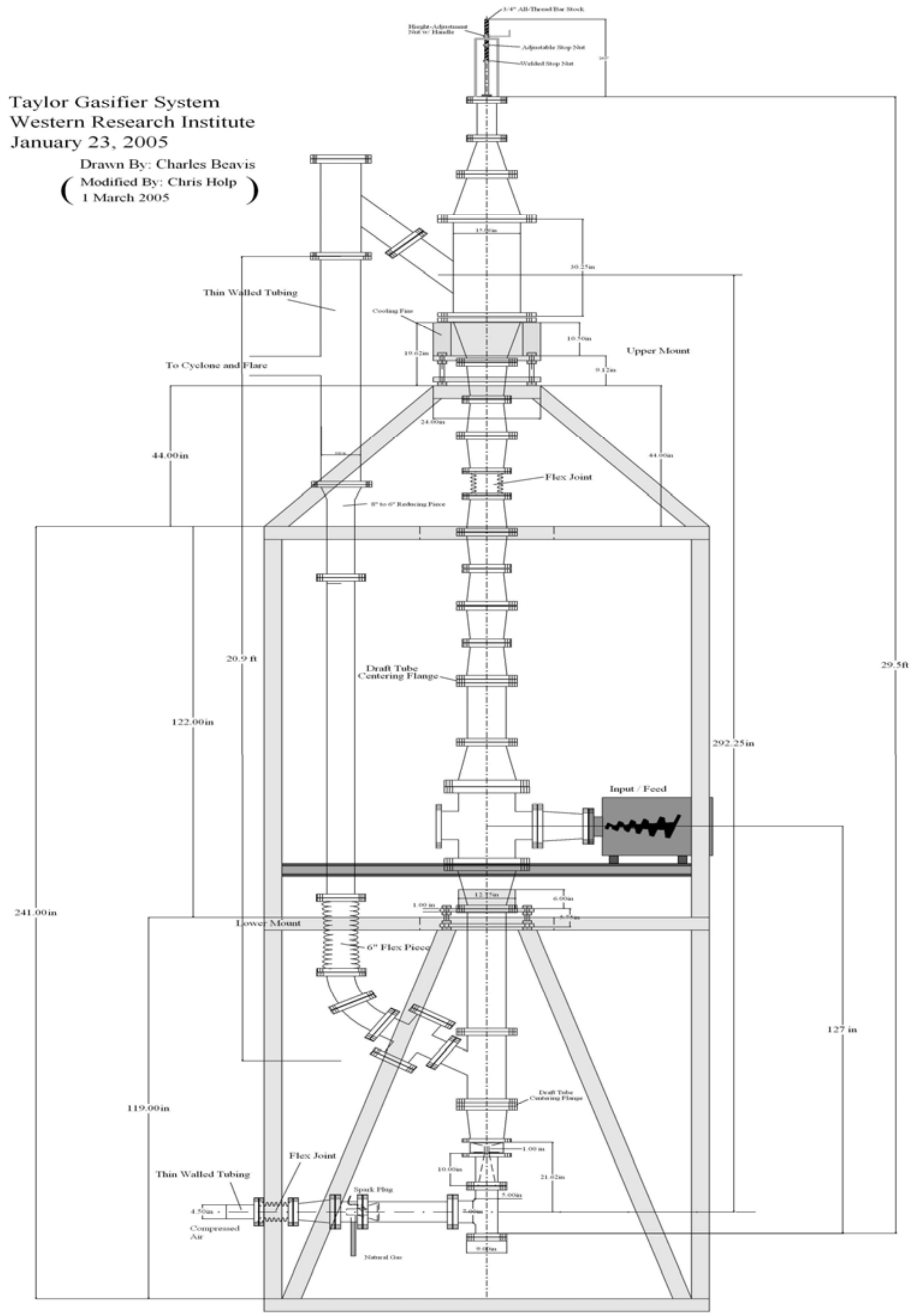
Rate payers would benefit significantly from the use of biomass energy resources produced in California. The first benefit is the production of energy products within the State of California. These products would add diversity to the source of energy for ratepayers and thus provide greater energy reliability. The second benefit is the reduction in material deposited in landfills. This will extend the life of existing landfills and possibly reduce the quantities of landfill off-gases escaping into the environment. Major portions of landfill gases are considered to be greenhouse gases. Another potential benefit from gasification technology is the ability to convert difficult-to-handle solid fuels into clean gaseous fuel that can then be burned in traditional prime movers, including large internal combustion engines and gas turbines; in emerging technologies such as solid oxide fuel cells (SOFC); or in production of liquid fuels.

[23] Tara Godvin "Rise of solar energy puts squeeze on silicon supplies" The Associated Press - Feb 17, 2006 Honolulu.

[24] http://www.ciwmb.ca.gov/Profiles/Statewide/SWProfile1.asp

Taylor Energy LLC proposed a novel gasification method for organic materials. Its major advantage would be the capability of producing synthesis gas from organic materials without using manufactured oxygen (made by consuming electricity). As shown in Figure 16, the proposed gasification reactor vessel was constructed of off-the shelf pre-flanged ductile iron components. The proposed gasification system had the potential to have lower capital cost compared to other gasification technologies.

Figure 16: Cross Section of Proposed Gasifier, Illustration Flanged Components Construction Approach



2.11.3 Objectives

The goal of this project was to prove the feasibility of a novel biomass-to-syngas process specifically designed for low-cost conversion of biomass into high-quality syngas suitable for solid oxide fuel cell (SOFC) power generation. The principal investigator established the following project objectives:

1. Produce syngas from 3 different feedstocks in a 1 MMBTU/hr test reactor with:
   a. 5-10% N_2 content
   b. <1% O_2
   c. 1-5% CH_4
   d. Energy Content of 200-350 BTU/scf
   e. Quality of 12.0 or higher ((H2 +CO)/ (CO_2+H_2O))

   The product gases were assumed to be filtered at atmospheric temperature in commercial application, and therefore tars, particulate, and alkali metals were not considered problematic and were not identified in the performance criteria.
2. Verify thermal conversion efficiency for biomass to syngas of 50 percent, with total conversion to electricity efficiency of 30 percent.
3. Extrapolate bench scale data to the farm scale and confirm projected system conversion efficiency of 70 percent (biomass-to-syngas) with total conversion to electricity of 42 percent.
4. Demonstrate projected cost of 3-5 cents/kWh and total capital cost of $18k/ (ton/day) for farm scale units.

2.11.4 Outcomes

1. The researcher tested chopped-straw in a 1 MMBTU/hr test-reactor at a rate of 3 ton/day with the following results:
   a. >50% N_2 content
   b. <2% O_2
   c. 1-5% CH_4
   d. Energy Content = 110-120 BTU/scf
   e. Syngas quality was not calculated, nor was the conversion efficiency.
2. The researcher did not demonstrate thermal conversion efficiency of 50 percent for biomass-to-syngas, nor total conversion to electricity of 30 percent efficiency. The researcher did not measure biomass-to-syngas conversion efficiency.

3. The researcher designed a farm-scale Process Development Unit (PDU—6 ton/day, 300 kW electric), and he produced simple CAD drawings. The PDU was designed for continuous operation and long-term life cycle projections. The researcher did not project conversion efficiency.

4. The projected cost for small-scale gasification equipment approached the performance objective of $18k/ton/day feed capacity; therefore, the researcher expected scaling the equipment to 50 ton/day (2 MW_e output) to be economically feasible, based on cost quotations for 6 ton/day PDU. The researcher estimated an electricity cost of $0.05/kWh if the biomass feedstock cost is zero.

5. The researcher determined performance parameters for the circulation system. Each of six bed materials were circulated effectively in the test-reactor at temperatures above 1200° F, with circulation rates exceeding 4 pounds per second when compressed air input was 150 scfm.

6. The researcher successfully demonstrated a novel, low-cost reactor construction method, using off-the-shelf flanged cast-iron spool-sections that bolt together. Tests proved heavy duty, ductile-iron pipe sections useful for high temperature applications at temperatures under 1350o F and atmospheric pressures.

2.11.5 Conclusions

This project did not establish the preliminary feasibility of the novel gasification reactor concept proposed.

1. The syngas product is neither useable in solid oxide fuel cells, nor in many traditional internal combustion engines nor turbines. It would require extensive cleanup and further processing to be feedstock for most liquid fuel production, including the Fischer Tropsch process. The high nitrogen content of the syngas could lead to high NO_X emissions. In addition, fuels with extremely low energy content are difficult, if not impossible, to burn in standard combustion systems.
2. Thermal conversion efficiency of 50 percent for biomass-to-syngas, with total conversion to electricity with 30 percent efficiency was not achieved. Low conversion efficiencies usually lead to larger, more expensive energy systems. Thus, very low conversion efficiency will likely offset any potential capital cost savings.
3. The researcher designed the PDU for continuous operation and long-term life cycle projections. Because the researcher did not calculate conversion efficiency it is difficult to determine the value of this unit.
4. While the researcher's projected cost numbers are near his goal, he may not have considered the effects of low conversion efficiency and high fuel nitrogen content.
5. The researcher successfully demonstrated effective bed circulation rates at temperatures up to 1350° F. The researcher demonstrated circulation rates of 4 pounds per second with air input of 150 scfm. Good circulation rates at elevated temperatures are important performance features necessary to avoid blocking the fuel circulation (for example, from

slagging or melting bed materials into large lumps) and to maintain gasification thermal profiles within the reactor.

6. The test did not demonstrate if the ductile iron would be effective in real-world gasification applications with higher gasifying atmospheres.

The tests conducted did not demonstrate the feasibility of the concept to lower the cost of gasification technologies for integration with solid-oxide fuel cells. Its feasibility for other power generation technologies, such as internal combustion or turbine based systems is questionable. The fabrication approach of using pre-fabricated spool sections shows promise to reduce costs, but the use of ductile iron in hot sections under conditions of gasifying atmospheres is questionable.

2.11.5 Recommendations

The researcher should monitor and document performance of the PDU with respect to conversion efficiency. Operating conditions that affect conversion efficiency should be determined and operating conditions that maximize conversion efficiency should be validated. The researcher should also determine performance with bed recirculation to determine ability to reduce char. The researcher should investigate techniques to reduce nitrogen in the produced syn-gas. Further research and development, if otherwise warranted, should include evaluating pre-fabricated spools composed of materials other than ductile iron, and tested in conjunction with gasifying atmospheres with appropriate gas clean-up. Such tests should, at minimum determine carry-through of tars, particulate, and alkali metals; gas product quality; and biomass to syngas conversion efficiency.

Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. This benefit would result from increased diversification of fuels used in generation of electricity and by making use of otherwise waste materials. In addition to increased affordability, this project should benefit California ratepayers by reducing the environmental impacts of electricity supply system, by the use of non-fossil fuels. This project also furthers the advancement of science technology by demonstrating greater cost reduction that can be achieved through innovative construction approaches, especially the use of pre-fabricated gasifier sections.

2.12 New Membranes based on Ionic Liquids for High Temperature PEM Fuel Cells

Awardee: Rutgers University

Principal Investigator: Jun John Xu

2.12.1 Introduction

Proton exchange membrane (PEM) fuel cells are considered a promising technology for stationary, distributed, power generation, in addition to their leading role among fuel cell technologies for transportation applications. State-of-the-art PEM fuel cells operate around 80°C. PEM systems are complex, requiring very high purity of hydrogen, complicated water and waste heat management, and relatively high platinum catalyst loading. However, PEM fuel cells operated at higher temperature ranges (120 to 150 °C) should yield significant cost and efficiency benefits, including: simpler heat and water management, improved catalysts' tolerance of impurities and higher power and higher energy efficiency of fuel cells from enhanced electrode kinetics.

The temperature limitation of current PEM fuel cell systems mainly results from the use of water in the PEM. Thus, the development of PEM fuel cells that can operate at higher temperature is widely considered as one of crucial paths to progress of PEM fuel cell technology. Despite the extensive recent efforts on high-temperature membranes, none of the membranes tested so far meets the requirements for operation of PEM fuel cells up to 150 °C.

In this project, a new type of membrane using gel-based ionic (anhydrous) liquids, acid and polymers was synthesized and characterized for PEM fuel cell use. The researcher measured thermal and electrochemical properties to determine whether the [acid/ionic liquid/polymer] composite could operate at 150 °C regardless of relative humidity. The proton transport mechanism, a fundamental property for fuel cells, of the membrane was analyzed using nuclear magnetic resonance (NMR) spectroscopy techniques.

2.12.2 Objectives

The goal of this project was to determine the feasibility of improving the performance, cost, and durability of high temperature PEM fuel cells using membranes of ionic liquid based gels. The researchers established the following objectives:

1. Verify the feasibility of the concept of [acid/ionic liquid/polymer] composite membranes for anhydrous proton conduction to enable operation of PEM fuel cells at 150 °C.

2. Screen or synthesize ionic liquids, acid and polymers that are thermally stable at elevated temperature and compatible with one another.
3. Prepare [acid/ionic liquid/polymer] composite gel-type proton-conducting membranes.
4. Determine if the prepared [acid/ionic liquid/polymer] composite can operate at 150°C regardless of relative humidity.
5. Determine whether the prepared [acid/ionic liquid/polymer] composite is thermally, chemically and electrochemically stable for H_2/O_2 fuel cell operation at 150 °C.
6. Determine whether the prepared [acid/ionic liquid/polymer] composite is stable against dissolution by water vapor.
7. Measure and analyze the proton transport mechanism.
8. Conduct a manufacturing cost analysis to confirm from the research findings that the projected cost of the new membranes of less than $100/m^2 continues to be supported.
9. Fabricate membrane-electrode-assemblies (MEA) and carry out fuel cell tests at 150 °C. The associated performance objective is that H_2/O_2 fuel cells based on the MEA will achieve current density of 0.25 A/cm^2 at 0.7 V at 150 °C. These performance parameters are superior to those of the state-of-the-art PEM fuel cell technologies.

2.12.3 Outcomes

1. The research did not result in a viable membrane. The majority of proposed polymer-ionic liquid combinations were found not viable due to either poor thermal stability of the polymer or to incompatibility of the ionic liquid and polymer.

2. Hydrophobic ionic liquids (EMITFSI, BMMITFSI), proton transfer ionic liquids ($PMIH_2PO_4$) and thermal engineering polymer (PBI) were successfully synthesized in the lab, while other ionic liquids and acids were obtained commercially. Ionic liquid $PMIH_2PO_4$ is very compatible with H_3PO_4 and PBI. Both synthesized $PMIH_2PO_4$ and PBI had demonstrated thermal stability up to 250 °C when tested in the isolated form.

3. The researchers prepared $H_3PO_4/PMIH_2PO_4$/PBI membranes with good mechanical properties. Acid/ionic liquid/polymer membranes based on the H_3PO_4 acid or HTFSI acid, EMITFSI, BMMITFSI or EMITF ionic liquid, and the PVDF-HFP polymer were fabricated. All membranes were homogeneous, freestanding and flexible with compact texture and sufficient mechanical strength. The researchers measured ionic conductivity of 1.0×10^{-3} ~ 2.0×10^{-3} S/cm at 150 °C under anhydrous condition, but found the membrane failed at temperatures above 120 °C.

4. The researchers found that H_3PO_4 acid and/or hydrophilic ionic liquid $PMIH_2PO_4$ was washed away from the substrate by hot water.

5. The researchers describe a three-dimensional hydrogen bonding network inside of the $H_3PO_4/PMIH_2PO_4$/PBI membranes based on their NMR spectroscopy. They conclude that proton conduction would occur mainly through the hydrogen bonding network by a "hopping mechanism."

6. The researchers collected data on the costs of various components for manufacturing the

membranes. The researchers neither reported the cost data nor completed a manufacturing cost analysis.

7. The researchers did not fabricate nor test membrane-electrode assemblies (MEA) using the new gel.

2.12.4 Conclusions

The research did not prove feasibility of a viable high temperature membrane with adequate proton conductivity and thermal and electrochemical stability. The proposed polymer-ionic liquid combinations are not viable due to either poor thermal stability of the polymer or to incompatibility of the ionic liquid and polymer, or both. Novel H_3PO_4/$PMIH_2PO_4$/PBI composite gel-type proton-conducting membranes were prepared using lab synthesized polybenzimidazole (PBI) and ionic liquid, $PMIH_2PO_4$. The investigated H_3PO_4/$PMIH_2PO_4$/PBI membranes are homogeneous, flexible, freestanding and with good thermal stability and wide temperature range of single-phase behavior. The membranes have acceptable ionic conductivity of 1.0×10^{-3} ~ 2.0×10^{-3} S/cm at 150 °C and under anhydrous condition. However, the researchers did not reach the goal of proton conductivity exceeding 0.1 S/cm at 150 °C.

2.12.5 Recommendations

The researchers should continue developing the membranes to further enhance the properties of the membranes. Long term stability of the membranes must be tested once thermal degradation is better controlled. It is also important to improve chemical cross-linking in the membranes to further enhance the stability of the membranes during fuel cell operation. In addition to electrochemical and thermal stability, the researchers should measure thermodynamic (for example, heat capacity, heat transfer coefficient) properties of promising membrane combinations to determine thermal management benefits. The researchers should investigate the use of cathrates chemistry structures to manage the leachate problem with phosphoric acid, and various doping agents to improve proton conductivity and reduce catalyst loading.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.
Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is from reduced environmental impacts of the California electricity supply system. Fuel cell air emissions are very close to zero. A secondary benefit is increased affordability of electricity in California, brought about by fuel cells' high fuel efficiency. If ultimately successful, this research may lead to increased use of PEM fuel cells, and hence a greater capture of the environmental benefits the technology promises. The potential of using ionic liquid gels to enhance fuel cell efficiency and cost performance is an enabling technology. As such, quantification of the benefits is premature.

2.13 Pulsed Ultrasound Water Treatment

Awardee: Sonipulse, Inc.

Principal Investigator: Robert W. Cribbs

2.13.1 Introduction

Concentrated animal feed operations (CAFO) can produce severely polluted wastewater. Under a 2002 EPA regulation all CAFOs discharging wastewater must apply for a National Pollutant Discharge Elimination System (NPDES) permit. This includes about 15,500 operations nationwide. Under provisions[25] that are still being resolved in 2007 the NPDES must include a Nutrient Management Plan (NMP). The EPA has proposed an effective date for the new regulation to be Feb. 27, 2009. The NMP must include the technology planned for the particular CAFO. Best control technology (BCT) for water borne pathogens (fecal coliforms) has not yet been determined. However there are only a small number of proven technologies. Both municipal water and industrial or agricultural wastewater are commonly treated with chlorine, chlorine compounds, or other chemicals for purification. These processes produce disinfection byproducts (DBP's) such as trihalomethanes (THM's) and N-nitrosodimethylamine (NDMA) which are recognized carcinogens (NDMA at .69 parts per trillion). Ultraviolet light is an alternative treatment but is energy intensive and provides no residual disinfection. Ozone is another electro-technology that can be used for water purification. This technology is energy intensive and provides no residual disinfection.

[25] www.epa.gov/guide/cafo/

Because the final regulations are not yet in place it is not known what benefits a new technology might provide to California CAFOs. Water purification in other application could benefit from a more energy efficient disinfection technology. To assess potential benefits for all applications the researcher in this project proposed to compare the energy consumption per acre-foot of water treated by his proposed method to that of ultraviolet light and ozone treatment of wastewater.

This project proposed to determine the feasibility of using pulsed, high frequency (HF) ultrasound to replace chlorine, chlorine compounds, ozone, or ultraviolet light to process both municipal water, industrial, or agriculture wastewater before discharging into receiving waters (surface water and groundwater). While conventional low frequency (LF) ultrasound had been investigated by others it had not proven economically feasible. The advancement of science in this project was the use of a high frequency ultrasonic transducer. The researcher hypothesized that the energy requirements of a pulsed, high frequency transducer would improve the economics. A schematic of the experimental apparatus is shown in Figure 17.

Ultrasound has been used in wastewater treatment with 20 kHz transducers.[26] The use of both pulsed and continuous, HF, high intensity ultrasound is common in the medical field. In the water and wastewater treatment industry, use of ultrasound is considered as one of the long-range advanced treatment methods to oxidize complex chemical and organic compounds and is attracting scientists due to ever more stringent treatment requirements. Numerous references to this technology exist in the literature.

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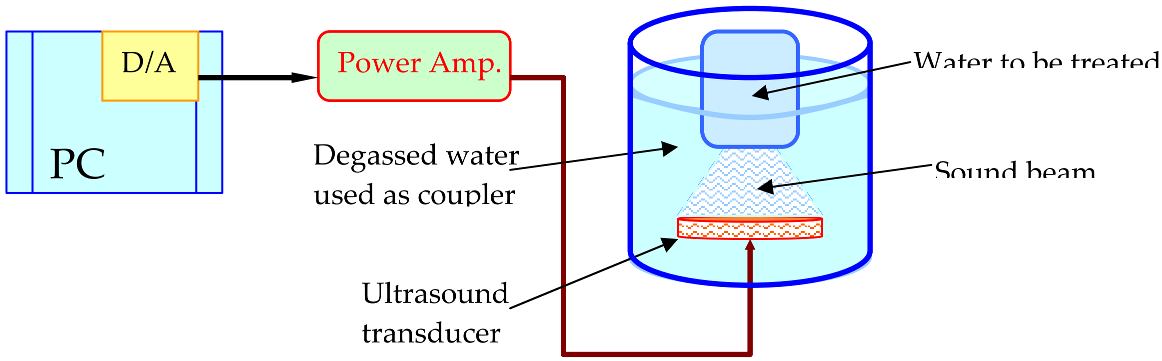
[26] Madge and Jensen (2002) Water Environment Research 74(2): 159-169

Figure 17: Schematic of Experimental Apparatus



2.13.2 Objectives

The goal of this project was to determine the feasibility of using high intensity, pulsed ultrasound to treat municipal water or other industrial or agricultural wastewater. The researcher developed the follow project objectives:

1. Design and build two ultrasonic pulse transducers, one to operate at 250 kHz and one at 1 MHz. Both should be capable of 1000 watts peak power.
2. Build a laboratory prototype water processor with a two gallon capacity and a treatment path of at least 20 inches.
3. Assemble mechanical components with electronic elements. Amplifier must be capable of driving both 50 ohm transducers at an average power of 100 watts.
4. Acquire raw water with contaminates levels of 500 to 2000 coliforms per 100 milliliters.
5. Demonstrate that pulsed ultrasound water treatment is capable of reducing coliform concentration to less than 2 per milliliter. Determine energy consumed in units of kWh/acre-foot.
6. Measure any changes in coliforms.
7. Demonstrate water purification at an energy consumption less than 20 kWh/acre-foot of wastewater. Energy consumption should be 12 percent lower than UV treatment and 60 percent lower and ozone treatment.

2.13.3 Outcomes

The following outcomes were reported by the researcher:

1. The researcher fabricated and tested two 1 MHz transducers. He did not test at the lower frequency (250 kHz). He claimed that he achieved cavitation and destruction of coliforms using the higher frequency. The researcher did not indicate the peak power capability of the transducers.
2. The initial laboratory prototype water processor was fabricated and modified twice during the water test program.
3. A disinfection system was procured and assembled. The final report indicated average power of 65 watts.
4. The researcher obtained his water samples from the Lake Natoma and a stream running through a local cattle ranch.
5. A total of 17 coliform tests were conducted for this project, consisting of 92 individual coliform colony tests. The tests conducted on 12 September demonstrated that sonification at 135 watts for 30 seconds reduced the coliforms by 50 percent and after 60 seconds removed all coliforms. The final tests conducted on 13 September consisted of 9 treatments and demonstrated that sonification at 195 watts for 5 seconds did not remove coliforms and after 10 seconds removed all coliforms.
6. The researcher conducted 17 coliform tests for this project. Those tests included 92 individual coliform colony tests
7. The researcher claimed that his process used about the same energy as UV disinfection. The energy consumed by this early prototype was claimed to be125 watt-minutes/gal. This corresponds to ~679 kWh/acre-foot or ~$68/acre-foot at $0.1/kWh. Many conversion factors were not accurate in the final report leading one to question the validity of these outcomes.

2.13.4 Conclusions

The main goal of this project was to determine the feasibility of high-intensity, pulsed ultrasound to disinfect water and wastewater. The results from this project show that pulsed ultrasound can destroy 100 percent of coliforms given sufficient time duration and ultrasound intensity. The remaining issue is the energy consumption of the ultrasound device. The researcher provided only limited data on energy consumption. Any further work must be structured to provide clear, unambiguous answers to the question of energy consumption

1. Had the researcher tested at the 250 kHz level he would have learned additional information related to the disinfection and energy consumption as a function of ultrasound frequency.
2. The test facility was limited in capabilities.
3. The average output power was less than the objective.
4. The objective was met.
5. Numerous tests were conducted. The final report contains limited information on these tests. The energy use for disinfection was poorly presented.

6. The final report contains an appendix with a listing of all the tests conducted.
7. There is no evidence in the final report to indicate that the researcher actually compared the energy use of UV, ozone and ultrasound except by models and literature surveys. Technical reviewers of the final report arrived at energy consumption number ranging from $2,217/acre-foot to $31,282/acre-foot depending on which sets of data in the final report were used in the calculation.

The final report does not clearly present data in a manner that allows outside reviewers to determine the results. The wide variation between what the researcher reported and what the reviewers calculated from the data in the final report suggest that this project did not prove the economic feasibility of ultrasound water purification on an economic basis.

2.13.5 Recommendations

Since this project was initiated several other researchers have investigated the potential for ultrasound water purification[27, 28]. Brizzolara et al had a company, Etrema Products, Inc., build a pilot-scale unit with a power output of 3kW. These "other researchers" recommend high contact times and high power densities for the destruction of *E. coli*. Some suggested that ultrasound be used in conjunction with reduced levels of chlorine for total disinfection. While the "other researchers" investigated the duration and intensity of the ultrasound the literature lacks a definitive study of the effect of ultrasound frequency. One researcher[29] reported "High frequency ultrasound is more beneficial than low frequency in the disinfection of water." The researcher in this EISG project used a higher frequency than other researchers. Because of the large developing body of knowledge regarding ultrasound disinfection of water, any proposal for future research work funded by a public agency must show that it is extending the existing body of knowledge in a significant manner. In addition, long term tests of this technology must be conducted to ensure long term water quality using pulsed ultrasound.

Benefits to California

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[27] Mohammad Hadi Dehghani, "Effectiveness of Ultrasound on the Destruction of *E. coli*", American Journal of Environmental Sciences 1 (3): 187-189, 2005

[28] Robert A. Brizzolara et al, "High-Power Ultrasound for Disinfection of Graywater and Ballast Water: A Beaker-Scale and Pilot-Scale Investigation", Naval Surface Warfare Center Carderock Div., Bethesda, MD. Report number A915854, June 2006

[29] SS Phull, et al, "The Development and Evaluation of Ultrasound in the Biocidal Treatment of Water", Ultrason Sonochem. 1997 Apr; 4(2); 157-64.

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research would be from increased affordability of the California electricity system. The premise for the potential benefits is the possible need to use electro-technologies to purify wastewater, especially from animal feed lots, prior to disposal in public waterways. Ultra-violet light and ozone treatment are two proven electro-technologies for water purification. The researcher in this project proposed a pulsed ultrasound water treatment that he claimed would use considerably less energy than the two existing technologies. The results from this project, while somewhat vague, indicate that this project did not achieve its goal of reducing energy consumed per acre-foot of water treated when compared with ozone or ultra-violet light treatment. Because of a lack of hard data, the Program Administrator cannot determine if ultrasound has the potential to become a competitive technology for water treatment. The process studied works on a technical basis. Future work must determine is pulsed ultrasound can be an economically sound process.

2.14 Test and Evaluation of Heat Transfer Parameters for CASE Tank System

Awardee: Lieberman Research Associates

Principal Investigator: Dr. Paul Lieberman

2.14.1 Introduction

This research involved the study of a heat transfer process that contributes to the use of a compressed air tank to store energy from such intermittent processes as wind turbines. The result of this storage is shown in Figure 18 below, where excess energy from the wind turbine can be stored and used at a later time, thus smoothing out the energy supply to conform with energy demand. A sketch of this proposed system is shown in Figure 19.

Figure 18: Exaggerated Example for Partition of Wind Power Using Compressed Air Storage of the Excess Power

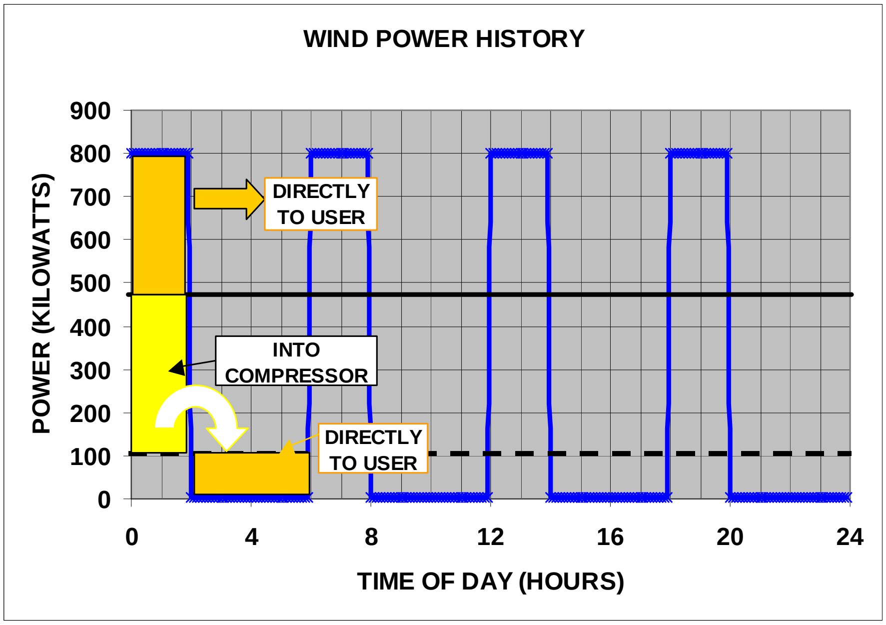
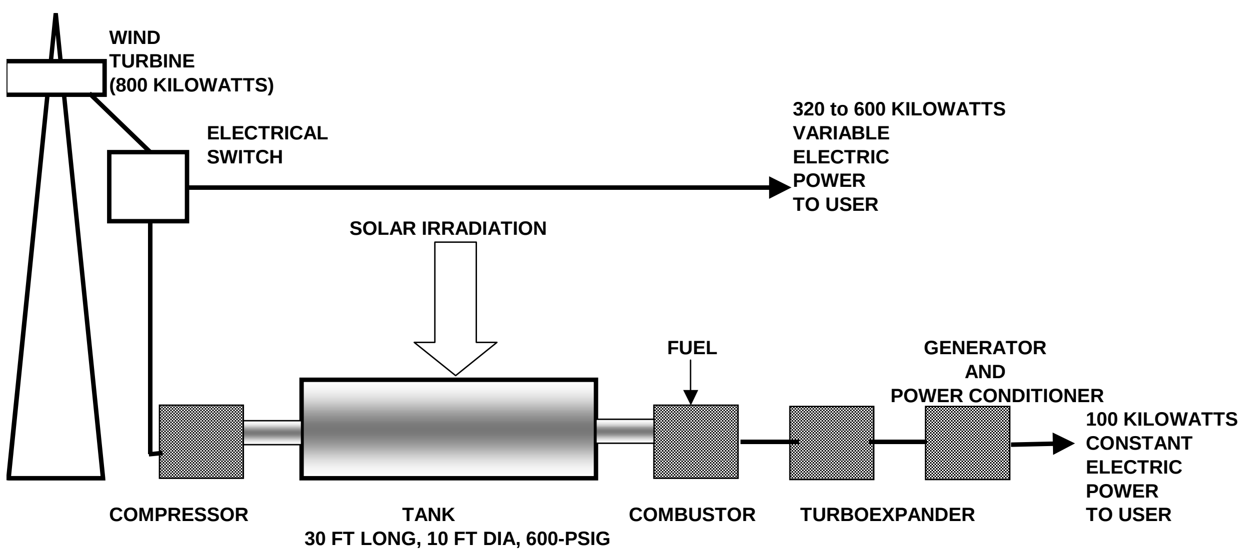


Figure 19: Wind Turbine Driven T-CAES System in a Cold Climate



California wind power plants could increase their useful electrical output if they could store excess power during high wind periods and sell it to consumers during high demand periods.

California's environment would then improve due to more economic utilization of the wind turbine energy. Such a storage method is studied in this project, the storage of energy from wind turbines using compressed air along with a novel extraction method that utilizes heat otherwise lost in decompression. This method is called a "Transportable Compressed Air Energy Storage" (T-CAES) system, named so because of the potential portability of using steel high-pressure tanks that can be move from site to site.
The benefit to the State of California for the installation of one hundred 450-kW T-CAES systems is the savings of 45 megawatts whereas the total summertime power consumption is ~44,000 megawatts with only 1 percent reserve. These one hundred 450-kW and 0.5-hour duration T-CAES systems correspond to $80,000,000 input to the manufacturers of these systems. The benefit to the State of California for the installation of ten 450-kW T-CAES systems is the savings of 4.5 megawatts whereas the total summertime power consumption is ~44,000 megawatts with only 1 percent reserve. These ten 450-kW and 4.0-hour duration T-CAES systems correspond to $40,144,000 input to the manufacturers of these "Wind Farm Power Smoothing" systems.

The innovations of the T-CAES system using steel tanks are in comparison with existing CAES systems using underground caverns. The T-CAES system eliminates the use of high maintenance equipment associated with fuel combustion to heat the compressed air used in the existing CAES cavern systems. The innovation is primarily the utilization of the thermal mass of the tank wall to transfer the heat stored during combustion, back to the compressed air when it is released to the turbo expander. This innovation makes compressed tank system more economical than other storage alternatives such as batteries or fuel cells, as well having a much longer life than these chemical storage methods.

2.14.2 Objectives

The goal of this project was to determine the feasibility of the T-CAES system in storing and recovering excess energy from such renewable energy sources as wind turbine. The researchers established the following project objectives:

1. Measure the heat transfer coefficient of the inner surface of a pneumatic storage tank during the storage tank air compression period, during the period of no activity while the tank is fully pressurized, and during the air expansion period (thermal inertia of the blow-down of air/nitrogen pressurized tanks). The reason for determining this information is to eliminate the need for any expensive anti-freeze filled copper tubes to restrict the range of air temperatures during the operation of the storage tank.

2. Compare two methods of heating compressed air from the storage tank and control valve to the turbo expander. The reason for this heating is that the air entering the turbo expander needs to be at 500°F for its efficient use. This heating of the pipeline to the turbo expander is only required for cold climates where co-generated chilled air is not

necessary. Heating to 500°F also assures low stresses on the turbo expander impeller blades. The two heating methods were:

3. A combustion heating system that externally heats a pipe filled with air exhausting from the storage tank through a control valve that feeds the turbo expander
4. Combustor systems that feed combustion products to the flowing air in the pipe feeding the turbo expander such that it feeds the turboexpander 500°F mixed combustion products and diluent air.

5. Through testing using a compressed air source and appropriate valves and sensors, measure the deviation from the Joule-Thomson temperature drop between the storage tank and downstream of a regulator. This portion of the T-CAES system is lumped with the storage tank thermal inertia to demonstrate the small drop in temperature in spite of the large pressure drops experienced.

6. Correlate the data from above and develop empirical relationships for the performance of the compressor, of the storage tank during pressure increases and decreases, and of the turbo expander for use in performing cost analyses.

7. Develop cost savings analyses utilizing the hardware of the T-CAES system for peak shaving of a commercial building, agricultural processing plant and an industrial facility. Cost models of the Time-Of-Use electric utility rates need to be combined with the power history of the electric power user to determine if there is a potential for cost savings. The required installation and operation costs of the T-CAES system must be compared to the cost savings to determine the number of years of operation to payback for the cost of the system.

8. Develop an analysis for power output smoothing of a Wind Farm using the hardware of the T-CAES system. An idealized wind history will be used to determine the storage tank capacity required.

2.14.3 Outcomes

The following outcomes have been accomplished in this program:

Outcome 1: The measured heat transfer coefficients for the storage tank during the quiescent storage period and during the in-flowing air and during the out-flowing air periods, were all higher than the anticipated values. This higher coefficient makes possible a size reduction of the storage tank and results in a cost saving of this most expensive component of the T-CAES system. The heat transfer coefficient for the storage tank satisfies a simple relationship based upon the instantaneous density of the compressed air in the tank during the quiescent period, and also during the flowing periods. The heat transfer coefficient during the flowing is within the transitional and turbulent regimes, whereas the heat transfer coefficient during the quiescent period is within the laminar regime.

Outcome 2: External heating of the downstream piping that feeds the turbo expander was not successful because of the extensive losses in heating the mass of the piping.

Outcome 3: The tests to determine the temperature drops in the compressed air were performed with a spherical tank. It was determined that the empirical relationship for laminar and turbulent flows for horizontal cylinders and vertical plates, bracketed the data for the sphere. The specific geometry of the tanks or pipes to be used in a T-CAES system was accounted for in the computer code that accepts the internal surface area of the tank (or pipe) and the wall thickness of the tank (or pipe). The following results were observed during the pressure-temperature change tests:

- For the highest pressure values(1200-psig) in the storage tank and the lowest pressure (100-psig) for feeding the one-stage turbo expander, the expected temperature drop was minimal because of the Joule-Thomson (isenthalpic) effect for the equation of state of air between the high and low pressure states. The isentropic expansion implies no heat transfer and results in a severe temperature drop that would feed cold air to the turbo expander that would process the cold air inefficiently.

- At the smaller pressure differences across the control valve(600 psig and 300 psig to 100 psig), the heat transfer from the surrounding metallic mass of the valve and mass of the ducting provided a small temperature increase even though there was a pressure drop.

- The small air temperature drop for high inlet pressures, and the small air temperature increase for lower inlet pressures, is beneficial to the operation of the turbo expander which needs high air pressure and high air temperature at its inlet.

Outcome 4: The correlation of the data gave the following results:

- The laminar natural convection relationship for horizontal cylinders correlated with the heat transfer data for the no-flow condition.

- The turbulent natural convection relationship for horizontal cylinders bounded most of the heat transfer data and correlated well with some of the heat transfer data obtained in the forced convection flow-condition.

- The flow-condition appears to be in the transition regime between laminar and turbulent. In the transition regime, extraneous disturbances such as valve adjustments in the flow can force the change between transition flow to turbulent flow.

Outcome 5: The Peak Shaving application of the T-CAES system capability applies to facilities more than 2 megawatts in peak power usage during the summer months where there are spikes of 450 kilowatts where there are less than four 15-minute triangular shaped spike histories. There are two scenarios for the T-CAES system. The first scenario generates electricity and co-generates chilled air. The second scenario generates electricity more effectively by using a limited amount of combustion so that the turbo expander receives compressed air at 100-psig and 500^{o}F, and exhausts to the ambient pressure air at just above room temperature without adding to thermal pollution.

The cost analysis performed for the peak shaving case showed that for a 2-Megawatt commercial building and a food processing plant, the payback period was 11-years based upon the earlier heat transfer coefficient that was lower than heat transfer coefficients measured in this program. Therefore the payback period will be reduced because the storage tank is the major cost item, which is determined by heat transfer coefficients.

Outcome 6: The cost analysis performed for the wind farm case included the larger heat transfer coefficients measured in this program which in turn permitted smaller storage tanks to be used to smooth the variable power history generated by wind farms. For the situation shown in Figure 18, when the wind speed peaks at 800 KW for two hours, 425 KW is sent to the consumer, while 375 KW compresses air, from which 100 KW is extracted over a later 4-hour period when the wind has died down. This strategy produces the best economics; if additional tanks are added to smooth the power even more, the costs go up prohibitively.

2.14.4 Conclusions

1. Prior to the test program the heat transfer coefficient was assumed to be h = 1 BTU/(Sq Ft – Hr-deg F) and the resultant pressure tank required a 60 feet long cylinder 10 feet in diameter to produce 100 kilowatts of electrical power for 1 hour of the turbo generator operation. The storage tank was confined to operate between 600-psig and 100-psig. As a result of the test program, the heat transfer coefficient was determined to be $1.5+2.125*\varrho$ where ϱ = air density in pounds per cubic foot for no flow during storage and at least twice that heat transfer coefficient when there is flow from the storage tank. For the same operating conditions as above, the required 60 feet long tank (h= 1BTU/hr sq ft deg F) now becomes 47.5 feet long ($h = 1.5+2.125*\varrho$). The introduction of a passive vortex generating

structure can further increase the heat transfer coefficient measured during the transition regime outflow period, can be doubled to the value associated with the turbulent regime. The anti-freeze filled copper tubing will not be needed to enhance the thermal inertia of the storage tank.

2. The atmospheric pressure, external combustion, heating of the ducting feeding the turbo expander is inefficient. The heating to 490°F is sufficient to attain overall system efficiency of 48.5 percent for a cold climate application. The exhaust air temperature from the turbo expander is ~90°F, so there is no thermal pollution.
3. At the control valve that feeds air from the storage tank with a maximum pressure of 600-psig to the turbo expander at a constant 100-psig, there is a small temperature drop across the control valve at the start of the exhaust process and eventually there is a small temperature increase across the control valve.
4. The data correlation indicated that the pressure-temperature models accurately reflected real-world testing of similar pressure situations.
5. For peak shaving, there are three scenarios for the Time-Of-Use of the electrical power grid applications:
6. Hot desert climatic site wherein solar thermal power is available and there is use for the chilled air generated by the turbo expander fed with air not heated by a combustor.
7. Cold climatic site wherein a combustor is used to feed the turbo expander 490°F air for high electric conversion efficiency.
8. Any climatic site that requires several peak shaving intervals during the day so that the compressor not only operates during the night but also during the day.
9. The T-CAES system that provides more than 450-kilowatts of electric power can have payback periods of 13-years. However, it is important to select a facility that has sufficient power usage wherein there are 450-kilowatt spikes. For the T-CAES to apply it is necessary for the power usage to have a particular type of electric power spikes. Furthermore, it is necessary to have both advance knowledge of daily power usages and a control system so as to set the threshold activation level of the T-CAES for turn-on and for turn-off.
10. This study evaluated the cost of a T-CAES system driven by an 800-kilowatt wind turbine.
11. This cost study evaluated a system comprised of compressor, storage tank, combustor, turbo expander, generator and signal conditioning have individual lifetimes of 50-years. The depth of discharge for the 600-psig air in the storage tank is 100-psig. The cost of the T-CAES system, as well as the cost of all the fuel, are combined and then divided by the total number of kilowatts supplied by the overall system. For a 1-hour delay between high power periods the cost is $0.019/kW Hr. For a 2-hour delay between high power periods the cost is $0.025/kW Hr. For a 4-hour delay between high power periods the cost is $0.103/kW Hr.

Summary of Conclusions: The concept of using the heat transfer characteristics of the compressed air along with the heat storage capability of the steel compressed air storage tank make it possible to eliminate or reduce the combustion of fuels to heat the compressed air when it is used to recover energy via a turbo expander. The higher heat transfer coefficient makes it possible to have a smaller and thus less expensive storage tank, which in turn improves the economics of the use of this system to enhance the recovery of excess power from a wind farm. Thus the proposed concept explained above was successfully demonstrated in this project.

2.14.5 Recommendations

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for follow on funding within the PIER program.

Receiving follow on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development is assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is the increased affordability of electricity in California based on the smoothing of the electrical supply curve of wind turbine power by using the T-CAES (Transportable Compressed Air Energy Supply) system. Up to 49.5 megawatts of electrical power could become available during peak usage hours each day from the T-CAES system installed at wind farms. If used for peak shaving in conventional electrical grids, the potential is for up to 450 megawatts of peak power. The cost of this electricity would be from $.02 to $.10 per kwhr using a 50-year life of the installed equipment. At present peak rates, the payback would be less than 13 years.

2.15 Wind Turbine for Low Speed Regimes: Hi-Q Rotor

Awardee: Hi-Q Products, Inc.

Principal Investigator: Todd Mills

2.15.1 Introduction

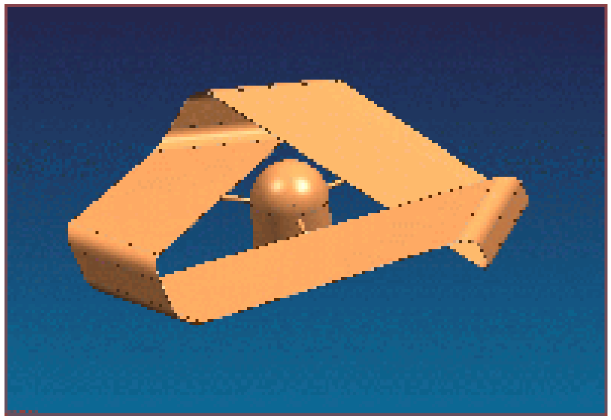
There has been considerable development of California's wind resource in recent years, as well as substantial improvements in the technology of wind machines. However, these developments have primarily concentrated on higher wind speed regimes (typically Class 4 and above), leaving the potential of lower wind speed areas largely underserved. Lower cost, more efficient low wind speed machines could unlock substantial additional wind resources, reducing environmental and price volatility impacts of traditional combustion-based generation.

The estimated technical potential capacity and energy available from lower wind speed regions (Classes 3 and 4) is nearly seven times that of higher wind speed regions, according to a 2005 California Energy Commission study[30]. This figure would increase further if the potential from Class 2 regions could be harvested. Wind machines whose efficiencies and costs make harvesting in low wind regions economically viable could unlock this potential.

The researcher proposed to build and test a wind turbine rotor using a new geometry that differed significantly from traditional horizontal axis "propeller-style" blades. The "Hi-Q Rotor" (Figure 20) uses a "continuous, single-strip geometry" that the researcher claims yields aerodynamic advantages over traditional designs at low and very low wind speeds. This advantage would make it suitable for use in low wind speed regions. As shown in Figure 1 below, the blade is a three-twist strip with a 6:1 ratio of length to width connecting the front end of the strip to the back end. It is envisioned to be made from aluminum, composite plastics, or advanced aero-elastic materials.

[30] California Wind Resources, Dora Yen-Nakafuji, May 9, 2005, CEC-500-2005-071-D

Figure 20: Hi-Q Rotor



2.15.2 Objectives

1. The goal of this project was to determine the feasibility of employing the continuous strip, twisted rotor as an alternative to blades commonly used for small wind turbines especially in low wind speed regimes. The researcher proposed to prove feasibility by comparing efficiencies of a prototype continuous strip, twisted rotor to standard blades of like size, weight, and diameter. The researchers established the following project objectives:
2. Confirm an initial prototype design by the project's team of experts.
3. Demonstrate with computational fluid dynamics (CFD) modeling a 7-14 percent efficiency advantage of the Hi-Q Rotor over a standard blade.
4. Compare performance of a carbon-fiber prototype Hi-Q Rotor with a comparable standard 18" wind blade using a friction device. Demonstrate a minimum 7 percent advantage of a prototype for class 2, 3, and 4 wind sites at 12 – 16.8 mph, generating a minimum of 11.18 watts, maximum 13.32 watts at baseline 15 mph.
5. Compare performance of a second prototype against standard. Demonstrate a 7-14 percent advantage.
6. Demonstrate that the proposed turbine design is more aesthetically pleasing as determined by a survey of 100 consumers.
7. Confirm that a Hi-Q Rotor manufacturing cost advantage of 15-20 percent less than standard blades continues to be supported.
8. Based on the data generated in this project show that the innovation can generate a 7-14 percent advantage over a standard blade at a class-3 wind site, reducing the current cost per kWh from 9¢ (NREL) to 8.37¢ - 7.7¢ kWh.

2.15.3 Outcomes

1. The design parameters for the first five rotor models to be analyzed were identified, and all required modeling nomenclature and variables to be analyzed were determined.
2. It was not possible to demonstrate the anticipated 7-14 percent advantage over a standard blade using CFD software. While the modeling work provided useful insights into the

impact of various rotor geometries, and would be useful in further development of a Hi-Q Rotor, it did not identify a Hi-Q Rotor model with superior performance over the conventional rotor that was modeled.

3. Since it was not possible to obtain an 18-inch standard blade for wind tunnel testing, comparisons were based on a theoretical performance curve for such a blade. Test results showed that the projected 7-14 percent advantage of the Hi-Q Rotor could not be demonstrated, although the tested prototype's performance did match the estimate for a standard design at several tip speed ratios. Comparisons also indicated that the Hi-Q design displayed a narrower range of tip speed ratios over which it could offer useful power coefficients than the modeled standard blade.
   After review of initial test data, the researchers speculated that the theoretical model for the standard blade was not providing an accurate basis of comparison to the Hi-Q Rotor prototype. A decision was made to replace the theoretical representation with a simple rotor made from two flat plates attached to a hub. The team felt that this would provide a better baseline comparison "as the current state of the [Hi-Q Rotor] technology was roughly equivalent to the state of rotor technology represented by a flat plate design".
4. Results of testing for the second prototype showed that the first prototype had superior performance. Both prototypes out-performed the flat-plate proxy for a standard blade at low wind speeds, and were able to begin rotation at lower wind speeds. The narrow range of attractive tip speed ratios observed in item 3 above was again evident for the Hi-Q rotor.
5. This objective was changed by the researchers to provide funds for fabrication and testing of an additional Hi-Q Rotor taking advantage of lessons learned from the prior testing.
6. The new prototype had an airfoil shape applied to the outer portion of the blades. It surpassed the performance of the flat-plate proxy for a standard blade by as much as 34 percent. Limited tip speed range was again evident.
7. Based on the assumption that the Hi-Q Rotor allows the same power output to be realized at a 25 percent lower tower height (where wind speed is less, but the assumed higher efficiency of the Hi-Q Rotor makes up for this difference), tower costs savings of between $2400 (18meter tower) and $4600 (37 meter tower) could be realized.
8. A calculation was provided that took into account projected net energy savings from deploying Hi-Q Rotor machines in low wind areas. On a national basis, the result was a projected energy cost of less than 8.7c/kWh, compared to a national proxy of 9c/kWh.

2.15.4 Conclusions

1. The first objective was met, and significant useful progress was made in understanding how best to represent the Hi-Q Rotor's geometry.
2. CFD modeling did not provide a scenario where a Hi-Q Rotor design outperformed the conventional design. (See "Outcome 2" above).

3. Although testing did not validate a performance improvement for the Hi-Q Rotor, the fact that its measured performance matched the modeled result for the flat-blade proxy of a standard design rotor at some tip speeds suggests that further refinement of the Hi-Q design could result in improvements over the standard design.
   It was unfortunate that a comparable 18-inch standard design blade could not be obtained for testing. The decision to base subsequent testing and comparisons on a simple rotor made up of two flat plate blades attached to a flat (non-aerodynamic) hub may have been the next best alternative, but the proposition that this would lead to reasonable comparisons needs to be critically evaluated. The argument that this simple proxy was comparable to the Hi-Q Rotor at its present early stage of refinement forms the underpinning of any conclusion that a fully-developed Hi-Q Rotor would out-perform a fully-developed conventional blade. A head-to-head comparison of actual wind tunnel testing is needed before any such definitive conclusions can be reached.

4. The discussion in item 3 above includes results from objective 4.

5. Addition of the airfoil drastically improved performance of this Hi-Q Rotor prototype. This helps support the researchers' proposition that comparing the earlier prototypes to a simple flat-plate design makes sense, but it does call the question of whether the more evolved design used in this task should properly be compared to this same simple proxy design.

   The original objective of sampling public receptivity to the Hi-Q Rotor design remains an important consideration, and should be included in further research.

6. It is true that a more efficient machine at low wind speeds closer to the ground could yield the same power output as a less efficient machine on the higher tower needed to access higher speeds for comparable output. However, the conclusion that lower towers would result from use of the Hi-Q Rotor assumes that a better economic decision would not be to use the Hi-Q Rotor on a higher tower to take full advantage of a site's potential. On the other hand, for sites where permitting and siting issues preclude use of high towers, a more efficient low wind speed machine may well capture energy that otherwise would be unavailable.

   Aside from the discussion of potential tower height savings, information was not provided for other aspects of manufacturing costs for the Hi-Q rotor package, as compared to a conventional horizontal axis wind turbine. An all-in cost comparison is needed to reach definitive conclusions about cost advantages.
7. Assuming the Hi-Q rotor's early indications of superior efficiency in low wind are validated by further research and testing, a more detailed analysis would be needed to establish whether the energy savings from harvesting low-wind regions result in lower cost electricity. Without doubt, additional wind generation would contribute to air quality, but the all-in cost of a Hi-Q installation compared to the cost of power from other sources would need to be carried out to establish a valid life-cycle comparison.

Overall, the results of this research are promising, but not definitive with respect to the Hi-Q rotor's ability to provide a significant advantage over other technologies in low wind regions. The limitations encountered in use of CFD modeling, unavailability of a suitable conventional blade, and limited manufacturing cost analysis make definitive conclusions difficult to reach at this stage.

The promise of low wind regions cannot be denied, and the Hi-Q rotor may be one of the successful technologies to harvest this resource. The experience gained in this project forms a sound basis for further research and refinement in rotor design, testing protocols, and ultimately manufacturing and commercialization potential.

2.15.5 Recommendations

The apparent lower range of useful power coefficients displayed by the Hi-Q rotor needs further evaluation; it is possible that this is simply an artifact of the testing methodology. However, if this lower "rangeability" is confirmed, any advantage of the Hi-Q rotor at very low wind speeds could be offset on a total annual energy basis by better performance of the standard blade at higher wind speeds at a given site. With a better understanding of the comparative range of useful output from the Hi-Q rotor and a standard blade, a more detailed analysis of its potential for specific wind sites could be conducted.

A logical next phase of research would be wind tunnel testing of further-evolved prototypes, compared against a commercially available standard blade. The proposition that as the Hi-Q rotor's design is optimized it will approach and ultimately surpass a standard blade can be tested by tracking the performance of each new prototype. Once this performance advantage is confirmed, subsequent phases could address detailed design of a full scale rotor, including field testing, manufacturing costs, life-cycle economics, and commercial potential.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for follow on funding within the PIER program.

Receiving follow on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system

- Increased affordability of electricity in California

If subsequent development and testing of the Hi-Q rotor leads to machines that can harvest wind energy economically from low wind speed areas, the primary benefit to the ratepayer from this research would be reduced environmental impacts of the California electricity supply. Clearly, additional capacity and energy from low wind speed areas has a substantial potential to displace electricity from natural gas-fueled generators. The California Energy Commission's comparison of potential from high wind speed areas versus low wind speed areas addressed earlier in this report suggests a seven-fold advantage for low wind speed potential (see footnote 1). Land use and visual impacts could also be mitigated through use of lower towers in sensitive areas, given the Hi-Q rotor's capability to harvest the lower wind speeds prevalent closer to the ground.

As California looks towards greater reliance on smaller, distributed generation resources, the Hi-Q rotor could allow economic deployment of wind machines at locations not suitable for larger, utility-scale turbines. These could include commercial and industrial sites, as well as municipal properties such as landfills, water pumping stations, and telecommunications sites.

2.16 A Unique Dielectric Light Injector for Ultra Efficient Cavity Converters: A Novel Approach for Advanced Solar Concentrator and Directed Laser Beam Applications

Awardee: United Innovations, Inc.

Principal Investigator: Ugur Ortabasi

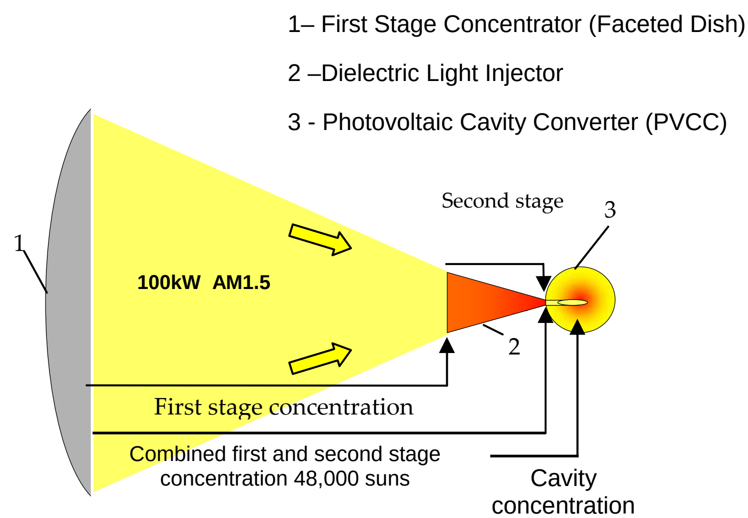
2.16.1 Introduction

The original goal of this project was to show how to design, fabricate, and test a novel Dielectric Light Injector (DLI) which would be used to feed a Photovoltaic Cavity Converter (PVCC) and yield increased efficiency of sunlight-to-electricity conversion. The intent of the effort was to achieve a cavity conversion efficiency of 45 percent.

If the outcome matched these goals, the available solar powered electricity available to the state would double for a fixed solar collector area. A doubling of solar-to-electrical conversion efficiency could be worth hundreds of millions of dollars.

The researchers proposed a solar light concentrator (Figure 21) based on use of a first stage ray compression scheme to concentrate the incoming sunlight. The first innovation was the use of a dielectric light injector made from sapphire to couple the first stage compressor to the second innovative component, a cavity containing solar cells and re-directing the concentrated light rays to focus the solar power onto a few cells. Next the researchers proposed using Rugate filters to pass selected wavelengths of light to a particular type of solar cell while reflecting the rest of the light, very efficiently, to other locations on the surface of the dielectric. There other types of solar cells would absorb the remaining light rays. Lastly Lambertian reflectors would fill the spaces between the solar cell materials.

Figure 21: Dish/PVCC System Equipped with a Dielectric Light Injector



2.16.2 Objectives

The goal of this project was to determine the feasibility of building a novel dielectric light injector to increase the performance of photovoltaic cavity converters for ultra-high efficiency solar photovoltaic concentrators. The researchers established the following project objectives:

1. Develop computer-based ray tracing and optimization for predicting light injector efficiency and determining flux uniformity inside the cavity.
2. Design system components, develop test procedures, and prepare CAD drawings describing the light injector and the integrating sphere.
3. Fabricate system components including light injector and integrating sphere. Assemble electronics.
4. Set up test stand at NREL (National Renewal Energy Laboratory) High Flux Solar Furnace facility in Golden, CO.
5. Conduct prototype testing of light injector and measure flux uniformity inside the cavity. Demonstrate light throughput greater than 95 percent and verify flux uniformity inside the cavity is within ten percent.
6. Perform manufacturing cost analysis with a goal of achieving $2 per watt manufacturing cost.

Three major issues prevented the researchers from adhering to these objectives during the performance of this project. First, additional computer simulation was required to achieve adequate uniformity of light intensity inside the cavity. Second, sapphire acquisition and machining costs were much higher than originally estimated. Third, the National Renewable Energy Laboratory does not provide services such as the high power sunlight testing facility for free. The researchers addressed the original objectives (1 to 6) only partially and undertook new tasks.

Without the approval of the Program Administrator, the researchers created ten tasks to replace project objectives. These ten tasks were:

1. Develop optical models for a dielectric light injector and for a polyhedron shaped photo voltaic cavity converter.
2. Optimize throughput performance of the dielectric light injector and the flux uniformity inside the cavity by using a Monte Carlo ray-tracing program.
3. Conduct parametric studies to identify the impact of cell population and Lambertian reflector on cavity photon utilization factor and on the conversion efficiency.
4. Develop CAD drawings for the dielectric light injector and for the polyhedron shaped cavity structure.
5. Refurbish a 200W Nd:YAG laser to provide a light source for testing.
6. Modify existing photo voltaic cavity converter to provide a cavity for testing.
7. Set up a test bed at United Innovations laboratory including the laser and the modified photo voltaic cavity converter prototype equipped with reflective (hollow) compound parabolic concentrator light injector.
8. Conduct tests including measuring I-V characteristics of the modified cavity and determination of conversion efficiency. Characterize flux uniformity inside the cavity.
9. Compare the test results with analytic results obtained under task 3 above.
10. Identify a dielectric material to replace sapphire and provide a plan to manufacture the dielectric light injector under a future program.

2.16.3 Outcomes

Two of the project outcomes matched the initial objectives of the proposal.

1. The researchers developed and used ray tracing in the optimization of the dielectric light injector. A problem developed with uniformity of light injected into the photovoltaic cavity converter. The researchers studied shape changes to make the density of rays more uniform, especially front-to-back, in the photovoltaic cavity converter.
2. The researchers used computer results to modify the injector design. They also completed computer generated drawings of the components.

No test procedures for sunlight were developed because no hardware was built nor was any high intensity sunlight available.

The researchers did not report any outcomes for objectives three through six.

Tasks 5 through 10 were devoted to Nd:YAG laser testing and evaluation as it is related to power beaming studies.

2.16.4 Conclusions

The first two objectives were met by the work done on the project.

1. The researchers dealt with the problem of uniformity of light injected into the photovoltaic cavity converter and they studied shape changes to make the density of rays more equal, especially front-to-back, in the photovoltaic cavity converter.
2. The researchers completed computer generated drawings of the dielectric light injector.

The cost of optical modeling performed by subcontractors greatly exceeded the budgeted amount. This cost overrun affected the performance of the project objectives. The cost of the dielectric light injector was higher than expected and also affected the performance of the project objectives. Objectives 3, 4, 5, and 6 were not addressed and therefore not met.

The laser work was not relevant to the solar power efforts because the laser wavelength of 1060 nm is not easily detected by silicon, the installed solar cells. The test that did take place found 11.2 percent efficiency for the Nd:YAG laser and researcher calculations showed the efficiency could become 40 percent for sunlight. The Program Administrator considers this is too much of an extrapolation to be considered significant. The efficiency of laser power beam conversion was also lower than the expected efficiency of over 60 percent.

2.16.5 Recommendations

While this project had ambitious and worthy objectives, it proved to be more costly to perform than originally estimated. The Program Administrator recommends that the researchers review the work done in this project and prepare a revised plan and budget to complete the work. In addition the Program Administrator recommends that the researcher find a commercial partner both to share the cost and to provide market requirement data. Testing with either actual sunlight or simulated sunlight is mandatory in any future work. Also the researchers must return to the original concept of testing dielectric light injectors rather than the reflective compound parabolic concentrator.

Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system

- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from a positive outcome of this research would be the reduced environmental impact of the California electricity system. This would be accomplished by the reduced cost and increased efficiency of solar energy. The objective of this research was to approach solar system efficiencies of over 40 percent. This could lead to decreased use of power plants using carbon-based fuels and decreased land area taken for the current commercial solar energy converters.

2.17 High Performance, Nanostructured Cathode for Lithium-Ion Rechargeable Battery

Awardee: University of California, Davis

Principal Investigator: Ning Pan

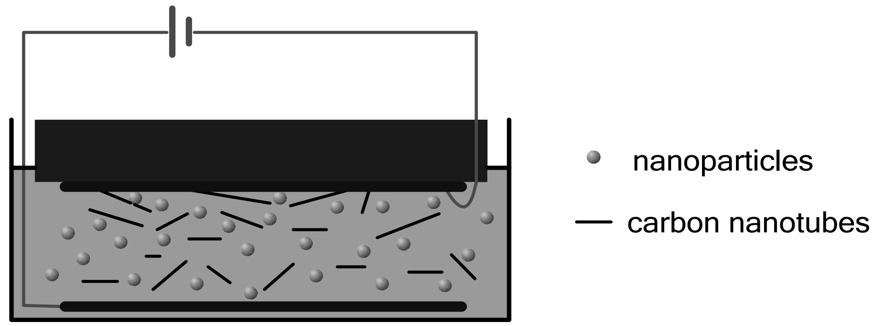
2.17.1 Introduction

Since their introduction a decade ago, Lithium Ion batteries have gained widespread preference in many applications, including portable consumer electronics to electric and hybrid vehicles. At the same time, many renewable resources, especially wind, suffering from intermittency, with output poorly correlated with periods of electric usage, are becoming more popular. Improved energy storage is a critical enabling technology of the future. Advanced battery technology may be one of the best means for storing energy and delivering it on demand in the future. Improvements to Lithium Ion battery may provide that advancement.

Wider spread use of lithium-ion batteries in larger sizes will depend on the cost and performance. Currently, the most widely used commercial cathode material for Li-ion rechargeable batteries is $LiCoO_2$ because of its stable electrochemical cycling and acceptable specific capacity. $LiCoO_2$ is relatively expensive and toxic. Therefore, a cheap and environmentally benign cathode material must be developed for large scale and widespread application. Stabilized layer-structured $LiMnO_2$ is just such a potential candidate because of its high capacity, lower cost and being less toxic than $LiCoO_2$. However, this material was generally prepared by a mixed hydroxide method or sol-gel method, which requires a complex synthetic process.

This project investigated a simple and low-cost synthesis process to synthesize electrodes using nano-tube structures utilizing $LiMnO_2$. Figure 22 provides a simple schematic of the electrode configuration.

Figure 22: Schematic Diagram of EPD Setup



2.17.2 Objectives

The goal of this project was to determine the feasibility of using designed Nanostructured cathodes for improving the battery performance of lithium ion rechargeable batteries.

The researchers established the following project objectives:

1. Demonstrate that nanosized $Li[Ni_xLi_{(1/3-2/3x)}Mn_{(2/3-1/3x)}]O_2$ powders with narrow size distribution can be produced using simple, low-cost, low temperature techniques.
2. Demonstrate that a stable $Li[Ni_xLi_{(1/3-2/3x)}Mn_{(2/3-1/3x)}]O_2$ /nanotubes suspension suitable for EPD method can be achieved.
3. Verify that EPD process is a simple method for large-scale fabrication of electrode films for rechargeable batteries.
4. Confirm that an ordered structure in which nano particles are assembled on the nanotubes can be obtained by EPD method.
5. Demonstrate that the new cathode has a 57 percent increase in capacity.
6. Confirm that the cathode has good cycle ability: capacity loss less than 5 percent after 500 cycles.
7. Verify that the cathode has good rate capability: the capacity will be 2 to 3 times higher than conventional lithium-ion battery at high discharge rate (10C to 50C range).
8. Confirm from the project findings that the projected 30 percent manufacturing cost reduction continues is reasonable.

2.17.3 Outcomes

1. The researchers demonstrated that nanocrystalline $Li[Ni_xLi_{(1/3-2/3x)}Mn_{(2/3-1/3x)}]O_2$ particles with narrow size distribution can be synthesized by the combustion method. The researchers produced nanoparticles with a relatively uniform size of about 35nm in diameter.

2. The research team prepared carbon nanotubes/[$Ni_xLi_{(1/3-2/3x)}Mn_{(2/3-1/3x)}$]$O_2$ suspension, and demonstrated the ability to fabricate large-scale electrodes by both electrophoretic deposition (EPD) and direct deposition methods.
3. A discharge capacity of 230mAh/g was obtained for the carbon nanotubes/[$Ni_xLi_{(1/3-2/3x)}Mn_{(2/3-1/3x)}$]$O_2$ composite electrodes fabricated by direct deposition method, which is about 60 percent increase in capacity compared to commercial $LiCoO_2$ batteries.
4. The composite electrodes were cycled for 50 cycles at a constant current of 5mA/g. The discharge capacity stabilized after the 3rd cycles and the capacity "fade" was found to be less than 5 percent after that, although there was a very large irreversible capacity in the first two discharges.
5. The addition of carbon nanotubes was shown to be effective in improving the rate capability, when tested at high discharge rates of 50mAh/g, the discharge capacity of the sample with higher carbon nanotube loading (5wt percent) was about 140mAh/g, which was about 2 times that of the sample with lower carbon nanotube loading (2.5wt percent).
6. The researchers also developed and tested a high power density supercapacitor made of EPD thin films of carbon nanotubes. The supercapacitors showed excellent cyclic behavior even at a very high scan rate of 1000mV/s, and a high power density of about 20kW/kg has been obtained.
7. The researchers demonstrated from the project findings that the projected 30 percent manufacturing cost reduction continues to be supported.

2.17.4 Conclusions

The project results indicate that EPD method is a feasible way to prepare nanocomposite thin films with ordered structure for use as Li Ion rechargeable battery electrode. The electrode had unacceptable resistivity, which may prove a fatal flaw. Some method other than hydrogen treatment is needed to be used to reduce the high resistance of the composite film. The results showed that carbon nanotubes are effective conductive filler to improve the electrochemical performance of Li[$Ni_xLi_{(1/3-2/3x)}Mn_{(2/3-1/3x)}$]$O_2$/nanotube composite electrode, even at a low loading of 5wt percent. A very high discharge capacity of 230mAh/g, which is about 60 percent increase in capacity was demonstrated. The electrodes were cycled for 50 cycles at a low discharge current of 5mA/g, and capacity fade was found to be less than 5 percent after it stabilized beginning with the 3rd cycle, although there was a large irreversible capacity loss in the first two discharges. The addition of carbon nanotubes was shown to be effective in improving the rate capability, when tested at high discharge rate of 50mAh/g. The discharge capacity of the sample with higher carbon nanotube loading (5wt percent) was about 140mAh/g, which was about 2 times larger than that of the sample with lower carbon nanotube loading (2.5wt percent).

The researchers also demonstrated that supercapacitors made of such EPD thin film electrodes showed excellent cyclic behavior even at a very high scan rate of 1000mV/s, and a high power density of about 20kW/kg.

2.17.5 Recommendations

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for follow on funding within the PIER program.

Receiving follow on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Future work on using carbon nanotube thin films by EPD as Li-ion battery anode or supercapacitor electrodes should be carried out. The unusual low resistance of the pure carbon nanotube thin films (after hydrogen treatment) prepared by EPD method is very encouraging; it is expected that this thin film will find more application in electrochemical energy-storage devices. For example, the fact that they are capable of fast charge/discharge in a cycling test makes them promising as electrodes for high power density supercapacitors and also anode candidates with good discharge rate capability for lithium-ion batteries.

An effective way to lower or eliminate the high resistance of the $Li[Ni_xLi_{(1/3-2/3x)}Mn_{(2/3-1/3x)}]O_2$ /nanotubes composite electrode by EPD needs to be found. We have found that the high electrical resistivity of the composite electrode by EPD was mainly due to the presence of considerable amount of oxygen-containing species on the functionalized nanotubes. But the hydrogen reduction approach was ruled out due to the reduction of $Li[Ni_xLi_{(1/3-2/3x)}Mn_{(2/3-1/3x)}]O_2$. One approach may be to decrease the density of the functional groups on the nanotube walls by reducing the treatment time of acid oxidation. Consequently, future work should investigate use of a stronger EPD electric field (high EPD voltage) so that nanotubes can still be driven to the deposition electrode, while reducing the oxidation.

Benefits to California

Public benefits derived from PIER research and development is assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research will be increased affordability of electricity in California.

High capacity lithium-ion rechargeable batteries using low-cost Mn-based materials will provide California residents an energy alternative to an inexpensive, reliable, state-of-the-art energy source, leading to savings to rate payers, it will also ensure energy diversity and reliability in the electricity supply. The potential impact to the consumers is revealed by the low raw materials price for manganese oxide ($2.29/kg) compared to cobalt oxide ($39.6 to 41.8/kg). This translates into the cost of the active material of about $0.5 for manganese oxide and $8 for cobalt oxide per 1000 cathodes, for example a reduction in the cost of about 93.75 percent. This confirms that the projected 30 percent manufacturing cost reduction continue to be feasible. These results about carbon nanotubes thin film supercapacitors during this project will pave a way to the integration of rechargeable batteries and supercapacitors to provide a new, cheaper and more powerful electricity source for electrical vehicles and/or hybrid vehicles, as well as for stationary applications using intermittent resources like wind.

2.18 Development of Magnesium Diboride-based Superconductor/Metal Matrix Composite Wire for use in Superconducting Transformers

Awardee: NOVE Technologies, Inc.

Principal Investigator: Matthew J. Holcomb

2.18.1 Introduction

Power loss in the transmission and distribution grid raises the cost of electricity to California ratepayers. The total U.S. national electric demand is supplied by a generating capacity of approximately 1000 GW (1032 GW nameplate capacity, 2003)[31]. In California peak electrical demand is approximately 60 GW[32] of which 81 percent is supplied in state and 19 percent is imported [33]. Electricity is typically generated at significant distances from its point of consumption. To minimize transmission loss, alternating current (ac) transmission lines operate at voltages from 69 kV to 765 kV[4]. The distribution system near the point of consumption operates below 69 kV[34]. Transformers are a major component of the distribution system; they are necessary to step up the voltage to the high voltage of transmission lines and then step down to as low as 120 V at the point of consumption. Electric losses composed of resistive losses in copper windings, magnetic losses in the transformer core, and losses due to inductive

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[31] http://www.eia.doe.gov/cneaf/electricity/page/capacity/existingunits2003.xls

[32] http://www.energy.ca.gov/electricity/2003-01-28_OUTLOOK.PDF

[33] http://www.energy.ca.gov/html/energysources.html

[34] http://www.eia.doe.gov/cneaf/pubs_html/feat_trans_capacity/w_sale.html

coupling to nearby conducting material in transformers add to the cost of electricity. If the copper wire in the windings could be replaced with superconducting wire operating at cryogenic temperatures, the resistive winding losses in the transformer could be reduced to virtually zero with overall savings to the California ratepayer.

Wires composed of high transition temperature superconducting (HTS) copper oxide materials could operate at relatively high temperatures and have small refrigeration requirements. The key impediment to their use in transformers has been the lack of a low cost, mechanically flexible wire of these inherently brittle materials. At present the leading method for fabricating flexible HTS wires is the powder-in-tube (PIT) method in which mixed precursor powders of the relevant metal oxides are placed in a silver tube and repetitively swaged and annealed to produce a superconducting tape or wire in a silver sheath. The large amount of silver in the sheathing makes the HTS-based wire expensive. In 2001 a new non-oxide superconducting material, magnesium di-boride (MgB_2), was discovered with a superconducting transition temperature (T_c) at 40^0 K[35]. MgB_2 wire does not require an expensive silver sheath and could provide low-cost superconducting operation at 20 to25^0 K with modest refrigeration if it could be formed into a practical, mechanically rugged wire.

A practical superconducting wire would provide payoff to the ratepayer in the form of lower transformer losses. In 1995 overall transmission and distribution (T&D) system losses were 7.2 percent, approximately 60 percent transmission line losses and 40 percent transformer losses[36]. Superconducting transformers could reduce the transformer loss by 30 percent[37], which could save California ratepayers approximately one percent net (7.2%X40%X30%) of the cost of electricity consumed. In other words T&D losses could be cut from 7.2 percent to approximately 6.2 percent. In 2001 Californians consumed 235 GWhr of electricity at a total cost to ratepayers of $27.5 billion[38]. Thus a reduction in loss of one percent from improved transformers could save ratepayers an estimated $275 million per year. In addition there could be a one percent reduction in NO_x, SO_x, and CO_2 production by the increase in efficiency.

The advancement of science needed to bring about this decrease in transformer losses is a low cost, practical method of producing MgB_2 wire. The method proposed by the researchers, Superconductor/Metal Matrix Composite (SMMC™) wire, was a modified PIT method. In their method a fine composite powder comprised of a pre-reacted MgB_2 powder and 20 to 30 volume percent (vol percent) of a soft "normal" metal (one not superconducting at the operating temperature) is placed in a low cost copper tube and swaged to a fine wire. In the absence of the soft metal, the hard superconducting MgB_2 particles would touch their neighbors at just a few points. In such a configuration the current carrying capacity would be low before returning to the normal state and would be suppressed to even lower values by ambient magnetic fields.

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[35] J. Nagamatsu, N. Nakagawa, T. Muranaka, Y. Zenitani, and J. Akimitsu, Nature **410** (2001) 63.

[36] http://climatetechnology.gov/library/2003/tech-options/tech-options-1-3-2.pdf

[37] http://66.102.7.104/search?q=cache:vuvOaV_UsvoJ:www.cefa.fsu.edu/sorrento_september03.ppt+losses+electric+grid&hl=en

[38] http://www.eia.doe.gov/emeu/states/sep_fuel/html/fuel_es.html

For effective operation a critical current density of the wire of over 10,000 A/cm^2 is needed. Although the normal metal in the composite would otherwise not be superconducting at the 20 to 25^0 K operating temperature, when the particles are a few microns in diameter the normal material is induced to be superconducting through its contact to with a superconducting material by what is known as the proximity effect. The induced superconductivity in the normal metal component increases the effective area of superconducting contact between MgB_2 particles and thus the current carrying capacity of the overall wire. Furthermore the wire core is made much less sensitive to ambient magnetic fields. The key advancement of science needed was finding a suitable, low cost MgB_2-based composite and a practical fabrication procedure to produce wire from the composite.

2.18.2 Objectives

The goal of this project was to determine the feasibility of demonstrating critical current densities (J_E) greater than 20,000 A/cm^2 at 20^{0}K in self-field, and greater than 10,000 A/cm^2 at 20^0 K in a one tesla (1 T) applied magnetic field for sections of MgB_2 superconducting wire 10 cm long. The researchers established the following project objectives:

1. Synthesize high-purity MgB_2 powder with enhanced surface area.
2. Test the proposed modified powder-in-tube wire fabrication process. Demonstrate capability to draw sections of wire shorter than 10 meters. Demonstrate capability to draw sections of wire longer than 10 meters.
3. Reconfigure in-house critical current measuring apparatus to accommodate 10 cm length wire in an external magnetic field and a 10 m length in self-field. Demonstrate engineering critical current densities in excess of 20,000 A/cm^2 at 20^{0}K in self-field and in excess of 10,000 A/cm^2 in a 1 T (Tesla) magnetic field. Measure the variation in the critical current density over a 10 m length of the conductor. Demonstrate less than 10 percent variation of the critical current density over a 10 meter MgB_2 wire.
4. Reconfigure in-house critical current measuring apparatus with a rapid thermal cycling attachment. Demonstrate degradation of the engineering critical current density of 10 cm lengths of MgB_2 wire of less than five percent after 100 thermal cycles from 300^0 K to 20^0 K.

2.18.3 Outcomes

1. The researchers produced high-purity MgB_2 powder with an average particle size less than 10 micron. X-ray diffractometry and SEM (scanning electron microscopy) studies confirmed that the powder was greater than 99 percent phase pure with a maximum particle size of approximately 10 micron with the majority of the particles less than 3 micron in average diameter.

2. The researchers synthesized MgB_2/gallium superconductor/metal matrix composites using high purity MgB_2 powder and 20 to 30 percent by volume gallium metal (Ga). From these composites they fabricated sections of mono-filament copper sheathed MgB_2 wire about two meters in length. The researchers found the mono-filament wire with 30 vol percent

gallium demonstrated the highest critical current. HyperTech Research drew this material into wire. HyperTech delivered three wires: 1) ~1 m of mono-filament copper sheathed MgB_2/Ga wire with a diameter of 0.40mm, 2) ~5 m of mono-filament copper sheathed MgB_2/Ga wire with a diameter of approx. 1.0 mm, and 3) ~30 m of an 18 filament monel sheathed MgB_2/Ga wire with a diameter of 1.0 mm. SEM micrographs of polished transverse cross-sections of the 1.0 mm diameter mono- and 1.0 mm diameter multi-filamentary wire displayed good filament uniformity along the length of the conductor.

3. A 25 mm diameter samarium-cobalt permanent magnet was mounted over an inverted hairpin sample section of wire to be tested. This magnet generated a field of only 0.2 T, however, and a number of attempts to increase the magnetic field at the sample using permanent magnets were unsuccessful. The primary obstacle to this task was the size restriction imposed by the ~38 mm opening of the standard liquid helium dewar. Although it was not possible to make measurements in 1 T magnetic field, the researchers estimated the transport properties in applied magnetic fields at 20^0 K based on previous measurements of the magnetic field dependent critical current of a MgB_2/Ga wire to 6 T at 4.2 ^{0}K. These earlier measurements showed that the critical current density decreased exponentially with increasing magnetic field (expected from the behavior of superconductor/metal/superconductor junctions in applied magnetic fields). Using this exponential dependence as an extrapolation function at 20^0K, the researchers estimated the MgB_2/Ga wire would have a transport J_E in excess of 8000 A/cm^2 in 1 T magnetic field at 20^0 K.

   The 10 cm long wire with the highest engineering critical current density in self field was a 0.4mm diameter, copper sheathed, 30 vol percent Ga mono-filament wire. This wire had an engineering critical current density of approximately 22,000 A/cm^2 at 20^0 K in self-field with one percent bending strain. The composite wire with the highest critical current was an 18 filament, 30 vol percent Ga MgB_2/Ga composite wire with a critical current greater than 130 A, at 20^0 K in self-field with a two percent bending strain and an engineering critical current density in excess of 17,000 A/cm^2. At these high current levels, however, the researchers observed significant heating at the contacts to the wire.

   The planned method to measure variations in current density over 10 meter long samples was not successful. The researchers adopted an alternative approach. They measured critical current variations of several 25 cm sections of wire taken from a 5 m length of mono-filament wire. Based on these short sample measurements, they inferred a variation of about seven percent in the transport properties of mono-filamentary MgB_2/Ga wire over a 5 m length of conductor.

4. A composite wire sample was cycled a total of 100 times from below 20^0 K to room temperature. Critical current measurements were performed after 10, 20, 22, 60, 90, and 100 thermal cycles. The researchers verified that the critical current of the multi-filamentary MgB_2/Ga wire varies less than five percent with 100 thermal cycles from approximately 20^0 K to room temperature.

2.18.4 Conclusions

1. This objective was successfully achieved.
2. This objective was successfully achieved.
3. The researchers achieved the sub-objective of less than ten percent variation in current density over a 10 cm length of wire. The original sub-objective to demonstrate a variation of less than 10 percent over a 10 m length of wire was not achieved.
4. This objective was met**.**

The main goal of this project was to demonstrate engineering critical current densities for 10 cm sections of MgB_2 composite wire of greater than 20,000 A/cm^2 at 20^0 K in self-field, and greater than 10,000 A/cm^2 at 20^{0}K in 1 T applied magnetic field. Feasibility of the basic wire fabrication concept was demonstrated in both mono-filament and, importantly, in multi-filament MgB_2 based wire. A majority of the current density goals were met. Overall, wire fabricated in this manner shows promise for use in superconducting device applications such as transformers, motors, generators, and MRI magnets operating at temperatures in excess of 20^0 K in modest magnetic fields.

2.18.5 Recommendations

The Program Administrator recommends that the effects of melting Ga in the wire be investigated. This could be done by storing wire above the melting point of Ga at 303^{0}K followed by micrographic analysis and transport measurements. Key questions to be answered are:

1. Is there embrittlement of the copper sheath by liquid Ga intergranular attack or Ga diffusion into the Cu sheath?
2. Does enough Ga diffuse into the Cu sheath to reduce its electron mean free path and spoil the thermal stability and stability against flux jumps?
3. Does Cu diffuse into the Ga reducing the electron mean free path in the Ga and spoiling the proximity effect?
4. What are the effects on the wire transport properties by annealing out cold work in the Ga component of the composite?
5. Since Ga expands 3.1 percent on solidification, what are the effects of the internal forces on the wire during thermal cycling?
6. What are the energy costs to maintain superconducting wire transformers in the superconducting state? How do the cooling costs compare to the savings due to reduced transformer losses?

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the

Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research would be increased affordability of electricity in California. A practical superconducting wire would provide payoff to the ratepayer in the form of lower transformer losses. In 1995 the transmission and distribution (T&D) system losses were 7.2 percent which were divided approximately as 60 percent line losses and 40 percent from transformers[39]. Superconducting transformers could reduce transformer loss by 30 percent[40] which would save the California ratepayer an estimated one percent of the cost of electricity consumed. In other words T&D losses would be cut from 7.2 percent to approximately 6.2 percent. In 2001 Californians consumed 235 GWhr of electricity at a total cost to the ratepayers of $27.5 billion[41]. At full market penetration of superconducting transformers, a reduction in loss of this magnitude would save California ratepayers an estimated $275 million per year. The cost of cooling the transformers would reduce this calculated savings. Because existing transformers have long projected life, full market penetration could take 20 to 25 years.

Beyond the one percent cost of electricity savings, several additional benefits could help drive a decision to use superconducting transformers. Reduced environmental impacts of the California electricity supply or transmission or distribution system could be achieved because the application of superconducting wire would facilitate a significant reduction in the size and

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[39] http://climatetechnology.gov/library/2003/tech-options/tech-options-1-3-2.pdf

[40] http://66.102.7.104/search?q=cache:vuvOaV_UsvoJ:www.cefa.fsu.edu/sorrento_september03.ppt+losses+electric+grid&hl=en

[41] http://www.eia.doe.gov/emeu/states/sep_fuel/html/fuel_es.html

weight of the transformers compared to copper transformers of the same power rating. Increased public safety of the California electricity system could be produced by superconducting transformers which could be sited in urban areas or inside buildings since they are cooled with more environmentally friendly cryogens, rather than flammable oils. Increased reliability of the California electricity system could be produced since superconducting transformers could also lead to increased grid stability (due to their inherent fault current limiting properties).

2.18.6 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The Principal Investigator wrote a paper, "Super currents in Magnesium Diboride/Metal Composite Wire," for publication in Physica: Superconductivity.

Engineering/Technical

The researchers have not indicated what additional work was planned. Their research and early development results on up to 30 m lengths of superconducting wire are encouraging. Additional later stage development of up to 1000 m lengths of wire still have to be done for the transformer market.

Legal/Contractual

The researchers were awarded three U.S. patents on the technology and submitted several additional patent applications.

Environmental, Safety, Risk Assessments/ Quality Plans

Environmental, safety, risk assessments, and quality plans have yet not been developed.

Production Readiness/Commercialization

The researchers have connections to companies that specialize in drawing superconducting wires. No production plans have been announced.

2.19 A New Physical Water Treatment Technology For Energy Efficient Chillers

Awardee: Choson Research Corp.

Principal Investigators: Wontae Kim, Daniel Cho

2.19.1 Abstract

The objective of this project was to develop a new physical water treatment (PWT) technology to prevent or mitigate both mineral and bio-fouling in the condenser tubes of water-cooled chillers. The technology, referred to as "new PWT technology," uses two inert electrode-grade graphite plates. The new PWT technology uses very high frequencies (for example, in the order of MHz) relative to solenoid-type coil PWT devices (for example, maximum 3 kHz). The project conducted a series of heat transfer fouling tests using a laboratory-scale cooling tower to circulate hard water through a copper heat transfer test section intended to simulate condenser tubes. The researchers increased the electric conductivity of circulating water to a level of 2,000 - 4,500 micro-mho/cm, simulating actual water conditions in the field. In addition, they produced complete water analyses, scanning electron microscope photographs of scale specimen, and photographs of scaled copper tube surfaces. The results from the fouling tests demonstrated the validity of the new PWT technology by achieving the objective of maintaining 90 percent of the peak heat transfer performance of a heat exchanger. The project also confirmed that the high-frequency electric fields of 3.5 MHz controlled water-borne microbial organisms and prevented bio-fouling on the heat transfer surface. The researchers concluded that the new PWT technology could be used as an energy conservation means, since clean chillers consume far less electricity than fouled chillers. The technology is mature for commercialization, and the next step would be a verification study in the field.

Keywords: Physical water treatment, PWT, mineral fouling, bio-fouling, water treatment

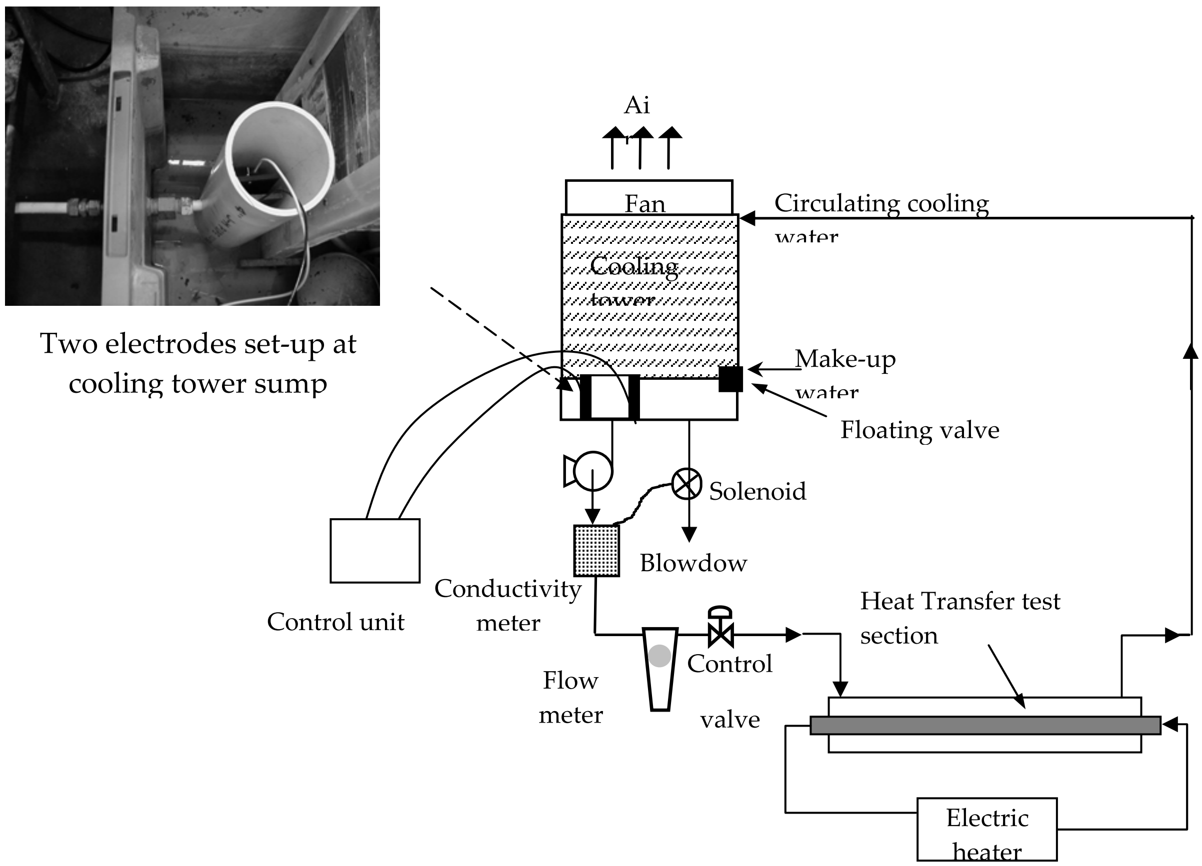
2.19.2 Introduction

Water-cooled air conditioning systems are used throughout residential, school, hospital, public, and commercial buildings. In California water-cooled systems are increasingly replacing air-cooled systems due to the potential to save electricity. One of the drawbacks of using water-cooled air conditioning systems, however, is that the condenser tubes develop mineral and bio-fouling problems which can significantly reduce overall performance and increase the energy cost of operation. The standard method for preventing fouling is the use of scale-inhibiting chemicals, which are added to circulating cooling water and discharged to the sewer. The use of such chemicals is expensive and increasingly being discouraged because of environmental concerns.

Several non-chemical or physical water treatment (PWT) methods have been introduced as alternatives to prevent fouling problems. However, these earlier PWT methods produce relatively weak pulsating magnetic and/or electrical fields. Limitations governed by the laws of physics result in these methods working only marginally well for mineral fouling and for bio-fouling control.

This study investigated a next-generation PWT concept designed to address both mineral and bio-fouling. The intended benefit of preventing both mineral and bio-fouling is to enable water-cooled air conditioning systems to run more efficiently throughout the cooling season and to reduce substantially peak electricity demand during the hottest days of the year. Figure 1 illustrates the concept.

Figure 1. PWT Conceptual Layout



2.19.3 Objectives

The goal of this project was to determine the feasibility of using advanced physical water treatment (PWT) in water-cooled air conditioners of 300 to 500 ton cooling capacity. The researchers established the following objectives:

1. Develop design specifications for new PWT technology.
2. Conduct electrical tests for field strength and frequency.
3. Fabricate prototype.
4. Fabricate fouling test facility by adding two electrodes and control unit.
5. Establish baseline performance for mineral and bio-fouling that can be used to establish the successful performance of new PWT.
6. Demonstrate long-term overall heat transfer coefficient at 90 percent level of the maximum value at a cycle of concentration of five and demonstrate bio-count less than 10,000 CFU/ml in bulk water and 100,000 CFU/ml at sessile surfaces.
7. Demonstrate a device cost of $2,500 per system for 300-600 RT chillers and demonstrate projected life-cycle cost of $500 per year for regular maintenance and 10 percent savings in electricity.

2.19.4 Outcomes

1. The researchers designed a prototype PWT for testing.
2. The researchers constructed a test device of two electrode-grade inert plates to measure electric field strength data as a function of the gap between the two electrodes immersed in water. To see the effect of power-supply strength on the electric field strength produced in water, they measured the generated electric field strength as a function of the gap between two electrodes, frequency of AC signal, and fluid media (water). To check the effect of power supply, they used two different size power supplies. For each power supply case, the gap between the two electrodes was varied.
3. The researchers fabricated a prototype of the new PWT technology using two graphite plates as two electrodes. The prototype consisted of plastic housing, two graphite plates, plastic flange to hold the plates in place, and water connection. The cooling water circulated through the gap between two electrodes so that all water could be treated by the direct electric pulsation of a very high frequency field. By positioning the electric wire source connection such that no contact with water was possible, they avoided electric leakage and any ionized byproducts of electricity. The researchers used a low voltage AC signal with ± 10 V. The field frequency was 1.2 kHz, and the measured electric field ranged from 0.5 to 1.35 V/cm, depending on the electrode gap.
4. The researchers added two electrodes at the sump of the cooling tower and connected them to a control unit with a square-wave AC power generator to demonstrate mineral fouling control. They connected a function generator with a very high frequency signal to the electrodes to verify bio-fouling control. The researchers obtained fouling resistance data and digital photographs using the laboratory-scale test rig with the new PWT technology running. To eliminate the effect of bio-fouling on the mineral fouling study, they used a standard biocide (glutaraldehyde).
5. The researchers conducted a bio-fouling test using the same fouling test facility without biocide in the circulating cooling water to establish a baseline.
6. The researchers demonstrated that the new PWT technology could keep the heat transfer surface from bio-fouling. There was near zero bacteria in the bulk water and on sessile surfaces (well below the 10,000 CFU/mL and 100,000 CFM/mL target levels) of the heat transfer surface treated by the new PWT technology. They measured the overall heat transfer coefficient in a counter heat exchanger and demonstrated that overall heat transfer coefficient was maintained at better than a 90 percent level (near-zero fouling level) of the maximum value at a cycle of concentration of five.
7. The new PWT system could be priced from $5,000 to $20,000 to the end user combined with standard side stream (centrifugal separator or backwash media) filtration for approximately 500 ton cooling tower size. The price would depend on

filtration grade and particle size, as well as the power output of the new PWT technology. The cost of the new PWT technology could be a one-time installed cost with minimal regular maintenance.

2.19.5 Conclusions

The project proved the feasibility of using direct pulsating electric field exposure to control bio-fouling and mineral scaling. The overall heat transfer coefficients in a heat transfer test section using a chiller tube were maintained at high efficiency in the case of both mineral control and bio-fouling control. Based on the findings in this project, cooling towers equipped with these direct pulsating electric field generators could be operated within 90 percent of maximum peak performance, resulting in significant energy savings as well as reduction of biological growth.

2.19.6 Recommendations

The researchers should conduct a test on a larger, near full scale, facility. Testing should include simultaneous mineral and biological fouling control. Specific attention should be made to electrode material, as the graphite electrodes in this project will likely not be durable enough for long-term commercial use in this application. The researchers should determine if electric fields or the associated magnetic fields are responsible for mineral and bio-fouling control. If the latter, it may be possible to avoid immersion of the electrodes in the circulating water, which may provide additional safety and durability.

The optimum frequency (MHz) should be determined through a series of tests by changing the frequency of the power supply over a broad range and correlating it with system size and configuration. Different size systems may require different pulse frequencies.

Long-term testing is necessary to validate the results of this project for commercial application and to optimize electric source and electrode design.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is from increased affordability of electricity in California. The increased affordability stems from increased energy efficiency of energy service in the form of air conditioning. Environmental benefits also should occur due to less chemical bio-fouling and mineral controls in the water cooler.

If the results of this project were commercialized and implemented widely in California, residential, commercial, and public buildings such as businesses, schools, and hospitals would benefit. Facilities that implement a PWT technology such as the one developed in this study would see operational cost savings in energy and water usage. Furthermore, peak energy usage could be reduced on the hottest days of the year, reducing the possibility of electricity shortages. The new PWT technology could allow existing air conditioning and chiller systems, if retrofitted to water cooling, to run far closer to their initial maximum efficiency.

Electrical energy requirements for the operation of water-cooled air conditioning systems in residential, commercial, and public buildings such as schools and hospitals account for a significant amount of total energy requirements in California. Assuming that 17 percent of total electrical energy consumption, or approximately 44 GWh, is used for cooling (vapor compression cooling cycles) in California, a 13 percent to 27 percent increase in chiller efficiency would represent a 6-12 GWh energy saving to California.

2.19.7 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

An affiliate of Choson Research performed a market survey using telephone interviews to determine the experiences facility managers have with scale build-up in heat transfer equipment. The firm contacted 4,391 facility managers from a customer pool of 40,000: 96 percent said they were aware of loss of heat transfer efficiency due to scale build-up and 92 percent use chemicals to control scale. Despite their current use of chemical treatment, 47 percent said they would be interested in a product that was guaranteed to significantly reduce the amount of scale build-up on their tubes and pipes. Water treatment companies as well as cooling tower manufacturers and distributors have a captive audience for marketing the proposed new PWT technology since they have an active customer base that is paying for such products and services regularly. Since the new PWT technology could greatly reduce the cost of providing the water treatment services and improve the overall performance of cooling towers and chillers, these organizations would benefit from increased profit margins with the installation of such a PWT system. The researchers have begun the process of developing technical and business relationships with such companies for the purpose of bridging the marketplace and customer needs.

Engineering/Technical

Key technical staff left the company stopping future development.

Legal/Contractual

The researchers have applied for a patent. They have not published any papers or publicly disclosed the concept in ways that would infringe on the patent's viability.

Environmental, Safety, Risk Assessments/ Quality Plans

Environmental, safety, risk assessments and quality plans are premature. Significant additional testing and optimization is required before the technology can be commercialized.

Production Readiness/Commercialization

During the course of this project, key technical personnel left the company. The researcher stated that continued development towards commercialization would require new staff. Therefore there are no plans to commercialize this concept.

2.19.8 Appendix A: Final Report

Submitted under separate cover.

2.19.9 Appendix B: Grantee Rebuttal To Independent Assessment

None submitted.

2.20 A Zero Current Ripple, Energy Efficient, And Reliable Low Cost Residential And Commercial Zero Emission Direct Power-Conversion System

Awardee: University of Illinois

Principal Investigators: Dr. Sudip K. Mazumder

2.20.1 Abstract

Many alternate energy sources – fuel cells, photovoltaic panels, wind turbines – require power conditioning before the raw form of the produced power can be used by a building owner or connected into the power grid for use by a wider community. Several problems existed with power-conditioning systems when this project was proposed. Relatively high cost and relatively low reliability were the two biggest problems. Two of the goals of this project were to reduce the cost of the power conditioning electronics to ten percent of the system cost, or $40 per kilowatt (kW) of nameplate power output, and to provide approximately five years of maintenance free operation. An additional goal of this project was to reduce the ripple current to the power sources, thus prolonging the operational life of those devices.

The results of this project show that the proposed design provided efficiencies of greater than 90 percent over 60 percent of its operating range. The ripple current was reduced by a factor of five to seven, somewhat less than the design goal of a ten times reduction. The measured reduction in ripple current could extend the operation life of fuel cells or photovoltaic panels. The cost of the proposed power electronics subsystem was not fully developed in the final report. The researcher claimed a cost of $38.56 per kW. Apparently this cost was for the bill of materials for the device.

While additional engineering work is required before production, the proposed power electronics could provide useful benefits to the fast growing photovoltaic industry in California.

Keywords: power electronics, power conditioning, cost reduction, alternate energy source, ripple current**.**

2.20.2 Introduction

Fuel cells and photovoltaic panels require power conditioning before the raw form of the produced power can be used by a building owner or connected into the power grid for use by a wider community. The power electronics system converts the low voltage, direct current (DC) output into higher voltage, alternating current (AC) used by most appliances. Several problems existed with power-conditioning subsystems when this project was proposed. Relatively high cost and relatively low reliability of inverters were the two biggest problems. Two of the goals of this project were to reduce the cost of the power conditioning electronics to $40 per kW of nameplate power output, and to provide up to 40,000 hours of maintenance free operation. An additional goal of this project was to reduce the ripple in the current drawn from the power sources thus increasing the life of fuel cells and photovoltaic panels.

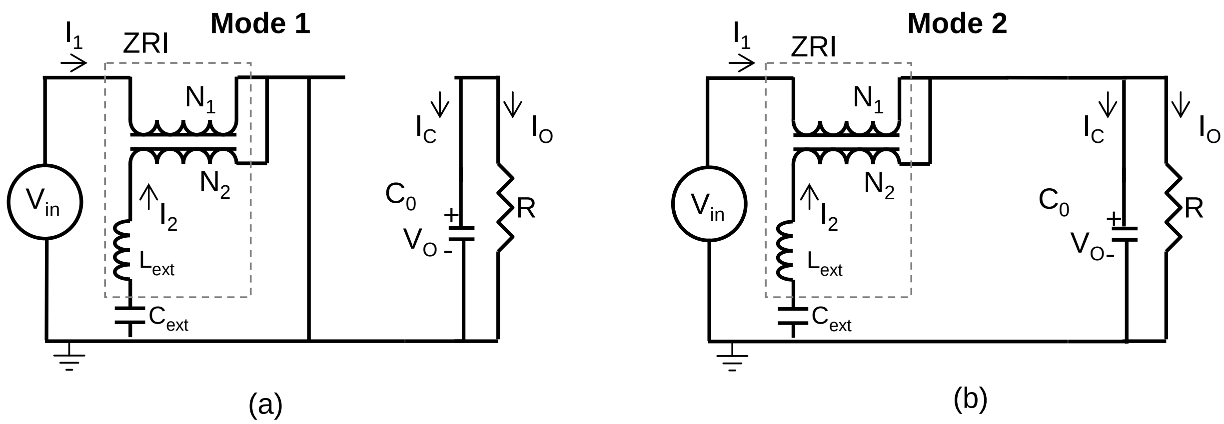
The U.S. Department of Energy operates a fuel cell program named SECA[42] (Solid State Energy Conversion Alliance). The administrator of that program has set year 2010 goals of $400 per kilowatt for a solid oxide fuel cell system exhibiting 45 to 50 percent efficiency. In that cost goal they allocated eleven percent for controls and power electronics. This is the basis for the $40 per kilowatt goal for the power electronics in this project.

Meeting the cost, reliability and efficiency goals for the power electronics subsystem could greatly enhance the deployment of fuel cells and photovoltaic panels in California. At the time this project was started power electronic subsystems were priced about $400 per kilowatt. In addition some power electronic subsystems did not operate reliably for 40,000 hours (about five years). Since high cost is a major barrier to the installation of fuel cells and photovoltaic systems, the proposed cost reduction of the power conditioning subsystem could increase the use of fuel cells and photovoltaic systems. As electrical power companies and users increase their reliance on local alternative energy sources there will be a reduction in demand on central power plants and a corresponding drop in transmission costs. In addition there will be a decrease in greenhouse gas emissions. Reliability of power conditioning subsystems has been improving since this project was started. Any new power conditioning system, such as the one developed in this project, would have to undergo accelerated age testing to prove reliability before it would be generally accepted and warranted by installers. Thus the benefits of the developed technology could be delayed by several years.

The zero ripple boost converter (ZRBC) (shown in Figure 23) is a key project innovation. It reduces the ripple current of the power electronics subsystem. It is a standard non-isolated boost converter, with the conventional inductor replaced by a zero-ripple inductor (ZRI). The ZRI is a two winding inductor, with the primary winding conducting the DC input current and the secondary winding conducting the AC current. The secondary winding of the ZRI is connected to an external trimming inductor and a filter capacitor as shown in Figure 23. Similar to the conventional inductor, the ZRBC has two modes of operation as shown in Figure 23.

Figure 23 Topological modes of the ZRBC when (a) S0 is turned ON and (b) S0 is turned OFF:

[42] www1.eere.energy.gov/hydrogenandfuelcells/pdfs/williams_fe_fuel_cells.pdf



2.20.3 Objectives

The goal of this project was to determine the feasibility of a low cost power-electronics subsystem (for residential and commercial applications) that interfaces seamlessly to fuel-cell or photovoltaic energy sources yielding multiple benefits such as lower cost, higher energy savings and power density, enhanced durability for the energy sources (fuel and photovoltaic cells) and increased reliability of power-conditioning subsystems. The researchers established the following project objectives:

1. Design and build a high frequency (20 kilo Hertz- kHz), five kilowatt power electronic prototype to convert 72~150VDC (volts direct current) into110 VAC (volts alternating current) at 60Hz.
2. Estimate a cost for the developed unit in quantities of 5000 per year. The goal is less than $40 per kW.
3. Design for 40,000 hour operational life. Demonstrate prototype can operate 200 hours without failure.
4. Demonstrate overall energy efficiency of greater than 94 percent at full load for single-phase output and greater than 93 percent for three-phase output.
5. Demonstrate ten times reduction of source-current ripple compared to existing state-of-the-art equipment.
6. Demonstrate 50 percent reduction in voltage stress on power devices.
7. Demonstrate less than five percent overshoot and undershoot during no-load to full-load and full-load to no-load transients.

2.20.4 Outcomes

1. The researcher designed and built a power electronic subsystem rated at five kilowatts for use with a fuel cell.
2. The researcher claimed cost for the proposed topology at $38.56. The final report did not provide a methodology to arrive at that cost, only a list of parts. The claimed cost may

only include the cost of parts with no provisions for labor, general and administrative costs, profit and other items that go into the price of a product.

3. The researcher performed a 200 hour endurance test. Unexpected current draw in one semiconductor caused excessive heating. The heat resulted in "a complete disruption of the functionality of the IC (semiconductor)". The researcher resolved this problem by reducing the supply voltage to 12 VDC from 15 VDC.
4. Test results show a full load efficiency of 92.1 percent. The prototype demonstrated 90 percent or greater efficiency over 60 percent of its power range. No three-phase results were presented in the final report.
5. Testing demonstrated ripple reduction of five to seven times using hand-wound magnetic components. The researcher claimed performance could be improved using a commercially available fabrication process, which has better control of magnetic parameters
6. The researcher performed tests that indicated a reduction in the variation of fuel utilization in the fuel cell. This reduction would lead to lower thermal cycling of the fuel cell electrodes.
7. The researcher performed transient tests and presented data in his final report. No interpretation of the data was presented. The researcher claimed he met the five percent overshoot and undershoot goals.

2.20.5 Conclusions

1. This goal was met.
2. The researcher did not perform a convincing manufacturing cost analysis to determine if this goal had been met. While this is a complex task, the researcher only provided a list of material with the associated cost of each item. True cost of the device must include materials, labor, direct and indirect overhead, profit, and distribution costs.
3. Lifetime of 200 hours was demonstrated. A long life goal of 40,000 hours is not yet confirmed and should be addressed in any subsequent work.
4. System efficiency generally met project goals. Because of continual improvements in efficiency by all manufacturers, one should compare project results with currently available power equipment
5. While the goal of ten times reduction in ripple was not reached, the researcher demonstrated a reduction of five to seven times. The demonstrated ripple reduction should increase the life of the source. The magnitude of the life extension was not quantified in this project.
6. Sufficient data were not presented to claim a 50 percent reduction in voltage stress.
7. The researcher should have presented a more complete analysis of the data to show that this goal was met. The only information provided was in figure captions.

The researcher built and tested a five kW power electronics subsystem tailored to fuel cells or photovoltaic panels. Tests confirmed that it operated at relatively high efficiency and low input ripple current. The researcher claimed a cost less than $40 per kW but did not present an analysis that confirmed this number. Future tests must confirm that the new design can operate with a mean-time-to-failure of greater than 40,000 hours. The final cost of the system will depend on the quantity sold each year. The customer base that is developing in California for photovoltaic systems may be large as 100,000 per year in coming years.

2.20.6 Recommendations

The development of the tested power electronics subsystem could have value to the California ratepayers who wish to generate electrical power locally using fuel cells or photovoltaic panels. Before the proposed system can go into production, it is essential that the development of the topology be completed. The Program Administrator recommends the following actions:

1. Create a cost model based on large scale manufacturing. Partner with a contract electronic manufacturer to create the cost model and the needed inputs. Re-establish the cost goal of $40 per kW.
2. Review all components and designs to assure that the cost/price target will be met.
3. Procure machine wound inductors. Test to determine ripple reduction improvement.
4. Test three phase system.
5. Design and operate an accelerated endurance test to confirm 40,000 hour lifetime. If necessary secure the services of a major test laboratory for this test.
6. Re-confirm system efficiency once all changes have been made.
7. Monitor the development of power electronic subsystems for vehicles. The U.S. government has set goals of $12 per kW for the inverter/motor system for fuel cell powered vehicles in the year 2010.[43] Other goals of that vehicle program include efficiency greater than 90 percent and a lifetime of 15 years.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system

[43] www.nrel.gov/vehiclesandfuels/powerelectronic/about.html

- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. Generation of electrical power locally leads to a reduction in the number of expensive peak demand power generators and to a reduction in the need for new transmission lines. In addition local generation allows the use of rejected heat from fuel cells and photovoltaic cells to be used for local water heating. Before these benefits can be used more widely, cost and reliability must be improved. The goals of this project are specific to the power electronics subsystem of the photovoltaic and fuel cell systems. Fuel cells and photovoltaic panels might provide a significant portion of California's electric energy needs if the first cost were lower and the reliability of the complete system higher. It is difficult to quantify the potential benefits of this project except to say that the researcher has made a significant step in the right direction to achieve the potential benefits.

2.20.7 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researcher's overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The developments in this project are marketable when long term reliability has been proven by accelerated age testing. Also the cost and price goals must be realized. Most new photovoltaic installations in California are candidates for the proposed power control subsystem. The researcher was talking to several companies about taking project results to market. At the conclusion of the project US Hybrid had expressed interest in this project.

Engineering/Technical

The design and construction of the 5kW prototype PES and its evaluation fulfills the technical goals of the proposal. Several recommendations for further engineering work are described above. The researcher believes that a product can be ready for market with two years of additional work and approximately $500,000.

Legal/Contractual

The researcher reported that he had received a patent for the work in this project. The patent information is:

> S.K. Mazumder, R.K. Burra, And K. Acharya, "A novel efficient and reliable dc/ac converter for fuel cell power conditioning", USPTO Patent Application number 20050141248, awarded in June 2007.

Environmental, Safety, Risk Assessments/ Quality Plans

Because this project has only generated a prototype and tested it for basic technical performance, there is no Quality Plan, no Reliability Analysis, Failure Mode Analysis, Manufacturability, Cost and Maintainability Analyses, Hazard Analysis, Coordinated Test Plan, and Product Safety and Environmental**.**

Production Readiness/Commercialization

Another round of development is needed before this system is ready for production. Since the researcher is associated with a university he must find an industrial partner that will take the product to production.

2.20.8 Appendix A: Final Report

Submitted under separate cover.

2.20.9 Appendix B: Awardee Rebuttal To Independent Assessment

None submitted.

2.21 Development Of A Wireless Lighting Control Network

Awardee: UC Berkeley

Principal Investigators: Edward Arens, Charlie Huizenga

2.21.1 Abstract

Providing commercial building occupants with control over their individual lighting levels could provide significant energy savings, allowing lights to be turned off when leaving an area, during periods of sufficient ambient lighting from other sources, or in response to either pre-planned or emergency peak demand reduction requirements. Such control is not available in many buildings, and the construction and occupant disruption required to retrofit with wired solutions may not be cost-effective. A distributed lighting control system using mesh wireless technology to allow occupants to control individual lighting fixtures was developed and tested

in this project. The test system was easily installed at each controlled fixture, and substantial on and off-peak reductions in lighting requirements were observed.

Keywords: wireless, lighting control, network, office lighting, distributed control, occupant control

2.21.2 Introduction

Interior lighting represents roughly 35 percent of commercial building[44] electricity use in California.[45] In many buildings, there is little opportunity reduce this usage by turning off unneeded lighting, such as in areas near windows during strong daylight hours, periods of low occupancy, or in rarely-used alcoves or storage areas in an open floor plan. This is due to inadequate controls for this type of selective lighting regulation, especially in older buildings where the cost of re-wiring and control equipment can be uneconomic.

A lower-cost solution using wireless control communications could allow flexible lighting control to be retrofitted in many buildings. This technology could allow individual occupants to adjust their local lighting, and also make it possible for building managers to control large banks of lighting in individual groups, rather than as a whole.

The researcher proposed to utilize research done at UC Berkeley in low-power wireless mesh networking to develop a network capable of controlling individual light fixtures in commercial buildings, and to test a system in an open plan office.

2.21.3 Objectives

The goal of this project was to prove the feasibility of an easy-to-install, lighting control system. The proposed system used low-power wireless transceivers to communicate between wireless switches that affix to partition walls and wireless relay devices that fit into a standard fluorescent fixture. The researchers established the following project objectives:

1. Develop wireless light fixture controllers with electromechanical relays and low-power radios
2. Develop wireless light switches which are interoperable with the wireless lighting fixture controls

[44] Defined as Small Offices, Large Offices, Schools, and Colleges for purposes of this report

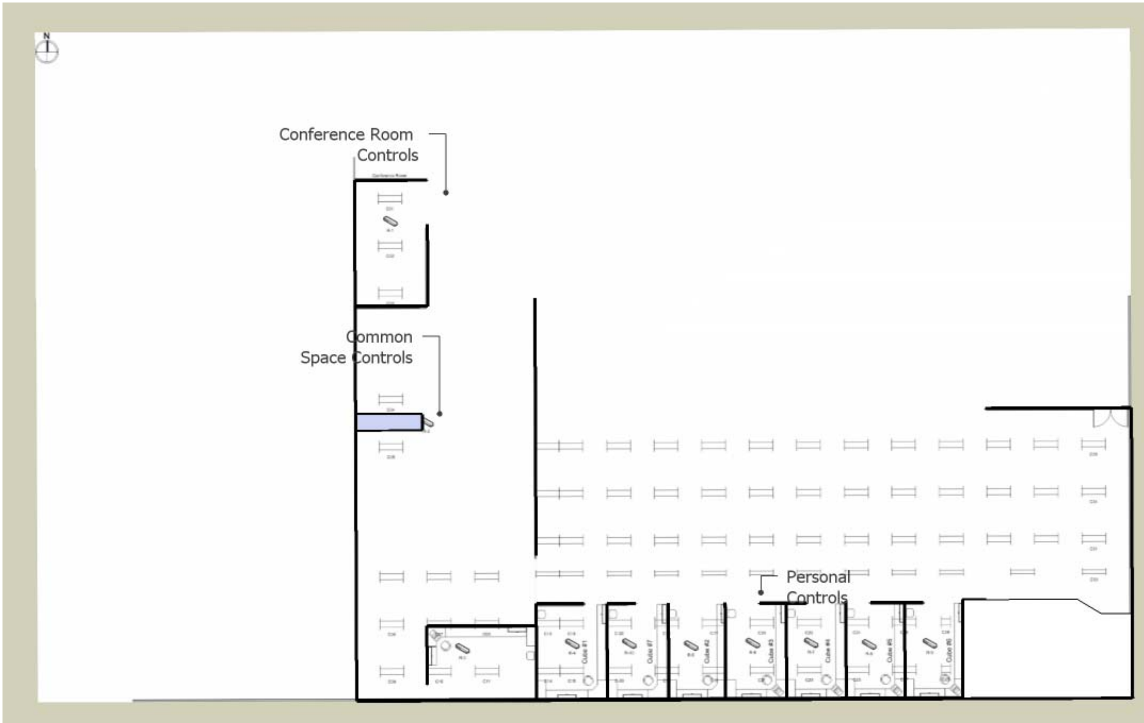
[45] Itron, Inc., "California Commercial End-Use Survey" prepared for the California Energy Commission, March 2006

3. Develop software that makes it possible to program light switches to actuate one or more light fixture controllers
4. Install the system in an open-plan office space
5. Evaluate costs and benefits of the system

2.21.4 Outcomes

1. Forty lighting controllers were built and successfully tested for operation. Schematic design was supplied by a consultant experienced in low-power radio and printed circuit board design and configuration. Components included Shrack 12VDC latching relays, and Crossbow Mica2Dot motes containing the radios and microcontoller (MCU).
2. Ten switches were built for use in the field test. Units were designed with one switch, two-switch, or four-switch configurations depending on where they were to be used. Switch power came from two AA batteries, which provided roughly 45 days of operation.
3. The software code (program) was written to control the micro-controllers and switches. Each controller/switch pair received a unique address prior to installation. A total of eight switches were programmed for occupants in open-plan office cubicles in the field test, with two cases allowing two different occupants to control the same light. In a file alcove, a single switch/controller was programmed to allow lights to be turned on, and automatically turn off after ten minutes. A conference room had a single switch programmed to control three light fixtures
4. The layout of the UC Berkeley open-plan office test site is shown below in Figure 24. The figure shows the locations of the module/switch configurations described in outcome 3.

Figure 24: Test Site Floor Plan


Conference Room Controls
Common Space Controls
Personal Controls

5. A total of 33 controllers were deployed in the field test. Installation of each fixture required an average of six minutes using UC Berkeley facility staff that had no previous experience with the system. Occupants readily understood and used the lighting control switches after a short period of adaptation and experimentation.

   A total energy reduction of 74 percent for all of the fixtures equipped with controllers was observed during the July 18, 2005 – January 9, 2006 field trial, with a 66 percent reduction for the controlled fixtures over individual cubicles. The larger overall reduction resulted from very limited lighting usage in the file alcove and conference room during the test, due to sufficient ambient light from nearby areas.

6. Using the observed overall energy reduction, annual consumption for the controlled fixtures was estimated to be 1,532kWh, compared to an estimated 5,930kWh without controls. This would result in an estimated $638 energy savings at $0.145 per kWh.

   The estimated production cost was $20 per controlled fixture in quantities of 10,000. Assuming an installed sales price of twice the production cost, and an estimated rebate of $0.05 per kWh saved, the test controllers at this location would yield a simple payback of 2.4 years.

2.21.5 Conclusions

The project proved feasibility of using a wireless mesh network to control individual lighting fixtures in a commercial application. Energy savings observed in the limited size field test are not necessarily representative of the potential savings across a wide range of California's commercial building stock. However, the field test and associated estimated production costs suggest that this approach should provide significant energy savings potential from retrofitting existing buildings that lack flexible lighting controls. The researcher identified a number of improvements for the next generation of devices, which would further enhance their commercial viability. These are discussed in the Recommendations section of this report.

Subsequent to this project, a start-up company was formed to commercialize the product. By mid-2008 the company (Adura Technologies) had successfully completed several installations.

1. The controllers were designed and built as planned. Use of prior research at UC Berkeley and an outside expert to produce the schematic ensured an efficient and successful conclusion for this step.
2. The switches were designed and built as planned.
3. The software was successfully designed and installed on the test modules. The decision to allow two users to control a common fixture that provided light to both cubicles helped simulate a typical lighting design. There were no documented occupant issues with the shared control approach.

4. Installation and user training were successful, and exceeded expectations for required installation time.
5. The field test met its objectives. The tests proved significant energy reductions among the test fixtures. In this limited test, all of the cubicles were located on south-facing windows. Consequently, it was not possible to assess the potential savings from cubicles that did not have immediate proximity to window lighting, where the ability to draw from ambient light would be significantly reduced.
6. The energy savings and estimated payback in the field test are impressive, although this small-scale test cannot be used to extrapolate similar savings across a wide range of commercial installations. There are likely to be installations offering lower savings (for example interior cubicles without outside light, OSHA or other minimum lighting code requirements, or task-specific lighting standards which require full illumination at all times), as well as buildings offering opportunities for equivalent or higher savings (for example, installations with only "all-on" or "all off" control of an entire floor's lighting, or where the original lighting design anticipated a high-illumination occupancy requirement and subsequent tenants have lower requirements).

2.21.6 Recommendations

Recommendations for the project are provided below. Since the technology developed in this project is now commercially available, many of these recommendations may have been implemented.

1. Add a second relay to the controller, to permit control of two ballasts in a single fixture, thereby improving flexibility and payback.
2. Enhance switch design so power is only drawn when the switch is activated, thereby extending the short battery life in the project to multiple years.
3. Develop a robust software application to allow customers to access and modify the system via a web-based client.
4. Conduct a wider field trial incorporating different building types and interior layouts to help estimate statewide savings potential. [46]

Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system

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[46] This step is no longer recommended, since the technology is now commercialized. Experience in the marketplace will provide future insights into penetration and build-out potential.

- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. The results in this project suggest that at commercial scale, this technology can yield substantial savings in lighting energy in many commercial buildings. Recognizing that actual savings would vary by building type, purpose, age, and retrofit potential (see item 6 in the Conclusions section above), this research was not intended to yield a thorough analysis of statewide energy savings potential. However, as an illustrative example, retrofitting 25 percent[47] of the four commercial building types identified in footnotes one and two and achieving an average 50 percent reduction in lighting energy would yield a total lighting energy savings of roughly 800 GWh/year. With roughly 10 percent of California's peak demand attributed to interior lighting, the technology should also provide peak reduction benefits in many installations.

2.21.7 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researcher's overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

Since this project was completed, the technology has advanced considerably, and became part of the product offering of Adura Technologies. Adura has successfully completed commercial installations[48], and recently received $5 Million in equity financing.[49] While many of the next steps relevant to the original project have likely been incorporated into Adura's commercial offerings

As with many energy savings technologies, market penetration for lighting control solutions will depend heavily on energy policy, legislation, and rebates.

Engineering/Technical

Underwriters Laboratory certification has been received and the system is in commercial operation at several sites.

Legal/Contractual

The researcher indicated that UC Berkeley has a pending patent on the core technology.

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[47] Continued rebates for lighting retrofits would likely be required to achieve this penetration rate

[48] See, for example http://greenbuildings.berkeley.edu/pdfs/bp2008_berkeley_lighting.pdf

[49] See http://www.aduratech.com/news-seriesa.php

Environmental, Safety, Risk Assessments/ Quality Plans

With the successful receipt of an ETL Listed Mark[50], there do not appear to be any remaining safety issues.

Production Readiness/Commercialization

The system is in commercial production. Adura Technologies has a licensing agreement with UC Berkeley for the core technology.

2.21.8 Appendix A: Final Report

Submitted under separate cover.

2.21.9 Appendix B: Awardee Rebuttal To Independent Assessment

None submitted.

2.22 Phase-Changing Frame Walls for Peak Demand Reduction, Load Shifting, and Energy Conservation in California

Awardee: University of Kansas Center for Research, Inc.

Principal Investigators: Mario A. Medina, Ph.D., P.E.

2.22.1 Abstract

This project evaluated the feasibility of using phase change materials (PCM) within traditional framed wall systems to reduce heat transfer rates across walls. Reduced heat transfer could shift electricity loads attributed to air-conditioning to off-peak hours. PCMs, once encapsulated in copper piping and attached to the studs in a ladder-like configuration, constitute a phase change frame wall (PCFW) system. This project evaluated PCFWs using two small-scale prototypes that varied in the percentage of PCM by unit weight of wallboard. Prototype tests

[50] The ETL Listed Mark is granted by Intertek, recognized by OSHA as a Nationally Recognized Testing Laboratory

indicated that heat transfer did not improve substantially with 20 percent PCM when compared to 10 percent PCM. The researchers then used field test results to calibrate a finite difference model which predicted the heat transfer rate reduction for a 1,700 square foot home, representative of a Title 24 compliant California residence. In contrast to field testing, computer modeling results indicated a significant improvement in heat transfer results by increasing PCM concentration from 10 to 20 percent. Results of the modeling indicated that heat transfer rates could be reduced by approximately 8 to 12 percent in coastal climates and 19 to 27 percent for transitional climates when averaging results from all exterior walls. This translated into a space-cooling load reduction of approximately 10 percent and energy consumption reduction of 7 percent in either climate. The incremental cost of adding PCMs to traditional wall framing systems was $5.35 per square foot of wall surface area, a 3.26 percent increase over traditional systems. The Program Administrator performed a rudimentary cost analysis and determined that the derived benefit of this technology, approximately $90 per year energy saving for a 2,000 square foot residence, did not justify the $12,000 capital outlay to install the system. In addition, this technology is not feasible due to numerous constructability and user acceptance issues including non-standard stud spacing, cripples, wall penetrations, maintenance, and health and safety issues.

Keywords: Framed wall, phase change material, thermal mass, load-shift

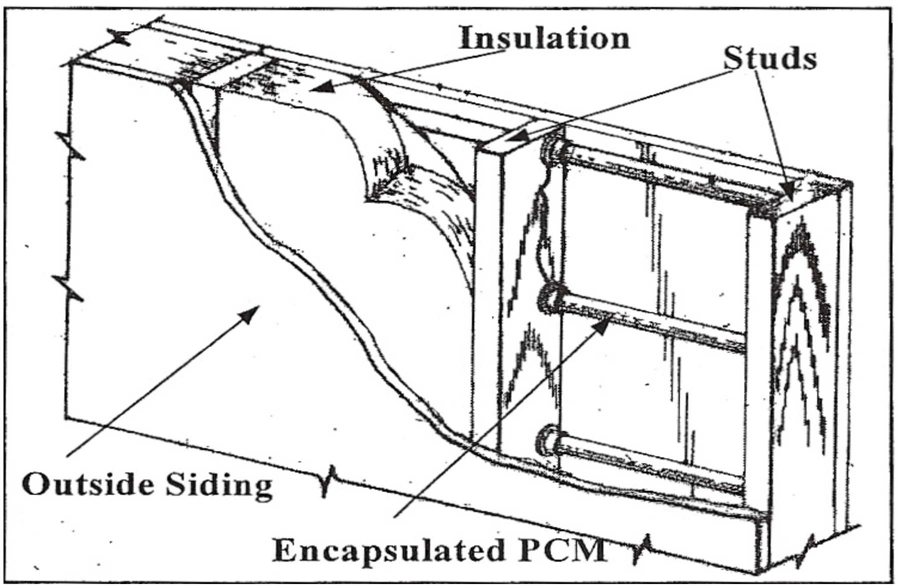
2.22.2 Introduction

The researchers focused on building end-use energy efficiency by using phase change materials (PCM) within the wall system to reduce peak air conditioning demand, shift demand to off-peak times, and conserve energy in California's coastal and transitional climates. Energy supply shortages, increases in energy consumption, and rate increases necessitate the adoption of technologies that will allow the consumer to maximize energy efficiency. This energy efficiency can be realized not only through more energy efficient processes, but also through load leveling. Air conditioning usage is particularly problematic as the demand peaks for all consumers within a region as the day progresses, causing enormous stress on the power grid. Utilities must be able to provide for the worst-case scenario resulting from the air conditioning load, leading to significant unused capacity during off-peak periods.

The proposed technology incorporates PCMs into traditional framed wall systems by encapsulating them in a series of horizontal pipes placed on the interior face of the wall. For purposes of installation the pipes are connected in a ladder-like arrangement with vertical supports attached to the studs prior to erecting drywall as shown in Figure 25. The inclusion of the PCMs within the traditional wall system constitutes the phase change frame walls (PCFWs) as described by the researchers. PCMs are materials that change from solid to liquid and back again as a function of temperature. During the phase change process, heat is absorbed by the PCMs, stored, and then released. The researchers sought to capitalize on the energy absorption and release processes as a means to reduce interior cooling demand and the energy storage process as a means to shift that demand off-peak.

Although this project focused primarily on space cooling within residential construction, the researchers suggested that the benefits can similarly apply to space heating and could also apply to other types of buildings. Based on computer modeling, the researchers anticipated that a 1,700 square foot house within the coastal or transitional climate could experience a decrease in cooling load of about 10 percent and a decrease in cooling related energy usage of 7 percent. They also suggested that usage of PCFWs could shift the peak load by several hours. On a larger scale, the ability to reduce demand and shift peaks allows utilities to reduce operating costs, with resultant savings passed on to the consumer. This reduction in energy usage also leads to a reduction in air pollutant emissions by the utilities.

Figure 25: Section of Phase Change Frame Wall (PCFW)



2.22.3 Objectives

The goal of this project was to determine the feasibility of using PCFWs for peak air conditioning demand reduction, thermal load shifting, and energy conservation in California's coastal and transitional climates. The researchers established the following project tasks and objectives:

1. Fabricate two sets of PCFWs, one set with 10 percent PCM concentration and one set with 15 percent PCM concentration. Percent concentration refers to the amount of PCM by weight in relation to the weight of the indoor wallboard. Prototypes will demonstrate peak wall heat flux reductions of at least 20 percent on average (for example when the heat fluxes from walls facing cardinal directions N, E, W, S are averaged).
2. Conduct prototype testing.

3. Conduct pre-retrofit thermal performance verification of test houses (one to remain as control house and one to be retrofitted after the initial verification testing).

4. Demonstrate that during calibrations the test houses are capable of being controlled as follows: while maintaining indoor air temperatures of 75°F ± 0.3°F, the houses will keep a temperature difference of less than 0.5°F between them, produce wall heat fluxes of less than 3 percent difference between equivalent walls in each house, and produce space-cooling load of less than 3 percent difference between both houses.

5. Conduct field test and data analysis for Swing Season I (October 2004 to November 2004), Winter Season (December 2004 to February 2004), Swing Season II (March 2005 to May 2005), and Summer Season (June 2005 to August 2005). Demonstrate that while the indoor air temperatures are maintained at 75°F ± 0.3°F (except when the indoor air temperature is allowed to fluctuate), the PCFWs will yield a wall heat transfer rate reduction of at least 20 percent on average with a maximum on west-facing walls (greater than 30 percent) and minimum on north-facing walls (not less than 5 percent), a more constant wall temperature over time of at least a 2°F swing less than the control wall, a load shifting of at least 30 percent of the thermal load to off peak times, and comparable levels (less than 5 percent difference) in indoor air humidity between both houses.
6. Refine computer model.
7. Perform model verification. Confirm that the model matches experimental data to within less than 10 percent difference on average. Confirm that PCFWs yield at least a 20 percent heat flux reduction (overall average) in simulated real-world cases.

8. Perform computer simulations. Confirm that overall cooling load is reduced by not less than5 percent, based on wall/ceiling area ratios.

9. Perform parameterization analysis. Confirm that compressor driven air conditioning can be reduced and even eliminated in some areas of California.

10. Perform Cost Analysis. Confirm from the project findings that the projected incremental cost of 0.83 percent increase per square foot for adding PCFWs continues to be supported.
11. Address important issues related to meeting the California Building Code in all respects, including energy[51] (Title 24, Part 6), structural, and safety issues.
12. Provide in-depth economic and market segmentation analyses for the proposed technology.

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[51]. California Energy Commission (2005). *Joint Appendices for the 2005 Building Energy Efficiency Standards for Residential and Nonresidential Buildings*, pg II-24. (http://www.energy.ca.gov/title24/2005standards/2004-10-26_400-03-001JAFM.PDF accessed April 15, 2008)

2.22.4 Outcomes

1. The researchers constructed two prototypes using 10 percent and 20 percent PCM concentrations. The change in concentration resulted from the California Energy Commission's request to use a heavier PCM, TH29, as opposed to the originally proposed and more flammable paraffin-based PCM. The average peak wall heat flux reduction was 27.1 percent for the PCFW at 10 percent concentration and 27.3 percent for the PCFW at 20 percent concentration.
2. The researchers conducted prototype testing of two 6' x 6' x 4' test houses.
   a) Researchers used digital programmable thermostats to maintain indoor air temperatures at 75°F ± 0.3°F. Indoor air temperatures were controlled to within 0.1°F between the two prototype houses. Wall heat flux differences between equivalent walls in each of the cardinal directions for the prototypes were as follows: 4.5 percent north, 3.5 percent south, 3.8 percent east, and 0.5 percent west. Researchers did not present space-cooling load data for the prototypes.

   b) Wall heat transfer rate reductions between the control prototype and the prototype retrofitted with PCFWs for each of the cardinal directions were as follows: 33.7 percent north, 25.6 percent south, 24.3 percent east, and 24.6 percent west, with an average reduction of 27.1 percent. Temperatures within the retrofit house were held more constant than the control house with the following reductions in temperature swing: 2.1°F north, 3.3°F south, 5.0°F east, 0.1°F west, with an average of 2.6°F. The researchers stated load shifting was approximately one hour.
3. The researchers conducted computer modeling.

   a) The computer model matched experimental data within a 13 percent difference. The model under-predicted heat transfer rates. Average peak heat transfer rate reductions for 10 percent concentration were 7.8 percent and 18.6 percent for coastal and transitional climates, respectively. Reductions for 20 percent concentration were 12.2 percent and 26.9 percent for coastal and transitional climates, respectively.

   b) Simulations resulted in a cooling load reduction of 6 percent for coastal climates and 14.3 percent for transitional climates. Simulations of the winter season resulted in a heating load reduction of 13.5 percent for both climates.

   c) Parametric analysis of the computer model resulted in a reduction in consumption of 7.2 percent which would allow compressor driven air conditioning to be reduced by 1/3 ton.
4. The researchers determined that inclusion of PCM and piping within the wall system increased construction costs by $5.35 per square foot of wall area. This is a 3.26 percent per square foot of wall area increase over traditional wall construction.
5. The researchers used EnergyPro software during the modeling process to ensure that the modeled home met California Title 24 requirements.

6. The researchers did not report market and segment analysis results.

2.22.5 Conclusions

1 .Because a heavier PCM (TH29 requested by the Energy Commission) would result in a smaller volumetric difference compared to the lighter originally proposed paraffin-based substance when going from 10 to 15 percent, the researchers were justified in modifying the original prototype PCM concentrations to 10 and 20 percent to provide a more significant difference between prototype models. Both prototypes met the performance objective for reduction in peak wall heat flux of at least 20 percent.

2 .Although the researchers reported that testing was done throughout the course of one year, data within the report are only presented for the summer season. Given that the phase change temperature of TH29, reported as 28 to 30°C (82 to 86°F), and the average maximum temperature for Riverside FS3, representative of the warmest climates zone studied, does not exceed 82° between the eight months from November to May,[52] it is highly unlikely that incorporation of PCFWs would be beneficial or relevant for any season other than summer in the transitional zone. The range of applicability for the more temperate coastal zone would necessarily be even less than for the transitional zone. Although an argument could be made that PCFWs could assist in maintaining heating within the interior of the building during the winter months, just as it is used to maintain the heat on the exterior of the building during the summer months, it would be highly unusual to find buildings heated in the winter within range of the phase change temperature of TH29. These issues are perhaps the reason that data were only presented by the researchers for the summer season. Such limited applicability presents a significant obstacle for this technology and the selected PCM.

   a) The digital programmable thermostats did not allow for temperature control within the original target of 75 ± 0.3°F. The researchers determined such control was not feasible given current systems and testing conditions. Temperature differences between the two prototypes were well within the goal of 0.5°F. Only west-facing walls met the objective of less than 3 percent difference in wall heat flux for the prototypes. Space-cooling load data for the prototypes were not presented for comparison with project objectives.

   b) The wall heat transfer average rate reduction of 27.1 percent exceeded the goal of 20 percent. The west-facing wall reduction of 33.7 percent exceeded the goal of 30 percent, and the north-facing wall reduction of 25.6 percent exceeded the goal of 5 percent. The average temperature swing between the control and retrofit prototypes

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[52]. Western Regional Climate Center, Riverside Fire Station 3, California (047470). *Period of Record Monthly Climate Summary, 1/1/1893 to 12/31/2007*. (http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca7470 accessed April 15, 2008)

was held within the proposed 2°F. The researchers did not present data to support the load shifting capabilities of PCFWs. Although it may be possible for a one hour shift to occur, this limited shifting ability is not likely to decrease the capacity requirements facing power providers.

3. The researchers did not disclose the name or nature of the computer model used. They described the model as a FORTRAN program that used an iterative process to predict temperatures and heat fluxes using finite difference principles. The researchers did not state the equations solved and presented no information about the type of difference formulation or the time step and stability parameters used to allow the model to be evaluated. Therefore, the Program Administrator could not evaluate the relevance or acceptability of the model used. Nevertheless, the assumptions used for the model are questionable. The researchers minimized the impact that the one inch diameter PCM-filled copper piping system would have on the configuration of the R-11 fiberglass batt insulation within the wall system. The pipes are located on the inside facing wall, with insulation batting behind them, presenting two significant issues. First, the facing on the batt will abut the piping system, causing the insulation to bridge between pipes. Insulation will not fill the spaces between pipes as assumed in the model because of this bridging. Second, the bridging effect will result in compression of the fiberglass batting as it must now be contained in a space 2.5 inches wide, rather than the full 3.5 inches. Compression has been shown to decrease insulation effectiveness from R-11 to R-8.9, [53] counteracting any benefits that might be derived from the PCMs. Considering the larger picture, the Program Administrator is concerned about the accuracy with which computer modeling can be used to extend the results based on the simple single-story, single room prototype to the 1,760 square foot, two-story slab-on grade house which was modeled.

   a) The researchers did not meet the objective to match prototype heat transfer data within 10 percent. The average peak heat transfer rate reduction met project objectives only for 20 percent concentration PCFWs in the transitional climate. The three remaining scenarios fell far short of the project objective. Whereas prototype testing revealed that the incremental benefit of increasing PCM concentrations from 10 to 20 percent was not warranted, computer modeling results showed the opposite. Peak heat transfer rate reductions were approximately twice as great when modeling the 20 percent PCFWs.

   b) The researchers met the objective for overall cooling load reduction. No prototype data or other evidence was presented to support the claim that heating load reduction can be achieved using this technology. The researchers did not analyze the prototype for winter months, nor did they validate the computer model using winter data.

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[53]. Owens Corning. *Insulation R-Values When Compressed in Framing Cavity*. (http://www.owenscorning.com/around/insulation/compressionchart.xls accessed April 15, 2008)

c) Although the simulations did show a reduction in energy consumption, the reduction was relatively minor and was not significant enough to eliminate the need for compressor driven air conditioning.

4. Although the researchers did not quantify the cost savings from the addition of PCFWs, the relative benefit derived from the PCFWs does not justify the 3.26 percent per square foot increase in cost. The Program Administrator assembled a ball-park cost estimate by considering that a typical 2,000 square foot home has approximately 2,300 square feet in exterior wall surface area. The incremental cost increase of the PCFWs is $5.35 times 2,300 square feet for a total of approximately $12,000. According to the researchers, addition of the PCFWs could reduce air conditioning energy consumption by 7.2 percent. The Program Administrator believes that this energy savings realistically would only apply to the summer months. Assuming a conservative average summer air conditioning expense of $300 per month for four months, the 7.2 percent savings over these four months totals approximately $90, resulting in an unacceptably long payback period. This problem is compounded by the lack of discussion of the service life of the PCM and/or ongoing maintenance needs (or costs).

5. The researchers briefly discussed constructability issues, minimizing what the Program Administrator believes to be the single largest barrier to the feasibility of the proposed technology. The researchers failed to address the impact of non-standard wall sizing, tolerances, cripples, coordination of plumbing, electrical and HVAC penetrations, construction inspection, or health and safety issues related to use of PCMs. Furthermore, health, safety, and construction issues are not eliminated upon completion of construction. Rather, these issues present themselves each time the homeowner hangs a picture or performs home improvements.

6. Although the researchers did not report market and segment analyses, the Program Administrator suggests that significant user acceptance issues would be revealed by such an analysis for the constructability and economic issues previously noted. The path to market will most certainly take a different direction than proposed herein, and will likely encounter significant obstacles.

2.22.6 Recommendations

Due to constructability issues, the researchers recommended alternate delivery mechanisms for the PCMs in the wall system, such as coating cellulose insulation with PCMs. While the researchers recognized the impracticality of the technology proposed in the final report, the researchers' recommended proposition is an entirely new technology that should not be considered an extension of the existing research. The technology proposed in this report is impractical, costly, and demonstrated only meager benefits to consumers and power providers.

Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. The potential reduction in space-cooling energy consumption of 7.2 percent translates into an annual savings of approximately $90 per household. Because of construction costs and other issues discussed in the Recommendation section above, the Program Administrator finds it unlikely that this technology will reach the marketplace and provide benefits to California ratepayers.

2.22.7 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The PCFW system is not sufficiently feasible or mature for development of a marketing plan, and the researchers have not developed one. The researchers have not yet identified products similar to the proposed technology.

Engineering/Technical

No additional work is this area has been reported.

Legal/Contractual

The researchers performed a patent search and applied for a patent for the technology.

Environmental, Safety, Risk Assessments/ Quality Plans

Because of technology immaturity, these plans have not been developed.

Production Readiness/Commercialization

The researchers reported the existence of a commercialization plan. They acknowledged that acceptance by the public is a significant commercialization risk.

2.22.8 Appendix A: Final Report

Submitted under separate cover.

2.22.9 Appendix B: Awardee Rebuttal To Independent Assessment

None submitted.

2.23 Bio-Solar Conversion Of Carbon Dioxide Into Hydrogen Via Bacteria Embedded In Colloidal Gas Aphrons

Awardee: University of California, Los Angeles

Principal Investigators: Dr. Laurent Pilon

2.23.1 Abstract

The goal of this project was to prove the feasibility of producing an affordable, efficient, and scalable photo-bioreactor for producing hydrogen from microbial reduction of carbon dioxide. The researchers focused on the design and optimization of a bio-solar panel using *Anabaena variabilis* consuming light and carbon dioxide as its energy and carbon sources, respectively, and producing hydrogen and oxygen. The researchers established that *Anabaena variabilis* can produce O_2 and H_2 simultaneously in a one stage batch reactor with a CO_2 and argon mixture. They reported metabolic behavior for a wide range of irradiances and CO_2 concentrations. However, even under optimum conditions, the H_2 production rate was much smaller than in a two stage reactor. The researchers described a simulation tool accounting for light transfer; cyano-bacterial growth; and CO_2, H_2, and O_2 mass conservation in photo-bioreactors containing cyano-bacteria and bubbles. They introduced bubbles to stir the reactor, deliver CO_2, and remove O_2 and H_2 gases. They sought optimum reactor thickness, bubble volume fraction, and bubble radius by maximizing the biomass and energy efficiencies. With that information, the researchers assembled and operated the optimum bio-solar panel in two stages. First, CO_2 was converted into biomass. Then they sparged the reactor with argon. The reactor produced hydrogen and oxygen. The light to biomass and the light to hydrogen energy conversion efficiencies observed experimentally are in agreement or slightly better than previously reported data. The researchers recommended additional reactor designs.

Keywords: *Anabaena variabilis*, cyano-bacteria, hydrogen production, carbon dioxide mitigation, photo-bioreactor modeling, batch reactor, photosynthesis

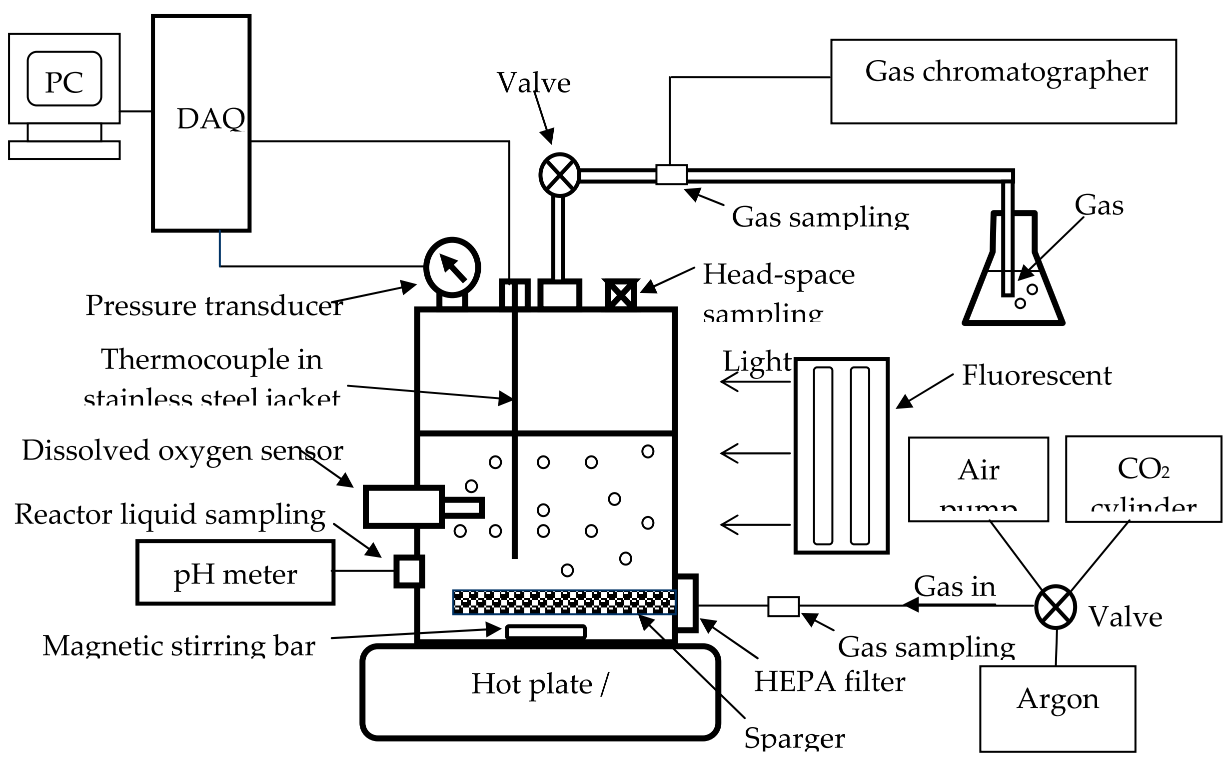
2.23.2 Introduction

California has a policy of reducing carbon dioxide emissions from all sources. Power plants fueled by carbon based fuels produce large quantities of CO_2. If the carbon dioxide could be separated from the exhaust stream, a second problem exists. How does one sequester the large quantities of CO_2 gas? The challenge of sequestering large quantities of carbon dioxide would be greatly reduced if one could convert it to useful by-products.

Researchers proposed cyano-bacteria based photo-bioreactors to convert CO_2 into hydrogen (H_2), oxygen (O_2), and bacterial biomass using solar energy. This conversion could consume about 80 million metric tons of CO_2 emitted from electricity generators located in California.

The process used to convert CO_2 consisted of a bio-solar panel using the commercially available cyano-bacteria, *Anabaena variabilis*. When CO_2 is bubbled through this photo-bioreactor the cyano-bacteria and solar energy convert the CO_2 into H_2 with O_2 and biomass by-products. Figure 26 shows a schematic of the test apparatus. The researchers optimized the parameters of the bacterial conversion.

Figure 26. Schematic of a Single Test Panel Bio-Solar CO_2 Converter.



2.23.3 Objectives

The goal of this project was to prove the feasibility of a photo-bioreactor to produce hydrogen from the microbial reduction of carbon dioxide. It focused on the design and optimization of a bio-solar panel using the cyano-bacteria *Anabaena variabilis* consuming light and carbon dioxide as its energy and carbon sources, respectively, and producing hydrogen and oxygen. The researchers established the following project objectives:

1. Define the optimum bacteria, liquid phase composition, gas concentration, and light intensity for bacteria growth and the metabolism for optimum H_2 and O_2 production.
2. Demonstrate the feasibility and operability of the proposed concept with a scaled prototype. Build a prototype 12 cm wide and 25 cm high. Determine thickness through system modeling and optimization. Demonstrate hydrogen production rate for the prototype photo-bioreactor at 2 L/h/L.
3. Demonstrate the proposed process is capable of converting 25 vol. percent of CO_2 intoH_2.
4. Develop a model to predict the experimental data within an error of ± 20 percent.
5. Offer final recommendation for design of the overall integrated unit design (conversion unit and fuel cell).
6. Perform scalability, manufacturability, and cost analyses of the subscale-integrated system.

2.23.4 Outcomes

1. The researchers proved that *Anabaena variabilis* can produce O_2 and H_2 simultaneously in a one stage batch reactor. They injected a mixture of argon (Ar) and CO_2 gases under irradiance greater than 10,000 lux. The optimum gas mixture was 5 vol. percent in Ar. Irradiance larger than 10,000 lux had no significant effect. However, under these optimum conditions the H_2 production rate was much smaller than in a two stage reactor.
2. The researchers assembled a 12 cm wide and 25 cm high photo-bioreactor prototype made of Plexiglas and operated it in a two stage process. They determined the optimal width at 4.5 cm. First, a mixture of 95 percent air and 5 percent CO_2 was continuously sparged into the reactor. The CO_2 consumption resulted in bacterial growth and biomass production. Once the nitrate concentration vanished, injecting argon bubbles provided enough interfacial area to remove the photo-synthetically produced O_2 and initiate the hydrogen production phase. Researchers maintained the temperature of the bio-solar panel at 30^{o}C ±1°C. The light to biomass energy conversion efficiency achieved experimentally was 10 percent. The maximum light to H_2 conversion efficiency attained by the bio-solar panel was 0.25 percent as compared with the theoretical maximum light to H_2 efficiency for cyano-bacteria using nitro-genase enzyme of 20.3 percent. The efficiencies were mainly limited by inhibition of the H_2 producing enzymes by the presence of O_2 and consumption of the produced H_2 by the cyano-bacteria in the presence of O_2 which was also produced by the cyano-bacteria. The

biomass yield based on consumed CO_2 was 0.39 kg dry cell/kg CO_2 consumed. The expected hydrogen production of 2L/h/L was not achieved. Because of the cell density limitation to 3.5 kg dry cell/m3 (compared with 70 kg dry cell/m3 needed for 24 h/L), the modified expected goal for photo-biological H_2 production rate was only 100 ml/h/L.

3. Compared with the maximum reported CO_2 to H_2 conversion of 15 vol. percent , the two stage photo-bioreactor converted only 1 vol. percent of the total CO_2 supplied and only 13 vol. percent of the CO_2 consumed by the cyano-bacteria into H_2.

4. The researchers developed a general simulation tool to simulate light transfer; cyano-bacterial growth; and CO_2, H_2, and O_2 mass transfer in a photo-bioreactor containing *Anabaena variabilis* and bubbles. This tool also computed the solar conversion efficiency into biomass and H_2 to assess the photo-bioreactor's performance. Researchers solved the steady state one-dimensional radiation transfer equation using the modified characteristics. Parameters studied included the bacteria concentration X, the interfacial area concentration A_i, and the scattering phase function. Finally, the model could be used in conjunction with mass transfer and microorganism growth models to design and optimize the reactor geometry and the sparging conditions for maximum hydrogen production and carbon dioxide consumption by bacteria.

5. Researchers recommended design improvements.

6. The researchers estimated the cost for scaling up the hardware and agitation devices using the best design to be roughly \$170 per m^2. The reactor should cost about \$1 per m^2 for photo-biological H_2 production to be competitive with other H_2 production technologies. The high cost is due to the slow H_2 production rates associated with photo-biological systems.

2.23.5 Conclusions

1. The two stage photo-bioreactor using *Anabaena variabilis* is more efficient that a single stage reactor for both H_2 production and O_2 mitigation.

2. The hydrogen production rates were only 5 percent of the expected rate. Further refinements are required to improve the operation's performance.

3. The conversion of CO_2 to H_2 was very low compared to expectations, about 25 percent of the optimal rate. Further improvements are required to bring this value up to acceptability.

4. The computer model developed combined with precise knowledge of the metabolism of the bacteria can be a very useful tool in design, scale-up, operation, and control of photo-bioreactors at industrial scale.

5. The researchers offered recommendations regarding design improvements to increase efficiency of light to H_2 conversion and CO_2 consumption. However, they wrote nothing about the integration of fuel cells.

6. The scale-up to industrial size based on this research is much too expensive ($170/mL) compared with the cost requirement ($1/m2) to be competitive.

In summary, researchers proved the concept of CO_2 conversion to H_2 in photo-bioreactors, but at a much lower conversion rate than is required for economic viability.

2.23.6 Recommendations

1. Improve the productivity of the cyano-bacteria through genetic engineering to achieve economic efficiencies and reliability.
2. Characterize the optical and metabolic behavior of the genetically engineered cyano-bacteria.
3. Develop a photo-bioreactor that allows light to penetrate deeper.
4. Experiment with alternate micro-organisms such as spiralina and purple photo-synthetic bacteria to enhance the efficiencies of H_2 production.

Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research would be in the reduced environmental impact of the California electricity supply by reducing CO_2 emission from fossil power plants by converting the CO_2 to H_2. If the project were successful, as much as 80 million metric tons of CO_2 could be absorbed and converted to H_2 annually.

2.23.7 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers had not surveyed potential customers for interest in a product based on this technology. They had not performed a market analysis.

Engineering/Technical

The researchers estimated it would take 5 to 10 years to complete product development and demonstration. They indicated they were working with partners to genetically engineer the desired bacteria.

Legal/Contractual

At the close of this project, the researchers reported they had not conducted a patent search, applied for any patents, nor published any paper describing this concept.

Environmental, Safety, Risk Assessments/ Quality Plans

If genetically modified bacteria are used, the researchers must assess the toxicity before they can be used at an industrial scale. Regulations to use such bacteria may be a commercial barrier.

Production Readiness/Commercialization

The researchers reported that venture capitalists were evaluating this process.

2.23.8 Appendix A: Final Report

Submitted under separate cover.

2.23.9 Appendix B: Awardee Rebuttal To Independent Assessment

None submitted.

2.24 Efficient Lighting by Sensing and Actuating with MEMS "Smart Dust" MOTES: A Feasibility Study

Awardee: University of California, Berkeley

Principal Investigators: Alice Agogino

2.24.1 Abstract

Lighting control in many commercial settings is limited to on and off, providing no ability to save energy by taking advantage of day lighting or occupant preferences for lower light levels, or to easily reduce light levels if energy costs rise. Occupant/motion sensors partially address this problem, but do not work well in multi-office environments.

The researcher hypothesized that if a large number of MEMS (microelectronic mechanical systems) devices could be scattered in a commercial environment, and if the feedback from the devices could be used to control the light output of the luminaries, then the resulting fine control of the lighting would provide dramatically better energy performance than currently available systems. The resulting system would increase the efficiency of office lighting, which accounts for a significant fraction of the electricity used by commercial buildings.

This research has demonstrated the technical feasibility of using MEMS devices for sensing, actuating, and personalizing dimmable fluorescent lighting systems at proof of concept level. The researchers present convincing arguments that the mote-based sensing and actuation system is capable of accomplishing the desired functions. A minor technical challenge in packet loss due to shielding in code-approved installations arose, but the researchers' proposed solution to this problem is likely to be effective. However, the technology does not appear to be economically feasible based on the researchers' estimates of the production costs of the system. The researchers suggest that the costs may be dramatically reduced over their current production estimates based on future technology developments, but the dimming ballasts remain a significant cost. However, the researchers also suggest that developing technologies in wireless actuation of dimming ballasts might further reduce system costs. Based on these arguments, the production cost estimates can only be accepted as order-of-magnitude accuracy, leaving open the possibility that reasonable payback periods could arise in the future.

Keywords: lighting control, MEMS, dimmable fluorescent lighting, personal lighting level, energy efficiency, reduced lighting cost

2.24.2 Introduction

The researchers addressed the problem of sensing and varying light levels in a commercial setting. Lighting control in many commercial settings is limited to on and off, providing no ability to save energy by taking advantage of day lighting or occupant preferences for lower light levels, or to easily reduce light levels if energy costs rise. Occupant/motion sensors partially address this problem, but do not work well in multi-office environments.

In this project the researcher set out to develop a low-cost, affordable system to sense light levels. The projected system would obtain data on occupant preferred light levels and modify light emitted by individual luminaires to optimize light distribution accordingly. The researcher proposed to address the problem using so-called "smart dust motes" (technically known as microelectronic mechanical systems or MEMS) to sense and vary the light levels. MEMS devices combine electronic and mechanical components etched in a silicon substrate, resulting in a very small, potentially inexpensive device.

The researcher hypothesized that if a large number of these devices could be scattered in a commercial environment, and if the feedback from the devices could be used to control the light output of the luminaries, the resulting fine control of the lighting would provide dramatically better energy performance than currently available systems. The resulting system would thus increase the efficiency of office lighting, which accounts for a significant fraction of the electricity used by commercial buildings.

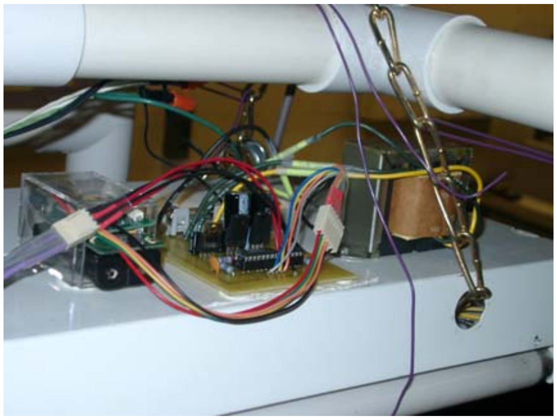
Based on their results in this project and publicly available statistics on electrical usage in California, the researcher estimated that electrical usage for office lighting could be reduced by approximately 55 percent, corresponding to about 2370 GWh in 2002. (A GWh is one thousand megawatt hours.) This calculation relied on a series of assumptions and extension of the results of this research to all commercial space in California, which obviously requires that the economics of the devices and the control system be extremely compelling, both for new construction and retrofitting. With sufficient market penetration the potential benefits could be very large. Commercial interior lighting accounted for 11 percent[54] of the peak demand in California in the year 2005. A 55 percent reduction in lighting demand could have up to a five percent drop in total electricity demand during peak periods.

MEMS technologies are frequently suggested for the development of low-cost distributed sensor networks with rich input data streams. However, this promise is yet to be realized because of the many prerequisite developments required. These include the supporting software and hardware to receive the sensor data and the control technologies for the energy application of interest (in this case, office fluorescent lighting systems). Therefore, the researchers proposed a feasibility project to design, fabricate, and test a MEMS-based fluorescent lighting control system, and determine its costs and potential energy savings.

The experimental apparatus for this project is shown in Figure 27 The receiver/actuator is shown on top of the luminaire in Figure 27a.

[54] www.energy.ca.gov/electricity/peak_load.html

Figure 27: (a) Actuation Hardware (b) Prototype Dimmable Lighting System

- 
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- *(a)*
- *(b)*

2.24.3 Objectives

The goal of this project was to prove the feasibility of using MEMS devices for sensing, actuating, and personalizing dimmable fluorescent lighting systems. The researcher established the following project objectives:

1. Design the mote-based lighting actuation module to include in a prototype open loop lighting actuation system.
2. Demonstrate technical feasibility for open-loop mote-based actuation. For a system without sensory feedback, demonstrate ability to steadily dim and maintain electric light at different distinct levels in response to wireless actuation commands.
3. Revise design according to results of open-loop experiments targeting maintenance of work surface illuminance within 15 percent of set point.
4. Measure power consumption of motes to support estimation of battery life for actuation module assuming a 14 hour per day, five day work week.
5. Complete the value function of the influence diagram decision-making engine, and set sensor quantity for sensor fusion and closed loop actuation and control.
6. Revise closed-loop, mote-based sensing and actuation system to build and install a prototype.

7. Obtain building manager approval to install the prototype, and use it to demonstrate that it is technically feasible to actuate light according to the set value without failure for 14 hours.
8. Obtain human subjects approval to expand testing to include use by human subjects.
9. Demonstrate system technically feasibility, and usability with human manual and software control over an extended time period.
10. Analyze data against benchmark to determine feasibility and potential energy savings.
11. Calculate the potential costs and benefits of the mote-based sensing and actuation system, targeting a two year payback period.

2.24.4 Outcomes

1. The researchers designed and constructed a prototype open-loop system. The system was constructed with 16 light settings, using all possible combinations (states) of the four input/output ports on the mote.
2. The researchers actuated the light setting for the prototype system among the 16 states, both along a pre-programmed schedule and with wireless actuation signals. However, they discovered in this process that three of the 16 states were indistinguishable, leading to some changes in the state definitions.
3. The researchers discovered that the dimming ballasts they used exhibited a hysteretic relationship between light output and input voltage. Further, they discovered that different ballasts exhibited different slopes for this relationship. This hysteresis and slope variability is important because it means that one cannot know the actual light output simply by knowing the input voltage applied. That means, in turn, the light intensity at a given surface cannot be controlled without a feedback loop from the actual light intensity provided, a more complicated control algorithm. As a result, the researcher revised the actuating module to correct for these problems. The device regulated work surface illuminance to within plus or minus five percent of the set point.
4. The researchers measured current draw and voltage for the motes, and used them to estimate a battery life of 14.8 months, assuming 14 hour days, five days per week.
5. The researchers conducted a literature review and interviewed and/or surveyed facilities managers to confirm their influence diagram and value function. The survey they conducted had a very small number of respondents (10), far too small to support statistical expansion to the overall population. Nonetheless, the researchers relied upon the feedback they received to modify their influence diagram, most importantly by adding the ability to provide additional dimming in response to electric rate changes.
6. The researchers designed and constructed a prototype closed-loop system. As they ran experiments with this prototype system, they discovered a need to increase setting resolution to more than 16 states and to improve the controller efficiency. The researchers modified the design and the prototype based on these findings.
7. The researchers obtained the necessary permissions and installed the prototype system. They operated the system for 17 hours without failure, and demonstrated that the system could maintain work surface illuminance within five percent of a constant set point over

that period. Additionally, they demonstrated the ability to track a moving set point within three percent over a 50-minute experiment. In preparation for this step, they recognized a need to provide on/off control in addition to dimming, and fabricated a control panel to allow users to select functionality.

8. The researchers developed a test plan to allow human subjects to use the lighting system in an office setting. They established the objectives of comparing user satisfaction and performance of the mote-based system with a commercially available day lighting sensor/dimming system (in this case, the Watt Stopper LS-301). The researchers planned to observe users interactions with the mote-based system. The researchers obtained the necessary permission to allow testing to proceed, and installed the system in a small office with a window. The Watt Stopper system was installed in the same office. They observed some packet loss problems with the system installed according to applicable codes. They were able to partially overcome these problems with mote relocation, but suggested that there were still challenges to overcome in this area. Generally speaking "packet loss" is a loss of some portion of the data.
9. The researchers tested the system with human occupants, and demonstrated that it could provide lighting levels stable enough to support their activities and that they could interact with the system to register their preferences. The human subject tests included use of the system by human occupants for only 20 minutes. The degree to which this represents an "extended time period" is arguable. The researchers did not conduct experiments sufficiently long or numerous to address their additional goals of comparing user satisfaction with the commercially available system or understanding how users interacted with the mote-based system. They recommended additional human subject testing to address these goals.
10. The researchers collected energy use data during system operations, and projected system hardware costs (both for the prototype and a theoretical production environment). Based on energy use data, the researchers determined that energy savings from the system were feasible, and calculated potential energy savings of 23 percent per year (or about $40 per year) for a 150 square meter office, compared to a non-dimming system.
11. The researcher estimated potential benefits for a system in a 150 square meter office at approximately $40/year, and a potential cost in a production environment of approximately $1875. This resulted in a simple payback of more than 45 years.

2.24.5 Conclusions

1. The researchers completed this goal satisfactorily.
2. Using this system, the researchers demonstrated the technical feasibility of open-loop mote-based actuation.
3. The researchers easily met this goal.
4. The researchers had no quantitative goal at the beginning of this project. The project administrator accepts the 14 month battery life as proof of feasibility in this area.
5. The researchers completed the value function of their influence diagram decision-making engine, and set sensor quantity for sensor fusion and closed loop actuation and control.

6. The researchers refined their design of a closed-loop, mote-based sensing and actuation system, and then built and installed a prototype.
7. The researchers demonstrated that it is technically feasible to actuate light according to the fused value without failure for 14 hours with the closed-loop system.
8. The researchers successfully completed this task.
9. Through short-term human subject testing, while successful, was not sufficiently long to prove feasibility of the approach.
10. The researchers obtained and analyzed cost and energy savings data against a benchmark of an undimmed system, to determine feasibility and potential energy savings.
11. The project did not meet its goal of a two year simple payback.

This research demonstrated the technical feasibility of using MEMS devices for sensing, actuating, and personalizing dimmable fluorescent lighting systems, at proof of concept level. The researchers present arguments that the mote-based sensing and actuation system is capable of accomplishing the desired functions. A minor technical challenge in packet loss due to shielding in code-approved installations arose, but the researchers' proposed solution to this problem is likely to be effective. However, the technology does not appear to be economically feasible based on the researchers' estimates of the production costs of the system.

The researchers suggest that the costs may be dramatically reduced over their current production estimates based on future technology developments, but the dimming ballasts remain a significant cost. However, the researchers also suggest that developing technologies in wireless actuation of dimming ballasts might further reduce system costs. Based on these arguments, the production cost estimates can only be accepted as order-of-magnitude accuracy, leaving open the possibility that reasonable payback periods could arise in the future.

2.24.6 Recommendations

The researcher should continue to test the system with human subjects. Packet loss problems must be addressed. Most important, the researcher should address the cost/benefit issue. Without significant cost reductions this system will not fare well in the marketplace. Any additional research work must place a large emphasis on cost reduction. In addition, the researcher should conduct a market assessment. That assessment should not only include the size of the market, but also competing technologies. The assessment of competing technologies should include the probable time to market for each and the segment of the market that each may dominate. The researcher could then develop a timeline for development that clearly shows the market opportunity window that must be targeted to achieve a significant market position. Another key part of a market assessment is to determine the percentage of commercial space having access to daylight.

Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply or transmission or distribution system. The reduction in impacts arises from a reduction of electrical energy use for commercial lighting. The potential reduction is quite significant. The researchers calculated office electrical lighting demand reduction of approximately 55 percent, assuming widespread adoption in California and incorporating a series of assumptions about the operating characteristics of the office space. In 2002, this reduction would have corresponded to approximately 2370 GWh of avoided electrical energy use and up to a five percent demand reduction. Because of the immature nature of the technology in this project, other solutions may come to the market before the project technology is commercialized. Already the Watt Stopper LS-301 is available in the marketplace. That device promises to deliver many of the same benefits.

2.24.7 Overall Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researcher's overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The mote-based light sensing and actuation system was not sufficiently mature for development of a marketing plan, and the researchers had not developed one. Since the project completion, the researchers have had contact with commercial lighting companies to discuss the possibility of commercialization. The researchers are publishing extensively in technical and professional literature and presenting this technology in relevant meetings and conferences. Because the researchers are working in a significant energy problem area, other scientists are seeking solutions in the same space. It is critical that the researcher in this project continually review the benefits of their solution vis a vis the competition.

Engineering/Technical

Through a serried of experiments, the researchers showed that a system could be designed and built, and that it could function satisfactorily. The primary challenges remaining include the reliability, size, and price of the motes and continued refinement of the control software.

Test participants have noted the large size of the current sensors as a negative. Task-oriented sensors (light sensors) with much smaller sizes have to be adopted before this technology can be commercialized. This task would require collaboration with mote platform manufacturers. Human testing also revealed the fused lighting readings did not match the perception of the users when they selected a customized setting. The researcher has launched an effort to develop auxiliary algorithms to accommodate these uncertainties.

Legal/Contractual

A formal patent search has not been reported. The researchers reported their intention to keep related intellectual property in the public domain.

Environmental, Safety, Risk Assessments/ Quality Plans

Because of technology immaturity, the plans have not been developed.

Production Readiness/Commercialization

The mote-based light sensing and actuation system is not sufficiently mature for commercialization. The researchers have not developed a commercialization plan.

2.24.8 Appendix A: Final Report

Submitted under separate cover.

2.24.9 Appendix B: Awardee Rebuttal To Independent Assessment

None submitted.