Energy Research and Development Division
FINAL PROJECT REPORT

ENERGY INNOVATIONS SMALL GRANT PROGRAM: 2009 INDEPENDENT ASSESSMENT REPORTS

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

San Diego State University
Research Foundation
Science • Service • Solutions

MAY 2014
CEC-500-2014-065

PREPARED BY:

Primary Author:
Rob Queen, Project Manager

San Diego State Research Foundation
5250 Campanile Drive,
San Diego, CA 92182-1858
(619) 594-1900

Contract Number: 500-98-014

Prepared for:

California Energy Commission

Raquel Kravitz
Program Manager

Mike Gravely
Office Manager
Energy Systems Research Office

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

DISCLAIMER

This report was prepared as the result of work sponsored by the California Energy Commission. It does not necessarily represent the views of the Energy Commission, its employees or the State of California. The Energy Commission, the State of California, its employees, contractors and subcontractors make no warrant, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the uses of this information will not infringe upon privately owned rights. This report has not been approved or disapproved by the California Energy Commission nor has the California Energy Commission passed upon the accuracy or adequacy of the information in this report.

PREFACE

The California Energy Commission Energy Research and Development Division 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 Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division 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.

Energy Research and Development Division 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: 2009 Independent Assessment Reports is the final 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 Energy Research and Development Division's Programs.

When the source of a table, figure or photo is not otherwise credited, it is the work of the author of the report.

For more information about the Energy Research and Development Division, 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 EISG program supports early phase development of promising new energy technology concepts. 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 research and development funding may become available to further develop the project.

Independent Assessment Reports 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 21 independent assessment reports for EISG grant projects awarded during 2009.

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

Please use the following citation for this report:

Queen, Robert. (San Diego State University Research Foundation). 2014. ***Energy Innovations Small Grant Program: 2009 Independent Assessment Reports.*** California Energy Commission. Publication number: CEC-500-2014-065.

TABLE OF CONTENTS

PREFACE i

ABSTRACT ii

TABLE OF CONTENTS iii

LIST OF FIGURES x

LIST OF TABLES xi

EXECUTIVE SUMMARY 1

CHAPTER 1: Introduction 2

CHAPTER 2: 2009 Independent Assessment Reports 4

2.1 Low Cost Energy Storage for Solar Thermal Power Plant 4

2.1.1 Abstract 4

2.1.2 Introduction 5

2.1.3 Objectives 7

2.1.4 Outcomes 8

2.1.5 Conclusions 8

2.1.6 Recommendations 9

2.1.7 Benefits to California 10

2.1.8 Technology Transition Assessment 11

2.2 Wind Power Generation on High-Rise Buildings in Urban Centers 12

2.2.1 Abstract 12

2.2.2 Introduction 13

2.2.3 Objectives 14

2.2.4 Outcomes 15

2.2.5 Conclusions 16

2.2.6 Recommendations 16

2.2.7 Benefits to California 17

2.2.8 Technology Transition Assessment 17

2.3 A Light Assisted Biomass Fuel Cell for Renewable Electricity Generation 19

2.3.1Abstract 19
2.3.2Introduction 20
2.3.3 Objectives 20
2.3.4 Outcomes 21
2.3.5 Conclusions 23
2.3.6 Recommendations 24
2.3.7 Benefits to California 25
2.3.8 Technology Transition Assessment 25
2.4 Solar Heat-Engine Driven Hydraulic Ram for Low Cost Irrigation 27
2.4.1 Abstract 27
2.4.2 Introduction 28
2.4.3 Objectives 32
2.4.4 Outcomes 33
2.4.5 Conclusions 34
2.4.6 Recommendations 35
2.4.7 Benefits to California 36
2.4.8 Technology Transition Assessment 37
2.5 Modeling Blade Pitch and Solidities in Straight Bladed VAWTs 38
2.5.1 Abstract 38
2.5.2 Introduction 39
2.5.3 Objectives 40
2.5.4 Outcomes 41
2.5.5 Conclusions 41
2.5.6 Recommendations 42
2.5.7 Benefits to California 43
2.5.8 Technology Transition Assessment 43
2.6 All AC Plug and Play Photovoltaic System 45
2.6.1 Abstract 45

2.6.2 Introduction 46
2.6.3 Objectives 46
2.6.4 Outcomes 47
2.6.5 Conclusions 47
2.6.6 Recommendations 48
2.6.7 Benefits to California 48
2.6.8 Technology Transition Assessment 49
2.7 Microbial Fuel Cells for Sustainable Wastewater Treatment 50
2.7.1 Abstract 50
2.7.2 Introduction 51
2.7.3 Objectives 56
2.7.4 Outcomes 57
2.7.5 Conclusions 57
2.7.6 Recommendations 58
2.7.7 Benefits to California 59
2.7.8 Technology Transition Assessment 60
2.8 Meteorological Buoy Technology for Offshore Wind Resource Assessment 62
2.8.1 Abstract 62
2.8.2 Introduction 63
2.8.3 Objectives 63
2.8.4 Outcomes 64
2.8.5 Conclusions 65
2.8.6 Recommendations 65
2.8.7 Benefits to California 66
2.8.8 Technology Transition Assessment 67
2.9 Microbial Fuel Cells to Generate Electricity from High-Solids Food Wastes 68
2.9.1 Abstract 68
2.9.2 Introduction 69

2.9.3 Objectives 71
2.9.4 Outcomes 72
2.9.5 Conclusions 72
2.9.6 Recommendations 73
2.9.7 Benefits to California 74
2.9.8 Technology Transition Assessment 74
2.10 A Low Cost Inverter with Battery Interface for Photovoltaic Utility System 76
2.10.1 Abstract 76
2.10.2 Introduction 77
2.10.3 Objectives 78
2.10.4 Outcomes 78
2.10.5 Conclusions 79
2.10.6 Recommendations 80
2.10.7 Benefits to California 80
2.10.8 Technology Transition Assessment 80
2.11 Photo Thermal Voltaic Skylight 82
2.11.1 Abstract 82
2.11.2 Introduction 83
2.11.3 Objectives 84
2.11.4 Outcomes 85
2.11.5 Conclusions 86
2.11.6 Recommendations 87
2.11.7 Benefits to California 87
2.11.8 Technology Transition Assessment 88
2.12 An Innovative Design for Cost and Energy Efficient Solar Cells 89
2.12.1 Abstract 89
2.12.2 Introduction 90
2.12.3 Objectives 91

2.12.4 Outcomes 92
2.12.5 Conclusions 93
2.12.6 Recommendations 93
2.12.7 Benefits to California 93
2.12.8 Technology Transition Assessment 94
2.13 Solution Processed Solar Cells from Abundant, Non-Toxic Materials 95
2.13.1 Abstract 95
2.13.2 Introduction 96
2.13.3 Objectives 96
2.13.4 Outcomes 97
2.13.5 Conclusions 97
2.13.6 Recommendations 98
2.13.7 Benefits to California 99
2.13.8 Technology Transition Assessment 99
2.14 Growth of Cavity Light Emitting Diode on a Reflective Substrate 100
2.14.1 Abstract 100
2.14.2 Introduction 101
2.14.3 Objectives 102
2.14.4 Outcomes 103
2.14.5 Conclusions 103
2.14.6 Recommendations 104
2.14.7 Benefits to California 104
2.14.8 Technology Transition Assessment 105
2.1.1G Abstract 106
2.1.2G Introduction 107
2.1.3G Objectives 107
2.1.4G Outcomes 108
2.1.5G Conclusions 109

2.1.6G Recommendations 110
2.1.7G Benefits to California 111
2.1.8G Technology Transition Assessment 112
2.2G Residential Gas-Fired Heat Pump Water Heater 113
2.2.1G Abstract 113
2.2.2G Introduction 114
2.2.3G Objectives 115
2.2.4G Outcomes 115
2.2.5G Conclusions 116
2.2.6G Recommendations 117
2.2.7G Benefits to California 117
2.2.8G Technology Transition Assessment 118
2.3G Advanced Control Techniques and Sensors for Gas Engines with NSCR 119
2.3.1G Abstract 119
2.3.2G Introduction 120
2.3.3G Objectives 126
2.3.4G Outcomes 127
2.3.5G Conclusions 128
2.3.6G Recommendations 128
2.3.7G Benefits to California 129
2.3.8G Technology Transition Assessment 130
2.4G The Development of a Prototype Natural Gas Fueled Homogeneous Charge Compression Ignition Engine for Hybrid Vehicles 131
2.4.1G Abstract 131
2.4.2G Introduction 132
2.4.3G Objectives 133
2.4.4G Outcomes 134
2.4.5G Conclusions 135
2.4.6G Recommendations 135

2.4.7G Benefits to California 136
2.4.8G Technology Transition Assessment 136
2.1T Metal Supported Solid Oxide Fuel Cells for APU Applications 138
2.1.1T Abstract 138
2.1.2T Introduction 139
2.1.3T Objectives 140
2.1.4T Outcomes 141
2.1.5T Conclusions 142
2.1.6T Recommendations 143
2.1.7T Benefits to California 143
2.1.8T Technology Transition Assessment 144
2.2T Lower Cost and Higher Density PHEV Battery 146
2.2.1T Abstract 146
2.2.2T Introduction 147
2.2.3T Objectives 148
2.2.4T Outcomes 148
2.2.5T Conclusions 149
2.2.6T Recommendations 151
2.2.7T Benefits to California 151
2.2.8T Technology Transition Assessment 153
2.3T Validated Multi-scale Analysis Tool for Mechanical Response of Aluminum Foams 154
2.3.1T Abstract 154
2.3.2T Introduction 155
2.3.3T Objectives 156
2.3.4T Outcomes 156
2.3.5T Conclusions 158
2.3.6T Recommendations 158
2.3.7T Benefits to California 159

2.3.8T Technology Transition Assessment 160

LIST OF FIGURES

Figure 1: Illustration of Thermal Storage Concept 7

Figure 2: Proposed Setup of Wind Deflectors and Wind Fences on High-Rise Rooftop 14

Figure 3: Proposed Wind Deflector Geometries Including Arc, Parabolic, and Curved Surfaces 14

Figure 4: A. Photo-Electrochemical Cell 20

B. Energy Scheme for a Photo-Electrochemical Solar Cell Containing a Biomass Photo-Anode and an Oxygen Counter-Electrode 20

Figure 5: Schematic of the Thermofluidics Engine Driving the Hydraulic Ram Module 30

Figure 6: Photographs of Alpha Prototype during Operation and Testing 31

Figure 7: Left. CAD Drawing Showing the Key Features of the Updated Hydraulic Ram 31

Right. The Apparatus Installed in the New Facility within the Borehole Sized Tank 31

Figure 8: Three Vertical Axis Wind Turbines in the Foreground 40

Figure 9: Project Test Bed 46

Figure 10: Twenty Gallon Test Reactor 53

Figure 11: A) Examples of Drilled PVC Piping Used for MFC Reactor 54

B) Reactor Frame Schematic 54

Figure 12: A) 3/8 Inch Crushed EC-100 Synthetic Graphite Granules
B) Graphite Pucks 55

Figure 13: Schematic of Wind Tunnel (Not to Scale) 63

Figure 14: Schematic Illustration of a Microbial Fuel Cell 70

Figure 15: Design of a Single Stage MFC Operated on Solid Media 71

Figure 16: The Fabricated 1.5 kW Prototype 78

Figure 17: Section through SLATS Collector 84

Figure 18: Heat Engine Components 84

Figure 19: a) I-V Curve for MOSSC Based on Cdo Quantum Dots, Tio_2, and Ethylenglicol 91

Electrolyte Containing I^-/I_3^- Tested at 1 Sun 91

b) Picture of the Cell 91

Figure 20: Schematic of LED Chip Structure. The Grown Epitaxial Metal Mirror (GEMM) is a Key Feature. 102

Figure 21: Schematic of Jet Ignition System Installed in a Side Ignition Engine 107

Figure 22: Optical Images of Combustion from 8° after Spark to 32° after Spark 108

Figure 23: NO_x Emissions under Various Air/Fuel Ratios, Fuel Type, and Ignition Type 109

Figure 24: Conceptual Packaged Heat Pump Water Heater Assembly 115

Figure 25: Construction and Operation of Continental Zirconium Dioxide Dual Cavity NO_x Sensor 123

Figure 26: CCC EGC2 Installed on Engine 124

Figure 27: Test Engine Controls 125

Figure 28: Schematic Diagram of the Test Engine 133

Figure 29: Comparison of Hydrocarbon Emissions from a Kohler Model ECH-749 Engine Fueled with Gasoline vs. CNG 135

Figure 29: Comparison of Hydrocarbon Emissions from a Kohler Model ECH-749 Engine Fueled with Gasoline vs. CNG 135

Figure 30: Ceramic Cells with Porous Sheet Metal Substrate 140

Figure 31: Complete Metal Substrate with Perforated Sheet Metal and Interconnect 140

Figure 32: Illustration of Convection Battery 147

Figure 34: Aluminum Foam 155

Figure 35: Conceptual Multi-Scale Modeling of a Sandwich Plate with an Aluminum Foam Core which Sustains an Impact 157

LIST OF TABLES

Table 1.1: 2009 EISG Projects with IARs Included in this Section 2

Table 1: Photo-Electrochemical Data for Continuously Illuminated TiO2 and WO3 in 0.5 M Glucose/0.1 M KCl at pH 7 in Anode Compartment Connected to Pt –Air Counter Electrode in 0.1 M KCl at pH 7 in Cathode Compartment 23

Table 2: Power Coefficient Comparisons 41

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 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 for grant projects that were awarded in 2009 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: 2009 EISG Projects with IARs Included in this Section

Project	Researcher	EISG Funding
Low Cost Energy Storage for Solar Thermal Power Plants	Hogue Engineering Company Robert A. Hogue	**$ 43,245**
Wind Power Generation on High-Rise Buildings in Urban Centers	San Jose State University Tai-Ran Hsu	**$ 50,000**
A Light Assisted Biomass Fuel Cell for Renewable Electricity Generation	University of California Frank E. Osterloh	$95,000
Solar Heat Engine Driven Hydraulic Ram for Low Cost Irrigation	Thermofluidics Ltd. Tom Smith	**$95,000**
Modeling Blade Pitch and Solidities in Straight Bladed VAWTs	Wind Harvest International Robert Thomas	$50,000
All AC Plug-and-Play Photovoltaic System	Solar Red, Inc. Joe Augenbraun	$95,000
Microbial Fuel Cells for Sustainable Wastewater Treatment	J. Craig Venter Institute Orianna Bretschger	$95,000
Meteorological Buoy Technology for Offshore Wind Resource Assessment	MetSpar, Inc. Dr. Rodney R. Gay	$95,000
Microbial Fuel Cells to Generate Electricity from High Solids Food Wastes	University of California Davis Farzaneh Rezaei and Jean S. VanderGheynst	$94,490
A Low Cost Inverter with Battery Interface for Photovoltaic Utility System	Texas A&M University Prof. Hamid A. Toliyat	$95,000
Photo Thermal Voltaic Skylight	SeaBotix, Inc. Richard Denton	$95,000
An Innovative Design for Cost and Energy Efficient Solar Cells	San Diego State University Gregory Kalyuzhny	**$95,000**
Solution Processed Solar Cells from Abundant, Non-Toxic Materials	Plant Solar Craig Peters	$95,000

Growth of Cavity Light Emitting Diode on a Reflective Substrate	Lightwave Photonics R. Jorgenson	$95,000
Advanced Low Temperature Natural Gas Combustion Using Jet Ignition	MAHLE Powertrain LLC Dr. William Attard	$95,000
Residential Gas-Fired Heat Pump Water Heater	Stone Mountain Technologies, Inc Michael Garrabrant	**$93,747**
Advanced Control Techniques and Sensors for Gas Engines with NSCR	Colorado State University John Gattoni and Daniel B. Olsen	$95,000
The Development of a Prototype Natural Gas Fueled Homogeneous Charge Compression Ignition Engine for Hybrid Vehicles	Rochester Institute of Technology James H. Lee	**$94,584**
Metal Supported Solid Oxide Fuel Cells for APU Applications	XCell Power, LLC Quoc Pham	**$94,887**
Lower Cost and Higher Density PHEV Battery	University of Missouri Galen Suppes	**$95,000**
Validated Multi-Scale Analysis Tool for Mechanical Response of Aluminum Foams	University of California, Los Angeles Ertugrul Taciroglu	**$49,999**

CHAPTER 2:
2009 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 2009 that have not previously been published.

2.1 Low Cost Energy Storage for Solar Thermal Power Plant

Awardee: Hogue Engineering Company

Principal Investigator: Robert A. Hogue

2.1.1 Abstract

An affordable means to store thermal energy could help lower the cost of electricity produced by concentrating solar power (CSP) plants while providing power generators and utility operators a means to deliver renewable power to the grid when needed most. The objective of this project was to evaluate the potential viability of storing energy generated by a large solar plant in the ground using ordinary dirt as a storage medium and to compare its cost with other energy storage techniques.

Researchers used finite element analysis software to model the performance of a ground storage system that was sized to support the needs of a 50 MWe solar power plant. Computer modeling results demonstrated that the concept is technically feasible. However the research team discovered that spacing between pipes buried in the ground needed to be less than originally projected, no greater than 0.15 meters. This significantly increased material and installation cost estimates. Researchers estimated the installed cost for the optimal design and compared it with other energy storage concepts in the marketplace or under development. The research team demonstrated that the system could be initially charged in about 20 days and could provide about 1000 MWh of recovered heat each day with a daily charging time of about nine hours.

The projected installed cost of the ground storage system was higher than anticipated. Therefore it likely could not compete with less expensive alternatives for heliostat/tower solar systems. However ground storage appears to be a lower cost option for parabolic trough concentrators compared to a conventional two tank molten salt storage system design.

This project used computer modeling for all results. No hardware was constructed or tested.

Keywords: Concentrating solar power, thermal storage, ground storage, parabolic trough, thermal charging, thermal discharging

2.1.2 Introduction

California's three largest utilities–Southern California Edison, Pacific Gas and Electric, and San Diego Gas and Electric–collectively provided 18 percent of their 2010 retail electricity sales with renewable power. These utilities are pursuing technologies to provide 33 percent of all retail electricity sales from renewable power sources by 2020.[1] New cost effective renewable technologies and concepts are essential if utilities are to meet the challenging 33 percent Renewable Procurement Standard (RPS) goal in California and to minimize the incremental cost to ratepayers.

Solar thermal power plants, otherwise known as concentrating solar power (CSP) plants, are one of several renewable energy resources competing to provide renewable electricity to the California electric grid and ratepayers. In general, CSP plants can operate more cost effectively when the plant output better matches customer demand. Electricity generated by utility scale solar power plants is not always coincidental with peak consumer electric demand, which normally occurs in the afternoon and early evening hours. An energy storage system can help increase the amount of electricity delivered by a CSP plant to the grid during peak conditions when it is needed the most. Thermal storage can also be used to supplement the lower quantity of solar heat generated during cloudy or partially cloudy days. Energy storage provides power generators and utility operators with the flexibility of delivering renewable power to the grid when needed the most and in a consistent more predictable manner.

The researchers in this project speculated that thermal ground storage has the potential to be a more practical and cost effective storage solution, especially for central station solar trough power plants. The primary benefit of ground storage is that the storage medium, dirt, has virtually no cost. The purpose of this study was to evaluate the potential viability of storing energy generated by a large solar plant in the ground using ordinary dirt and to compare its cost with other energy storage techniques.

Thermal energy storage has yet to be widely adopted by the solar industry because of cost issues. A two-tank molten salt storage system is widely regarded as the most probable storage type for CSP applications where storage capacity is required. During the course of this project researchers also discovered other interesting technologies under development that have the potential to reduce cost. One such system is called a thermocline tank. The tank is a refinement to conventional molten salt storage and operates similarly to a home water heater. Hot salts are removed from the top of the tank, cooled as they make steam, and returned to the bottom, cooler part of the tank. Most of the tank is filled with small inexpensive rocks that hold the heat and minimize the need for expensive salts. Although performance of the thermocline tanks has yet to be demonstrated at power plant scale, it has the potential to be a more cost effective solution compared to the two tank molten salt system for parabolic trough applications. Furthermore, the German Aerospace Research Agency has been working on another concept that stores sensible heat in ordinary concrete blocks. This work suggests that the use of concrete

1 Former California Governor Arnold Schwarzenegger signed Executive Order (EO) S-21-09 on September 15, 2009, directing the California Air Resources Board (CARB) to adopt regulations requiring 33 percent of electricity sold in the state to come from renewable energy by 2020.

or inexpensive rocks as storage media could be quite attractive and competitive with molten salt storage for all CSP applications.

The research team recognized the opportunity to significantly reduce the cost of thermal energy storage using new techniques and less expensive storage media. For the purposes of this project, researchers focused their work on a ground storage concept using dirt as a storage medium. They used finite element analysis software to model the performance of a ground storage system sized to support the needs of a 50 MWe solar power plant. The researchers proposed a simple design using an insulated curtain surrounding the ground storage area with a light roof above grade. See Figure 1 below.

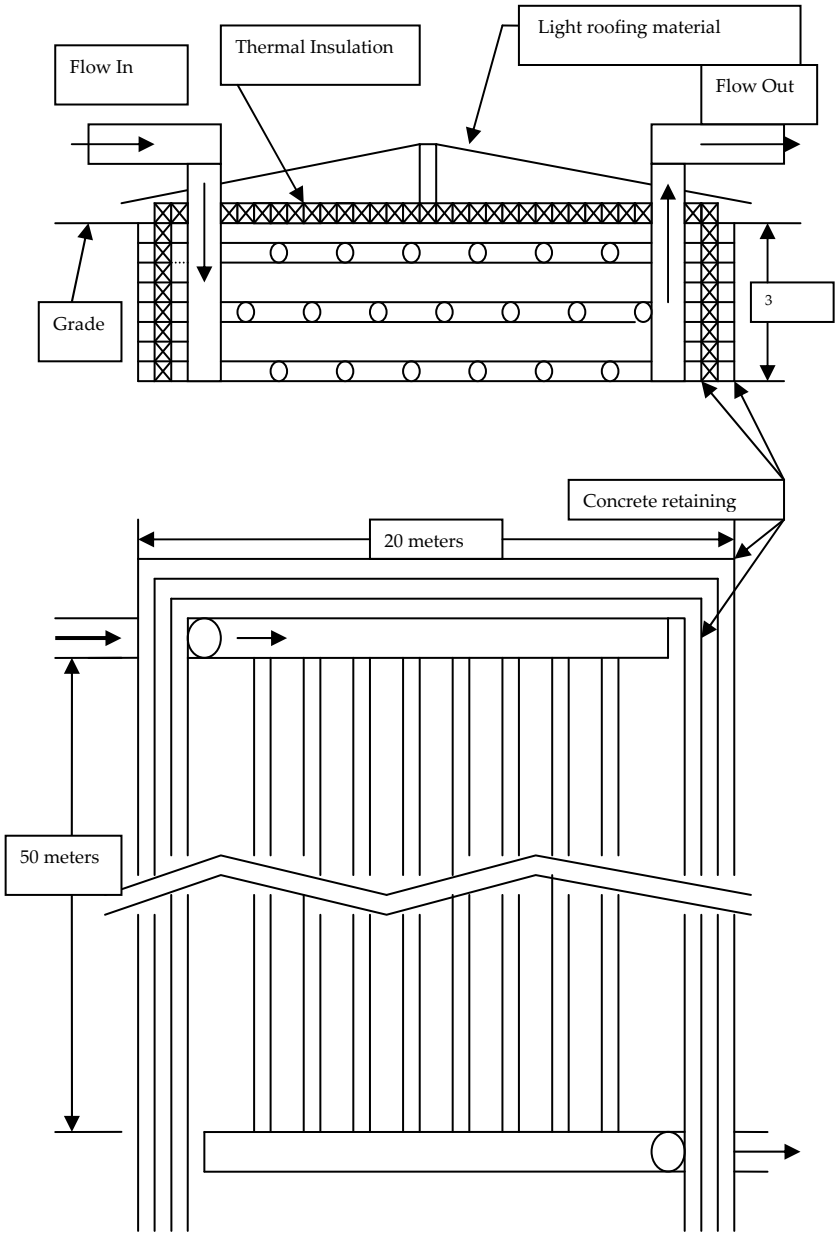
Computer modeling results demonstrated that the concept is technically feasible. Software modeling helped optimize system performance by varying pipe distribution and spacing between pipes. The research team discovered that spacing between pipes buried in the ground needed to be much less than originally projected, no greater than 0.15 meters. Less spacing between pipes significantly increases material and installation costs. The research team concluded that the system can be initially charged in about 20 days and can provide about 1000 MWh of recovered heat each day with a daily charging time of about nine hours. Researchers also prepared a bill of materials, estimated the installed cost for the optimal design, and compared it with other energy storage concepts in the marketplace or under development.

Researchers concluded that the ground storage concept is technically feasible and estimated the installed cost to be about $74 per kWh, based on 0.15 meters spacing between pipes. This cost is higher than the published cost of $36 per kWh for molten salt storage used with heliostat/tower solar systems. However the cost of ground storage is less than the estimated cost of $87 per kWh for molten salt storage used with solar parabolic trough applications. The cost of molten salt storage is much higher for solar trough systems due to the additional requirement of expensive heat exchangers. It appears, therefore, that ground storage is suitable for parabolic trough solar applications but not heliostat/tower solar plants.

The researchers also conducted due diligence on other emerging technologies under development. The team found that the use of thermocline tanks could potentially lower the cost of thermal energy storage for all solar system applications to approximately $62 per kWh. The researchers also acknowledged a study by the German Aerospace Research Agency which estimated that energy storage systems using concrete as storage medium could be built for $39 per kWh.

Researchers have concluded that there is an opportunity to significantly lower the cost of thermal energy storage compared to conventional two tank molten salt systems. Ground storage has the potential to be a competitive solution for solar parabolic trough systems. Further study is needed to optimize the design parameters and validate cost projections of ground storage systems for various sizes and configurations. The research team suggested a scaled down prototype needs to be constructed and tested to validate performance, reliability, and durability under various operating conditions. Finally, researchers recommended a parallel effort to further study other advanced heat storage concepts including the use of thermocline tanks and inexpensive concrete or rocks as a heat storage medium.

Figure 1: Illustration of Thermal Storage Concept



2.1.3 Objectives

The goal of this project was to determine via computer modeling the feasibility of storing heat generated by a solar plant in the ground using dirt as the storage medium and comparing its estimated costs with those of competing storage systems. The researchers established the following project objectives:

1. Establish that the ground storage system operates like a heat exchanger with a log mean temperature difference (LMTD) less than 5° C.

2. Confirm that soil temperatures are above 385° C after charging the storage system.
3. Demonstrate that the storage system can be initially charged in less than four weeks of accumulated heating time during a summer.
4. Demonstrate that the fully charged storage system provides 1000 MWh plus or minus 10 percent of heat during six hours of discharging.
5. Demonstrate that after discharging for six hours the storage system can be recharged in 12 hours or less to provide 1000 MWh of heat.
6. Confirm that the use of ground storage can lower the cost of electricity generated by CSP plants to ratepayers by more than $0.02 per kWh as compared to molten salt storage.

2.1.4 Outcomes

1. At two meter spacing between the pipes, the calculated LMTD was 31° C and thus did not meet the goal. However when the spacing between the pipes was reduced to 0.5 meters, the LMTD was calculated to be 1.4° C, thus meeting the target.
2. The soil temperature was above 385° C at 0.5 meter spacing between pipes.
3. The system design with 0.5 meter spacing approaches steady state after 20 days.
4. The objective was not met at 0.5 meter spacing. However when the spacing between pipes was further reduced to 0.15 meter, the heat recovered was within +/- 10 percent of the target of 1000 MWh for six hours of discharging time.
5. After discharging, only nine hours of charging time were required to recover 1000 MWh of heat within 10 percent.
6. Reduced spacing between pipes increased direct cost estimates compared to the original design. As such, the ground storage system does not provide a savings of at least $0.02 per kWh for ratepayers.

2.1.5 Conclusions

1. Ground storage has characteristics of a conventional heat exchanger, but only with very tight spacing between the pipes, in this case 0.5 meters.
2. Earth soil can readily absorb heat in a consistent, predictable manner but only with very tight spacing between pipes.
3. The system design (modified to 0.5 meter spacing between pipes) quickly achieved steady state conditions.
4. A fully charged system was able to consistently generate electricity, but only when pipeline spacing was further reduced to 0.15 meter. This significantly increased material and installation costs.
5. After discharge, the system was able to recharge relatively quickly.

6. The excessive material cost of building a ground storage system with extremely tight spacing between pipes limits its practical use to certain applications, in this case, solar parabolic trough systems.

The use of molten salts as a storage method for CSP heliostat/towers appears to be the most competitive solution in the marketplace at this time. However molten salts are too expensive for parabolic dish concentrators, thus making room for alternate energy storage system concepts such as ground storage. In this study researchers proved that the proposed ground storage system is technically feasible. Storing heat in the ground performs well enough to support the charging and discharging requirements of a thermal storage system. No major technical obstacles were uncovered. Finite element modeling of the proposed design established that the system can be charged with about 1000 MWh of heat over a nine hour period and discharged to provide six additional hours of heat to a 50 MWe power plant. The heat storage bed can be initially charged in fewer than four weeks of accumulated daylight hours during a summer season.

The greatest practical barrier of ground storage is installed cost. Spacing between pipes was significantly reduced compared to initial design estimates, thus driving up material and installation costs. Researchers determined that ground storage does not compete well with the use of molten salts for CSP heliostat/towers. However the concept is still valid and can be considered as potentially viable method of heat storage for other CSP applications such as parabolic trough systems. The technical advancements and conclusions from this project can also be used to evaluate the viability of other energy storage systems using solids with relatively low thermal conductivity, such as concrete blocks or inexpensive rocks.

2.1.6 Recommendations

The proposed concept appears to be technically feasible but needs additional modeling work before any conclusions can be reached concerning its feasibility for use with CSP parabolic trough systems. The Program Administrator recommends that the researchers:

1. Compare the use of ground storage to other promising concepts such as thermocline tanks using concrete or inexpensive rocks.
2. Determine optimum soil characteristics such as thermal conductivity, density, moisture content, and particle size.
3. Optimize heat exchanger pipe material, size, and internal mixers if any.
4. Optimize flow rate of the heat exchange fluid.
5. Once the potential feasibility of using ground storage has been established, construct a prototype to validate projected characteristics of the storage system, heat exchange system, and optimized soil characteristics.
6. Test the integrity of the system and ensure that it meets standard industry safety and permitting requirements.

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.

2.1.7 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.

California's three largest utilities–Southern California Edison, Pacific Gas and Electric, and San Diego Gas and Electric–collectively provided 18 percent of their 2010 retail electricity sales with renewable power. These utilities are pursuing the means to provide 33 percent of all retail electricity sales from renewable power sources by 2020.[2] New cost effective renewable technologies and concepts are essential for utilities to meet the challenging 33 percent Renewable Procurement Standard (RPS) goal in California.

Solar thermal power plants, otherwise known as concentrating solar power (CSP) plants, are one of several renewable energy resources competing to provide renewable electricity to the California electric grid and ratepayers. In general, CSP plants can operate more cost effectively when the plant output better matches customer demand. Electricity generated by utility scale solar power plants is not always coincidental with peak consumer electric demand which normally occurs in the afternoon and early evening hours. An energy storage system can help increase the amount of electricity delivered by a CSP plant to the grid during peak conditions when it is needed the most. Thermal storage can also be used to supplement the lower quantity of solar heat generated during cloudy or partially cloudy days. Energy storage provides power generators and utility operators with the flexibility of delivering renewable power to the grid when needed the most and in a consistent and more predictable manner.

Researchers estimated that ground storage could reduce the direct installed cost of energy storage from $87 per kWh to $74 per kWh compared to conventional molten salt storage

2 ibid.

techniques for parabolic trough applications. The potential use of thermocline tanks could potentially further lower the cost to about $62 per kWh. The market projection of ground storage has the potential to reach 100 percent of all solar parabolic trough applications planned for California. According to the California Energy Commission (CEC), a total of 2,350 MW in solar parabolic trough system capacity has been approved for installation in California by 2020.[3] Assuming that these systems will eventually be installed with six hours of storage, the total amount of energy storage capacity needed is approximately 14,100 MWh.[4] If researchers can reach the cost target of $62 per kWh, the total market value of energy storage potential for parabolic trough systems in California between now and 2020 is approximately $874 million. Clearly, the market potential for energy storage is quite large and additional thermal storage research work is warranted.

2.1.8 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 have contacted engineering/construction companies providing design and construction for power plants. The researchers have stated that they plan to take the technology to market via a partnership with a construction company or engineering/construction company.

Engineering/Technical

The researchers planned to submit a proposal for over $1 million to the U. S. Department of Energy. They estimated they need an additional two to three years to complete engineering work.

Legal/Contractual

No patents have been filed. The researchers conducted an informal literature search and produced no evidence of potential infringement on existing patents or intellectual property.

Environmental, Safety, Risk Assessments/ Quality Plans

Existing industry standards and practices can adequately mitigate any risk associated with the potential use of synthetic oil for the heat transfer fluid as a substitute for pressurized water.

Production Readiness/Commercialization

The concept is not yet sufficiently developed for commercialization.

---

3 http://www.energy.ca.gov/siting/solar/index.html

4 2,350 MW x six hours storage = 14,100 MWh

2.2 Wind Power Generation on High-Rise Buildings in Urban Centers

Awardee: San Jose State University

Principal Investigator: Tai-Ran Hsu

2.2.1 Abstract

The goal of this project was to determine the feasibility of developing wind deflectors and wind fences to mitigate and control turbulent airflow. The researchers used computational fluid dynamics (CFD) modeling for an arced wind deflector atop a mid-rise building. Although both CFD modeling and field measurements showed decreased wind turbulence, predicted and measured results showed poor correlation. Due to budget and time constraints, the researchers were unable to include modeling and testing of two additional wind deflector configurations or wind fences as proposed. The researchers used CFD modeling to analyze a cluster of three high-rise buildings in San Francisco with and without wind deflectors, but results were not field tested.

Keywords: Wind power, rooftop, wind turbulence, wind deflector, CFD

2.2.2 Introduction

As the demand for energy increases, renewable energy sources become more critical to ensure that future energy demands are met. According to the Energy Information Administration, wind energy provided about 1.3 percent of the nation's electricity in 2008. In 2011, the California Energy Commission reported that wind energy provided 5.1 percent of California's electricity supply.[5] The Center for Sustainable Energy notes that costs for wind energy capture have decreased fourfold since 1980 and could easily contribute 20 percent of California's electricity supply by 2020.[6] Incentive for this increase is further provided by California Senate Bill X1-2 requiring sales from renewable energy sources totaling 20 percent by 2013, 25 percent by 2016, and 33 percent by 2020.[7]

The vast majority of wind power production is found in open oceans, wind farms, and rural settings. Urban installations are hindered by significant wind turbulence over high-rise rooftops. The researchers sought to mitigate the wind turbulence so that rooftop wind turbine installations could be feasible. The researchers proposed to develop and test wind deflectors and wind fences for use in high-rise wind power installations. Figure 2 shows the proposed configuration of these devices on top of a high-rise building. Figure 3 shows three types of wind deflector configurations proposed for testing.

The researchers proposed to use a computational fluid dynamic (CFD) model to analyze wind flow patterns with and without wind deflectors and wind fences and then validate findings through field testing. Due to budgetary and time constraints, the researchers did not include wind fences in either modeling or field validation. Additionally, the researchers only tested the arced configuration for the wind deflector in modeling and field validation. Although both model predictions and field measurements indicated a decrease in wind turbulence with the inclusion of a wind deflector, predicted and measured results showed poor correlation. Ratios of measured to predicted values ranged from 2 to 7, as compared to the 20 percent accuracy proposed. Field testing was limited to one mid-rise building on the campus of San Jose State University and did not include any measurements taken from high-rise buildings as proposed. CFD modeling was performed for a high-rise in San Francisco, but the researchers did not attempt to validate findings through field measurements.

---

5 California Energy Commission (CEC) (2011), Total Electricity System Power. http://energyalmanac.ca.gov/electricity/total_system_power.html

6 Center for Sustainable Energy (2012), Wind Turbines, http://energycenter.org/index.php/technical-assistance/renewables/wind-turbines?gclid=CLCtzO2J6LECFWYZQgodIB8AQA

7 California Senate (2011), SB 2 X1 (Simitian), Energy: Renewable Energy Resources

The proposed technology may be used in high-rise urban settings. Although deflectors might decrease wind turbulence sufficiently to make wind turbine installation feasible, there are no direct benefits to California ratepayers as a result of the proposed technology. The researchers speculated on the generation capacity and carbon emission reduction possible in San Francisco as a result of wind power installations atop high-rise buildings. However, the assumptions for

the analysis are immoderate, speculative, and only indirectly result from the use of wind deflectors.

Figure 2: Proposed Setup of Wind Deflectors and Wind Fences on High-Rise Rooftop

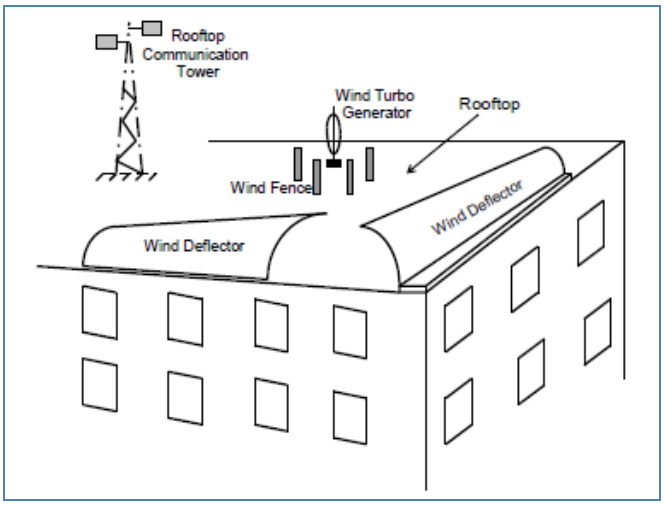


Figure 3: Proposed Wind Deflector Geometries Including Arc, Parabolic, and Curved Surfaces

2.2.3 Objectives

The goal of this project was to determine the feasibility of developing wind deflectors and wind fences to mitigate and control turbulent airflow. The researchers established the following project objectives:

1. Design and assemble a system for measuring wind velocity around and over rooftops of high-rise buildings including: cup anemometers, wind vanes, data logger system, temperature/humidity sensors, atmospheric pressure meter, solar panels, and mast. Demonstrate that this integrated system will measure wind velocity within error of +/- 5 percent.

2. Measure an isolated 12-story building on campus with equal dimensions on each side. The same measurements will be made on building-to-building proximity. Adjacent high-rise buildings in San Francisco (or San José) will also be measured.

3. Assess data collected in Objective 2 to develop data sets.

4. Create a regional climatology profile to be used in modeling work.

5. Mitigate by 50—100 percent turbulent wind flow over rooftops of standalone and adjacent high-rise buildings on three sets each of optimized geometry wind deflectors and wind fences.

6. Validate on site measurements within +/- 20 percent by performing simulations using a commercial computational fluid dynamics (CFD) program on buildings using the measured wind data in Objectives 2, 3, and 4 on the buildings described in Objective 2.

7. Fabricate three wind deflectors made of aluminum sheets with distinct geometry for field tests. Each will have dimensions of up to 6 feet tall and 10 feet long.

8. Test the effectiveness of wind deflectors produced in Objective 7 for mitigating air turbulence on the rooftop of a high-rise building as specified in Objective 2 with +/- 5 percent accuracy.

2.2.4 Outcomes

1. The researchers selected the eight story mid-rise Duncan Hall building on the campus of San Jose State University on which to perform field measurements. The site chosen was an existing field laboratory. It was chosen because there were wind measurement stations and equipment and a data acquisition facility already installed and the need for additional equipment and training was relatively insignificant. The researchers did not present calibration measurements for the equipment.

2. The researchers measured wind velocity near the center of an H-shaped eight story mid-rise. They did not take measurements for a 12 story building, either on the San Jose State University campus or in San Francisco. The building measured did not have equal measurements on each side.

3. The researchers analyzed historical measurements taken at Duncan Hall to provide mean and maximum wind speed and direction. Results were posted online at http://www.met.sjsu.edu/~cordero/windclimatology/.

4. The researchers summarized online wind data by month for Duncan Hall.

5. The researchers proposed to design and construct three wind deflectors, as shown in Figure 2, to be installed at the edge of the building. Only the arced configuration deflector was constructed. The proposed edge installation was modified by splitting the deflector in the center to avoid a surveillance camera mounted on the guard rail. Additional configurations not in the original scope of work included placing the deflector facing downward 21 feet from the edge of the building and moving the deflector in its upright position between 2 and 17 feet from edge of the building.

6. The researchers performed CPD analyses for each of the installation configurations for the arced deflector. Results of these analyses were on the order of 2 to 7 times lower than field measured results.

7. Researchers produced two sections of an arced deflector, with each section 6 feet in length. The frame was constructed using curved wooden ribs, and the curved surface was covered with aluminum sheet metal.

8. See Objective 6.

2.2.5 Conclusions

1. The researchers did not meet the objective to design, assemble, and calibrate a system for measuring wind velocity as stated. The existing system was not portable, thus the researchers were unable to use it in the high-rise setting as proposed. Further, the researchers did not demonstrate that the system was accurate within 5 percent. The researchers noted in the final report conclusion that the existing system was inadequate to measure highly localized and intense wind turbulence flows in the field, which contributed to poor correlations between predicted and measured results. Site selection and instrumentation appeared to be driven by convenience rather than relevance to the project objectives.

2. The researchers did not meet the objective to measure wind velocity on a 12 story high-rise building with equal dimensions, nor were adjacent high-rise buildings measured.

3. The researchers partially met the objective to assemble and analyze wind data collected from Objective 2. However data collected did not meet the high-rise or building configuration criteria established under Objective 2.

4. The researchers did not meet the objective to characterize average annual and seasonal winds for high-rise buildings. Data collected at the mid-rise Duncan Hall were not pertinent to high-rise buildings, and data were analyzed only on a monthly basis rather than seasonally or annually.

5. The researchers did not meet the objective to design and test three wind deflectors and wind fences to mitigate 50—100 percent of the turbulent wind flow. Wind fences were not designed, modeled, or tested. Only one of the proposed wind deflectors was designed and tested. Field measurements and CFD analysis showed a decrease in wind turbulence through the addition of the arced deflector, regardless of installation location or configuration. However results were not accurately quantifiable or verifiable. (See Objective 6). The researchers neglected to address the effect of the break in the originally proposed edge installation due to the security camera and provided no justification for selection of alternate installations of the arced deflector.

6. The researchers did not meet the objective to validate field measurements within 20 percent accuracy. Rather, predicted and measured results varied by a factor of 2 to 7.

7. The researchers did not meet the objective to fabricate three wind deflectors. Only the arced deflector was constructed.

8. The researchers did not meet the objective to validate CFD modeling.

2.2.6 Recommendations

The researchers were not successful in determining the feasibility of using wind deflectors and fences to mitigate and control turbulent wind flows over high-rise rooftops in urban settings. They performed only a small portion of the proposed testing. They constructed no wind fences and only one of the three proposed wind deflectors. In addition, none of the testing was done

on a high-rise building. Further, CPD analyses correlated poorly with field measurements and could not be validated. Results were not statistically significant to support the determination of the reduction in turbulence that could be expected through the use of wind deflectors. As part of continued development of this technology, the Program Administrator recommends that the following tasks be completed:

1. Perform all proposed testing on in a high-rise setting on a square or rectangular building typical of urban settings.
2. Design, fabricate, and install the remaining two proposed wind deflector configurations and the wind fences.
3. Calibrate the CPD model and enhance instrumentation sufficiently to validate the CPD model.
4. Test deflectors for their ability to withstand impact and contain debris from catastrophic failure of wind turbines.
5. Perform a cost/benefit analysis.

2.2.7 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 public from this research is reduced environmental impacts of the California electricity supply or transmission or distribution system. The proposed technology provides indirect benefits as it is intended to make rooftop installation of wind turbines on high-rise buildings feasible. The researchers speculate on the generation capacity and carbon emission reduction possible in San Francisco as a result of wind power installations atop high-rises. However the assumptions for the analysis are immoderate, speculative, and benefits only indirectly result from the use of wind deflectors.

2.2.8 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 have not performed a market analysis. This technology is applicable to high-rise urban residential and commercial installations.

Engineering/Technical

The researchers faced significant challenges in validation field measurements with CPD analysis. Significant quantities of additional wind measurement stations will be required, as well as labor intensive modeling efforts to validate the CPD model.

Legal/Contractual

Deflectors and wind fences are patentable technologies. The researchers have not performed a patent search or applied for provisional patents. Design will need to be completed prior to patent application.

Environmental, Safety, Risk Assessments/ Quality Plans

Environmental, Safety, Risk Assessments, and Quality Plans have not yet been developed. Although there are no risks identified with regard to the wind deflectors and wind fences, the researchers note that rooftop wind turbine installation may have noise implications and may be hazardous due to flying debris in the event of catastrophic failure.

Production Readiness/Commercialization

The researchers have not developed a commercialization plan. The proposed technology is not sufficiently developed to pursue commercialization.

2.3 A Light Assisted Biomass Fuel Cell for Renewable Electricity Generation

Awardee: University of California

Principal Investigator: Frank E. Osterloh

2.3.1Abstract

This project provided proof of concept for a solar energy driven biomass fuel cell. The potential application is the production of electricity from wastewater using only air and light as resources. The proposed device uses a photo-electrochemical cell (either a nanostructured titanium dioxide or tungsten trioxide film as photo-anode and a platinum air electrode as cathode in separate compartments). The researchers tested devices under various conditions, and the highest light conversion efficiency (1.7 percent) and power output (0.73 mW cm-2) was found for the TiO2 electrodes under 395 nm illumination. The limited performance was constrained by the substrate concentration in the water and by the electrical resistance of the synthetic wastewater. The project proved the scientific concept, but additional work is needed for the device to be deemed technically feasible.

Keywords: Solar energy, photovoltaic cell, photo-electrochemical cell, waste water, fuel cell, TiO2, biomass

2.3.2Introduction

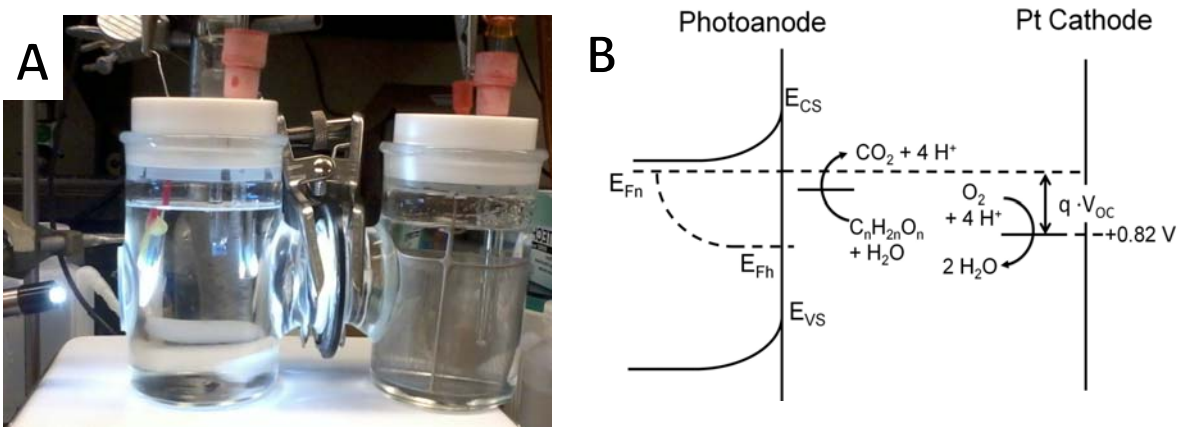
Expanded development of renewable energy remains a high priority policy for California. At the same time, treatment of municipal wastewater in California consumes significant electricity and energy, even though wastewater contains a potentially energy-useful organic fraction. Developing advanced technologies that can beneficially use the organic fraction in wastewater, especially in a single step operation, could help California meet renewable energy policies while simultaneously reducing energy consumption for treatment and turn a burden into a resource. A single step operation as described here should prove simpler to engineer and build than a system that separately gasifies (e.g., through anaerobic digestion) the organic fraction in wastewater, cleans the gas, and then uses the clean gas in some sort of prime mover such as a combustion turbine or fuel cell.

One approach to single step cleanup and generation is the microbial fuel cell (MFC) that can beneficially transform organic material in wastewater into electricity, carbon dioxide, and water. An MFC uses electrodes coated with thin films of electro-active bacteria. However, the power output and efficiency demonstrated by the MFC to date is low (~25 mW cm^{-2}), and the bacteria are easily poisoned by contaminants in the wastewater.

A potentially promising alternative is the use of a light-assisted inorganic electrochemical fuel cell in which a light propels an electrochemical reaction at an electrode. Such devices rely on a semiconductor to produce reactive electron hole pairs, which in this case oxidize the organic material in the electrolyte/wastewater. To complete the circuit, oxygen from the air reduces water at the platinum cathode. The experimental device is shown physically in the left panel of Figure 4 and electrochemically in the right panel.

Figure 4: A. Photo-Electrochemical Cell

B. Energy Scheme for a Photo-Electrochemical Solar Cell Containing a Biomass Photo-Anode and an Oxygen Counter-Electrode



2.3.3 Objectives

The goal of this project was to develop a solar energy driven biomass fuel cell to convert organic material in wastewater into H_2O and CO_2 while generating electrical energy. The researchers established the following objectives:

1. Fabricate photo-anodes from titanium oxide and copper (I) oxide and confirm expected structure and optical properties.
2. Measure the electrochemical onset potentials for the oxidation of glucose, oleic acid, and gelatin, and demonstrate that the photo-anodes are stable under electrochemical bias and are able to oxidize substrates at potentials <+1.5 V versus normal hydrogen electrode (NHV) in neutral solution (pH=7).
3. Repeat measurements above with glucose solution under electrode illumination with light from 300 W Xe-arc lamp, and demonstrate oxidation onset potential of <+0.82 V (against normal hydrogen reference electrode) with current density of ~15 mA/cm^2.
4. Perform voltage current measurements under monochromatic illumination, calculate incident photon to current conversion efficiency of the cell as a function of wavelength, and demonstrate greater than 5 percent photon to current conversion efficiency at less than +0.82 V applied bias.
5. Build photo-electrochemical reactor according to design specifications (Nafion membrane and Pt/air counter electrode) and demonstrate stability of reactor components in contact with glucose, oleic acid, and gelatin solution (pH=7) over >24 hour period.
6. Conduct voltage and current measurements using the reactor above under irradiation with O_2 in the cathode compartment and glucose in the anode compartment, and demonstrate open circuit potential of greater than 0.5 V, short circuit current of ~15 mA/cm^2, and fill factor of greater than 0.5 in the presence of glucose.
7. Perform long-term photo-anode irradiation test, and demonstrate less than 10 percent degradation in efficiency over a 10 day operation period.
8. Repeat measurements under Objectives 3, 4, and 6 with oleic acid, gelatin, and authentic wastewater from a local water treatment plant, and demonstrate efficient power conversion (>5 percent) with these alternate substrates.

2.3.4 Outcomes

1. The researchers fabricated titanium dioxide (TiO_2) and tungsten trioxide (WO_3) instead of copper photo-anodes. Using scanning electron microscopy, the researchers showed that the TiO_2 photo-anode film consists of particles about 25 (± 5 nm) in size. The WO_3 film consisted of sheet-like particles over a range (0.2 μm to 0.5 μm) of sizes, with variable thicknesses about 23 ± 6 nm. The researchers measured the average thickness of the TiO_2 and WO_3 films as 17 μm and 3.5 μm, respectively.
2. The researchers measured the glucose oxidation potential with the TiO_2 electrode at 2.02 V and with the WO_3 electrode at 2.04 V. The researchers set conditions for both oxidation potential measurements at 1.0 milliamp per square centimeter (mA/cm^2) in 0.5 molar glucose, 0.1 molar KCl, pH = 7 solution. The researchers conducted this first measurement without light shining onto the photo-anode.

3. The researchers illuminated the photo-anode using a high intensity lamp and again measured oxidation potentials. Under illumination, photocurrents were observed at both electrodes with glucose added to the electrolyte solution. The researchers detected onset potential of -0.6 V for the TiO_2 film and a photocurrent of 1.0 mA/cm^2. For the WO_3 electrode, the researchers measured values of 0.2 V onset and 0.8 mA/cm^2 photocurrent.

4. The researchers measured the light conversion efficiency (incident photon to charge carrier efficient or IPCE) at three different wavelengths of light. For the titanium dioxide photo-anode, the researchers measured an IPCE maximum value of 1.14 using 370 nm light. For the tungsten oxide photo-anode, the researchers measured an IPCE maximum value of 0.16 using 395 nm light.

5. The researchers constructed a photo-electrochemical test reactor as shown on the left in Figure 4. It had separate vessels for the photo-anode and the oxygen platinum cathode that were separated by a paper membrane.

6. The researchers measured the electricity generation produced by the TiO_2 and by the WO_3 photo-anode immersed in water, aqueous glucose, and synthetic wastewater. The photo-anode was combined with a platinum air cathode to create a complete circuit. The researchers measured power output of the solar biomass fuel cell for each combination of system and solution. The greatest efficiency measured at 1.7 percent was obtained for TiO_2 in aqueous glucose under illumination of 395 nm light as shown in Table 1. When the researchers used real sunlight, the efficiency decreased to 0.56 percent.

7. The researchers measured performance degradation of 10 percent and 18 percent for TiO_2 and WO_3 during a 3,000 second (fifty minute) test under 395 nm or 435 nm illumination.

8. The researchers conducted tests with synthetic wastewater. They ruled out actual wastewater because of the variation of chemical composition depending on time of the day and the producer and because of potential health risks to the investigator. The researchers did not test with oleic acid or gelatin. The synthetic wastewater consisted of many components. The pH of the solution was 7.6.

Table 1: Photo-Electrochemical Data for Continuously Illuminated TiO2 and WO3 in 0.5 M Glucose/0.1 M KCl at pH 7 in Anode Compartment Connected to Pt –Air Counter Electrode in 0.1 M KCl at pH 7 in Cathode Compartment

Material	Illumination	V_{oc} (V)	I_{sc} (A)	FF	P_{El} (W)	Efficiency (percent)	Reference
TiO_2	395 nm at 0.043 W/cm²	1.13	4.30E-3	0.15	7.29E-04	1.7	This work
WO_3	435 nm at 0.025 W/cm²	0.51	1.7E-4	0.16	1.39E-05	0.05	This work
TiO_2	Sunlight at 0.1 W/cm²	1.15	3.20E-3	0.15*	5.52E-04	0.56	This work
WO_3	Sunlight at 0.1 W/cm²	0.45	2.00E-4	0.16*	1.44E-05	0.01	This work

*estimated, based on 395/435 nm irradiations

2.3.5 Conclusions

1. The researchers demonstrated fabrication of photoactive cells that combine titanium dioxide or tungsten trioxide electrodes with a platinum air electrode. The scanning electron microscopy (SEM), X-ray diffraction (XRD), and optical spectroscopy (UV/vis) results showed that nanocrystalline TiO_2 and WO_3 electrodes could be fabricated from premade nanocrystals (TiO_2) or from sodium tungstate solution. The researchers met this project objective.

2. The researchers achieved an electrical power output of up to 0.55 mW per cm², under sunlight using a 0.5 molar glucose solution. This is equivalent to 0.6 percent solar energy conversion. The researchers met the objective for oxidation of substrate, but not for efficiency.

3. The electrochemical scans showed that the over potentials for glucose and water oxidation are the same for WO_3 and TiO_2. In both cases the oxidation potential for glucose is slightly larger than that for water oxidation. Lower glucose oxidation potentials may be evident at lower or higher pH values.

4. The IPCE measurements indicated that photo-catalytic glucose oxidation under UV irradiation is less effective on WO_3 than on TiO_2. On the other hand, WO_3 has a better response above 400 nm, where the IPCE values for TiO_2 are zero. The electrical output of the solar biomass fuel cell loaded with 0.5 M glucose solution depended strongly on the electrode material and illumination wavelength. The researchers met this objective.

5. The researchers constructed a functional test reactor used in performing measurements. The researchers completed this objective.

6. Power output under the conditions tested was minimal at very low efficiency. The researchers did not achieve this objective.

7. The 3,000 second degradation test revealed a decay of performance of 10 percent and 18 percent for TiO_2 and WO_3, respectively. The decay may have been partially due to depletion of glucose in the near-anode electrolyte solution, but other unknown factors may also have played a role. The researchers met the objective of measuring decay, but they did not determine specific factors leading to rapid degradation, nor how or if it would continue under longer time periods.

8. The results of the project show promise, but the researchers did not perform tests on actual wastewater. The diverse chemical and physical properties (e.g., turbidity, color) of wastewaters may constrain application of the technology. The researchers did not complete this objective.

The researchers demonstrated that TiO_2 and WO_3 based photo-electrochemical cells produce electricity from organic contaminants in simulated wastewater. The TiO_2 photo-anode showed higher photo-catalytic activity for biomass oxidation than the WO_3 anode. Efficiencies under sunlight were less than 0.6 percent and 0.01 percent for the devices tested and must be raised by at least a factor of 20 to 200 for this technology to become feasible and cost competitive with current wastewater treatment processes.

2.3.6 Recommendations

For commercial applications, the efficiency of the device needs to be raised by 20 to 200 times to achieve values around 10 percent of solar energy conversion efficiency. Ten percent is generally accepted as the lower threshold for commercial viability of a sun-operated device. To achieve higher efficiencies, the Program Administrator recommends the researchers should:

1. Investigate alternative photo-anode materials and geometries, including mixed anode materials, to capture a larger fraction of the sunlight spectrum. Other counter-electrode materials should be tried as alternatives to platinum, which may be too expensive for widespread application.

2. Investigate the device's sensitivity to various physical and chemical properties of wastewater, including turbidity and color.

3. Investigate the disinfecting capabilities of the device under various pathogen loadings.

4. Map the device's performance under various organic loading (concentrations) of wastewater, including differing organic chemicals.

5. Determine causes of performance degradation and develop techniques to maintain performance over longer time periods.

6. Determine the chemical oxygen demand reduction in wastewater from treatment with the device.

2.3.7 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 or transmission or distribution system. This project represents a proof of concept whose impact on California is difficult to estimate. The principle costs of the light-assisted fuel cells are from the fabrication of the reactor and the photocatalytic materials. Wastewater contains organic waste equivalent to about 4 kJ of free energy per liter, which at a flow rate of 100 L/h could provide up to 100 W of electrical power. This is based on a chemical oxygen demand of 220 mg/L of typical wastewater and 100 percent conversion of organics into CO_2 and water. With 20 percent efficiency, well above the less than one percent demonstrated for the incident photon to current conversion, this provides an additional 45 W per square meter of irradiated device area, bringing the total to 145 W for a device with a one square meter of irradiated electrode area. Assuming a device area of 300 square meters to be used in a typical wastewater treatment plant, 43 kW of electrical power could be provided to the wastewater treatment facility in the summer.

Ratepayers may have to wait five years or more to benefit from the research pursued in this project. The technology is still in a very early stage with several significant hurdles to overcome.

2.3.8 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 have published a paper in a scientific journal that describes their work, an important first step in establishing a connection to the market. Ultimately additional papers in scientific as well as in trade journals will be crucial aspects of a marketing plan, as will clear identification and working with market players including both suppliers and customers. The researchers will need to collaborate with established firms in the wastewater treatment industry and work cooperatively with regulators, such as regional water quality control boards. The researchers acknowledge that basic science and concept optimization must precede any further marketing or commercialization.

Engineering/Technical

Given the concept's state of development, it is premature to identify much in the way of engineering or technical efforts, other than those common to wastewater treatment and electrical generation. The researchers currently have no development partner.

Legal/Contractual

The researchers claim to have identified a patentable technology, although they had not yet filed for patent protection at the end of this project.

Environmental, Safety, Risk Assessments/ Quality Plans

There is no known safety or environmental risk unique to this technology concept compared to other wastewater treatment techniques. The researchers will ultimately have to demonstrate adequate and appropriate disinfectant of discharged treated wastewater and develop necessary testing, monitoring, and retreatment protocols.

Production Readiness/Commercialization

The concept is not ready for production or commercialization.

2.4 Solar Heat-Engine Driven Hydraulic Ram for Low Cost Irrigation

Awardee: Thermofluidics Ltd.

Principal Investigator: Tom Smith

2.4.1 Abstract

Agriculture accounts for over 2.0 percent of California's $1.85 trillion gross state product and is highly dependent on the use of electricity for irrigation. Irrigation of crops is equivalent to 4.0 percent of total electricity consumption. New technologies are needed to increase water pumping efficiency and reduce greenhouse gas (GHG) emissions.

The purpose of this project was to investigate the feasibility of a new water pumping concept that uses a solar heat engine driven hydraulic ram. Similar to Stirling engines, solar heat engines (otherwise known as Fluidyne engines) use liquid pistons to pump water. This concept can be integrated with water efficient drip irrigation that can reduce energy and water consumption for agricultural applications.

In this project researchers designed, developed, and fabricated a solar heat engine test frame and collector system along with a novel, double-acting hydraulic ram module. Initial laboratory work achieved thermosiphon functionality. The researchers then fabricated two identical Fluidyne engine prototypes and used them to complete several commissioning tests. They established project goals to confirm whether the engines could deliver 16 Wh of energy with a thermal efficiency of at least 2.0 percent and demonstrate reliable performance against an arbitrary load or water head. Measured thermal efficiency of the heat engines fell marginally short by 0.4 percent against the target goal of 2.0 percent under a load of 12 meters head. The researchers subsequently built a three meter tall prototype of the hydraulic ram module with the aim of pumping 1,000 liters per hour (L/hr) against a head of 15 meters. Measured flow rate of that unit was lower than expected. The research team constructed an improved prototype using empirical test results from the first prototype and new computer modeling software. The final prototype produced an equivalent flow rate of 800 L/hr against a head of 15 meters.

Integration of the heat engine with various hydraulic ram concepts had to be simulated using computer modeling due to potential health and safety concerns of performing this work in a lab environment. A manufacturing cost analysis confirmed that the hydraulic ram could be built within the cost target range of $4—$10 per hydraulic watt output using any type of drive (heat engine or other). Future work is necessary to demonstrate the technical viability of a fully integrated system.

Keywords: Irrigation, Fluidyne engine, hydraulic ram, oscillation, shock, pump, solar, heat engine, feasibility, flow rate, thermofluidics

2.4.2 Introduction

Agriculture accounts for over 2.0 percent of California's $1.85 trillion gross state product[8] and consumes about 4.0 percent of the State's electricity to produce, process, and store more than 200 food and fiber crops.[9]

The California Energy Commission (CEC) has established a goal to assist the agricultural industry (food and fiber production, food processing, irrigation districts) in adopting energy efficient technologies and management practices which reduce production costs and minimize negative environmental impacts while improving economic sustainability. For instance, water-efficient drip irrigation can cut water use by as much as 75 percent for certain agricultural applications. Electric and diesel motors are the most popular water pumping devices currently used by the agricultural community. Replacing these products with more efficient, cost effective technologies could result in direct operating cost savings and lower GHG emissions. Certain advanced irrigation techniques require the use of additional filtration and pressure balancing to function reliably, resulting in significant head loss. Integration of renewable energy can help mitigate increases in energy demand of advanced irrigation systems and reduce the operating costs of water pumping systems in general.

The purpose of this project was to investigate the feasibility of a new renewable water pumping technology based on a solar heat engine and hydraulic ram. This concept would be ideally suited for drip irrigation with the potential of reducing operating costs and increasing the attractiveness of water efficient drip systems. The primary hurdle for all renewable water pumping systems is high initial cost, making it difficult to compete with the electric grid or diesel engines without the benefit of government subsidy or incentives.

The vast majority of renewable water pumping technologies in the marketplace use solar photovoltaic (PV) to generate power. Numerous companies, including WorldWater Corporation, BP Solar, Grundfos, Kyocera, Dankoff, Lorentz, and Siemens sell solar PV water pump products. The overall market for this product, however, is somewhat limited because of the relatively high product cost and the use of expensive, fault prone electronics required for interface with the electric pump.

The commercial viability of solar thermal pumping engines has not enjoyed the same level of success as the solar PV water pumps, mostly due to limited technical capabilities of smaller scale products and the relatively high capital cost of larger engines. Small scale solar thermal engines are typically based on Stirling and Brayton/Ericsson (air/gas) cycles,[5] while larger scale engines are based on the Rankine (steam/vapor) cycle.[6]

---

8 "Design of a solar energy conversion system based on a parabolic trough concentrator and an Ericsson engine," Alaphilippe M., Bonnet S., Castaing-Lasvignottes J., Stouffs P, proceedings of the 12th ISEC, pp 63-73, 2005

9 References: Correspondence with Edward Norum at the Centre for Irrigation Technologies, CSU Fresno and G. J. Bom at Practica Foundation http://www.practicafoundation.nl/products/under-development/solar-pump/; "Solar power units with screw expanders," Merigoux, J. M.; Pocard, P. Solar energy: International progress; Proceedings of the International Symposium-Workshop, Cairo, June 16-22, 1978. Volume 3. New York, Pergamon Press, Inc., 1980, pp. 1293-1317; "Energy-losses through entrance condensation in small vapor engines." G. J. Bom, Solar Energy, 50(3): 223.228, March 1993.

Two phase Stirling (or Stirling-Rankine) cycles, introduced in the 1970s, provide many of the individual advantages of Stirling and Rankine cycles while avoiding their respective disadvantages. Unlike Rankine cycles, a two phase Stirling cycle avoids the need for expensive valves, precision porting, and a feed pump. A two phase Stirling cycle relies on the relatively simple two piston Stirling mechanism and uses a phase change which can significantly lower the cost and complexity of heat exchangers and temperature/pressure losses.

Walker and Agbi initially conducted pioneering work on the two phase Stirling cycles.[7] Fluidyne (liquid piston) Stirling engines were introduced in 1973.[8] These early engines used dry air cycles, and the liquid pistons were only useful for work transfer. In both mechanical and Fluidyne Stirling engines, evaporation was found to increase specific power significantly, but at an unacceptable cost to efficiency. The pressure amplitudes that were achievable in the past were low for geometric and dynamic reasons. However if indicated pressure amplitude could be increased, temperature amplitude would also increase, thus improving efficiency. Furthermore, increasing the pressure amplitude in a Fluidyne engine facilitates a higher pumping head, greatly increasing the range of possible applications. Performance improvements depend on heat exchanger design and the dependence of piston phasing on the load.

The researchers discovered that a single component two phase Fluidyne engine, patented by Franklin in 1979,[9] could be used for water pumping applications. This was presumably the subject of classified work at the United Kingdom Atomic Energy Authority (UKAEA) site at Harwell. However, no results of prototyping efforts appear to have ever been published. In 2001, Smith investigated a means of impedance matching the engine described by Franklin to its load with funding provided by the Energy Innovations Small Grant (EISG) program (project number 51978A/00-21). This led to a proof-of-concept prototype and, subsequently, to the publication of a doctorate thesis[10] that won a number of awards afterwards. A new company, Thermofluidics Limited, was created to complete development and commercialization of the technology.

Thermofluidics successfully scaled flow rates to 1,100 L/hr (unknown heat input) as a domestic heater and 600 L/hr as a solar pump using a 600 watt electrically heated thermosiphon. Its experiments were all conducted at low (zero to two meters) head, and the technology could not draw water from more than about 1.5 meters below the pump. In many agricultural applications, the water level (or head) is several meters below ground. A more effective and robust solar water pumping device was needed.

---

7 "Thermodynamic Aspects of Stirling Engines with Two-Phase, Two-Component Working Fluids," G. Walker and B. Agbi, pp. 1-8 in Trans. Can. Soc. Mech. Eng., Vol. 2, No. 1, Montreal, 1973; "Optimum Design Configuration for Stirling Engines with Two-Phase, Two-Component Working Fluids," G. Walker and B. Agbi, ASME 73-WA/DGP-l, 1973.

8 "Improvements in or related to Stirling cycle heat engines." C. D. West. British patent number 1487322, November 1974.

9 "Thermally actuated pump", E. Franklin. British patent number 2017227, May 1979.

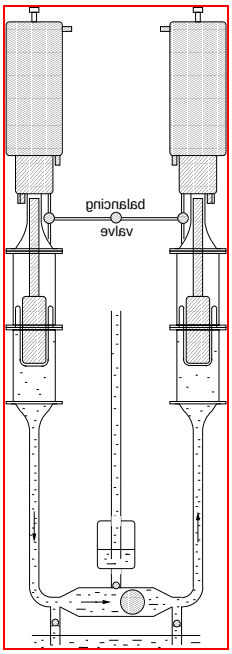
10 "Thermally driven oscillations in dynamic applications", T.C.B. Smith., PhD. thesis, University of Cambridge, 2005.

In 2006, an Aztec Business Alliance MBA (Master of Business Administration) consulting project on Thermofluidics' technology[11] concluded that a feasible solar thermal pumping engine for California agriculture would need to pump around 10,000 L/hr to a minimum of 15 meters (or about 49 feet) of head. It would need to do this reliably, with minimal (yearly) service

intervals, and at a cost comparable to state-of-the-art PV and other thermal based products. A pilot scale plant demonstrating 1,000 L/hr at 15 meter head over five cycles with less than five percent degradation in performance would be sufficient to confirm technical feasibility.

The research team attempted to meet these objectives using a solar heat engine and hydraulic ram. The innovation did not eliminate dependence on inertia, but instead coupled a single component two phase Fluidyne engine to a double-acting hydraulic ram (DAHR) via a long U-tube. The apparatus is shown schematically in Figure 5.

Figure 5: Schematic of the Thermofluidics Engine Driving the Hydraulic Ram Module



The two Fluidyne engines (left and right) operate in antiphase to drive a forcing flow through the hydraulic ram (bottom). The ram has two distinct modes of operation. The oscillation draws water through non-return (check) valves (bottom left and right) and forces it into a discharge reservoir (center) at high pressure. The ram may be situated at any height with respect to the engine. A balancing valve co-joins the displacer cylinder of each Fluidyne engine to balance their output.

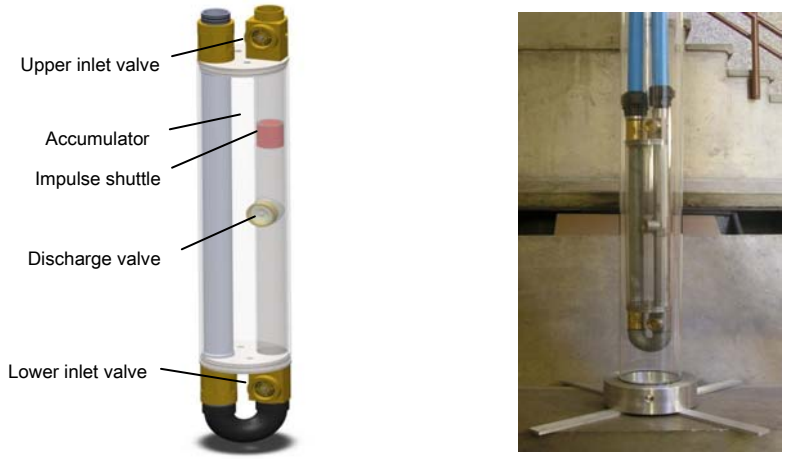
Each Fluidyne engine contains a number of significant improvements over previous technology, resulting in increased pressure amplitude and efficiency. The operation of two Fluidyne engines in antiphase should increase the stalling pressure amplitude, which tends to be limited by the condensing stroke in a single Fluidyne engine. The hydraulic ram behaves as a form of fluidic

11 "Thermofluidics: Transitioning to the Market Place". Kahn A. & Weinstein A. SDSU – Aztec Business Alliance MBA consulting program, final report.

gear, enabling the head in the driving flow to be augmented significantly beyond the pressure amplitude developed by the engine. The research team fabricated an initial alpha prototype to demonstrate technical feasibility followed by a scaled-up beta version that was constructed and tested for potential field trials. Figure 6 illustrates photographs of the alpha apparatus. Figure 7 describes the beta version.

Figure 6: Photographs of Alpha Prototype during Operation and Testing

Figure 7: Left. CAD Drawing Showing the Key Features of the Updated Hydraulic Ram Right. The Apparatus Installed in the New Facility within the Borehole Sized Tank



This project successfully demonstrated that a double-acting hydraulic ram could be used to pump water for low cost irrigation applications in California. Overall the hydraulic ram concept worked very well, delivering 800 L/hr at 15 meters head. The researchers successfully overcame several unforeseen and material challenges in what was already a challenging project in terms of ambition, scope, and timeframe. The research team developed simulation software to help optimize the design of the (second) beta ram prototype, fabricated a beta test unit, and designed and built a twin pneumatic driver system to mimic heat engine performance. Researchers were

able to achieve relatively high system efficiency levels in a short period of time, contrasting well with more established technologies (e.g., solar PV water pumps) which have benefited from years of research and investment.

Testing of the prototypes met some, but not all of the objectives set out in the original statement of work. The original project objectives were challenging. Additional development and refinement is needed to optimize operating conditions and system efficiency. For example, further efficiency improvements in the hydraulic ram could be achieved simply by using another test facility to minimize structural vibration of the apparatus. The selected experimental facility must also be able to accommodate a fully integrated system, using heat engines as the drive system for the hydraulic ram. Full integration would allow for additional hydraulic ram characterization tests that were outside the scope of this project. The component packaging of the ram could also be improved by moving away from the standard U-tube to a concentric design. Future testing should take place in more aggressive/corrosive environments including various California climate zones over longer time periods to demonstrate robust and reliable operation. Finally, the researchers recommended validation of the newly developed numerical optimization models to explore the feasibility of using this concept for deeper water pumping applications.

Commercialization of the ram technology will be subject to the successful completion of field trials. Initial target markets for this technology are farmers, in particular, fruit growers. The research team envisions licensing the technology to enable manufacturing, distribution, sales, and service activities. Several market stakeholders have indicated preliminary interest in the ram technology. The research team is also exploring potential partnerships with pump manufacturers in the United States to help commercialize the technology.

The researchers are confident that original performance targets (1,000 L/hr at 15 meters head) can eventually be reached with additional development and testing, opening the doors to field trials and opportunities to obtain financing. An initial manufacturing cost analysis showed that the hydraulic ram can be competitive with other products in the market. The manufacturing cost of the prototype hydraulic ram module, independent of the system used to drive the oscillation, is about $2.40 per hydraulic watt. This is largely driven by the cost of the water pipe connectors rather than the cost of the core ram pump. The target manufacturing cost for a fully integrated system was $4.00—$10.00 per hydraulic watt. Thus there is considerable room to add the cost of a heat engine (or even other potential drive systems) within the cost target range, excluding government cost subsidy or incentives. Once this has taken place, a higher precision manufacturing cost analysis can then be undertaken to validate the viability of the concept.

2.4.3 Objectives

The goal of this project was to prove the feasibility of a solar heat engine driven hydraulic ram. The researchers established the following project objectives:

1. Demonstrate thermosiphon/heat pipe functionality to within 10 percent of published performance data by the Institute for Solar Technologies in Switzerland (SPF Collector Catalogue).

2. Confirm that the Fluidyne engine can deliver 16 Wh to an arbitrary load with a thermal efficiency of at least 2.0 percent, based on calibration in Objective 1. Repeat over five start-stop cycles with less than or equal to 5.0 percent decay in performance.
3. Demonstrate output of 1,000 liters per hour (L/h) at 15 meters head from the hydraulic ram on lab test.
4. Demonstrate 500 L/hr output at 15 meters head from the hydraulic ram driven by a single Fluidyne engine and solar heat source.[12]
5. Repeat performance Objectives 2 and 4 with a second Fluidyne engine driver.
6. Demonstrate 1,000 L/hr output at 15 meters head with twin Fluidyne engines and solar heat source. Repeat over five start-stop cycles with less than or equal to 5.0 percent decay in performance.[13]
7. Confirm projected unit manufacturing cost of $4—$10 per hydraulic watt.

2.4.4 Outcomes

1. Test data confirmed acceptable thermosiphon/heat pipe functionality.
2. The target power output of 16 Wh was met on only one occasion. The bulk of test results consistently measured two Wh short of the intended target. The best thermal efficiency level recorded was 1.6 percent, 0.4 percent short of the intended target.
3. The alpha initial prototype of the hydraulic ram module fell substantially short of the required flow rate, reaching only 140 L/h at 15 meters head. The new 15 meter tall beta prototype achieved an equivalent flow rate of 800 L/h at 15 meters head.
4. No data/results were presented per the agreed modified schedule of work. This task and associated objective were amalgamated into Objective 6. Due to unavoidable health and safety concerns solely relevant to the experimental facilities, the integration of the two technologies had to be simulated through the fabrication of pneumatic replica Fluidyne engines. These replicas were designed to provide as similar an input to drive the ram as possible. Agreed changes to the statement of work meant that Objectives 3, 4, and 6 were addressed simultaneously with the final apparatus.
5. Both Fluidyne engines were fabricated to an identical specification. Initial tests were carried out on the original Fluidyne engine and later tests were conducted on the other. Under the same test conditions, both units could be expected to perform comparably.
6. The completed apparatus with pneumatic replica Fluidyne engines provided the aforementioned 800 L/h at a load of 15 meters head. By the completion of this project the

12 It was agreed with EISG staff at Milestone 3 that the ram would be powered by a pneumatic Fluidyne engine driver for Objectives 4 and 6, due to health and safety concerns about the solar Fluidyne engines that related solely to the test environment.

13 See footnote above.

prototype had logged over 50 hours of service without noticeable deterioration in performance.

7. A manufacturing cost analysis indicated that the hydraulic ram integrated with a drive system (not necessarily a heat engine) could provide an output of $0.70—$3.30 per hydraulic watt without subsidy. This leaves considerable room to add the cost of a heat engine or other potential drive for a fully integrated system.

2.4.5 Conclusions

1. Acceptable power transfer can be achieved by operating the collector as a two phase thermosiphon/gravity return heat pipe across a wide range of power inputs and inclination angles.

2. The researchers conducted numerous commissioning tests at different loads to characterize Fluidyne engine performance. Although measured results fell short of target power output, proof-of-concept was achieved. Further technology refinement could potentially meet performance goals.

3. The alpha prototype of the hydraulic ram module fell substantially short of the required flow rate even though it was capable of pumping well in excess of the required load, most likely due to lower than anticipated efficiency. The researchers elected to design and build a beta prototype based on results from alpha prototype testing and the added benefit of computer modeling. The new 15 meter tall beta prototype achieved an equivalent flow rate of 800 L/h. Test results also indicated that increases in flow rate can be achieved by increasing the input drive power.

4. The fabrication of pneumatic replica Fluidyne engines and simulated integration with the hydraulic ram module served as a successful experimental alternative for the purposes of this project. Objectives 3, 4 and 6 were addressed simultaneously with the final apparatus.

5. The researchers concluded that performance data for each Fluidyne engine was identical under varying load conditions.

6. Once valve settings on the drive system were set, the apparatus could be started, powered down, and re-started, providing the same performance for a given input power. Additional efficiency measurements demonstrated the hydraulic ram efficiency peaked at 47.3 percent, a considerable achievement.

7. A final cost analysis for the completed apparatus could not be completed as the direct connection between the heat engine and the ram could not be made within the constraints of the testing environment. However the concept has the potential to be cost equivalent to other renewable water pumping techniques (e.g., PV electric pumps).

This project successfully demonstrated that a double-acting hydraulic ram could be used to pump water for irrigation applications in California. The researchers developed simulation software to help optimize the design of the second beta ram prototype, fabricated a beta test unit, and designed and built a twin pneumatic driver system to mimic heat engine performance.

The fabricated prototypes met some, but not all of the objectives set out in the original statement of work. The hydraulic ram concept worked well, and an increase in the driving power could provide higher flow rates. Measured efficiency levels are promising.

2.4.6 Recommendations

While the design team considered that the main technical hurdles of the concept have been resolved in the course of this project, significant development work remains. The Program Administrator recommends that the researchers:

1. Increase input hydraulic driving power to the ram to optimize operating performance. The ram and the heat engines could be scaled up slightly to reach the required thresholds.
2. Add additional instrumentation and data acquisition to help optimize system efficiency. Future prototype development could be improved if additional instrumentation (i.e. pressure transducers) were installed to allow more accurate resolution of the shock propagation in the U-tube.
3. Confirm manufacturing cost of a completed apparatus. The researchers estimated the manufacturing cost of the prototype hydraulic ram module, independent of the system used to drive the oscillation, at about $2.40 per hydraulic watt. This was largely driven by the cost of the water pipe connectors rather than the cost of the core ram pump. The target manufacturing cost for a fully integrated system was $4.00—$10.00 per hydraulic watt.
4. Conduct testing at ambient conditions representing various California climate zones.
5. Integrate the proposed concept with solar collectors to more closely represent the system envisioned for irrigation applications.
6. Measure ram performance at higher input power for more thorough documentation of system performance across a wide range of operating conditions.
7. Develop incremental modifications to improve efficiency. For example, empirical evidence suggested that a significant amount of energy was lost as vibration due to the way in which the apparatus was secured to the stairwell.
8. Validate the newly developed numerical optimization models to explore the feasibility of using this concept for deeper water pumping applications.
9. Integrate the heat engines directly with the hydraulic ram and perform appropriate testing once a more suitable test facility has been found. This would clear the path for an extensive set of field trials at an outdoor location. The current reliability test included more than five start-stop cycles, whereas continuous runs over many hours in a more aggressive/corrosive environment would be required to help ensure reliable operation. Integration of the hydraulic ram module with the heat engines as a sealed unit would also increase the range of operating conditions under which the system can be tested.
10. Develop a concentric design alternate to the standard U-tube design. This would be a more efficient use of available space and would permit the ram to fit down smaller

boreholes. This is important given that the cost of borehole drilling increases drastically with larger hole sizes.

11. Develop a detailed commercialization plan. Financing will likely be required to offset the capital cost of this concept. The research team envisions licensing the technology to enable manufacturing, distribution, sales, and service activities. The IFC (International Finance Corporation)/World Bank could participate in a future financing round. The research team should also continue to explore potential partnerships with pump manufacturers in the United States to help commercialize the technology.

12. Investigate other potential applications besides irrigation where heat is available to drive the process. A good example and a compelling fit for California is the use of geothermal resources where heat can be made easily available seven days per week, 24 hours per day, thereby simply replacing grid or diesel fuel options.

2.4.7 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 potential public benefits to California and the Californian taxpayer are savings in energy consumption, more cost effective water pumping solutions, and reduction in carbon dioxide emissions.

The results of this project indicate that it could be feasible to build a product that would cost between one quarter and one third of existing PV based products. An economic analysis suggests that the proposed renewable concept could provide a payback of 10 to 20 years, compared with use of conventional resources such as the electric grid or diesel products. The researchers estimated a California total addressable market potential of $150 to $500 million per year across all water pumping applications. The proposed initial target market for this product is drip irrigation which, if fully commercialized, could reduce conventional energy consumption by 1.0 to 3.0 gigawatt-hours (GWh) and eliminate 1.3 to 2.0 million metric tons of carbon dioxide (CO_2) emissions per year.

Since the project was completed, Thermofluidics has continued to develop the technology. The efficiency of the hydraulic ram has increased from 47.3 percent in the EISG project and now regularly achieves efficiency levels in excess of 75 percent.

Thermofluidics is also developing a much larger scale pump under contract with the UK Government's Environmental Agency. This pump is designed for large scale river pumping and offer higher flows for heads up to 5 m. Please see the Thermofluidics website for more information at www.thermofluidics.com.

2.4.8 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 proposed concept could eventually serve residential, commercial, and industrial markets. The initial beachhead market is drip irrigation. Preliminary interest in the ram technology has been received from several market stakeholders. The research team is exploring potential partnerships with pump manufacturers in the United States to help commercialize the technology.

Engineering/Technical

Further technology development work is needed before this concept can be considered ready for commercial deployment. The researchers plan to confirm that the actual Fluidyne engine integrated with the hydraulic ram module can provide the performance indicated in this report.

Legal/Contractual

The research team filed a patent, which is wide-ranging and not application specific. The heat engine component of the technology is published under patent application number WO2005121539, which was granted in a number of key regions including the United States, Australia, New Zealand, and Canada. The team also filed a United Kingdom patent application number PCT/GB2010/051934.

Environmental, Safety, Risk Assessments/ Quality Plans

Since the researchers were not able to test a fully integrated system that combines the heat engines directly with the hydraulic ram during this project, they need to ensure that there are no safety or environmental risks associated with this system design that could otherwise restrict market penetration.

Production Readiness/Commercialization

The concept is not yet sufficiently developed for commercialization. Many US and non-US organizations have shown an interest in developing this technology further. A current list can be obtained from Thermofluidics.

2.5 Modeling Blade Pitch and Solidities in Straight Bladed VAWTs

Awardee: Wind Harvest International

Principal Investigator: Robert Thomas

2.5.1 Abstract

Vertical axis wind turbines are designed to capture wind resources near the ground. At ground level the wind velocity is lower than at 300 feet or so above the ground, and the wind is more turbulent. These characteristics lead to a lower energy harvest from these machines compared with horizontal axis wind turbines operating approximately 300 feet above the ground. Doubling the height of the tower increases the wind speed by 10 percent and the expected power by 34 percent. Increasing tower height five times increases the wind speed by about 25 percent and almost doubles the power available.

More efficient vertical axis wind turbines could improve the harvest from near ground machines. To achieve that result the researchers in this project hired Iopara Inc. to create an aerodynamic model of a vertical axis wind turbine (VAWT) using data from an existing array of VAWTs. The results of the modeling showed that vertical axis wind turbines with solidities lower than 33 percent could achieve a higher wind energy utilization coefficient (Cp) than those with higher solidities. The researchers modeled three versions (12.375 percent, 16.5 percent, and 24.75 percent solidities) with a predicted maximum Cp between 47 percent and 49.5 percent. The turbine with 16.5 percent solidity achieved the highest wind energy utilization in the modeling. Modeling showed that an improvement in the blade end design could theoretically improve the turbine's output by around 6 percent, which would bring the 16.5 percent solidity turbine's Cp close to the Betz limit. The modeling also showed that the placement of support columns upwind of the rotors would have a negligible effect on turbine efficiencies. The distance rotors are placed apart from one another and their orientation to the wind can benefit turbine energy output, but more research is needed. Analysis of the levelized cost of energy (LCOE) showed that the best LCOE can be achieved by the 12.375 percent solidity turbine because it has fewer blades, resulting in lower capital cost and making up for a slightly lower Cp. The model predicted a LCOE of less than 3 cents per kWh in a 14 mph wind for the 12.375 percent solidity turbine. LCOE was calculated without a discount rate for invested funds.

Keywords: VAWT, vertical axis wind turbine, wind energy, cost of energy generation, torque limitation, turbine solidities, blade end drag, blade arm drag, coupled vortex effect, capacity factors, Cpmax, aerodynamic modeling

2.5.2 Introduction

California mandates that utilities provide 33 percent of their energy from renewable energy sources by 2020. While wind energy is a key component of renewable energy, few existing turbines utilize near ground wind resources. Researchers in this project developed a vertical axis wind turbine to access the turbulent and lower velocity winds located near the ground. They claimed this would allow generation of wind resources in areas that prevent the installation of tall wind turbines and would increase the efficiency of existing wind farms through the addition of VAWT turbines below the tall horizontal axis wind turbines. The researchers' plan included determining the best solidity of a high capacity factor vertical axis wind turbine (VAWT), reducing parasitic drag, and determining the blade pitch angles necessary to perfect a torque limiting device. The results of this project provided the information necessary for the researchers to design an improved straight bladed VAWT model.

The researchers employed Iopara Inc. to conduct an aerodynamic analysis. Through computer modeling, Iopara Inc. found a number of design modifications that could increase the overall efficiency of the researchers' VAWT and could allow the turbines to utilize more effectively near ground wind resources. The researchers and contractor also investigated a torque limiting device that operated by pitching the blades to limit torque on the generator as wind speeds increase.

Iopara Inc. analyzed several different rotor solidities and found a rotor solidity of 16.5 percent would provide the highest power coefficient (C_P = 49.38 percent at TSR = 3.01 with coupled vortex effect and TSR as the ratio of tip speed to wind speed). The performances of the different rotor solidities of the researchers' turbine were calculated using the same amplification factors and calibrated for the rotor solidity of 16.5 percent. Calibration of the amplification factors for the other rotor solidities would require additional CFD simulations not undertaken in this project.

The LCOE showed that the 12.375 percent, 16.5 percent, and 24.75 percent solidity model turbines will all have very competitive energy costs in a 14 mph wind, which is about the lowest wind resource in which commercial wind farm based turbines are installed. The 12.375 percent VAWT had a calculated LCOE of less than 3 cents per kWh.

The researchers found that there is no significant change in the power coefficient for the cases with or without columns. This conclusion was based on the calculation of the power coefficient for two different TSRs and by analyzing the torque for one blade in each configuration.

The researchers also investigated the effect of wind direction for a three rotor configuration (Figure 8). The results predicted that northwesterly wind directions can result in a slight increase in the power coefficient for both the co-rotating and counter-rotating rotor configurations. This increase was more likely in the case of the co-rotating rotors. The power coefficient (C_P) history (time) plots showed that southwesterly wind directions introduced a lag in C_P values, while northwesterly directions showed an opposite trend. The results suggested that the turbine could be sited to take advantage of the northerly wind and thus preserve the omni-direction advantage of vertical axis wind turbines in an overall sense.

These new research findings should benefit the design of vertical axis wind turbines and result in more efficient and cost effective turbines. Project results suggest a potential to utilize near ground wind resources in commercial wind farms. Some wind farms could increase energy production with the addition of these low level wind turbines. Since existing wind farms have already purchased land, fencing, and roads, the addition of LAVTs at these sites would bear less infrastructure costs.

Figure 8: Three Vertical Axis Wind Turbines in the Foreground

2.5.3 Objectives

The goal of this project was to prove the feasibility of a design for a low solidity, high capacity factor, vertical axis wind turbine. The researchers created the following objectives to prove feasibility:

1. Test the uncalibrated CARDAAV model. CARDAAV is a computer program based on the Double Multiple Streamtube model. It was developed by I. Paraschivoiu and is used to determine the performances of straight-bladed vertical axis wind turbines. Test the model with a high solidity single turbine design where performance data is available. The CARDAAV must operate stably and produce results that are within 10 percent of the test data in at least the TSR (ratio of tip speed to wind speed) range equal to and greater than TSR at C_P max. Repeat test runs with CARDAAV and computational fluid dynamics (CFD) to account for the coupled vortex effect.

2. Achieve a levelized cost of energy (LCOE) of $.035 per kWh to produce a low cost turbine for lower wind resource sites by using the researchers' cost of goods sold with a 25 percent margin plus expected delivery, installation, shared wind farm facility, maintenance and repair costs, along with a zero inflation rate and no income from tax benefits and other extra sources.

3. Improve efficiency of the theoretical C_P max from .32 to .495 by effectively selecting the most cost effective rotor solidity, designing the blade arm fairing and blade arm

connections, and properly spacing the distance between rotors and placement of upwind columns.

4. Finalize the turbine blade pitch angles to within one degree of the ideal in higher wind speeds by finalizing computer modeling runs.

2.5.4 Outcomes

1. Results of the power coefficient comparison between CFD prediction and WHI 530G model test data were within 10 percent of the CFD prediction except when TSR=3. See Table 2.

Table 2: Power Coefficient Comparisons

Rotor configuration	CFD Prediction	Test Data Results	Percentage (Test Data/ CFD Prediction)
1 rotor TSR = 2.0	0.265	0.261	98.5
1 rotor TSR = 2.4	0.242	0.241	99.6
1 rotor TSR = 3.0	0.153	0.134	87.6
3 rotors TSR = 2.0	0.34	0.331	97.4

2. The most cost effective version of the turbine had 12.375 percent solidity. Using a single speed generator, the researchers projected a LCOE of 2.8 cents per kWh in a 14 mph wind resource. The researchers calculated the LCOE for the smaller sized 24.75 percent solidity model with four blades at 4.26 cents per kWh in a 14 mph resource. The LCOE in a 17 mph resource was about half of that number for the smaller diameter turbine. If these cost numbers can be achieved, the redesigned turbines would be among the most cost effective of any wind turbine in the industry. Note that a discount rate of zero was used in the LCOE formula.

3. Using properly sized end plates at both extremities of the blades, the researchers increased the maximum efficiency (power coefficient) by 1.77 percent for their WHI 1500 wind turbine. For the WHI 3000 they increased the maximum efficiency by 6.24 percent. The greater sensitivity to blade tip effect for the WHI 3000 could be explained by the wider rotor aspect ratio (diameter/height ratio) compared to the WHI 1500.

4. The final computer analysis of torque limiting pitch at 2 mph increments indicated that the blade pitch must vary from 6.5 degrees at 24 mph to 14 degrees at 60 mph to keep maximum power output below 75 kW. An increased pitch is required at higher wind speeds to limit the power and turbine torque.

2.5.5 Conclusions

The results from Iopara's analysis provided the information necessary to implement an efficient fairing design for the researchers' VAWTs. Model results showed the rotor solidity of 16.5 percent would provide the highest power coefficient and that a maximum blade thickness of c/3 would produce optimal parasitic drag values for lenticular cross sections. Column placement

analysis recorded no significant change in the power coefficient in cases with or without columns, and the placement of the turbines in relation to wind direction can be done to benefit the power coefficient. Final CFD simulations of different turbine spacing identified particular behavior of the WHI 3000 and determined that a TSR equal to three has a strong vortex effect, which may allow the researchers' turbines to be placed in close proximity to one another or in the vicinity of horizontal wind turbines. The best turbine in terms of the lowest LCOE was the 12.375 percent solidity with a single speed generator. The researchers calculated a LCOE of less than 3 cents per kWh over a 40 year projected life.

The researchers were successful in determining efficiency improvements for VAWT using computational methods. Field demonstration of these improvements must follow to verify the actual improvements.

2.5.6 Recommendations

The researchers plan to continue development of the proposed technology to commercialization. As part of continued development of this technology, the Program Administrator recommends that the following tasks be completed:

1. Complete calculations for a wider range of wind speeds and turbulent flow analysis.
2. Evaluate the impact of wind speed on efficiency.
3. Measure and classify the wind resource below tall wind turbines at California wind farms. Locate and evaluate other locations with low level wind resources (greater than 14 mph) that could be sites for the low vertical axis wind turbines.
4. Evaluate the transmission capacity at each wind farm in California to determine how much power can be added to the existing infrastructure.
5. Evaluate the impact of air flow disturbance on turbines in an arrayed configuration.
6. Identify suitable fabrication materials and perform failure analyses at various wind speeds.
7. Perform a complete economic analysis for comparison to alternative technologies. Compare the addition of vertical axis wind turbines to the addition of photovoltaic arrays at existing wind farms.
8. Perform a detailed market analysis and pursue commercialization.

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.

2.5.7 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 public from this research is increased affordability of electricity in California. This benefit derives from potential improvement of wind farm capacity factors by adding low vertical axis wind turbines below the existing horizontal axis turbines. The benefit also derives from potential higher efficiency of the vertical axis wind turbines. Before making an estimate of the economic value of this technology, one must quantify the wind resource near the ground at each of the wind farms. It is possible that the vertical axis wind turbines described in this project could be installed in areas that do not allow tall horizontal wind turbines. These areas have not yet been identified, so no quantitative benefit can be determined.

This project helped WHI (the researchers' company) attract capital and partners. WHI is a California-based company with offices and staff based in the State. The company's success could result in growth in its staff in the State.

2.5.8 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 plan to introduce their Model 636G LAVTS into the United Kingdom's market in 2012. They are planning a Model 3000 for introduction by 2014. The researchers have not performed a detailed market analysis, but have talked with wind farm owners and developers.

Engineering/Technical

The researchers plan to retrofit existing Model 530G turbines in Palm Springs, California, to validate the low solidity modeling results from this project. They also plan to develop a torque limitation system. WHI intends to do this by modifying its existing Model 530G array to test 16.5 percent (2 blades) and 24.75 percent (3 blades) solidity versions of this model turbine. Resulting strain and load gauge and power performance data will be used to calibrate Iopara's aerodynamic model and improve its predictive capacities. After this the researchers plan to test prototypes of a variable speed and direct drive technology on the Model 636G LAVTS that WHI is introducing into the UK and Europe in 2012. Once the torque limitation device is developed, a prototype of the Model 3000 LAVTS can be developed and tested with or without a variable speed device.

Legal/Contractual

The researchers claim to have performed an extensive patent search to obtain the patent on the coupled vortex (Patent No US 6784566). No patents resulted from this project.

Environmental, Safety, Risk Assessments/ Quality Plans

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

Production Readiness/Commercialization

The researchers claim to have the capacity to produce and install wind turbines based on this technology. They are seeking financial partners to help finance the growth of their company.

2.6 All AC Plug and Play Photovoltaic System

Awardee: Solar Red, Inc.

Principal Investigator: Joe Augenbraun

2.6.1 Abstract

While solar panel designs have improved and costs declined, there has been little improvement in associated installation and maintenance costs. This project investigated the feasibility of a panel attachment system intended to provide ease of installation, rapid attachment/removal, and compliance with relevant codes for down force and uplift forces. The researchers in this project met their objectives for reliable and easy snap in/snap out operation. Issues with the testing apparatus and choice of materials precluded meeting the goals for strength required for code compliance. The researchers identified a path for future development and testing to address these issues.

Keywords: PV mounting system, roof mount, solar, PV

2.6.2 Introduction

The California Solar Initiative is helping drive adoption of PV systems throughout the State. Although module designs have improved and prices have dropped, there has been little improvement in the installation and maintenance costs of solar energy systems. This has become a significant barrier to more rapid adoption of systems and fulfillment of California's vision for renewable technologies.

A faster installation system could lower costs and increase adoption of solar, providing benefits to customers and the environment. A method for quick attachment/removal of individual panels could also decrease long term maintenance costs associated with the need for individual panel replacement/service or accessing the underlying roof.

This project addressed a proprietary panel attachment system that offered a means of quickly attaching/removing panels and a simplified installation process. The researchers' test bed is shown in Figure 9.The researchers indicated that the product was primarily intended for residential markets, but it could also serve commercial markets. This represented a narrowing of focus and improved clarity over the original proposal in which they stated one or the other of these markets was to be the primary target at various places in the narrative.

Figure 9: Project Test Bed

The figure above is configured for the uplift test. To configure this for down force testing, the test roof was turned upside down.

2.6.3 Objectives

The goal of this project was to determine the feasibility of a plug and play photovoltaic system that could enable mass deployment of residential and small commercial photovoltaic systems. Key features of the planned system were an install and uninstall time of less than five minutes per panel, ability to withstand wind uplift pressure in excess of 38.5 pounds per square foot (psf), and continued attachment mechanism integrity over more than 10 attachment/removal cycles. The researchers established the following project objectives:

1. Verify through simulations a deflection of the locking latch of less than one-half inch under wind load and a locking latch movement of greater than two inches from locked to open position.

2. Verify a prototype's proper engagement and release operation.

3. Conduct physical testing of samples to verify:
   - Less than 10 percent mechanical failures of mounts on 100 snap in/snap out cycles
   - Structural integrity under downward forces up to 113 psf (ASTM 1830)
   - Wind uplift resistance in excess of 38.5 pounds per square foot through testing at increasing loads of: up to -16 psf (UL Class 15), up to -24.2 psf (UL Class 30), up to -40 psf (UL Class 60), and up to -50 psf (ASTM 1830, roughly equivalent to 130 mph wind)
   - Outdoor performance of the panel and micro inverters for each panel consistent with the research emphasis on all AC, including electrical output, anti-islanding circuitry, voltage, current, and frequency output when connected to a load
   - Panel and bracket watertight performance under a 30 minute spray test
4. Demonstrate from project findings that projected balance of system costs (minus inverter) are less than $2/Wp.

2.6.4 Outcomes

1. Simulation results indicated a deflection of 0.4 inches under a 38.4 psf load applied to the entire panel and a latch movement of four inches from fully open to fully closed.
2. The final prototype operated smoothly between fully open and closed positions with less than 10 pounds of applied force.
3. The researchers tested a mock panel consisting of OSB sheathing mounted on stainless U-channels in lieu of an actual solar panel to eliminate the perceived risk that an actual panel could shatter during potential catastrophic failure of the mounting system. The 201 grade stainless steel called for in the design was not available in the limited quantities required for the research, so the researchers substituted 304 stainless steel. No failures of the latching mechanism occurred over 100 cycles. A failure occurred in the down force test at 22.7 psf and in the uplift test at 33.5 psf. Substitution of a mock panel and the early failures made performing the planned outdoor electrical performance and watertightness testing impossible.
4. Fabrication costs from five sheet metal parts manufacturers ranged from $0.096 to $0.213/Wp, assuming a 320Wp panel with six foot spacing between mounting posts. A time and motion study of a mock installation using only the prototype panels indicated that average panel installation time in a 5 kW system would be 1.4 man hours including all electrical connections and setup. Including $0.10/Wp for other balance of system costs (excluding inverter) yielded an estimated total cost of roughly $0.54/Wp.

2.6.5 Conclusions

The researchers did not meet the goals for down force and uplift strength, although the research suggests a path for further improvement in material selection and testing that may lead to better results in subsequent development. In a limited time and motion study, preliminary cost assessments were favorable using the researchers' assumptions. If this is borne out in future

research, this system could be a viable alternative to existing commercial installation alternatives.

1. Modeling work was successful and provided a sound basis for evolving a final design expected to meet the project objectives.
2. The final prototype met the objectives for range of motion and ease of operation.
3. The latching mechanism met the objective for reliability under repeated operation cycles. The early failures in the down force and up lift tests appeared to be attributable to use of a mock panel rather than a commercial unit and use of 304 rather than 201 grade stainless steel in the prototype. This led to failures in the prototype frames before the latching mechanism could be tested to the loading objective. It is unclear whether testing with a commercial panel and 304 material would lead to targeted performance, although it would allow completion of the electrical and watertightness tests.
4. The lack of detail for the time and motion study in the Final Report limits the confidence in the conclusions for projected cost in a real world installation. However, assuming the projected installation costs from the prototype installation study hold under field conditions, the proposed system has potential to significantly lower installation costs.

2.6.6 Recommendations

Any subsequent research and testing should use commercial solar panels and materials intended to be used in future product offerings. A larger installation test should be conducted and include specific testing for several roof configurations (at a minimum flat and sloped), choice of roofing materials, and type of solar panels. Testing should also address long term environmental exposure and fatigue life of the materials and designs. The Program Administrator recommends redesigning the test rig using 201 stainless steel and testing it for X number of cycles of fatigue with the value of X set by a conservative estimate on the loading of the frame on the roof over 25 years of life.

Use of the all AC concept should either be omitted from future research titles and discussion or be expressly included in the scope and details of such proposals.

2.6.7 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. Adoption of renewable technologies, including the California Solar Initiative, is underway, and reduction of system installation costs will be an important driver of

increased penetration. The researchers claim their mounting system will save approximately $1.20 per Wp. A savings of this magnitude in balance of plant costs would have a significant benefit to adopters of solar PV technology.

2.6.8 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 stated that they completed a survey of potential customers' interest in the product prior to grant application, but they did not provide details. The researchers claimed several large players have expressed interest, but they did not name any of those parties.

Engineering/Technical

With additional funding of approximately $150,000–$250,000, the researchers intend to resolve the lack of down force strength and complete a design for the manufacturing cycle in less than a year.

Legal/Contractual

The researchers completed a patent search and five applications prior to grant application. They stated that they have secured a patent or patents.

Environmental, Safety, Risk Assessments/ Quality Plans

The researchers provided a comprehensive list of recommended future development and testing, including the need to have the final product design pass compliance testing at a recognized laboratory such as Underwriters Laboratory.

Production Readiness/Commercialization

The researchers indicated several large players have expressed interest in helping take the technology to market and that a commercialization plan is in place. The researchers also claim to have a proprietary business development plan.

2.7 Microbial Fuel Cells for Sustainable Wastewater Treatment

Awardee: J. Craig Venter Institute

Principal Investigator: Orianna Bretschger

2.7.1 Abstract

Treatment of wastewater is an energy intensive process. Technology improvements are needed to reduce treatment costs and, ultimately, consumer water rates. A 2005 report issued by the California Energy Commission (CEC) entitled "California's Water-Energy Relationship" elucidates the energy costs of wastewater treatment and emphasizes the need for more efficient, less energy intensive treatment strategies. Otherwise energy consumption and operating costs for the treatment of wastewater are expected to increase in California due to a growing population, more stringent environmental regulations, and limited water resources, especially in Southern California.

The goal of this project was to determine the feasibility and scalability of using microbial fuel cell (MFC) systems to help decrease primary sludge volumes and the formation of secondary biomass and residual waste gas in wastewater treatment applications. Researchers designed, constructed, and tested a large-scale 100 gallon system to ascertain the viability, feasibility, and scalability of using MFCs for wastewater treatment applications.

The 100 gallon MFC was able to remove 80 percent of total suspended solids (TSS) and volatile suspended solids (VSS) plus 89 percent of biological oxygen demand (BOD) of the sample wastewater feedstock in a seven day residence time under continuous flow conditions. Researchers demonstrated that using an MFC can reduce waste water treatment costs plus recover 13 percent of the energy bound in sludge during treatment process. Sludge degradation produced a maximum power density of 1.0 watt per cubic meter (W/m3) across the MFC. Degradation rates acquired from the open circuit control system verified that accelerated degradation of BOD, TSS, and VSS occurred as a function of current production within the MFC.

The results of this project indicate that implementation of MFCs can accelerate sludge degradation rates in a potentially energy neutral fashion with the production of electricity. The total potential value of electricity produced using MFCs in wastewater treatment plants across California is estimated to exceed $23 million per year. However, researchers concluded that the concept is not yet practical or cost effective primarily because the incremental capital cost of a scaled-up MFC reactor is too high compared to other conventional wastewater treatment techniques. Practical use of microbial fuel cells (MCF) is most likely best suited for smaller scale municipal wastewater treatment plants due to the relatively higher capital cost compared to conventional techniques. Additional research is needed to optimize performance, improve power density at a lower capital cost, alleviate clogging issues, and confirm energy savings relative to other wastewater treatment techniques.

Keywords: Microbial fuel cell, sludge degradation, wastewater treatment, energy recovery, electrodes

2.7.2 Introduction

Treatment of wastewater is an energy intensive process. Technology improvements are needed to reduce treatment costs and, ultimately, consumer water rates. The nexus between water and energy has risen to the forefront of topics among stakeholders in California. A 2005 report issued by the California Energy Commission (CEC) entitled "California's Water-Energy Relationship" elucidates the energy costs of wastewater treatment and emphasizes the need for more efficient, less energy intensive treatment strategies. State wastewater processes in 2001 (including delivery, treatment, and disposal) resulted in the consumption of over 2000 gigawatt hours (GWh) of electricity and 2.7 trillion British thermal units (BTU) of natural gas.[14] Energy consumption and operating costs for the treatment of wastewater are expected to increase in California due to a growing population, more stringent environmental regulation, and limited water resources in Southern California.

The United States Environmental Protection Agency (U.S. EPA) Wastewater Management Fact Sheet[15] states that energy costs can account for 30 percent of the total operation and maintenance cost at wastewater treatment plants. Wastewater treatment plants account for approximately 3 percent of the electric load in the United States. It is expected that demand for electricity from these plants will increase by nearly 20 percent over the next 15 years. Reducing the amount of energy used in waste water treatment plants represents an important energy conservation opportunity for both California and the U.S.

Electricity used to treat wastewater across the state averages about 2500 kWh per million gallons treated. The volume of sludge produced by a typical waste water treatment plant is about 1.0 percent of the volume of influent wastewater to be treated.[16] In 2007 the City of San Diego (with a population of 1.2 million) processed nearly 800 million gallons of sludge, translating to 33,250 tons of biosolids.[17] If these data are extrapolated to the entire State of over 36 million people, an estimated 24 billion gallons of sludge is produced in California in a single year. The cost of treating sludge for the entire State, therefore, is estimated to be approximately $300 million per year, assuming average cost of electricity of $0.05/kWh. This cost is conservative since it does not include energy that is required for secondary or tertiary treatment and/or disposal of residual wastewater liquids.

Decreasing energy consumption in wastewater treatment plants can be accomplished through several strategies including implementing energy efficient equipment and practices, recovering energy during treatment processes, and optimizing treatment methods to minimize overall disposal costs of wastewater effluents and biosolids.

---

14 CEC "California's Water - Energy Relationship, Final Staff Report" (2005) p. 174

15 EPA "Wastewater Management Fact Sheet" (832-F-06-024), Office of Water (2006) http://water.epa.gov/scitech/wastetech/upload/2008_01_16_mtb_energycon_fasht_final.pdf

16 IWA Water Wiki http://www.iwawaterwiki.org/xwiki/bin/view/Articles/REDUCTIONOFSLUDGEPRODUCTIONINWASTEWATERTREATMENTPLANTS

17 San Diego Metropolitan Wastewater Department "FY08 Metropolitan Wastewater Final Budget" (2008) http://www.sandiego.gov/mwwd/pdf/mwwdbudget.pdf

The goal of this project was to design a more efficient and cost effective wastewater treatment technique that could address all three strategies. Researchers also attempted to address the feasibility and scalability of MFCs for the treatment of recalcitrant sludge, one of the most problematic and costly products resulting from conventional wastewater treatment processes. The research team determined that the use of microbial fuel cells (MFC) has the potential to reduce sludge formation plus decrease overall energy consumption and wastewater treatment costs under a single technology platform. The products/benefits from a MFC system are reduction in sludge; direct production of electricity, which is inherently more efficient compared to the more conventional waste-to-energy technique of producing and conditioning biogas from the sludge via digesters and then using it as feedstock for a cogeneration system; treated non-potable water to secondary levels; and reduction in carbon dioxide.

In this project the researchers used catalytic activity generated by bacteria that was attracted and attached to the conductive surfaces of the MFC system (electrodes) to reduce sludge formation, thus forming electrochemically active bio-films. The bacteria/bio-films were then able to extract electrons from organic components in the sludge and transfer them to the electrode. The bacteria must perform this electron transfer to the electrode surface to maintain biological functions. In essence, the bacteria breathe the electrode surface to live. MFC systems were designed to immediately move energy away from the bacteria, therefore accelerating their metabolism and increasing sludge reduction rates.

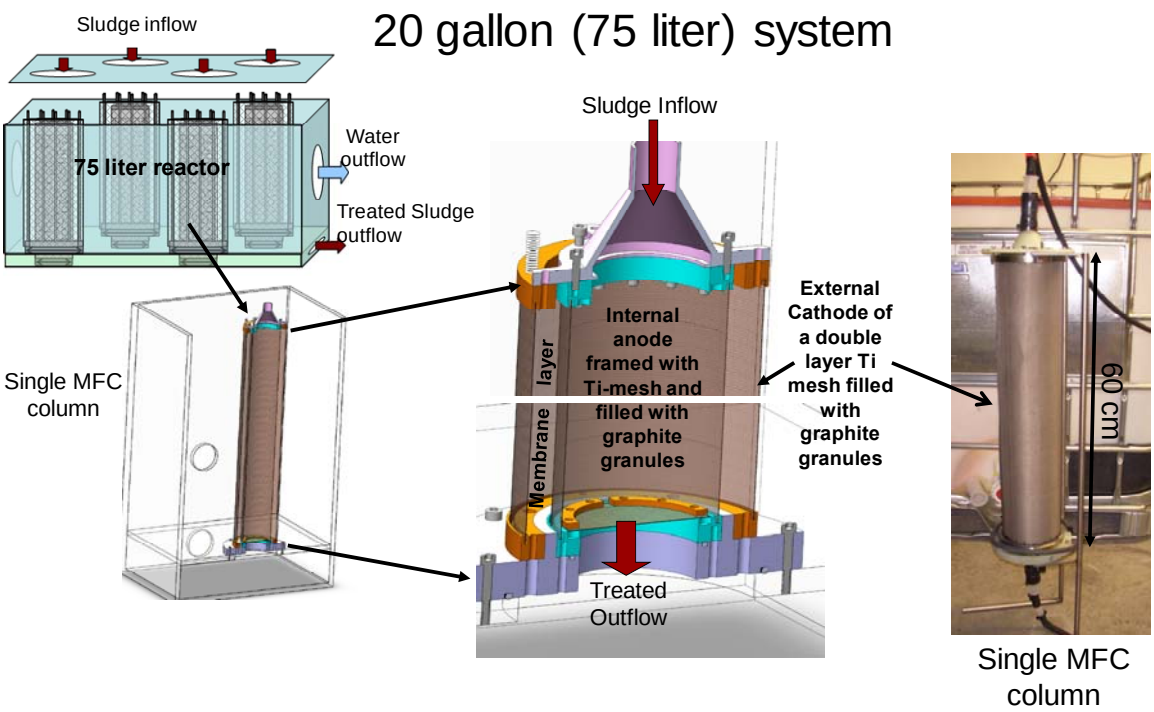
Completion of the MFC reaction took place in a physically separate, but electrically linked, compartment where different bacterial bio-films used the cathode electrode as a source for energy during the reduction of oxygen. In the cathode compartment, bacterial growth was limited by the energy source being delivered across the circuit and therefore biomass (sludge) production was reduced relative to traditional aerobic treatment systems.

There is little prior research in the area of large-scale MFC treatment of municipal sludge. Existing publications are largely focused on laboratory scale treatment (30—500 milliliters) of sludge using systems constructed from cost prohibitive electrode materials for cathode catalysts such as platinum. More cost effective materials including stainless steel, cobalt oxides, and titanium have recently been evaluated in various laboratories for catalytic and biocompatible properties. The results are encouraging. Micro-scale MFC systems operating with sludge as a fuel source in the laboratory demonstrated an ability to degrade between 40—80 percent of the initial organic content within 12 hours of residence time. [18]

Researchers in this project initially used an existing 20 gallon MFC reactor that was previously constructed and tested as a proof of concept for scalability (Figure 10). The 20 gallon reactor was also used to validate different electrode configurations prior to the final construction of the 100 gallon system.

18 Logan, B.E., et al. "Microbial Fuel Cells: Methodology and Technology", Environmental Science and Technology (2006) 40(17): p. 5181-5192

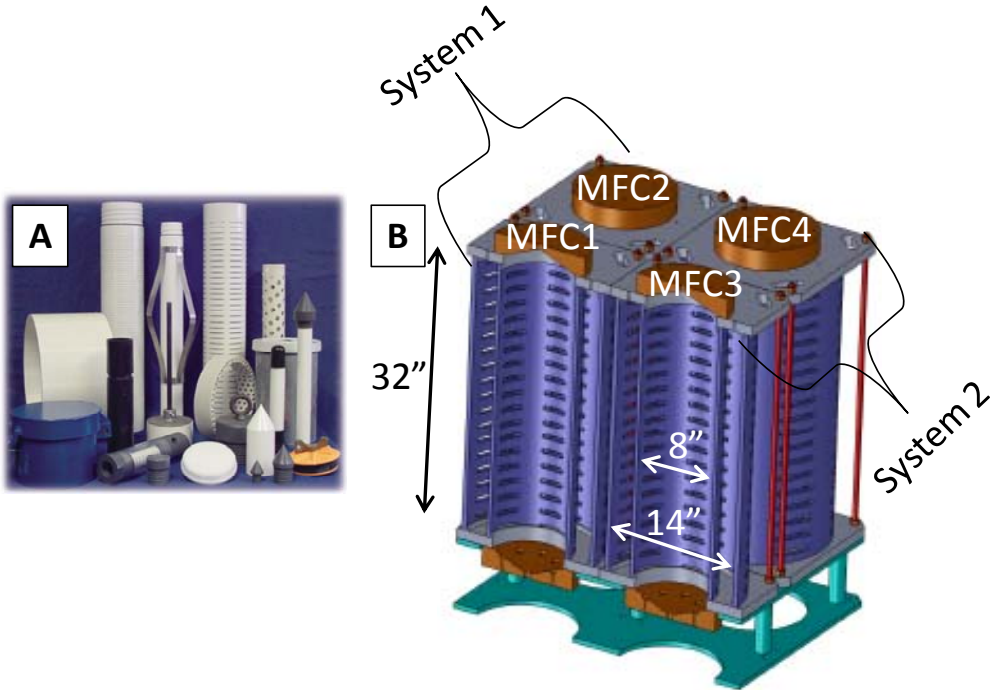
Figure 10: Twenty Gallon Test Reactor



Researchers then designed, constructed, and tested a large-scale 100 gallon microbial fuel cell (MFC) system with municipal sludge such as inoculum to ascertain the viability, feasibility, and scalability of using MFC technology for wastewater treatment applications. Figure 11 illustrates samples of polyvinyl chloride (PVC) drilled piping that the researchers used for the construction of the 100 gallon MFC reactor, plus a schematic for the reactor frame. The researchers specifically designed reactors to fit inside a pre-existing primary holding tank submerged in water. They then circulated the sludge through each MFC reactor using independent peristaltic pump tubing fixed to the end caps of each reactor and peristaltic pumps. The test apparatus was able to process 100 gallons of sludge under continuous flow in one 12 hour period. The researchers monitored biological oxygen demand (BOD) degradation rates, power production, and the economics of scale using industrially available materials.

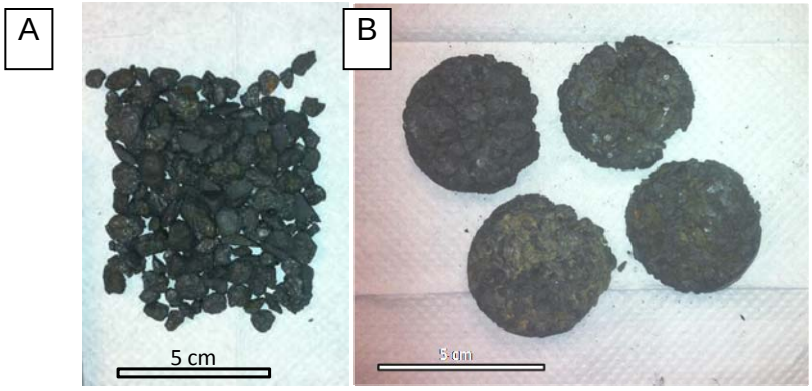
Figure 11: A) Examples of Drilled PVC Piping Used for MFC Reactor

B) Reactor Frame Schematic



The anode and cathode electrodes were both of a packed bed design. The research team previously utilized (1/4 inch x 10) crushed synthetic graphite granules as the packing material at the anode and the cathode. The graphite granules resulted in very little pore space in the electrode volume, which created clogging issues when sludge was introduced to the packed bed anode. The team modified the anode electrode configurations for the larger 100 gallon reactor using larger (3/8 inch x 10) crushed graphite granules and formed differently sized granules into stackable pucks with conductive graphite epoxy. (See Figure 12). The researchers also used the pucks as packing material, and they provided a conductive surface that facilitated movement of electrons as well as viscous liquids.

Figure 12: A) 3/8 Inch Crushed EC-100 Synthetic Graphite Granules
B) Graphite Pucks



The researchers received primary sludge samples from the San Elijo Joint Powers Authority Water Treatment Plant. They pretreated samples to remove large flocks and diluted them with tap water to prevent clogging. They performed full water quality analyses for the pretreated sludge samples and after every seven days exposed to reactor treatment. The researchers stored the pretreated sludge samples in two 50 gallon drums and recycled them through the reactor systems once every 24 hours at a flow rate of 100 milliliters per minute. They configured each system such that samples flowed consecutively from the stacked orb anode to the crushed graphite granule anode and back into the sample drum.

The researchers extracted samples for water quality analysis directly from the drums. To prevent settling, each sample drum was mechanically stirred for 10 minutes each day prior to sampling. The researchers did not perform constant mixing to avoid aerobic sludge degradation. They exposed each drum to the same mixing conditions except for two days when one of the stir paddles fell off the motor. Some data variability was obvious during this time period but subsequently normalized when the paddle was replaced.

The MFC system removed approximately 80 percent of volatile suspended solids (VSS) and total suspended solids (TSS) and 89 percent of biochemical oxygen demand (BOD) in a seven day period, reducing the concentrations to 59 milligram per liter (mg/L), 53 mg/L, and 130 mg/L, respectively. The researchers found initial removal rates corresponding to higher loading rates to be near 200 mg/L/day for VSS, TSS, and BOD at mesophilic temperatures. These data suggested that mesophilic MFC removal rates were equivalent to thermophilic anaerobic digesters that require heat input to operate efficiently (assuming that anaerobic sludge digesters reduce BOD values from 10,000 mg/L to 350 mg/L in a 40 day period). Additional analysis is recommended to confirm the energy savings of MFC systems for waste water treatment applications compared to conventional systems.

Researchers determined that the use of MFCs can reduce waste water treatment costs and recover approximately 13 percent of the energy bound in sludge during treatment process. The researchers estimated one kilogram (kg) of sludge to produce at least 4 kWh of thermal energy from combustion.[19] The energy bound in the chemical form of sludge may also be released

19 Shizas, I. and D.M. Bagley "Experimental Determination of Energy Content of Unknown Organics in Municipal Wastewater Streams", Journal of Energy Engineering (2004) 130(2): p. 45-53

through direct oxidation of the material by microbial action. The microbial oxidation of solid and soluble compounds contained in sludge results in a more efficient conversion of chemical to electrical energy relative to combustion. Assuming that 33,250 tons of sludge (roughly 30 x 10^6 kg) are produced annually by 1.2 million people in San Diego (roughly 30 million kg), approximately 15.6 million kWh can be recovered through MFC treatment assuming a coulombic efficiency of 13 percent (30 million kg x 4.0 kWh/kg thermal x 0.13 ~ 15.6 million kWh). At a rate of $0.05/kWh, this energy recovery could yield $780,000 per year. Extrapolating across the entire state of 36 million people, use of MFC technology places the value of energy produced from waste recovery by more than $23 million per year. These figures are regarded as conservative as they do not include efficiency gains associated with mesophilic reactors which accelerate degradation rates.

Researchers estimated the incremental capital cost and expected performance of a scaled-up (ten million gallon per day) MFC reactor operating at full capacity to determine its potential viability compared to other conventional wastewater treatment techniques. They based the financial value of electricity produced on an assumed buyback rate from the electric grid at $0.05 per kilowatt-hour (kWh). They based payback calculations on the incremental capital cost of a scaled-up MFC reactor, the value of electricity produced, an additional $50,000 per year for equipment maintenance costs, and a 4 percent annual inflation rate. They compared these financial assumptions to reported capital and operational costs for treatment plants in California. Based on the results of this simple financial analysis, the researchers concluded that the concept is not yet practical or cost effective primarily because the incremental capital cost of a scaled-up MFC reactor is too high compared to other conventional wastewater treatment techniques.

Practical use of microbial fuel cells (MCF) is most likely best suited for smaller scale municipal wastewater treatment plants due to the relatively higher capital cost compared to conventional techniques. Additional work is needed to assess long term system performance and durability, reduce capital cost, and develop a more in depth understanding of the microbial dynamics and activities associated with MFC sludge degradation. The research team also recommended exploration of sludge pretreatment methods to alleviate the clogging issues associated with delivery of large solids to the system. Finally, a more advanced financial analysis will be required to incorporate higher maintenance costs over time, capital financing, depreciation, etc.

2.7.3 Objectives

The goal of this project was to determine the feasibility and scalability of microbial fuel cell (MFC) systems for decreasing primary sludge volumes, secondary biomass production, and waste gas production during wastewater treatment. The researchers established the following project objectives:

1. Decrease material costs from $450,000 to $20,000 per cubic meter ($m^3$) or less by investigating new designs and materials.
2. Demonstrate a 70 percent reduction in total suspended solids (TSS) from 22,000 milligrams per liter (mg/L) to 6,600 mg/L in a ten day period.

3. Demonstrate a 50 percent reduction in biological oxygen demand (BOD) from 4,500 mg/L to 2,250 mg/L in a five day residence time.
4. Demonstrate decreased methanogenesis (waste gas) from 1.4 to 0.7 parts per million (ppm) over ten days.
5. Demonstrate odor reduction (H_2S) from 21 to 11 ppm over five days.
6. Optimize system operation for sludge reduction at low peak demand (64 mg/L per day) and electricity production at high peak demand (1.0 kW/m^3).
7. Confirm that the capital cost of MFC systems will be cost competitive with other renewable energy technologies which cost $4,000—$6,000 per kW or with existing electricity generation technologies ($1,000—$2,000 per kW).
8. Confirm that scaled MFC systems can provide significant savings ($66 billion annually) for California by reducing energy demand and sludge disposal volumes during wastewater treatment.

2.7.4 Outcomes

1. The research team was able to reduce material costs to $40,000/m^3 which was a 90 percent cost reduction relative to other laboratory systems.
2. The research team demonstrated an 80 percent reduction in total suspended solids (TSS) and volatile suspended solids (VSS) over a seven day period at lower loading rates than described in the objective.
3. The research team demonstrated an 89 percent reduction in BOD in a seven day period at lower loading rates than described in the objective.
4. Methane concentrations were not directly measured in the reactor due to the dynamic gas exchange occurring in the reactor catholyte.
5. Researchers observed odor reduction but did not quantify the reduction. They measured sulfide concentrations during the water quality analyses. However sulfide species are highly reactive. Thus measurements from the sample drums may not have accurately reflected the real time sulfide concentrations in each reactor.
6. The microbial fuel cell achieved a maximum sludge reduction rate of 138 mg/L per day while operating with a 1000 ohm resistor applied across the external circuit. In addition, MFC produced an observed maximum power density of 1.0 W/m^3.
7. The cost analysis indicated that microbial fuel cells are not yet cost competitive compared to other renewable energy concepts or electric generating technologies.
8. Researchers were not able to quantify potential savings to California ratepayers regarding the use of MFC devices in wastewater treatment plant facilities.

2.7.5 Conclusions

1. The reduction in material costs is encouraging and suggests further improvements to design and construction may lower costs even further.

2. Loading rates appear to have an impact on removal rates of TSS and VSS. Additional research is needed to better understand the relationship between loading and removal rates.
3. Loading rates appear to have an impact on removal rates of BOD. Additional research is needed to better understand the relationship between loading and removal rates.
4. Researchers were not able to demonstrate a decrease in methanogenesis as a direct result of electrogenesis. More work is required to quantify these relationships. Furthermore, system modifications are needed which enable appropriate sample collection for more accurate analysis.
5. Additional monitoring equipment is required to quantify odor reduction.
6. MFCs can provide efficient sludge treatment. Test data suggest that removal rates can be increased if smaller loads are applied to the circuit. In addition, maximum power density increases over time. As the reactor performance improves, the performance metric of 1 kW/m^3 could possibly be realized. More evaluation is necessary to validate these findings.
7. MFCs are not yet cost competitive with other renewable energy technologies. System capital costs must be decreased further and higher power densities must be recovered. More robust cost models are needed to calculate the real annual savings associated with MFC technology.
8. Researchers were not able to confirm significant savings for California ratepayers. Additional research is necessary to lower the capital cost of MFC reactors and more accurately determine the energy savings potential compared to more conventional wastewater treatment techniques.

Clearly the results of this work are mixed. Researchers demonstrated that MFCs can provide efficient sludge treatment by accelerating degradation of TSS, VSS, and BOD. However, loading rates appear to have a significant impact on removal rates, and the research team was not able to accurately measure reductions of methane and/or odor. Although the power density achieved by this project was disappointing, the researchers are optimistic that it can be improved dramatically as reactor performance improves. MFCs are not yet cost competitive with other waste to energy conversion techniques. However they may have some market value for smaller scale municipal wastewater treatment plant applications.

2.7.6 Recommendations

Further research is needed before microbial fuel cells can be considered for commercial use in municipal wastewater treatment plants. The Program Administer recommends the following activities:

- Perform long term evaluations of at least one full year of continuous electrochemical and wastewater treatment testing. Long term data collection will provide more information

about the durability and reliability of these systems, especially relative to energy recovery.

- Conduct addition research to better understand the relationship between loading rates and removal rates for TSS, VSS, and BOD.
- Quantify the reduction of methane and odor and explore various pretreatment methods to alleviate the clogging issues associated with delivery of large solids to the system.
- Optimize materials selection and fabrication processes to reduce capital costs.
- Use more cost effective and durable materials to improve reliability, lower capital cost, and reduce operation and maintenance costs.
- Develop a more robust cost model to calculate the real annual savings associated with MFC technology.
- Develop a business plan/market assessment to verify the market potential for this product and ensure that performance targets compare favorably with other options in the market.
- Develop methods to improve power density at a lower capital cost.
- Conduct field testing to optimize and validate the performance and reliability of the technology in a real world working environment.

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.

2.7.7 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 United States Environmental Protection Agency (U.S. EPA) Wastewater Management Fact Sheet states that energy costs can account for 30 percent of the total operation and maintenance cost of wastewater treatment plants. Wastewater treatment plants account for approximately 3.0 percent of the electric load in the United States, and it is expected that demand for electricity from these plants will increase by nearly 20 percent over the next 15 years. Reducing the amount of energy used in waste water treatment plants represents an important energy conservation opportunity for both California and the U.S.

Wastewater treatment is an energy intensive process that consumes an average of 2,500 kWh per million of gallons of treated water in California. The volume of sludge produced by a typical wastewater treatment plant is about 1.0 percent of the volume of influent wastewater to be treated. In 2007 the City of San Diego with a population 1.2 million processed nearly 800 million gallons of sludge, translating to 33,250 tons of biosolids. If this were extrapolated to the entire State of over 36 million people, an estimated 24 billion gallons of sludge would have been produced by California in 2007. The cost of treating sludge for the entire State is estimated to be approximately $300 million per year (assuming average cost of electricity of $0.05/kWh). This cost does not incorporate the energy required for secondary or tertiary treatment and disposal of the liquid portions of wastewater.

Researchers concluded that a MFC would be able to reduce waste water treatment costs and recover 13 percent of the energy bound in sludge during treatment process. The potential value of capturing and converting sludge to electricity using MFCs across tCalifornia is more than $23 million per year. These figures are regarded as conservative as they do not include efficiency gains associated with mesophilic reactors which accelerate degradation rates.

2.7.8 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 indicated that Synthetic Genomics and JCVI are working together to establish a new company for the purpose of bringing this technology to market.

Engineering/Technical

There are significant technical hurdles/risks which need to be addressed before this concept can be considered ready for commercial deployment. The researchers estimate that further development and completion of a prototype will require about three years and up to five million dollars.

Legal/Contractual

Researchers conducted a patent search and did not detect potential infringement of intellectual property. One patent application has been filed (2011/088348) and is now pending review by the U.S. Patent Review and Trademark Office.

Environmental, Safety, Risk Assessments/ Quality Plans

While there is no obvious safety or environmental risk associated with this system design, the concept must meet difficult regulatory requirements associated with municipal wastewater treatment plants. If additional research is pursued, the integrity of the system will need to be thoroughly tested to ensure that it meets standard industry safety and permitting requirements.

Production Readiness/Commercialization

The concept is not yet sufficiently developed for commercialization, although it is encouraging that two established companies are interested in bringing this technology to market.

2.8 Meteorological Buoy Technology for Offshore Wind Resource Assessment

Awardee: MetSpar, Inc.

Principal Investigator: Dr. Rodney R. Gay

2.8.1 Abstract

This research involved development and testing of technology for obtaining accurate wind speed data from a floating spar buoy with a tall mast equipped with wind speed and buoy motion sensors.

Researchers applied an algorithm developed to calculate true wind speed by accounting for the effects of buoy motion on measurements from NRG#40 cup anemometers and Gill WindMaster three dimensional sonic anemometers to evaluate results from land and ocean based testing. The researchers compared test data from stationary and moving towers. The first test was on land using a movable and a stationary tower. The second test was in the ocean using a floating buoy and a stationary tower on the Ventura, California, pier.

Results showed excellent agreement between moving and stationary sensors, with correlation coefficients of approximately 0.98– 0.99 for measurements averaged over two minutes or longer. The small improvement produced by the correction algorithm suggested that the impact of sensor motion almost completely averaged out over these time periods and may not be necessary under the tested conditions of buoy motion.

Keywords: Wind speed measurement, wind speed assessment, offshore wind, offshore wind power, meteorological buoy, met tower, cup anemometer, sonic anemometer

2.8.2 Introduction

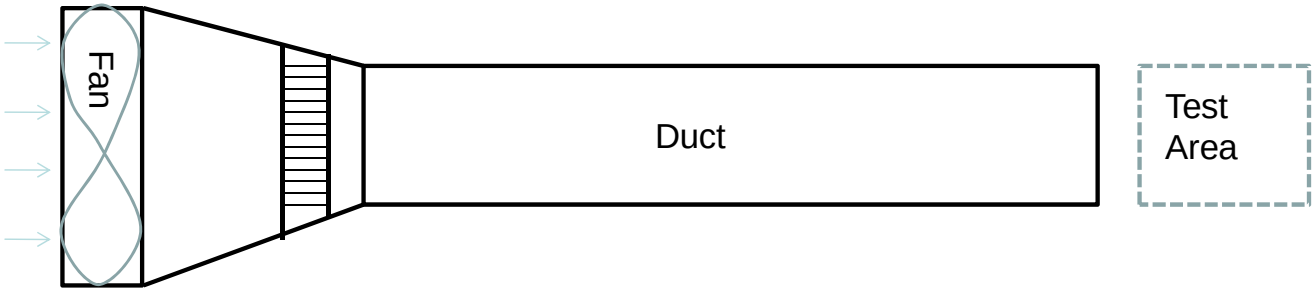
Meeting California's aggressive goals for renewable resources will require development of all viable sources, including wind. While land based wind development is proceeding well, finding an acceptable method for harvesting offshore wind remains elusive. Lack of comprehensive data on the location and magnitude of offshore wind presents an immediate obstacle to policy makers and potential developers seeking to harvest this resource.

While there remain substantial economic and policy issues to be resolved, California ratepayers could benefit from inclusion of offshore wind in their resource mix if these issues were resolved. Providing an accurate and economic method for assessing offshore potential is a critical first step.

This research proposed to validate that wind speed sensors on a moving buoy, when corrected for the effect of buoy motion on true speed measurements, could provide an accurate and potentially more economic approach to offshore wind resource assessments. The corrections would be based on an algorithm using measured pitch, roll, and yaw to account for their impact on the sensor's perceived wind speed and turbulence.

The researchers designed and built a wind tunnel (Figure 13) to allow tests to be conducted outside the enclosed duct section of the wind tunnel. This arrangement made it easy to deploy and adjust the position of wind speed sensors and related equipment. The flow straightening pipes and long duct were intended to produce a relatively large test area wherein the wind speed was approximately uniform.

Figure 13: Schematic of Wind Tunnel (Not to Scale)



Test area is outside the duct of the wind tunnel.

2.8.3 Objectives

The goal of this project was to determine the feasibility of developing and verifying the technology necessary to acquire accurate true wind speed data from moving wind speed and buoy motion sensors on a floating spar buoy with a tall mast. This information would be used in assessing potential offshore wind farm locations. The researchers established the following project objectives:

1. Design and construct a tilt platform that can dynamically move the tower over a 20 degree horizontal range in a manner similar to the motion expected for a floating spar buoy.
2. Develop data logging software that can record data and perform buoy motion and wind speed calculations to correct the observed data to true wind speed for all sensor types to be tested.
3. Demonstrate that average wind speed and turbulence from the moving tower on the tilt platform match corresponding measured data from a stationary tower within 2.0 percent.
4. Confirm that buoy measurements in the ocean match fixed tower measurements on land with a correlation coefficient of 97 percent or better.

2.8.4 Outcomes

1. The researchers added a preliminary calibration step to the scope of work to determine the wind sensors' response to changes in incoming wind direction. This involved building a small wind tunnel to provide a coherent air stream into sensors held at varying angles. The two constructed towers, one fixed and one able to tilt and to change position, formed the test bed for the land based step. The researchers completed testing as planned for the commercially available cup type[20] and 3d sonic type[21] wind speed sensors used in the project.
2. The researchers developed the required software and used it during testing in Outcomes 3 and 4 below. The data reduction software's calculation speed limited the sampling rate to one measurement per second.
3. The land based tilt testing typically employed a pitch angle variation from roughly -18° to +26° over a six to nine second period, similar to what was expected in the ocean testing phase. Overall results showed that data from the stationary and moving towers agreed well, with a 98 percent correlation coefficient, although the data correction software was not able to remove the second-by-second fluctuations caused by sensor movement in the tilting tower. Typical average wind speed from the moving tower was 1.0 percent less than for the stationary tower.
4. Two cup anemometers and one 3D sonic anemometer mounted on the top of a 15 meter tall spar buoy anchored roughly 60 feet west of the end of the Ventura, California, pier were the test bed for the ocean based step. A 3D sonic anemometer mounted at the end of the pier at roughly the same height as the buoy instruments provided the stationary reference.

   The two minute average wind speeds for both the cup and sonic anemometers nearly matched the pier's instrument with correlation coefficients of 0.984 and 0.995,

20 NRG#40

21 Gill WindMaster three dimensional sonic

respectively. Corresponding ten minute correlations were 0.987 and 0.982. Average five hour wind speeds at the buoy were 2.1 percent and 1.7 percent higher than the pier.

Calculated turbulence intensities of roughly 39 percent for the spar's instruments were essentially identical to those of the pier unit.

2.8.5 Conclusions

The researchers met the overall objective and demonstrated that accurate wind speed and turbulence measurements are possible from both moving and stationary sensors at a buoy spar height of 15 meters when averaged over periods of two minutes or longer. Similar conclusions could apply for spar heights approaching those of potential offshore wind machines where the sensor motion would be significantly larger, although further testing would be necessary to validate this assumption.

An unexpected result of the testing was that the conclusions above were valid without sensor motion corrections for the ranges of motion specified in the research objectives. This provided further encouragement that spar mounted sensors could be viable for offshore wind mapping.

1. The researchers met this objective, including an enhanced pre-testing calibration step to determine sensor response to varying pitch angles using a fabricated wind tunnel.
2. The researchers developed the required software and used it during testing at the land and water based steps. The one second per sample speed limit may have accounted for the limited success in demonstrating a marked improvement in true wind vs. apparent wind calculations described in Objectives 3 and 4 below.
3. As expected, results from the movable sensor tower showed higher apparent wind speeds when tilting into the wind and lower speeds when tilting away. Software corrections for sensor movement yielded calculated true wind speeds with less variation than the unadjusted data but still greater than the stationary sensor. Given the overall close agreement in correlation coefficients, the software's contribution to true wind speed accuracy appears to be negligible.
4. The ocean tests gave similar results to those in Objective 3, with very good agreement between moving and stationary sensor readings averaged over two minutes or greater. The calculated correction for changing pitch angles on the moving sensor was small (roughly .50 percent), although the pitch angle changes were also relatively small (+/- five degrees), suggesting a proportionally larger benefit with greater changes in pitch angle. The higher wind speed readings from the buoy were relatively small and may have been caused by the pier structure's impact on wind speed vs. the unobstructed path to the buoy's sensors.

2.8.6 Recommendations

This research provides a sufficient basis to conclude that further work on an algorithm for making the last bit of fine tuning of measurements from moving sensors is not the most useful next step. Instead, the question of how spar buoys can be economically scaled up to heights

approximating those in the likely size range for offshore wind machines appears more fruitful for future inquiry.

The researchers stated that the U.S. Department of Interior has determined that no permit or permission is required to deploy the buoy in United States waters. At this juncture this has not been tested by an actual application, and there may be additional legal or regulatory oversight if a project is proposed. Issues of public perception, impact on navigation and avian populations, and longevity of the buoy in the marine environment are additional concerns. The researchers should address all of these issues.

The researchers found a business practice patent owned by General Electric dealing with using floating meteorological buoys to prospect for wind farms. They also found European papers dealing with using buoys for wind farms that were published before the GE patent. Some aspects of this project may be patentable. The researchers should determine what intellectual property rights they could claim. They should also determine if the General Electric patent could impede market development of this concept.

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.

2.8.7 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 California electricity supply or transmission or distribution system. This is accomplished by improving the prospects for economical electricity generated by offshore wind. There are also potential benefits in transmission, depending on the tradeoff between the higher cost of undersea cables and the likely shorter transmission path due to closer location of the supply to a major load center.

This research did not address details of the cost/benefit tradeoff from deployment of full-scale spar buoys, nor the public policy issues surrounding such deployment. These remain logical items for further study and research.

2.8.8 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 have talked to several developers and received considerable interest. One offshore wind project developer offered to cooperate with the researchers to demonstrate the technology. The research team talked to investors during the project and received considerable interest, but the GE patent discouraged them.

Engineering/Technical

The researchers plan to demonstrate a tall spar buoy. Objectives of the demonstration would be to establish deployment and maintenance costs less than the currently available alternatives. An East Coast offshore wind developer offered the opportunity to deploy the project buoy next to its fixed bottom met tower. The researchers estimated that additional engineering development could be completed in approximately one year with a budget near $1.4 million.

Legal/Contractual

The researchers have no patents nor any active applications related to this research.

Environmental, Safety, Risk Assessments/ Quality Plans

The biggest risk is the slow pace of the development of offshore wind in the U.S., although this is countered by the more rapid pace of development that exists in the European and East Asian markets.

Production Readiness/Commercialization

The researchers stated that an offshore wind developer offered to cooperate in a demonstration project, although no firm plans have been announced.

2.9 Microbial Fuel Cells to Generate Electricity from High-Solids Food Wastes

Awardee: University of California Davis

Principal Investigator: Farzaneh Rezaei and Jean S. VanderGheynst

2.9.1 Abstract

California agricultural residues such as food processing wastes can provide an untapped source of feedstock for bioelectricity generation. These residues are ideal for renewable energy production because they are abundant, and their use for fuel does not compete with food production. Around 4 million tons of food and processing waste is produced each year in California. Of these residues, the non-meat portion is about 228 thousand tons per year, with tomato pomace (TP) and grape pomace (GP) accounting for 88 percent. In this project the researchers proposed to use food processing wastes as feedstock in a microbial fuel cell (MFC) to treat the waste and to generate electricity simultaneously. An MFC is a device that produces electricity from the direct oxidation of organic or inorganic matter by microorganisms. While there are many reports on using wastewater to produce electricity in MFCs, there are fewer projects on electricity generation in a MFC using high solids materials.

This study demonstrated the feasibility of power generation from grape and tomato pomace leachate, as well as solid tomato pomace (TP) at as high as 120 gram of TP per liter of media. However pre-acclimation of the anode was essential to obtain any power output, especially when using grape pomace. Using TP at 67 grams per liter, almost 80 percent of the initial solid material was consumed during the power generation cycle. The maximum power generated when the MFC was operating on TP leachate was 592.3 mW/m^3. When the MFC was operated on 120 g/l TP, it produced up to 449 mW/m^3. While this is a very small amount of electricity, the data showed the potential of using the MFC to treat these types of wastes while producing some electricity.

Keywords: Food processing waste, microbial fuel cell, high solid content, tomato pomace, grape pomace

2.9.2 Introduction

In California around 4 million tons of food and processing waste is produced each year. Of these residues, the non-meat portion is about 228 k tons per year, of which tomato pomace (TP) and grape pomace (GP) account for 88 percent.[22] Worldwide, tomato production largely dominates the agricultural industry, with 152 million tons produced internationally in 2009 and 68.7 k tons in California alone. Almost one-third of all tomatoes are utilized for processed foods, making tomatoes the primary vegetable crop used for this purpose.[23] Tomato processing products, including ketchup, salsa, paste, sauce, juice, and canned tomatoes, remain ubiquitous in the modern day consumer household, with 73 pounds per capita annual consumption.[24]

High production inevitably coincides with a heavy waste stream, as up to 10 percent of the tomato remains after processing as byproduct tomato pomace, which consists of leftover skins, seeds, and pulp.[25] Unutilized tomato processing wastes present a potential environmental hazard as they can accumulate and spoil quickly, providing a breeding ground for microbes, insects, and various disease-causing pests. Conversely, tomato pomace, along with other food processing and agricultural residues, are promising feedstocks for bioenergy generation because they are abundant and do not compete with food for arable land. However, some constituents in these feedstocks promote ash slagging, fouling, and corrosion in thermo-chemical conversion systems and microbial growth inhibition in biological conversion systems. While water leaching is an effective approach to remove these inhibitors, it leads to an accumulation of leachate enriched in organic/inorganic compounds that must be treated. Therefore, further methods to divert and treat solid waste and leachate from these sources of biomass need to be developed for their long term, environmentally neutral management concurrent with harvesting their untapped energy content.

The microbial fuel cell (MFC) is a device (Figure 14) to produce electricity from the direct oxidation of organic or inorganic matter by microorganisms.[26] In an MFC, exoelectrogens, a group of bacteria with the ability to produce electricity by direct transfer of electrons outside the cell to a solid electron acceptor, act as catalysts in the oxidation reaction occurring in the anoxic anode chamber of the fuel cell. The electrons then flow through a circuit to the cathode side where they combine with oxygen to produce water. Electricity generation in an MFC has increased in just a few years to 100,000 times its original value using an air-cathode MFC.[27] Concurrent with chemical oxygen demand (COD) removal, the highest power density in a

---

22 G. C. Matteson, B. M. Jenkins, *Bioresource Technology* 98, 3098 (2007).

23 V. Heuze, G. Tran, D. Bastianelli, P. Hassoun, F. Lebas, T. R. Chaudes, Ed. (2011).

24 C. A. Carter. (Giannini Foundation of Agricultural Economics, University of California, Davis, California).

25 M. R. Ventura, M. C. Pieltain, J. I. R. Castanon, *Anim Feed Sci Tech* 154, 271 (2009).

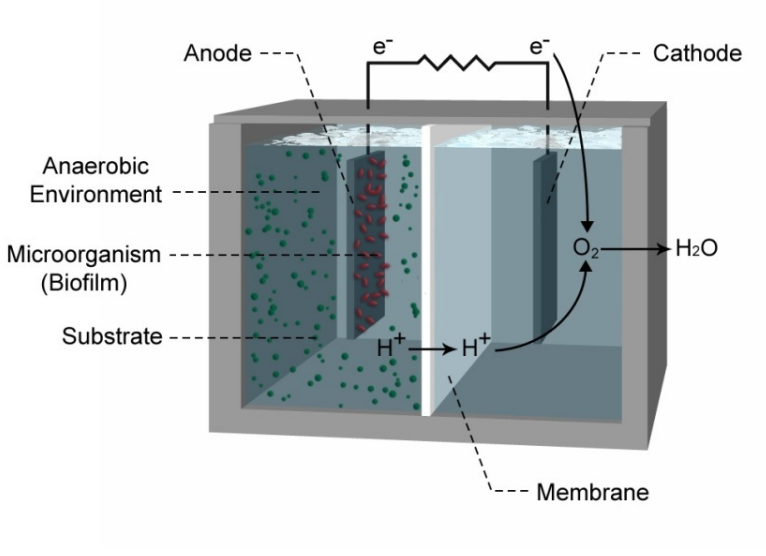
26 R. M. Allen, H. P. Bennetto, *App.l Biochem. Biotechnol.* 39, 27 (1993).

27 B. E. Logan, Microbial Fuel Cells. J. W. Sons, Ed., (John Wiley & Sons, Inc

New Jersey, NY, 2008).

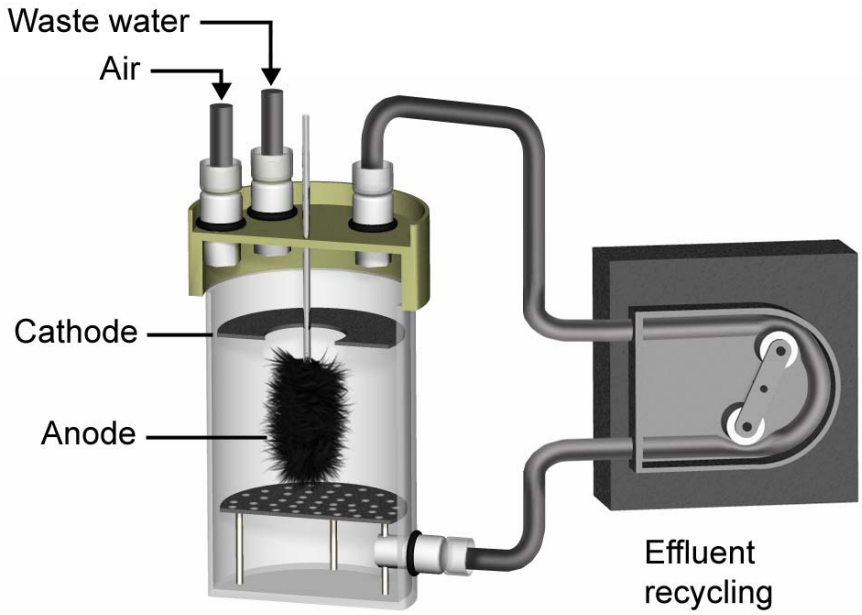
laboratory scale MFC is around 6.9 W/m^2 (per device cross section), with estimates that MFCs could generate up to 17 W/m^2 or 19 W/m^2 depending on the MFC design. Different types of wastewater have been utilized as carbon sources in MFCs with successful electricity generation. However the type of wastewater has a significant effect on MFC performance. As a result, current state-of-the-art MFCs are mostly successful in utilizing dilute, soluble, and easily degradable carbon sources (e.g., municipal wastewater with biochemical oxygen demand of less than 300 mg/L), thus missing the opportunity to harness the rich energy content of high strength wastewater (e.g., animal wastewater from the livestock industry with chemical oxygen demand of 100,000 mg/L). Although MFCs have recently been shown to effectively treat complex materials such as landfill leachate from municipal waste and cattle manure at various concentrations, few studies have investigated MFC performance in the direct degradation of solid wastes such as food processing biomass.

Figure 14: Schematic Illustration of a Microbial Fuel Cell



The goal of this research was to establish the MFC as a technology that could be integrated into California's biomass resource base (i.e., food processing and agricultural residues) and preserve water by treating and reusing agricultural leachate. Demonstrating successful degradation of solid residues and treatment of leachate inside the MFC was important to establish the long term viability of this technology. This research focused on evaluating MFC power production using TP and GP in both their leachate and solid forms. See Figure 15.

Figure 15: Design of a Single Stage MFC Operated on Solid Media



The feedstock is packed into the bioreactor between the cathode and the screening support at the bottom of the reactor. Wastewater is trickled over the feedstock initially to establish a microbial community that hydrolyzes the organic solids. Treated liquid is recycled back to the cathode by a pump.

2.9.3 Objectives

The goal of this project was to prove the feasibility of producing electricity from high solids food processing residues and/or leachate from stored or fresh food processing residues. The researchers established the following objectives:

1. Demonstrate organic acid production (in a form of COD) to be a minimum 0.02 g/g dry feedstock after 28 days of ensilage.
2. Demonstrate leachate from ensiled feedstock contains more than 0.5 g/l total organic acid (in a form of COD) and leachate from fresh feedstock contains at least 0.5 g/l total sugar (in a form of COD) by varying leaching treatments (solid to liquid ratios and time).
3. Demonstrate feasibility of operating the MFC on solid material with a target for electricity generation higher than 150 mV (using 1000 ohm resistance).
4. Confirm effectiveness of trickling liquid over the solid by increasing the power generated by at least 50 percent.
5. Demonstrate feasibility of operating MFC on leachate from ensiled feedstock in feed batch mode to generate voltage higher than 300 mV (1000 ohm external resistance).
6. Demonstrate feasibility of operating MFC on leachate from fresh feedstock in continuous mode to generate voltage higher than 300 mV (1000 ohm external resistance).

7. Target electricity generation of higher than 300 mV (1000 ohm external resistance) with minimum 80 percent COD removal. No methane gas should be produced.
8. Demonstrate energy efficiency in a form of electricity to be at least 60 percent (e.g., 60 percent of the available electrons have been harvested as current) with a target goal of 500 mV (1000 ohm external resistance).
9. Demonstrate that the food waste stream could yield 570 GWh of electricity, assuming an electricity yield of 14.7 kJ per gram of organic matter in the feedstock and that grape pomace and tomato pomace consist of 70 percent organic matter that can be converted.

2.9.4 Outcomes

1. No data was reported.
2. With a leaching ratio of 1:30 the COD of the leachate reached 5.73 and 9.44 g/L for TP and GP, respectively.
3. The researchers supplied the MFC with a solution of 67 g/L of TP in 50 mM phosphate buffer solution (PBS). The MFC maintained a high, stable voltage averaging 0.265V over a period of 1455 hours. The voltage maximum was 0.302 V during that test.
4. The proposed design for the solid state MFC was not successful due to the possible connection between the anode and the cathode. The highest voltage with this configuration was 80 mV which dropped quickly, possibly due to a short circuit. The researchers suggested using a sediment fuel cell for future work in this area.
5. Using buffer concentration of 200 mM PBS and a TP loading of 120 g/L, the researchers achieved an average voltage of 0.335V over a 670 hour test. The final report is not clear whether the feedstock was fresh or ensiled.
6. See the above outcome.
7. The researchers reported about 82 percent COD removal with a maximum power output of 592.3 mW/m^3. The researchers did not report a voltage for that test. They also did not report on the production of methane gas.
8. The researchers did not report on the energy efficiency of the MFCs they tested.
9. The researchers did not provide calculations of electricity that could be produced from tomato and grape pomace using microbial fuel cells. They produced no calculations of public benefits.

2.9.5 Conclusions

Conclusions from this project were:

1. The researchers did not report work in this area.
2. The project far exceeded the goal.
3. This goal was easily met.
4. The researchers did not meet this goal.

5. The researchers met the goals for Objectives 5 or 6. It is not clear which objective was the object of the test.
6. See Conclusion 5.
7. The researchers partially met this goal. Voltage was not reported directly and no mention was made of methane gas.
8. The researchers did not report on this objective.
9. The researchers did not address this objective.

The Program Administrator concludes:

The results from this project indicated that it is feasible to generate power from grape and tomato pomace leachate, as well as solid tomato pomace at 120 grams of TP per liter of media.

- Overall TP leachate produced the highest power at 592.3 mW/m^3.
- The GP leachate produced lower energy as compared with TP leachate (or solid TP) possibly due to the presence of inhibitors such as phenolic monomers.
- The researchers generally met the primary goal of producing electricity from high solids food processing residues and/or leachate from stored or fresh food processing residues. Unfortunately other goals listed as objectives were either not undertaken or not reported.

2.9.6 Recommendations

Several critical issues have been identified, and significant effort is required to resolve these issues to advance this technology toward product development and commercialization. The Program Administrator recommends that the researchers undertake the following activities to advance this technology:

1. Complete work scope planned for this project.
2. Seek a partner in the food processing industry. This partner should help to set goals and should provide assistance in bringing the technology into productive use.
3. Reassess the possibility of patenting certain features of the MFC design or process.
4. Modify the design of the solid state MFC and identify the main obstacles to power generation from this system.
5. Evaluate grape pomace to determine if inhibitors are present that reduce power generation.
6. Evaluate other sources of food processing waste that could be used in a MFC for power generation and treatment.

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.

2.9.7 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 of this project is reduced environmental impacts of the California electricity supply or transmission or distribution system. The benefits from this project would be primarily in reduced environmental impacts of the electricity supply. No regulated gasses should be generated as a result of this type of electricity generation. In addition, wastewater could be cleaned of up to 80 percent of its chemical oxygen demand (COD). Waste solids could be greatly reduced in the non-meat food processing industry. The research in this project did not progress far enough to estimate the probable benefits for California.

In other food processing areas prototype MFCs have been installed and tested. In May, 2007, the University of Queensland, Australia, completed a prototype MFC in cooperation with Foster's Brewing. The prototype converted brewery wastewater into carbon dioxide, clean water, and electricity. While the MFC produces a negligible amount of power, the production of clean water is important to Australia.

2.9.8 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 have not conducted a market survey nor have they contacted potential customers/users of this technology.

Engineering/Technical

The researchers did not provide any insight into future engineering plans.

Legal/Contractual

The researchers claimed they had nothing unique to patent. The work done in this project was application of known technology to new materials.

Environmental, Safety, Risk Assessments/ Quality Plan

Because of the early stage of development, the researchers had not addressed these plans as of the end of their project.

Production Readiness/Commercialization

The researchers do not intend to continue this development effort towards commercialization. They claim it is too early in the development process to consider commercialization.

2.10 A Low Cost Inverter with Battery Interface for Photovoltaic Utility System

Awardee: Texas A&M University

Principal Investigator: Prof. Hamid A. Toliyat

2.10.1 Abstract

Due to a recent surge in energy assurance planning, distributed energy (DE) systems are receiving greater attention. Among different types of DE, photovoltaic (PV) generation, wind turbine generation, and fuel cells have attracted scrutiny because they are relatively pollution free. Power electronics in these energy systems convert generated electricity into consumer-usable and utility-compatible forms. But the addition of power electronics adds cost to DE capital investments as well as creating some reliability issues. Therefore widespread use of DE demands power electronics topologies that are less expensive and more dependable. Based on a report by Sandia National Laboratory,[28] the inverter currently is a costly and complex component of PV systems, and its mean time to first failure (MTFF) is unacceptable. Low inverter reliability contributes to unreliable systems and a loss of confidence in renewable technology. Therefore, new technologies are required to achieve the goal of a high performance, high reliability inverter.

In this project researchers developed a multi-input, multi-output high frequency ac link inverter as the power electronics interface for photovoltaic (PV) cells with a built-in battery energy storage system (BESS). In this inverter a single stage power conversion unit fulfilled all the systems requirements, i.e., inverting dc voltage to proper ac, stepping up or down the input voltage, maximum power point tracking (MPPT), generating low harmonic ac current, and input/output isolation. This inverter was, in fact, a partial resonant ac-link inverter in which the link was formed by a parallel ac inductor/capacitor (LC) pair having low reactive ratings. Due to the intermittent nature of solar energy, an energy storage system is usually added to the PV system to deliver reliable power and to draw the maximum power from the PV arrays. Therefore multi-input, multi-output systems are common in PV systems. Most of the currently existing topologies have two or more power stages which results in lower efficiencies. Moreover, dc electrolytic capacitors, which cause the most severe reliability problems for inverters, are an integral part of a two stage system containing a dc-dc inverter and an inverter. The proposed inverter was believed to overcome the abovementioned shortcomings. It was a single stage, compact, and light power conversion system with zero voltage turn-on and soft turn-off of the switches, resulting in very small switching losses. It did not contain any electrolytic capacitor at the link, which increased the reliability of this inverter.

Most of the technical goals were achieved. However product cost must be aligned with current market prices.

Keywords: Photovoltaic inverter, soft switching, partial resonant inverter, multi-input/output inverter, hybrid system

28 Inverter Reliability Program, http://energy.sandia.gov/?page_id=12998

2.10.2 Introduction

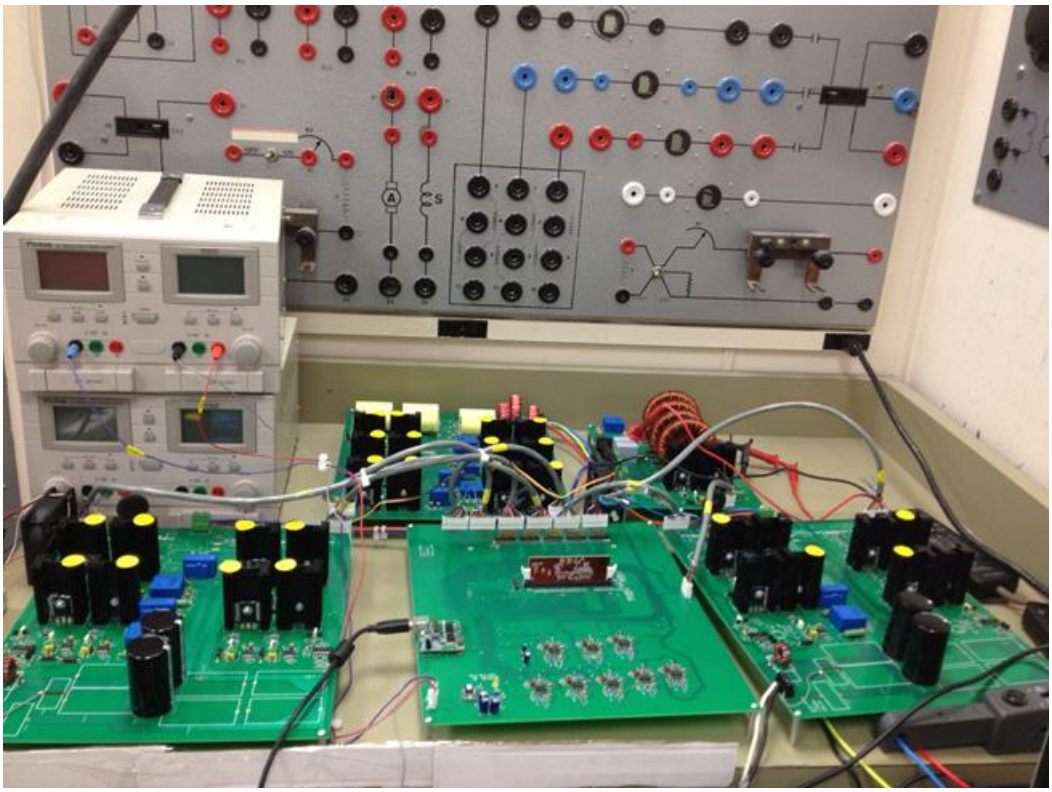
Due to recent interest in energy emergency assurance planning, distributed energy (DE) systems are receiving greater attention. Among different types of DE, photovoltaic (PV) generation, wind turbine generation, and fuel cells have attracted scrutiny because they are relatively pollution free. Power electronics in these energy systems convert generated electricity into consumer usable and utility compatible forms. But the addition of power electronics adds cost to the DE capital investments as well as creating some reliability issues. Therefore widespread use of DE demands power electronics topologies that are less expensive and more dependable. Based on a report by Sandia National Laboratory,[29] the PV inverter currently is a costly and complex component of PV systems, and its mean time to first failure (MTFF) is unacceptable. Low inverter reliability contributes to unreliable systems and a loss of confidence in renewable technology. Therefore new technologies are required to achieve the goal of a high performance, high reliability inverters.

In this project researchers developed a multi-input, multi-output high frequency ac link inverter (Figure 16). This inverter was the power electronics interface for photovoltaic cells and included a built-in battery energy storage system (BESS). This unit fulfilled all the systems requirements, i.e., inverting dc voltage to proper ac, stepping up or down the input voltage, maximum power point tracking (MPPT), generating low harmonic ac current, and input/output isolation. This inverter was a partial resonant ac link inverter in which the link was formed by a parallel ac inductor/capacitor (LC) pair having low reactive ratings. Due to the intermittent nature of solar energy, an energy storage system is usually added to a PV system to deliver reliable power and to draw the maximum power from the PV arrays. Therefore multi-input, multi-output systems are common in PV systems. Most of the currently existing topologies have two or more power stages which result in lower efficiencies. Moreover, dc electrolytic capacitors, which cause the most severe reliability problems for inverters, are an integral part of a two stage system containing a dc-dc converter and an inverter. The proposed inverter was believed to overcome the abovementioned shortcomings. It was a single stage compact and light power conversion system with zero voltage turn-on and soft turn-off of the switches which resulted in very small switching losses. It did not contain any electrolytic capacitor at the link, which increased the reliability.

---

29 Sandia's finding: "The inverter system must continually perform a far greater number of switching operations over its lifetime than other high-power counterparts in other industries. There is a large diversity in the operating environment of the inverter system, many of which are much harsher than those associated with traditional power applications. The overall system lifetime cost must decrease for photovoltaics to be financially viable. Currently the cost and reliability of PV modules is improving faster than the rest of the system. One way to improve system costs is by improving inverter reliability. While PV modules have been rated for 30 years, inverters are typically rated for 5-10 year lifetimes. In the field, inverter failures and subsequent replacement rates have been as often as every 2 years. The inverter is a complex system consisting of control software and many components, each of which can fail."

Figure 16: The Fabricated 1.5 kW Prototype



2.10.3 Objectives

The goal of this project was to prove the feasibility of a 1.5 kW prototype inverter. The inverter was designed for five modes of operation with photovoltaic, battery, and utility connections. Objectives included the following:

1. Show validity of the design through calculations for a 1.5 kW system.
2. Investigate the control strategies for power conversions.
3. Show calculated and measured efficiencies are 95 percent and the efficiency measured in simulation is 97 percent.
4. Show the calculated and simulated power reversal time is 1 ms.
5. Demonstrate the estimated weight (without an inductor) is 10 lb, the weight of the inductor is 3 lb, and the weight of the total system is 13 lb.
6. Demonstrate efficiency of the fabricated circuit of more than 97 percent.
7. Show an estimated price of less than $1000.
8. Demonstrate a cost of solar electricity of 31 cents per kWh.

2.10.4 Outcomes

1. The researchers verified the validity of the design through both simulation and experiment.

2. The researchers established the proposed control strategies and verified them through both simulation and experiment.
3. The efficiency of the inverter at 800 W was 92 percent. The inverter was designed for 1.5kW, but the resistive load available in the researchers' lab only supported tests up to 800W. The researchers stated that the efficiency at full power should be higher. The measured efficiency was close to the estimated efficiency, and the switching losses were assumed to be zero.
4. The resonating frequency of the LC filters in this project was above 1 kHz, which resulted in less than 1 ms power reversal time.
5. The weight of the fabricated inverter was less than 10 pounds.
6. The efficiency at 800 W (53 percent of the rated power) was 92 percent.
7. The cost of inverter components was $1158. This included extra parts which were purchased as backups. The printed circuit board fabrication cost was not included. In mass production it could be low. The overall cost of the system components was close to $1000.
8. The cost of the solar electricity using this inverter was 25 cents/kWh.

2.10.5 Conclusions

1. The researchers met this objective.
2. The researchers met this objective.
3. It is not clear if the researchers met this objective.
4. The researchers met this objective.
5. The researchers met the weight objective for the complete inverter.
6. The researchers did not meet this objective due to laboratory limitations. This will be a key objective to verify in any subsequent development activity.
7. The researchers met their cost objective. Market assessment studies need to determine what selling price is acceptable in the current market. By June of 2012 the average U.S. market price of inverters was $0.712 per continuous watt. This was about the cost of the researchers' components alone. The researchers did not calculate a market price which would include warranty cost, overhead, distribution, taxes, packaging, and other costs of doing business.
8. While the researchers easily met this objective, it was not a tough challenge. In addition, the cost of solar electricity depends on many factors, only one of which is the inverter. Therefore this outcome is not too meaningful.

The researchers generally met the primary goal of proving feasibility of a flexible inverter to be used with photovoltaic systems.

2.10.6 Recommendations

The Program Administrator recommends that the researchers undertake the following activities to advance this technology:

1. Demonstrate 97 percent efficiency at 1.5 kW. This should be accomplished before any additional research is started. It is a key measurement of success.
2. Determine if the proposed inverter can be built for significantly less money so it can sell at current or future market prices.
3. Perform a market review of best of class inverters to determine if the proposed inverter continues to have a potentially higher efficiency and lower cost.
4. If this inverter can be built to sell at a competitive price, seek a partner in the solar energy industry to take it to market.
5. With the partner, perform market assessment studies to determine the appropriate size range.
6. Redesign the inverter for mass production.

2.10.7 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 of this project is reduced environmental impacts of the California electricity supply or transmission or distribution system. In 2012 solar electricity prices were around 28 cents per kWh in sunny climates. According to the researchers, the project inverter could reduce the cost of solar electricity by at least 10 percent to 25 cents/kWh. Unfortunately, during the performance of this research, market prices for inverters fell. Unless the researchers can redesign for significantly lower cost, the potential higher efficiency inverter will not get to market.

2.10.8 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 have not conducted a market survey nor have they contacted potential customers/users of this technology.

Engineering/Technical

The researchers estimated that they would need two or three years and $300,000 to complete engineering development.

Legal/Contractual

The researchers claimed they had completed a self search and do not believe that their product infringes on any other patent. At the completion of this project they had not filed for patent protection.

Environmental, Safety, Risk Assessments/ Quality Plan

Because of the early stage of development, the researchers had not addressed these plans as of the end of their project.

Production Readiness/Commercialization

The researchers plan to pursue a partnership with a manufacturer or a utility to take the product to market.

2.11 Photo Thermal Voltaic Skylight

Awardee: SeaBotix, Inc

Principal Investigator: Richard Denton

2.11.1 Abstract

The goal of this project was to establish the technical and economic feasibility of producing electricity from a medium temperature photo thermal voltaic (PTV) system at 10 percent efficiency. The researchers concentrated light via a low cost tracking solar collector. The light produced steam that powered a rotary vane positive displacement motor. The project team utilized waste heat from the condensation portion of the Rankine cycle for space heating or domestic hot water.

The researchers integrated a Rankine cycle motor/generator powered by a SLATS (Survivable Low Aperture Trough Solar) solar concentrator into a commercially available residential skylight. The PTV system was intended to capture more of the total energy available in a given solar collection area than a similarly sized photo voltaic (PV) system. Although both systems are capable of converting sunlight to electricity, PV systems are unable to operate at high enough temperature to contribute to heat capture without degrading solar cell performance. To prove competitive with PV systems, the PTV system would need to exceed 10 percent efficiency. Using the industry standard of 1 kW/sq-meter for available solar energy, the researchers were able to demonstrate an overall efficiency of 11.1 percent. The prototype was capable of producing 100 W ± 5 percent electrical output and 600 to 650 W per hour of thermal energy. The researchers calculated a return on investment of three years for the PTV system, compared to 15 years for a PV system. Failure analyses were able to confirm a minimum life of five years for the proposed system.

Keywords: Rankine, rotary vane, photo thermal voltaic, solar, concentrator, SLATS, parasitic, saturated, superheat

2.11.2 Introduction

The use of photo voltaic (PV) energy systems has been encouraged through extensive government incentives. However the adoption of such systems has been hindered by return on investment periods typically in the range of 15 years. For residential usage, solar energy capture is either in the form of electricity producing PV cells or solar hot water heating. Presently there are no systems available on the market capable of combining these benefits. The researchers proposed a photo thermal voltaic (PTV) system integrated into a commercially available residential skylight to generate energy and heat for use in space heating or domestic water. The PTV system would be capable of providing heat output at 140° F, which could be used for space heating or domestic hot water. For the system to be competitive with PV energy systems, it would need to operate at greater than 10 percent efficiency. Because PV systems are unable to operate at high temperatures without solar cell degradation, the heat production provided by the PTV system would serve as an additional differentiator. However, the single largest differentiator would be the three year return on investment that may be realized with the PTV system when compared to 15 years for PV systems.

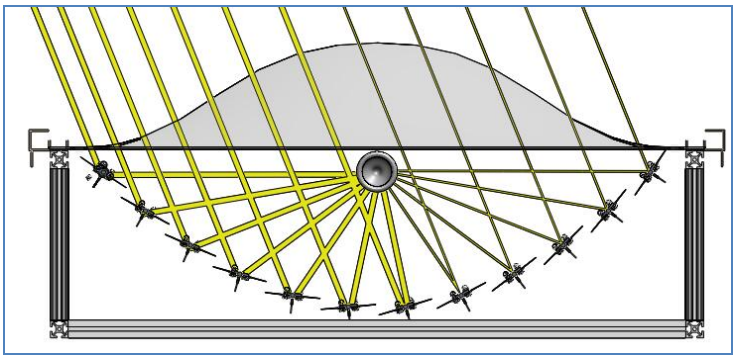
The proposed PTV system concentrates reflected solar energy collected within a parabolic trough onto an evacuated tube filled with distilled water (Figure 17). The average temperature of the working fluid exiting the collector is 380° F. The fluid vaporizes, generating the pressure needed to drive the heat engine and induction generator (Figure 18). Expended gas is then condensed and cooled to 140° F, with waste heat from the condenser exchanged to a hot water reservoir for domestic use prior to recirculation to the solar collector.

In fabricating the prototype, the researchers selected a commercially available over-the-counter pneumatic motor based on longevity, reliability, and low manufacturing cost. They selected distilled water as the working fluid based on its thermal properties, low cost, availability, and environmental friendliness. The researchers designed the rotating cylinder for the rotary vane motor with lip seals to reduce leakage by more than 95 percent and were able to achieve approximately 56 percent mechanical efficiency. (Thermal efficiency at the temperatures selected has a maximum Carnot value near 25 percent. Thus the combined efficiency must be less than 14 percent.) Using the industry standard of 1 kW/sq-meter for available solar energy and accounting for component efficiencies, the researchers were able to demonstrate an overall efficiency of 11.1 percent. The prototype was capable of producing 100 W ± 5 percent electrical output and 600 to 650 W per hour of thermal energy. Heating of the cooling water to 140° F fell short of success due to a design error which neglected the heat loss during transfer through the walls of the heat exchanger. This may be corrected by raising the operating temperature of the system.

The proposed technology may be used in residential and other small scale settings. One PTV unit would nominally displace the light output of one three-tube magnetically ballasted 2 x 4 fluorescent trough lamp and would be capable of providing 70 percent of the domestic hot water needs for a typical home. The researchers estimated that 35,700 PTV units (the anticipated market penetration) would reduce peak demand in California by nearly 4 MW annually. The researchers also included a breakdown of emissions reduction that would result from a typical neighborhood that included 20 of the PTV units. They calculated a return on investment of

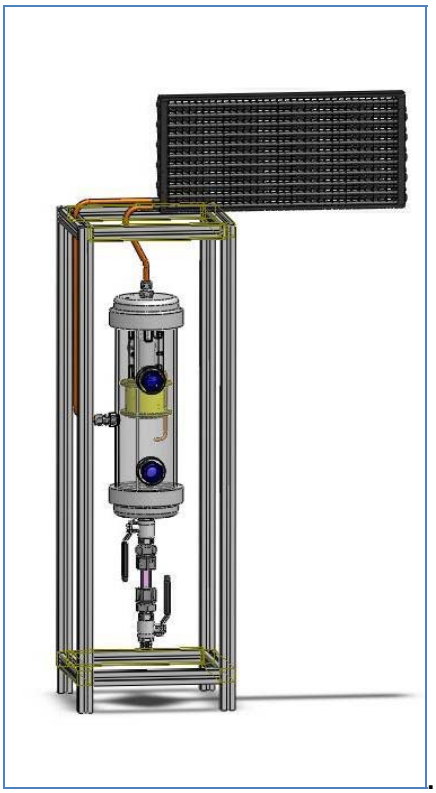
three years for the PTV system, compared to 15 years for a PV system. Failure analyses were able to confirm a minimum system life of five years for the proposed system.

Figure 17: Section through SLATS Collector



Slats Rotate to Optimize Solar Capture.

Figure 18: Heat Engine Components



2.11.3 Objectives

The goal of this project was to establish the technical and economic feasibility of producing electricity from a medium temperature photo thermal voltaic (PTV) system at 10 percent overall efficiency by concentrating light via a low cost tracking solar collector to produce steam and to power a rotary vane positive displacement motor, while utilizing waste heat from the

condensation portion of the Rankine cycle for space heating or domestic hot water. The researchers established the following project objectives:

1. Fabricate prototype. Prototype will provide 100 W electrical output and 0.5 kW to 0.6 kW hot water output at 140° F.
2. Fabricate a test stand. Install instrumentation to record incoming solar radiation, percent insolation absorbed by receiver, gross collector thermal output, generator electrical output, and net solar hot water output. Demonstrate that the test stand is capable of measuring thermal and electrical parameters within an error of ± 5.0percent.
3. Provide test plan meeting EISG approval.
4. Test prototype to demonstrate collector can produce 320° F minimum temperature for Rankine cycle operation, 100 W electrical output, and 0.5 kW to 0.6 kW hot water output.
5. Perform manufacturing cost analysis as follows: installed cost at $6 per output watt, manufacturing cost of $4 per output watt, and mass manufactured motor cost of $40 per unit. Confirm from the project findings that an installed unit has a simple payback in less than five years.
6. Perform durability analyses. Perform 1,825 power up/down cycles approximating five years usage (365 days times five years) for component failure. Perform 100 continuous hours HALT stress testing at 400° F (60° F above maximum operating design). Develop efficiency degradation curve and extrapolate expected life for subtasks. Confirm from the project findings that the unit will be capable of performing for a minimum of five years.

2.11.4 Outcomes

1. The researchers fabricated a prototype capable of providing 100 W electrical output, with approximately 15 percent unutilized steam which could have produced an additional 10 W electrical output. The working fluid exiting the collector was 380° F, and the heat sink was maintained at 140° F. Fabrication of the prototype included a novel eccentric cylinder with lip seals to minimize leakage and efficiency losses. The researchers tested the resulting mechanical efficiency of the motor at approximately 56 percent, with an overall system efficiency of 11.1 percent. Additional test results are evaluated for Objective 4.
2. Researchers selected testing equipment to conform to the target 5.0 percent error margin. Measuring instrumentation had a manufacturer's accuracy rating of ± 2.0 percent.
3. The test plan was included in the project proposal and was approved by EISG.
4. The researchers performed prototype testing over five days from 10 am until 2 pm. They measured working fluid and heat sink fluid temperatures at 10 second intervals throughout the testing period. Phase 1 testing used a 1 kW heating element as the heat source to isolate performance of the components. Phase 2 testing used the concentrating solar collector as the heat source. The researchers performed Phase 1 testing for eight hours to measure motor efficiency. Phase 2 testing allowed for determination of the

overall system efficiency of 11.1 percent. The target level of 320° F was met in less than 15 minutes. The average system output was 92 W ± 5.0 percent. However, at peak solar output the system produced 100 W ± 5.0 percent, with a potential to capture an additional 10 W by using vented steam. Although 600 to 650 W per hour were conducted to the cooling water, the goal to heat the cooling water to 140 degrees F was not achieved due to heat loss during transfer through the heat exchanger walls. This was a design error that could easily be fixed by operating at a slightly higher temperature. Alternative solutions include capturing the vented steam to provide additional heating or exploring slightly lower temperature output for domestic use.

5. The researchers performed a high level cost analysis to compare the effects of government rebates on PTV systems when compared to PV systems. Both systems were assumed to cost $6 per watt. Because PTV systems qualify for additional domestic hot water rebates, they are more highly subsidized than PV systems. According to that calculation PV systems have a payback period of 15 years, and PTV systems have a payback period of three years.

6. Highly accelerated life testing (HALT) revealed virtually no contact surface wear on the vanes, seal PTFE thickness, seal shim thickness, and PTFE adhesive thickness. The silicon glue adhesive used to hold the PTFE to the shim material exhibited a 50 percent reduction in thickness. Additionally, the seals exhibited a trailing edge wear pattern. Nevertheless there was no evidence of mechanical failure in the simulated five year period.

2.11.5 Conclusions

1. The researchers met the objective to fabricate the prototype. Performance measures are addressed in Objective 4.

2. The researchers met the objective to provide measurement accuracy of ± 5.0 percent.

3. The researchers met the objective to provide an EISG approved test plan.

4. The researchers met the performance objectives for the PTV system. The subsidiary goal to provide cooling water heated to 140° F was not met. However the researchers proposed several alternatives to rectify the design error.

5. Although the researchers met the objective to perform a cost analysis, they only offered a comparison of government rebates for each system. The actual manufacturing costs were assumed to be identical in both cases, but the researchers provided no justification for this assumption. There is little evidence of a robust analysis of cost to the customer. Rankine systems typically require some form of annual inspection and maintenance. This was not included in any cost analysis.

6. The researchers met the objective to confirm that the system would perform for a minimum of five years.

Regulations could be a problem for a home/office based product. The ASME Boiler Code generally covers all steam generation over 15 psig and water boilers over 160 psig with water temperatures over 250° F. While local jurisdictions specify where the Code is applied, it is hard

to get bureaucratic officials to take chances. Parts of the Code specify that stainless steel cannot be used in water wetted parts of a steam generator. The Code only allows alloy 800, a much more expensive alloy. It also requires extensive tracking of all materials and manufacturing processes.

2.11.6 Recommendations

The researchers were successful in demonstrating the viability of the PTV system as a source of electrical energy and domestic hot water. They plan to continue development of the proposed technology to commercialization. As part of continued development of this technology, the Program Administrator recommends that the following tasks be completed:

- Performance test the servo required to rotate the reflectors.
- Redesign the system to operate at higher temperatures, capture waste steam, or explore the viability of water that does not meet the 140° F goal.
- Investigate actual manufacturing costs for the PTV unit.
- Implement design modifications to address minor wear observed during HALT testing.
- Perform a rigorous cost analysis independent of anticipated governmental incentives.
- Seek independent laboratory testing and certification.
- Hire an independent expert to evaluate annual maintenance and certification costs, ASME Code issues, lubrication, corrosion, and other system issues.
- Determine which regulations apply to the manufacture and use of Rankine systems when deployed in California homes and businesses.
- Investigate the need for small additions of anti-corrosion chemicals to the working fluid.
- Conduct a thorough economic analysis of alternatives. Since an office would receive sunlight through the skylight without the photovoltaic device, determine the advantage of adding the thermal photovoltaic device. Is the thermal energy worth the extra investment?

2.11.7 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 public from this research is increased affordability of electricity in California. The researchers estimated that 35,700 PTV units (the anticipated market penetration)

would reduce peak demand in California by nearly 4 MW annually. The researchers also included a breakdown of emissions reduction that would result from a typical neighborhood that included 20 of the PTV units. They calculated a return on investment of three years for the PTV system, compared to 15 years for a PV system. Failure analyses were able to confirm a minimum system life of five years for the proposed PTV. Additionally, this would result in reductions in nitrates, sulfates, carbon dioxide, and particulate emissions each year through reduced dependence on coal power plants, gas, and oil. In 10 hours of operation, a PTV system would produce 1 kWh of electricity (worth about $55 per year) and save about 430 grams of CO_2 when compared with generation using natural gas.

2.11.8 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 have not performed a market analysis. This technology is applicable to residential and small scale commercial installations. Return on investment is highly dependent upon government regulations and incentive programs.

Engineering/Technical

The researchers have not yet completed design and testing of automated controls needed to operate the system. They estimate that it would take about one year and between $100,000 and $250,000 to complete the engineering and product development phases.

Legal/Contractual

The researchers have performed a patent search and applied for provisional patents. They will incorporate design modifications resulting from this project into the patent prior to provisional patent expiration.

Environmental, Safety, Risk Assessments/ Quality Plans

Environmental, Safety, Risk Assessments, and Quality Plans have not yet been developed. While the researchers do not anticipate negative effects with regard to public safety or the environment, systems employing live steam are highly regulated for safety. Regulations may require extensive record keeping during manufacture. This may add to the cost of the final product.

Production Readiness/Commercialization

The researchers have developed a preliminary commercialization plan that will require revisions based on the results of this project. They will need support to pursue commercialization.

2.12 An Innovative Design for Cost and Energy Efficient Solar Cells

Awardee: San Diego State University

Principal Investigator: Gregory Kalyuzhny

2.12.1 Abstract

The primary goal of this research project was to develop and test a novel design for an efficient and inexpensive solar cell system. This system was based on semiconductor oxide thin films (such as titania or iron oxide) sensitized with nanocrystals of other semiconducting metal oxides (such as cadmium oxide or copper oxide). The project activities included the preparation and characterization of nanocrystals and thin films of semiconducting metal oxides with optimal opto-electrical properties. The interaction of these materials with titania was enhanced by powder processing technologies. The researchers attempted to create a novel design for metal oxide sensitized solar cells (MOSSC) based on the well-established idea of the solar cell semi-conductive band gap layer sensitization. In this MOSSC the cost of the metal oxide sensitizer was lower by several orders of magnitude compared to the cost of ruthenium based dyes commonly utilized in the previously studied dye sensitized solar cells (DSSC). The materials studied in this project could reduce the price of sensitized solar cells and make them commercially competitive with conventional technologies. This new type of solar cell would not contain any major organic components. This is advantageous because it presents a potential for increasing the lifespan of the cell due to the high durability and stability of metal oxides.

The researchers provided a solid scientific basis for research in this area. Unfortunately the work has not yet resulted in energy conversion efficiencies that are competitive with existing technologies. Cost goals and estimates were not included in this project, so it is not easy to project a product cost should the work lead to higher efficiency solar cells.

Keywords: Dye sensitized solar cells, semiconductor nanoparticles, metal oxide nanoparticles, metal oxide thin films, cadmium oxide, titania, freeze drying

2.12.2 Introduction

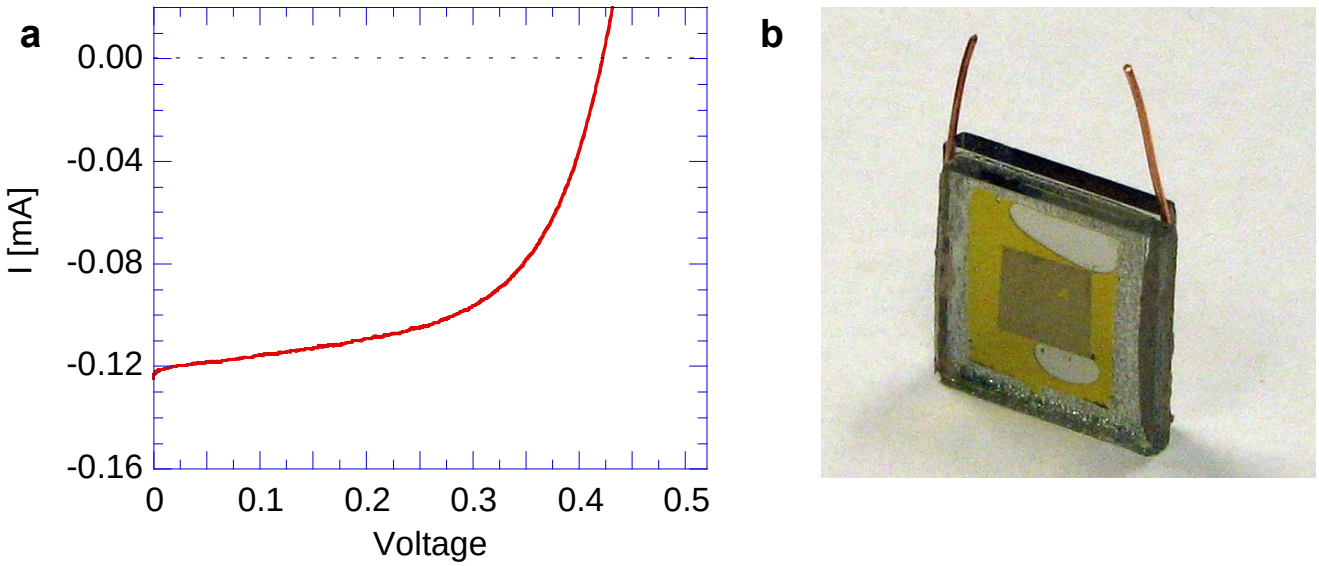
The primary goal of this research project was to develop and test a novel design for an efficient and inexpensive solar cell system. This system was based on semiconductor oxide thin films (such as titania or iron oxide) sensitized with nanocrystals of other semiconducting metal oxides (such as cadmium oxide or copper oxide). The project activities included the preparation and characterization of nanocrystals and thin films of semiconducting metal oxides with optimal opto-electrical properties. The interaction of these materials with titania was enhanced by powder processing technologies. The researchers attempted to create a novel design for metal oxide sensitized solar cells (MOSSC) based on the well-established idea of the solar cell semi-conductive band gap layer sensitization. In this MOSSC the cost of the metal oxide sensitizer was lower by several orders of magnitude compared to the cost of ruthenium based dyes commonly utilized in the previously studied dye sensitized solar cells (DSSC). The materials studied in the group's MOSSC would drastically reduce the price of sensitized solar cells and make them commercially competitive with conventional technologies. This new type of solar cell would not contain any major organic components. This is also advantageous because it presents a potential for increasing the lifespan of the cell due to the high durability and stability of metal oxides.

The researchers synthesized 2—5 nm amphiphilic $CdO/Cd(OH)_2/CdCO_3$ quantum dots (QD) which can be converted to the single CdO phase by heating. They also assembled thin film solar cells based on titania which were sensitized with CdO QD. These devices showed a photocurrent conversion efficiency of 0.17 percent. This relatively low efficiency was likely due to the low position of conduction band of CdO QD relative to titania. The researchers replaced the titania with other semiconductors such as Fe_2O_3 and CuO and developed an original method of preparation of thin films of these materials. The MOSSC based on thin films of Fe_2O_3 modified with CdO QD showed an energy conversion efficiency of about 0.03 percent. The researchers obtained similar results for cells based on Fe_2O_3 thin films sensitized with N3 dye. This system showed 0.02 percent photocurrent conversion efficiency. The researchers tested the effects of various preparation steps on the efficiency of the conventional DSSC based on titania sensitized with N3 dye in order to apply that knowledge to the construction of MOSSC. They found that freeze drying of the TiO_2 surface layer as well as addition of small amounts of titanium butoxide to the suspension of titania used for preparation of solar cells produced a porous, beneficial surface for dye absorption and electron transport and improved DSSC efficiency.

The researchers first attempted to sensitize TiO_2 with CdO QD by drop casting a methanol solution of CdO QD onto FTO slides coated with TiO_2. The best efficiency achieved was 0.03 percent with a fill factor (FF) of 0.55. The results of MOSSC testing are shown in Figure 19.

Figure 19: a) I-V Curve for MOSSC Based on Cdo Quantum Dots, Tio2, and Ethylenglicol Electrolyte Containing I−/I3− Tested at 1 Sun

b) Picture of the Cell



The objectives of this project were to:

1. Synthesize metal oxide QD.
2. Attach QD to titania surface through chemical methods and/or sintering metal oxide QD with TiO_2 nanoparticles.
3. Prepare titania substrates by freeze drying and anodization assisted deposition.
4. Fabricate solar cells using various QD/TiO_2 electrodes and redox couple/electrolytes.
5. Optimize Steps 1—4 to improve solar cell power efficiency and durability.

2.12.3 Objectives

The goal of this project was to determine the feasibility of using semiconductor metal oxide quantum dots (QD) as a sensitizer for solar cells based on morphologically optimized titania (TiO_2). The researchers specified the following project objectives:

1. Confirm the composition and size of CdO QD with XRD and TEM and demonstrate sufficient (> 0.1) light absorbance in the visible region (400—800 nm).
2. Demonstrate the feasibility of the synthesis by showing QD of these materials with diameter < 30 nm or less by UV/vis spectroscopy, TEM, and XRD.
3. Demonstrate the fact of doping with elemental analysis (presence of 1—5 atomic percent of dopant) and that doping enhances light absorbance of QD in the visible region. Ten percent or greater increase is expected per weight of the sample.
4. Demonstrate that the proposed methods of TiO_2 deposition lead to improvement in MOSSC efficiency by at least 1 percent and/or durability.

5. Demonstrate that sensitization by metal oxide QD does take place and that resulting MOSSC efficiency is comparable (1—15 percent) with the one for conventional DSSC.

6. Demonstrate that MOSSC efficiency is comparable (1—15 percent) with the one for conventional DSSC.

7. Demonstrate that proposed electrolyte/redox couples provide efficient (1—15 percent) and durable (days) MOSSC.

8. Demonstrate that MOSSC based on optimized QD are more efficient by at least 1.0 percent and/or durable when compared to regular QD.

2.12.4 Outcomes

1. The researchers synthesized and characterized 2—5 nm $CdO/Cd(OH)_2/CdCO_3$ QD with TEM, ED, optical spectroscopy, and NMR. These QD could be converted to the single CdO phase by heating. The QD were soluble in both polar and unpolar solvents and had significant (> 0.1) absorbance in the visible part of the spectrum.

2. The method of synthesis of the CdO QD based on the reaction of CdO powder with PEGA could not be extended for other metal oxide QD. Instead the researchers developed an original method of preparation of thin films of metal oxides such as Fe_2O_3 and CuO. The method was based on thermal decomposition of spin-coated thin films of corresponding trisbipyridine metal complexes. The resulting thin films were characterized by optical microscopy and SEM, XRD, and optical spectroscopy. The researchers did not report diameters.

3. The researchers were not able to observe effects of doping with Mn, W, Mo, and Cu introduced during the synthesis. The optical spectra of CdO QD remain unchanged. They tried using other metal oxides and salts on the stage of synthesis CdO QD. All these attempts were unsuccessful.

4. No data were reported on efficiency improvement or durability.

5. The researchers constructed and tested thin film solar cells based on titania and sensitized with CdO QD. The best efficiency was 0.17 percent. To improve that number they used films of Fe_2O_3 or CuO as a replacement for the titania layer and developed the method of preparation of those films. The MOSSC based on thin films of Fe_2O_3 modified with CdO QD showed efficiency of 0.03 percent. These efficiencies were well below those of conventional DSSC.

6. The researchers used conventional DSSC as a reference for testing of various components of MOSSC. The best solar cell efficiency they achieved for DSSC sensitized with N3 dye was 5.1 percent with a fill factor of 57.0 percent. This is considerably higher than the efficiencies they achieved with MOSSC.

7. The researchers tested several electrolytes and redox pair combinations. They prepared solar cells based on I^-/I^{3-} solution in 3-methoxypropionitrile where iodide was in the form of a mixture of lithium iodide and 1,3-dimethyl-3-imidazolinium iodide. The researchers

claimed these cells showed the highest efficiency of all the MOSSC designs tested, but they did not state a specific efficiency. They presented no durability data.

8. Results on this task were incorporated into Outcomes 1, 2, 3, and 5.

2.12.5 Conclusions

1. The researchers met the objective.
2. While the proposed method was not successful, the researchers developed a successful alternative.
3. The researchers did not meet this objective.
4. There is no evidence of successful completion of this objective.
5. Energy conversion efficiencies were considerably lower than the standard.
6. The researchers did not meet this objective.
7. Lack of presented data indicates that this objective was not met.
8. Objective not met.

Overall the researchers did not prove feasibility of a lower cost, more efficient solar cell.

2.12.6 Recommendations

The researchers have many ideas to extend the work done in this grant. These ideas are presented in the Final Report. The Program Administrator has the following recommendations:

1. Evaluate the progress of all dye solar cell research reported since the original proposal was submitted. Dye solar cell research has made considerable progress.
2. Determine which elements or findings of the current project could be used to leapfrog existing technology.
3. Create a new research plan.
4. Set definite energy conversion efficiency objectives. Determine what is needed to meet those objectives.
5. Set definite cost/price objectives. Create a cost model to track all costs. Work with a solar cell manufacturer to determine how costs translate into product price.

2.12.7 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 public from this research is increased affordability of electricity in California. The benefit would accrue in the area of electricity generation. The researchers' goal was to produce a low cost solar cell. However they never specified a cost goal. They claimed they achieved this goal because they were using low cost materials. Since the final material content has not yet been established, it is not possible to estimate a final cost or price of a resulting commercial solar cell. Also, the researchers obtained very low energy conversion efficiencies, about 0.03 percent. Silicon based solar cells routinely exhibit energy conversion efficiencies of 15 to 17 percent.

In July 2013 Ecole Polytechnique Federale de Lausanne (EPFL) reported that a team led by Professor Michael Graetzel produced a dye sensitized solar cell with an efficiency of 15 percent.[30] Those cells achieved 14.1 percent efficiency in an independent test. Professor Graetzel is working with an industrial partner, Dyesol Limited, to bring these new dye solar cells to market. These cells could provide near term benefits to Californians. Cost/price of these solar cells was unknown in mid 2013.

2.12.8 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 have not performed a market analysis, nor have they interviewed potential customers or industrial partners.

Engineering/Technical

The researchers plan to continue work in this area. They have estimated they will need about $250,000 and two or three years to complete development work.

Legal/Contractual

The researchers have not conducted a patent search, nor have they applied for or received a patent for work done in this project.

Environmental, Safety, Risk Assessments/ Quality Plans

Cadmium oxide (CdO) is a known toxic material. Waste disposal of the cell can be a problem. The researchers' goal is to find a non-toxic metal oxide to replace CdO in solar cells.

Production Readiness/Commercialization

At the completion of the project the researchers had no plan to commercialize this concept.

30 http//actu.epfl.ch/news/dye-sensitized-solar-cells-rival-conventional-cell-efficiency,pdf

2.13 Solution Processed Solar Cells from Abundant, Non-Toxic Materials

Awardee: Plant Solar

Principal Investigator: Craig Peters

2.13.1 Abstract

Researchers in this project studied the feasibility of producing copper/zinc/tin/sulfide, $Cu_2(Zn,Sn)S_4$ or CZTS, thin films for photovoltaic cell application. The researchers proposed and tested CZTS for PV use using solution based techniques. They developed two solution approaches: one based on ZnS nanoparticle colloids and another based on $ZnCl_2$ metallic complex chalcogenide solution. The researchers also studied CuSnS thin films, a promising PV material based on its abundance, to investigate their limitations as a solar absorber layer. The researchers found that the CZTS thin films they produced via the solution routes contained secondary phases. They concluded that the CZTS PV concept evaluated could not compete with existing thin film PV technologies (e.g., CdTe and CIGS). Results from this EISG grant clearly elucidate the challenges of making high quality, single phase CZTS thin films from solution. The researchers concluded that the CZTS technology studied is not feasible. Accordingly, there are no plans for further testing.

Keywords: Solar cells, abundant materials, solution processing, thin films, photovoltaic cells, $Cu_2(Zn,Sn)S_4$, CZTS

2.13.2 Introduction

Expanding the use of renewable energy remains a central component of California energy policy. Increasing the use of solar photovoltaic (PV) technology for electricity remains difficult due to its noncompetitive costs relative to traditional power generation technologies. PV costs must be reduced by nearly an order of magnitude to compare favorably with grid supplied electricity. The United States currently has more than 900 gigawatts (GW) of installed electrical power generation capacity, while existing PV devices represent less than 10 GW.

Cu_2ZnSnS_4 (CZTS) is a promising PV material because it has an ideal spectral bandgap (~1.45 eV) and high absorption coefficient (>104 cm-1). Theoretically, only a few microns of CZTS are necessary to obtain power conversion efficiencies approaching 24 percent. CZTS is comprised of cheap, abundant, and non-toxic materials which could allow for large scale deployment without negative environmental tradeoffs or material shortage driven cost inflation. CZTS could emerge as a disruptive PV technology, replacing Si and competing thin film materials.

In this project the research team studied the feasibility of producing high quality Cu_2ZnSnS_4 (CZTS) thin films using solution processing for PV application. CZTS is comprised of abundant non-toxic materials and has the potential to scale to large annual PV production. Solution deposition techniques do not require vacuum and can have higher throughput rates that in principle could result in lower overall module costs.

2.13.3 Objectives

The goal of this project was to determine if high quality CZTS thin films could be produced in laboratory scale and provide 10—15 percent efficiency in PV application. The researchers established the following objectives:

1. Demonstrate synthesis of Cu_2S, SnS and ZnS nanocrystals and inorganic Sn_2S_6 inorganic ligands and achieve size distribution of nanocrystals of +/-20 percent.
2. Substitute organic ligands with inorganic ligands with <1 ppm carbon remaining in film after deposition and film formation.
3. Achieve CZTS polycrystalline films determined by X-ray diffraction (XRD), energy dispersive x-ray spectrometry (EDS), and Raman spectroscopy with XRD peaks matching peaks in the literature with the <112> peak as the out-of-plane orientation. Verify homogeneity of CZTS stoichiometry in film using EDS with fine scale (<7 nm) precision. Confirm absence of secondary phase formation (e.g., zinc sulfide) using Raman scattering.
4. Determine processing conditions that lead to continuous CZTS films with large grains. Verify using scanning electron microscopy (SEM) imaging.
5. Achieve films with a doping density of 1016—1017 cm^{-3}, hole mobility y of >102 cm^2 V-1 s-1, and a minority carrier lifetime of greater than five nanoseconds.
6. Input materials parameters into AMPS-1D modeling software to determine future PV cell performance.

7. Achieve an initial solar cell power conversion efficiency of 9 percent with a final target of 12—15 percent at 0.35—$0.45/Wp cost when in full production.

2.13.4 Outcomes

1. The researchers developed two solution based methods for producing CZTS thin films. The research team formed solutions by dissolving $ZnCl_2$ into hydrazine solution and mixing with Cu and Sn based metal chalcogenide complexes (MCCs). They also produced CTS solutions from Cu and Sn based MCCs using previously published approaches.

2. The researchers changed the direction of their efforts away from organic ligand based chemistry to inorganic ligands. This eliminated the task to reduce the organic contamination level.

3. The research team found that single phase CTS thin films could be formed at relatively low temperatures but that the films had small grain sizes. The team also found that increasing the processing temperature resulted in larger grains at the expense of increased secondary phase (zinc sulfide) formation. The researchers measured average grain sizes as ~150 nm and ~500 nm for the films made from $ZnCl_2$ and hybrid inks, respectively, after annealing the films at 525° C.

4. The researchers produced continuous and crack-free CZTS films using the $ZnCl_2$ solution based approach, as shown by electron microscopy. They measured the surface roughness of this film at less than 10 nm.

5. The researchers determined that additional effort on film growth was needed and diverted from the task of achieving films with photoactive metrics: a doping density of 1016—1017 cm^{-3}, hole mobility of >102 cm^2 V-1 s-1, and a minority carrier lifetime of >5 ns. The researchers attempted to fabricate CZTS solar cells and deposited cadmium sulfide (CdS) on thin films and were able to deposit quality zinc oxide (i-ZnO) and Al doped ZnO on glass. They did not complete the characterization of a CZTS solar cell. They fabricated CIGS solar cells with efficiencies of 8.6 percent using the same methods as used to produce CZTS solar cells. The researchers focused on studying film growth using $ZnCl_2$-MCC solutions.

6. The researchers reported that the CZTS films fabricated under this project contained secondary phases, which they believe significantly reduced the performance of the materials.

7. The researchers postponed further modeling until CZTS films could be produced without secondary phases.

2.13.5 Conclusions

1. It is possible to produce CZTS thin films using solution deposition. The researchers completed this objective.

2. Using inorganic ligands reduced the need to remove organic ligand residuals and reduced the number of processing steps. Therefore this objective became unnecessary.

3. The zinc chloride based ink provided good grain size and surface roughness when annealed at 525° C but at the expense of secondary phases in the film. The secondary phases rendered the photovoltaic properties of the film unacceptable for application. The researchers completed this objective but did not confirm absence of secondary phase formation, as zinc sulfide was evident in the film.

4. Continuous and crack-free CZTS films using the $ZnCl_2$ solution based approach are possible. The hybrid ink produced a cracked and rough surface physically unacceptable for PV use. The researchers completed this objective.

5. The researchers did not measure the photovoltaic properties of the films. They did not complete this objective.

6. At this stage CZTS films annealed to achieve appropriate physical properties (grain size, surface roughness) have unacceptably high levels of secondary phase materials that preclude the films use as competitive PV cell material. The researchers did not achieve this objective.

7. The researchers did not produce an operable CZTS thin film PV cell. They did not achieve this objective. Micro-cracking of films resulted in device shunting which cannot achieve meaningful power conversion efficiency or important measurements such as doping density.

Fabricating a photovoltaic device with acceptable power conversion efficiency using the solution based approaches in this project does not appear feasible at this time. The competitive cost environment has changed since the project began, and it is uncertain whether solution processing can provide any cost or performance advantage.

2.13.6 Recommendations

The Program Administrator recommends the following actions:

1. The researchers should investigate the impact that solute polarity has on film formation and consider using a solvent different from the chemical specie providing electropositive cations. Hydrazine is a polar solvent and may account for some of the film formation difficulties. Other solvents, including hydrazine compounds, may alleviate some of the cracking and secondary phase production.

2. Further, the researchers should determine if hydrazine's hygroscopic nature precludes its use as a solvent in atmospheric based processing, as any small amount of moisture absorption would likely render produced films unacceptable even with subsequent drying and annealing. This would result in part by facilitating and likely accelerating secondary phase formation.

3. Finally, the researchers should investigate the impact of film drying speed on the film's physical properties, including grain size, surface roughness, and continuity. While slower drying time would facilitate better physical properties, it also would lead to increased secondary phase formation. As the researchers showed in this project, it may not be feasible to overcome these countervailing phenomena.

2.13.7 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. While highly speculative, the scientific results from this feasibility study could ultimately help lead to the development of efficient CZTS solar cells. It is premature to quantify the economic or environmental benefits based on a study that did not demonstrate the feasibility of solution processed CZTS solar cells.

2.13.8 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

Undertaking marketing or developing connection to the market is premature given that the concept was not shown to be technically feasible. Sharing the scientific results of the project may help to establish wider recognition of PLANT Solar corporate bona fides.

Engineering/Technical

Developing engineering and technical requirements is premature since the concept was not shown to be technically feasible.

Legal/Contractual

Establishing legal or contractual arrangements is premature given the status of the technical concept.

Environmental, Safety, Risk Assessments/ Quality Plans

There are no known environmental or safety risks unique to this concept. Hydrazine is a toxic and hazardous chemical, but safety protocols have been developed, and it is widely used in numerous industries. This issue may become moot if the researchers find a different solvent is preferred.

Production Readiness/Commercialization

The product concept is not ready for production or commercialization.

2.14 Growth of Cavity Light Emitting Diode on a Reflective Substrate

Awardee: Lightwave Photonics, Inc.

Principal Investigator: Robert Jorgenson

2.14.1 Abstract

This project sought to determine the feasibility of growing a gallium nitride based light emitting diode (LED) in the configuration of an optical cavity structure. Researchers grew the LED active element epitaxially on a reflective conductive mirror substrate with the objectives of providing a means to increased light extraction and reducing manufacturing costs. They demonstrated structures composed of (0001) AlN/(111) HfN/(0001) GaN epitaxial layer structures on sapphire substrates. The epitaxial HfN layer provided a highly conductive back reflector for potential subsequent growth of light emitting diode (LED) epitaxial structures. The researchers measured the HfN mirror reflectivity to be 80 percent for 530 nm LED emission. Smooth (0001) AlN films less than 1500 nm thick yield single crystal growth as determined by x-ray diffraction. In one case the researchers fabricated a light emitting, but non-optimized, LED, showing it is possible to grow epitaxial LED structures. These results allowed the researchers to conclude that a feasible path to increase LED light extraction and to reduce manufacturing costs is available. However more work is required to fully explore the limits of performance.

Keywords: Light emitting diode, optical cavity, gallium nitride, mirror, hafnium nitride, epitaxy

2.14.2 Introduction

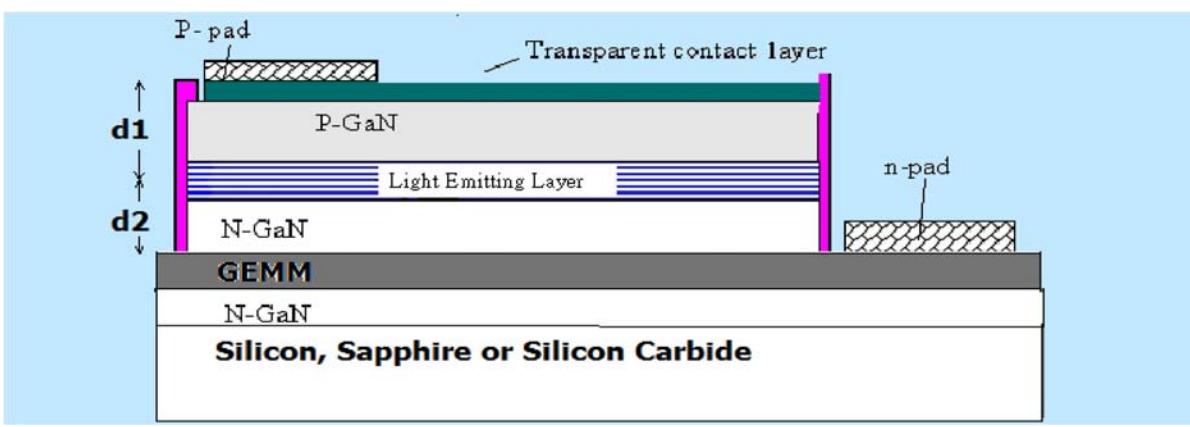
Inefficient lighting is recognized to be a worldwide problem. Accordingly, governments around the world have passed measures to phase out incandescent light bulbs for general lighting in favor of more energy efficient alternatives. In the United States a gradual phase-out began in 2012 with 100 watt bulbs and progressed with discontinuation of the 75 watt variety. In California, lighting comprises approximately one-fourth of the State's electricity use. In the two largest sectors of the economy, lighting consumes about 22 percent of a household's electricity use and 35 percent of a commercial building's total electricity use. The two major candidates to replace incandescent bulbs are compact fluorescent (CFL) lamps and light emitting diode (LED) lamps. While the light efficacy of incandescent sources is about 15 lumens per watt (lm/W) and halogens are 17.4 lm/W, CFLs and LEDs are approximately four times greater at 60 lm/W. LED lamps are significantly longer lived, lasting 25,000 hours. For example, a single LED replacement for a 60 watt incandescent has an average 20,000 lumen-hour light output in its lifetime, while it would take 22 incandescent bulbs, 27 halogen bulbs, and 3 CFLs for the same total light output. At the current average residential cost of electricity in California of about $0.15/kWh, the lifetime cost of electricity for the LED would be $147 compared to $157 for the CFLs and $629 for the incandescents. Higher first cost, however, is a perceived consumer issue. At the present time 60 W incandescent bulbs cost $0.40, a CFL equivalent costs $1.74 and an LED equivalent cost $8. Thus the roughly $8 premium a consumer pays for the LED light and a smaller premium for the CFL returns a net saving of almost $500 in electricity. CFLs have the disadvantage of a more complicated disposal because they each contain a few milligrams of mercury, a hazardous waste. It is useful to note that most mercury vapor inside fluorescent light bulbs becomes bound to the inside of the light bulb as it is used. EPA estimates that the rest of the mercury within a CFL, about 11 percent, is released into air or water when it is sent to a landfill, assuming the light bulb is broken. EPA also estimates the United States is responsible for the total release of 103 metric tons of mercury emissions each year with more than half of these emissions coming from coal-fired power plants. If all 272 million CFLs sold in 2009 were sent to a landfill (versus recycled), they would add 0.12 metric tons, or only 0.12 percent, to United States mercury emissions caused by humans. In spite of the significant saving in lifetime cost of operation and the greater ease of disposal, consumers have been slow to adopt LED lights because of higher first cost. Therefore there is great interest in lowering the first cost of LED lamps by simplifying their manufacture and by making them more efficient in order to overcome consumer resistance.

If the first cost of LED lamps could be significantly reduced, it would promote their increased market share over incandescent and CFL lamps, leading to greater efficiency, lower greenhouse gas emission, and greater ease of disposal, all of benefit to the California ratepayer. For example, California's total electrical consumption for 2013 was estimated to be 310,516 GWh. The lighting component (1/4) of this would account for 77,629 GWh. In 2010 nationwide bulb purchases were about 70 percent incandescent, 28 percent CFL, and < 2.0 percent LED. Assuming these proportions approximate that of California lighting, incandescent bulbs consume 54,340 GWh of electricity per year. Replacement of all the incandescents by LEDs that are four times as efficient would save about 41,000 GWh per year. At an average California residential price of electricity of about $0.15/kWh this represents a saving of $6.15 B to ratepayers. The saving in electricity consumption would also reduce GHG emissions. At a

typical emissions rate (electric) of 0.524 lbs CO_2 per kWh (PGE), there could be a yearly savings in GHG emissions of 9.8 MMT of CO_2 equivalent. Clearly these are just approximate estimates, but they serve to illustrate the importance of greater LED market penetration due to first cost reduction and especially reduced electricity consumption.

The advancement of science or technology that was proposed in this project was a novel internal mirror placement and novel material to reduce GaN LED cost and increase efficiency. The new approach is shown schematically in Figure 20. This innovation would produce higher performance with high yields over the two conventional approaches to LED fabrication. In the most common approach in the modern standard LED, a polycrystalline metal mirror is placed at the bottom of a transparent sapphire substrate and the light-producing active region is grown on the top surface. This LED is less costly to produce and has high manufacturing yields. However the design separates the mirror too far from the active region to achieve strong optical cavity effects. This penalizes performance. The flip chip approach places the mirror closer to the active region to give better performance, but at the expense of manufacturing complexity. The growth substrate of either sapphire or silicon carbide must be removed, the device flipped, a polycrystalline mirror deposited on the GaN surface, and the device placed on a sub-mount structure. Removal of the growth substrate requires either laser lift-off or backside chemical mechanical etching, resulting in higher production costs and lower manufacturing yields. In this proposal, researchers grew a high quality GaN layer on a substrate and then grew a lattice-matched metallic mirror (GEMM) epitaxial on top. Finally, the researchers grew a standard GaN-based LED on the GEMM. This approach yielded the high performance of the flip chip without having to remove the substrate. An important design feature would adjust the distance from the mirror to the light emitting active region so that an anti-node of the optical standing wave would produce constructive interference in the active region. Finally, the distance of the light emitting active region from the top transparent conductor would also be adjusted to an anti-node, further increasing constructive interference.

Figure 20: Schematic of LED Chip Structure. The Grown Epitaxial Metal Mirror (GEMM) is a Key Feature.



2.14.3 Objectives

The goal of this project was to determine the feasibility of growing a gallium nitride based optical cavity light emitting diode (LED) structure epitaxially upon a reflective substrate to

increase light extraction and reduce manufacturing costs. The researchers established the following project objectives:

1. Deposit optimized grown epitaxial metal mirror (GEMM) on growth substrate. Demonstrate reflectivity > 80 percent. Demonstrate x-ray diffraction (XRD) FWHM values below 500 arc seconds. Demonstrate that GEMM deposition results in a smooth surface appropriate for subsequent epitaxy of LED structure with RMS roughness value less than 2 nm as determined by atomic force microscopy (AFM).

2. Deposit epitaxial LED structure and optimize n-GaN crystal quality for subsequent growth of multi quantum well (MQW) light extraction efficiency by adjusting the epitaxial stack dimensions. Demonstrate that n-GaN deposition results in a smooth surface appropriate for subsequent epitaxy of MQW structure with RMS roughness value less than 2 nm as determined by atomic force microscopy. Show a 35 percent improvement in light extraction efficiency compared to control LED.

3. Fabricate a fully processed packaged LED prototype to compare with control LED. Demonstrate that the new LED is 35 percent brighter than control LED.

4. Perform manufacturing cost analysis for 530 nm LED. Confirm from the project findings that the projected manufacturing cost of less than $0.01 per lumen continued to be supported.

2.14.4 Outcomes

1. The researchers grew an HfN metal mirror with reflectivity of greater than 80 percent, an XRD FWHM value of 394 arc seconds, and an AFM RMS value of 0.468 nm.

2. The researchers, together with several collaborators, explored growing GaN films on top of ZrN and HfN mirrors by different growth techniques. Preliminary results were not completely successful. Characterizing the top GaN layer by x-ray diffraction was complicated by the presence of the bottom GaN layer.

3. The researchers and collaborators from Ohio State University produced a functioning but low efficiency LED with the GEMM base structure. However there was not enough time to gather empirical data to evaluate device efficiency compared to the reference LED.

4. For the same reason, there was not enough time to complete the cost analysis objectives of the project.

2.14.5 Conclusions

1. Researchers successfully grew an HfN metal mirror with correct properties. Accordingly, they met this goal.

2. Researchers grew GaN films on the GEMM, but crystal quality goals were not achieved.

3. Researchers fabricated a preliminary low efficiency LED prototype, but they did not achieve the performance goals.

4. Researchers did not perform a manufacturing cost analysis for a 530 nm LED. Therefore they did not meet this goal.

The main goal of this project was to determine the feasibility of growing a gallium nitride based optical cavity light emitting diode (LED) structure epitaxially upon a reflective substrate to increase light extraction and to reduce manufacturing costs. Researchers established partial feasibility of this approach in that they demonstrated a high quality reflective GEMM. However, they produced only one functioning LED, and it was of low quality. Overall the approach seems to have a good chance for success.

2.14.6 Recommendations

The Program Administrator recommends that the researchers pursue their plan to grow GEMM mirrors on AlN coated substrates to characterize and optimize the subsequent GaN films on top of the GEMM. Once GaN growth conditions on GEMM are established, the researchers should investigate the replacement of the bottom AlN with GaN to simplify device manufacturing and reduce cost.

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.

2.14.7 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. If the first cost of LED lamps could be significantly reduced, it would promote their increase in market share over incandescent and CFL lamps, leading to greater efficiency, lower greenhouse gas emission, and greater ease of disposal, all of benefit to the California ratepayer. For example, California's total electrical consumption for 2013 was estimated to be 310,516 GWh. The lighting component (1/4) of this would account for 77,629 GWh. In 2010 nationwide bulb purchases were about 70 percent incandescent, 28 percent CFL, and < 2 percent LED. Assuming these proportions approximate that of California lighting, incandescent bulbs consume 54,340 GWh of electricity per year. Replacement of all the incandescents by LEDs that are four times as efficient would

save about 41,000 GWh per year. At an average California residential price of electricity of about $0.15/kWh, this represents a saving of $6.15 B to ratepayers. The saving in electricity consumption would also reduce GHG emissions. At a typical emissions rate (electric) of 0.524 lbs CO_2 per kWh (PGE), there could be a yearly savings in GHG emissions of 9.8 MMT of CO_2 equivalent. Clearly these are approximate estimates, but they serve to illustrate the importance of greater LED market penetration due to first cost reduction and especially reduced electricity consumption.

2.14.8 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

LPI is in contact with customers who are sampling the materials deposited on growth substrates.

Engineering/Technical

The researchers will try to circumvent the problem of growing a GaN top layer on a GaN bottom by replacing the bottom layer with AlN.

Legal/Contractual

Since receiving the EISG grant the company was awarded a $500,000 NSF SBIR grant for related but different work. It reports receiving patents US8253157, US7915624, US7842939.

Environmental, Safety, Risk Assessments/ Quality Plans

The researchers have not created plans in these areas.

Production Readiness/Commercialization

The researchers report that several LED manufacturers are eager to use their technology.

2.1G Advanced Low Temperature Natural Gas Combustion Using Jet Ignition

Awardee: MAHLE Powertrain LLC

Principal Investigator: Dr. William Attard

2.1.1G Abstract

Researchers in this project evaluated the feasibility and benefits of a jet ignition system for on-road vehicles using natural gas fuel in internal combustion engines. The objectives of the project were to demonstrate near diesel-like peak thermal efficiency, demonstrate up to a 20 percent improvement in fuel economy, and demonstrate that NO_x emissions meet CARB emission standards without post-combustion treatment. The researchers used two experimental test rigs to assess the pre-combustion chamber ignition system. Preliminary results demonstrated a peak thermal efficiency of 42.5 percent, a 20.6 percent improvement in fuel economy when compared to the baseline spark ignition system. Results simultaneously recorded 0.08 g/kWh NO_x equaling over a 99 percent reduction compared to the baseline system. This indicates the combustion system can meet CARB standards without any lean NO_x exhaust treatment. Using the pre-combustion chamber ignition system as presented is one potentially feasible way that will allow future engines to achieve efficiency and emission benefits, provided other engineering issues can be resolved. Longer duration tests are needed to demonstrate technical feasibility.

Keywords: Lean burn, fuel economy, efficiency, NO_x emissions, combustion, pre-chamber, jet ignition, natural gas

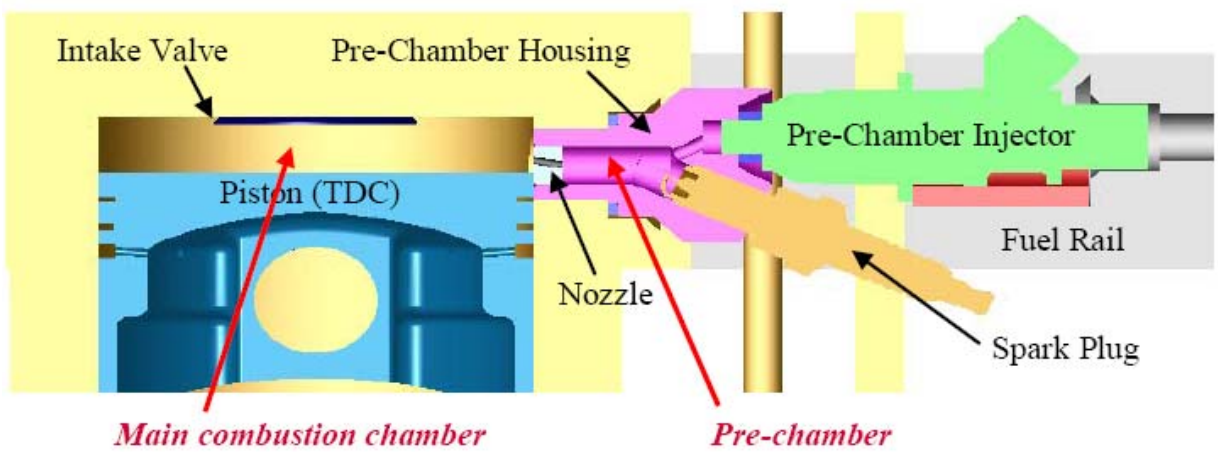
2.1.2G Introduction

Natural gas is an abundant and clean burning fuel with large and expanding reserves in the United States. Achieving the targets of California's Global Warming Solutions Act (AB32) and its component part the Low Carbon Fuel Standard (LCFS) will require greater substitution of alternative low carbon fuels like natural gas for petroleum based fuels. As a major contributor to California's emissions of carbon dioxide, the transportation sector especially needs the technological capability to replace petroleum based fuels with natural gas. In this application natural gas can reduce carbon dioxide emissions by 25 percent. The reduction can be even larger if natural gas is enhanced with greater fuel use efficiency.

Current reciprocating engines using lean fuel-to-air ratios and spark ignition technology with natural gas as fuel have problems associated with slow burn rates and high hydrocarbon (HC) and carbon monoxide (CO) emissions. High HC and CO are indicative of incomplete fuel combustion and low fuel efficiency. Slow fuel charge burn rates are associated with single point combustion initiation such as with spark plugs.

To overcome these issues this project coupled natural gas fuel with a pre-chamber ignition system called turbulent jet ignition. This system ignites the main combustion chamber fuel charge with a jet flame rather than a spark plug, resulting in multiple flame fronts and more rapid burn. A spark plug is used to initiate the jet flame. The system is illustrated in Figure 21.

Figure 21: Schematic of Jet Ignition System Installed in a Side Ignition Engine



2.1.3G Objectives

The goal of this project was to determine the feasibility a turbulent jet ignition system for use in natural gas fueled reciprocating engines. The researchers established the following objectives:

1. Demonstrate that the test bed is calibrated and capable of measuring performance, efficiency, and emission parameters to within plus or minus 1.0 percent.
2. Demonstrate that the test bed is capable of recording combustion and visualization images.
3. Demonstrate performance, efficiency, and emissions data for 10 speed-load points.
4. Demonstrate combustion optical images for three speed-load points.

5. Demonstrate that a prototype turbulent jet ignition system is capable of operating a natural gas fueled engine with adequate combustion stability.

6. Demonstrate near diesel-like peak thermal efficiency (~45 percent).

7. Demonstrate engine NO_x emissions can meet CARB standards without any lean NO_x after-treatment.

8. Demonstrate up to a 20 percent improvement in fuel economy.

2.1.4G Outcomes

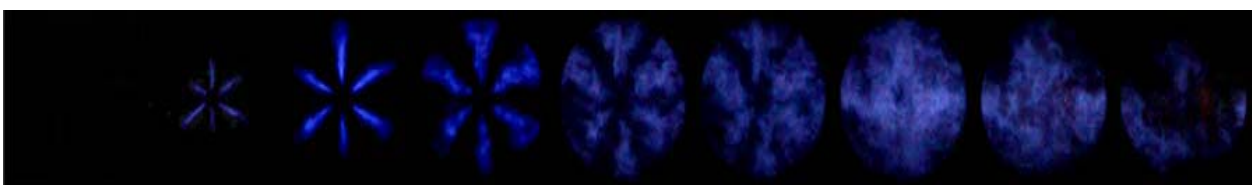
1. The researchers assembled and calibrated a metal piston engine test bed. They measured performance to within plus or minus 1.0 percent before and after experimentation. The researchers completed this objective.

2. The researchers assembled a second rig with quartz window piston for optical test and recorded combustion visualization images. They completed this objective, but under testing the quartz combustion window failed. Later more complete testing was discontinued.

3. The researchers recorded performance, efficiency, and emissions data at 10 load points. They completed this objective.

4. The researchers collected optical images of the combustion for both spark and jet ignition for comparison. Figure 22 shows a representative series of images for one combustion condition (lamda=1.8). The series of images show 8° after spark (left) to 32° after spark, looking up through the quartz piston head.

Figure 22: Optical Images of Combustion from 8° after Spark to 32° after Spark

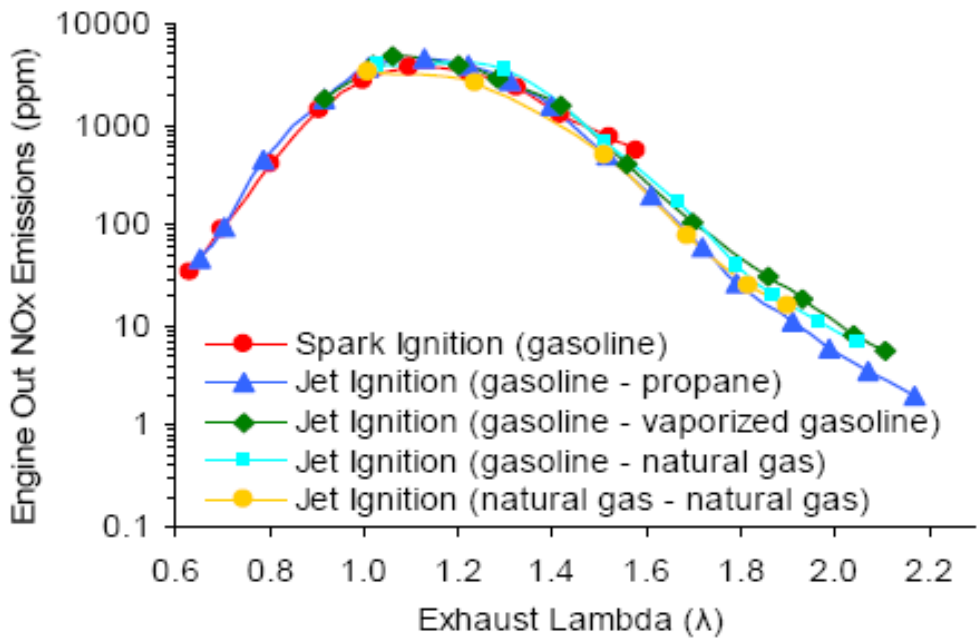


5. The researchers operated the jet ignition system using natural gas as fuel while maintaining combustion stability at near lamda (λ) of 2.0, a lean burn condition.

6. The researchers collected limited data under operation of the jet ignition system indicating peak thermal efficiency of 42.5 percent. The researchers encountered failures of the dynamometer and high engine oil consumption with leakage into the combustion chamber. Neither issue was associated with the jet ignition system's design or operation but limited the ability to collect further data.

7. The researchers recorded NO_x emissions as shown in Figure 23. They encountered failures in the test rig as noted above, and only limited data were collected.

Figure 23: NOX Emissions under Various Air/Fuel Ratios, Fuel Type, and Ignition Type



8. The researchers calculated that a 20.6 percent improvement in fuel economy was achieved when compared to the baseline spark ignition system, based on limited data under varying loads. They did not measure fuel economy under an engine mapping or constant load scenario.

2.1.5G Conclusions

1. Carefully instrumented and commissioned test equipment can measure performance to plus or minus 1.0 percent precision and accuracy.
2. Engine lubrication system failure ended testing before long-term data could be collected. The failure of the lubrication system did not appear to be from use of the turbulent jet igniter.
3. The researchers obtained visual images of combustion showing multiple flame fronts, but piston failure stopped further testing. The failure did not appear to be from use of the turbulent jet igniter.
4. Performance using natural gas and the turbulent jet igniter exceeded performance using gasoline.
5. The researchers demonstrated combustion stability at very lean fuel-to-air ratios, up to λ =2.0.
6. The lower flame temperature diminished NO_x formation and may allow use without exhaust treatment while improving thermal efficiency.
7. Based on limited data, fuel economy should be improved with this system.

The main goal of this project was to determine the feasibility and benefits of a natural gas fueled

turbulent jet ignition system to improve on-road vehicle engine thermal efficiency and emissions. The researchers demonstrated the technical possibility of using a jet ignition system on natural gas fueled reciprocating engines. They have not yet demonstrated the commercial feasibility of the concept. The full potential of a natural gas fueled pre-chamber jet ignition combustion system was not realized due to engine mechanical failures not related to the technology. No reliable engine data could be collected at ultra lean conditions past λ=1.9 due to high oil consumption.

2.1.6G Recommendations

The program administrator recommends the following actions:

1. Complete longer term testing, including durability, after repairing or replacing the metal and optical engines. Testing with a metal engine would be more important than additional testing with optical engines, as flame propagation appears to have been adequately characterized by the current project. Longer test regimes would provide details of the combustion process at ultra lean conditions and establish the lambda limit. More complete testing should provide information regarding specific efficiency and emission benefits in a fully functioning power train. In addition, the researchers should investigate the effects of different piston top designs and compression ratios on performance and emissions.

2. Investigate application of the jet ignition system in other power train applications and determine effects on performance of different load cycles.

3. Complete a market assessment to determine if single fuel (natural gas only) or dual fuel (natural gas ignition with gasoline primary fuel) would provide the quickest and most sustainable path to commercial acceptance.

4. Complete a cost analysis and determine life cycle costs or payback period, including effects on manufacturing and engine maintenance.

5. Refine product design based on testing and develop engineering, manufacturing, and maintenance requirements. Once multiple cylinder engines are developed, begin the CARB certification process. Begin development of necessary OBD II data collection and analysis needs (e.g., cylinder misfire recognition).

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.

2.1.7G Benefits to California

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

- Reduced environmental impacts of the California energy supply and distribution system
- Increased public safety of the California energy system
- Increased reliability of the California energy system
- Increased affordability of energy in California

The primary benefit to the ratepayer from this research is from increased affordability of energy in California. Secondary benefits are from reduced environmental impact of the California energy supply and distribution system.

Achieving the low carbon fuel standard has been estimated by numerous market economists as potentially increasing the cost of transportation fuels in California by 15 percent to over 30 percent. Substituting natural gas for petroleum derived fuels or biofuels with low carbon intensity provides consumers with lower cost fuel while lowering carbon emissions by 25 percent. Other consumer benefits of natural gas fueling include:

- More stable fuel prices relative to gasoline due to less dependency on foreign oil since the majority of natural gas is domestically produced using hydraulic fracturing to greatly expand resources.
- Decreased ground level ozone from lower emissions of carbon monoxide, volatile organic compounds, and nitrous oxide emissions.

The researchers estimated cost savings by performing a case study for two typical vehicles, a mid-size passenger car (Toyota Camry) and an SUV (Chevrolet Tahoe). Results indicated that over a 10 year lifetime a pre-chamber natural gas vehicle could offer substantial fuel cost savings in the range of $8,000—$14,000, but at unknown first costs. The analysis also highlighted the financial benefits of a natural gas vehicle relative to a hybrid gasoline vehicle. While the Toyota Camry hybrid provides a $4000 cost savings over a 10 year period relative to the baseline model, the more expensive Chevy Tahoe hybrid results in a $400 loss relative to the baseline gasoline vehicle due to minimal improvement in fuel economy. If the buyer had selected a natural gas fueled engine rather than a hybrid, his savings would have been between $10,000 (spark ignited) and $14,000 (jet ignited) over a 10 year period for the Chevrolet Tahoe. A major contribution to the savings is the lower cost of natural gas in comparison to gasoline.

California uses approximately 18 billion gallons of diesel and gasoline per year and emits about 170 million metric tons of CO_2 from the transportation sector. Assuming even a modest 1.0 percent market penetration of pre-chamber jet ignition natural gas technology and a 20 percent fuel economy improvement (relative to spark ignition), use of the turbulent jet ignition technology could provide a fuel cost savings of about $350 million and a CO_2 emissions saving of about 0.66 million metric tons, but again at unknown cost.

2.1.8G 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 have published papers describing the technology and results obtained without disclosing information important to proprietary protection. The researchers stated that several engine manufacturers for both light and heavy duty applications have expressed interest in collaborating with them to further develop the technology. The researchers conducted a market analysis for Class 4 and above vehicles. This type of medium and heavy duty vehicle is targeted for natural gas conversion due to high fuel usage and re-fueling infrastructure.

Engineering/Technical

Durability is the most important technical issue that needs to be demonstrated. The researchers estimated that completion of the development process could require 3 to 10 years and millions of dollars.

Legal/Contractual

The researchers have completed a professional patent search that revealed no patent conflicts or infringements. They have applied for patent protection (number 2012/0103302 A1).

Environmental, Safety, Risk Assessments/ Quality Plans

There are no known safety or environmental risks associated with the technology. Durability will be a quality issue until it can be proven, and it will need to be addressed in quality assurance plans.

Production Readiness/Commercialization

The product concept is not yet ready for production or commercialization.

2.2G Residential Gas-Fired Heat Pump Water Heater

Awardee: Stone Mountain Technologies, Inc

Principal Investigator: Michael Garrabrant

2.2.1G Abstract

This project demonstrated the feasibility of a high efficiency gas fired single effect absorption cycle domestic water heater. A compact prototype sized to fit on top of a 75 gallon storage water heater tank delivered a coefficient of performance (COP) of 1.7 at 68° F ambient and 90° F inlet water temperature in a breadboard configuration. Estimated system COP with an integrated condensing flue gas heat exchanger was 1.5. Under the DOE Residential Water Heater Test Procedure the estimated energy factor was 1.3 after considering storage tank heat losses and parasitic power draws. In a commercial package these results could yield an estimated total installed cost close to current best available technologies at as much as 1.4 times their efficiency. At this time the roughly 10 year payback against traditional water heaters remains a concern, especially in California's hard water regions where water heater life may be less than 10 years and when water softening is included in a system.

Keywords: High efficiency water heater, heat pump, absorption, ammonia water, NO_x

2.2.2G Introduction

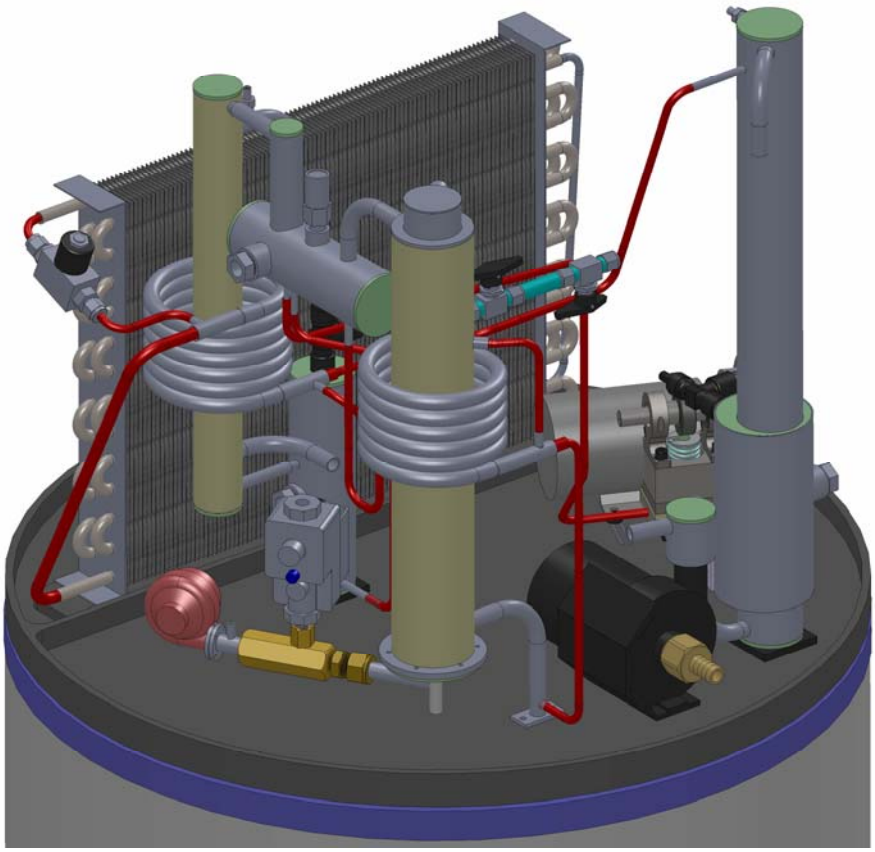
California's roughly 10 million residential gas water heaters account for over 40 percent of residential natural gas use, with corresponding fuel cost and emission impacts. The typical basic non-condensing unit has a primary energy factor (EF)[31] of roughly 0.6 and an installed cost of roughly $1,000. Although more efficient approaches are being brought to market, including tankless units with EFs of roughly 0.82 to 0.92 and condensing gas storage units with EFs of roughly 0.82, these approaches are significantly more costly and range between roughly $1900 and $2200 installed. The extended payback periods at these costs present a significant barrier to more widespread adoption in California.

Improving payback for advanced water heating designs can significantly increase their penetration, thereby reducing natural gas usage, saving customers' money, and reducing emissions. While some improvements in installed costs are anticipated as production volumes increase, a more promising approach appears to be significantly increasing overall heating efficiency.

The researchers in this project proposed to demonstrate the feasibility of a gas fired residential heat pump water heater with an EF of 1.5 in a package size compatible with a standard 75 gallon storage water tank. The proposed design (Figure 24) incorporated a simple single effect NH_3-H_2O residential heat pump sized to fit within a 24 by 18 inch enclosure attached on top of a typical water heater's tank and an integrated condensing heat exchanger.

31 A measure of water heater efficiency, taking into account both overall heating efficiency and passive losses to the ambient environment.

Figure 24: Conceptual Packaged Heat Pump Water Heater Assembly



2.2.3G Objectives

The goal of this project was to determine the feasibility of a gas fired residential heat pump water heater to achieve an energy factor (EF) of 1.5 in a package size approximately equivalent to an electric residential heat pump water heater. The researchers established the following project objectives:

1. Design heat pump heat exchangers based on a single effect cycle which will fit into an envelope small enough to fit on top of a standard 75 gallon storage water heater tank, approximately 24 inches in diameter and 18 inches tall.
2. Demonstrate heating output of at least 2.8 kW and a cycle COP of at least 1.5 on a breadboard test facility.
3. Verify that projected manufacturing costs support an installed cost of $1,800 in 2010 dollars.

2.2.4G Outcomes

1. The researchers utilized previously developed modeling and designs for a single effect NH3-H2O adsorption heating cycle as the starting point for the project. The next step was optimization of a baseline cycle from this prior work for performance over a range of operating conditions typical of domestic water heating applications. The resulting set of cycle set points for temperature, pressure, flow rate, species concentration, and

physical state, as well as related heat exchanger parameters, formed the basis for detailed design of a test prototype. All components of final design, including two inches of foam insulation could fit within a 24 inch diameter, 22 inch tall enclosure.

2. The researchers built a breadboard system consisting of full-scale components from the detailed design in Objective 1 with associated controls and measurement instrumentation. Preliminary testing led to several design modifications, including using air cooling instead of fluid cooling for the evaporator to reduce component size. Applying the breadboard test results to a complete system, including a storage tank with an integrated condensing heat exchanger, suggested an overall system COP ranging from 1.45 to 1.53 at 68° F ambient and 90° F return water temperatures. The corresponding energy factor at this range would be roughly 1.3. Predicted total heating capacity under similar conditions was between 2.45 and 2.81 kW.

3. Estimated direct manufacturing cost for a packaged heat pump water heater ranged between $1035 (10,000 units) and $872 (50,000 units). Corresponding total installed cost ranged between $2,144 and $2,670. Compared to a standard domestic water heater, estimated annual savings would be roughly $123, for a simple payback of nearly 10 years without incentives.

2.2.5G Conclusions

The researchers largely met the objectives for this project, although further refinement and testing is indicated as described below:

1. The analysis and design in Objective 1 led to a well-defined and documented specification for a prototype heat pump. The prototype components were not assembled into an actual 24 by18 inch envelope for testing, as the researchers opted for a wall-mounted breadboard arrangement that facilitated instrumentation and component access. Based on the dimensions of the individual prototype components, the design would not meet the 18 inch target height in the Objective, even after substitution of air cooling for fluid cooling in the evaporator design. The researchers' conclusion that further refinement could result in a final height of 19 inches appears reasonable, although this would need to be validated in future research.

2. The researchers provided excellent documentation of the prototype's design, fabrication, and testing that confirmed this objective was met. Since no testing was conducted with the components assembled within the targeted enclosure, it is not known whether results would be different when operated in the close proximity required in the specified envelope or at smaller scale for use in 40 and 50 gallon water heaters.

3. The researchers' cost estimates and payback calculations were well supported in the Final Report. The proposed heat pump approach appears to be competitive with other advanced designs on installed cost, and its projected higher efficiency could make it a more desirable choice for installations where the greater height of the design can be accommodated. However, the roughly 10 year payback against traditional water heaters remains a concern, especially in California's hard water regions where water heater life may be less than 10 years and when water softening is included in a system. It is also not

clear whether the design could be successfully scaled down for use with the more common 40 and 50 gallon water heaters in many residences. The payback equation could improve if more aggressive valuation of environmental benefits from improved efficiency is adopted in California.

2.2.6G Recommendations

The Program Administrator recommends moving from the proof of concept work completed in this project to more detailed design, fabrication, and testing of commercial prototypes. This work should include an emphasis on reducing costs, likely market acceptance, and compliance with prevailing codes and standards governing water heater hardware and installation. Specific steps could include:

- Design and fabricate a storage tank with internal heat exchanger optimized for maximum transfer of heat pump output to the tank's water.
- Include smaller tank sizes (40 and 50 gallons) in the design work.
- Investigate regulations regarding the use of ammonia in residential settings.
- Finalize a combustion design.
- Field test prototype tank/heat pump units across a wide range of inlet and outlet temperatures, cycling intervals, and DOE specified EF rating measurements.
- Conduct market research to firm up the potential penetration of a commercial system.

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.

2.2.7G Benefits to California

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

- Reduced environmental impacts of the California energy supply and distribution system
- Increased public safety of the California energy system
- Increased reliability of the California energy system
- Increased affordability of energy in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California energy supply and distribution system.

If a gas fired heat pump unit were commercially available with performance similar to estimates in this project, it could reduce CO_2, and NO_X emissions by a factor of 2.24 and cut customers'

fuel bills for water heating in half compared to a standard gas fired water heater. Realizing significant statewide penetration and savings would require overcoming the initial first cost disadvantage, which could be accelerated if aggressive incentives were provided.

2.2.8G 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

There are roughly one million gas fired residential water heaters purchased annually in California. The researchers estimated that 5 percent of the market would adopt this premium product. There would be competition from other high efficiency technologies in this space. No formal market study was completed. There is no indication that the researchers connected to another firm to aid them in marketing this innovation in California.

Engineering/Technical

The researchers estimated a cost of about $2 million and a time period of two to three years to complete engineering and demonstration.

Legal/Contractual

The researchers completed a limited patent search, and an application was pending at the completion of this project.

Environmental, Safety, Risk Assessments/ Quality Plans

The researchers identified a robust set of recommendations for further work in all of these areas, including independent certifications and field testing.

Production Readiness/Commercialization

There is a significant body of work ahead to develop a commercial product and move it to market. Incorporation of a development and commercialization partner is essential to success, both from a financial and expertise viewpoint. The researchers indicated that potential partners have expressed interest, although details were not given.

2.3G Advanced Control Techniques and Sensors for Gas Engines with NSCR

Awardee: Colorado State University

Principal Investigator: John Gattoni and Daniel B. Olsen

2.3.1G Abstract

California state law supports expansion of combined heat and power (CHP) as an environmentally beneficial technology, but it has the most stringent emission control standards in the country. Emission standards are especially tough for mechanically driven distributed generation (DG) devices such as natural gas internal combustion engines, turbines, and microturbines. Typically these systems require the use of post-combustion emission control systems in order to meet CARB 2007 emission requirements.

The use of non-selective catalyst reduction (NSCR) systems with lambda sensors is commonly used as post-combustion emission control treatment for natural gas stationary engines. NSCR requires complex fuel control within a narrow band of tolerance to work properly and achieve the desired level of emissions for criteria pollutants such as nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOC). Lambda sensor accuracy is the most critical element for successful operation of current fuel controllers. However lambda sensors are reported to have reliability issues over extended operating periods and/or when transients are introduced. A more reliable solution is needed.

The goal of this project was to evaluate the feasibility of utilizing a NO_x sensor installed downstream of the NSCR catalyst system along with a minimization control algorithm for feedback air/fuel ratio control. Such a system would enable precise control of the fuel to air equivalence ratio to ensure proper NSCR catalyst system operation and maintain emissions at acceptable levels over a wide spectrum of operating conditions. Researchers performed testing on an 80 kW nominally rated Cummins-Onan generator set (gen set) that was reconfigured utilizing an electronic carburetor with lambda feedback, NSCR catalyst assembly, instrumentation, and a data acquisition system. The researchers developed a comprehensive test plan and completed testing using lambda sensor feedback control as a baseline for comparison. They then developed a minimization control algorithm for feedback air/fuel ratio control using the LabView software package and repeated test measurements using a NO_x sensor installed downstream of the NSCR catalyst. The software was optimized on the LabView platform and uploaded to an on-board engine microprocessor for final testing.

Lab test results indicated that the concept has the potential of meeting and maintaining CARB 2007 emission targets over a variety of engine operating conditions. Further development and optimization of the control algorithm and control parameter values is necessary and recommended. Field testing, market assessment, and cost analysis of the proposed technology will help determine its viability and market potential. The research team is currently working with a manufacturing partner on a commercialization plan.

Keywords: NSCR, NO_x sensor, lambda sensor, minimization control algorithm, internal combustion engine, electronic gas carburetor, air/fuel ratio control, catalyst

2.3.2G Introduction

California state law supports accelerated adoption of distributed generation (DG) and combined heat and power (CHP) applications. The State policy foundation supporting accelerated deployment of CHP can be found within the AB-32 (Global Warming Solutions Act) Scoping Plan and AB-1613 (Waste Heat and Carbon Emissions Reduction Act).

California has the most stringent emission control standards in the country. In particular, the California Air Resources Board has established a set of emission standards, known as CARB 2007, for mechanically driven distributed generation (DG) devices including spark ignited (SI) natural gas internal combustion engines, turbines, and microturbines. Criteria pollutants targeted by CARB 2007 include nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOC). For example, NO_x emissions are limited to 0.07 pounds per megawatt-hour (lb/MWh), which is considered to be an extremely difficult challenge for engines.

Engines typically require the use of complex post-combustion emission control systems to meet CARB 2007 regulations. Such systems typically require continuous calibration. The most popular emission control technique used for engines is non-selective catalyst reduction (NSCR) with lambda sensors for continuous monitoring and controlling of engine air/fuel ratio (AFR). Although successfully deployed in the marketplace, NSCR requires complex fuel control strategies to work properly with a very narrow equivalence ratio operating range.

Current use of NSCR emissions control technology is reported to have reliability issues over extended operating periods and/or when transients are introduced. Lambda sensor accuracy is the most critical element for successful operation of current fuel controllers. These systems require regular system calibration to meet exhaust emissions regulations. Expensive mobile exhaust emission testing equipment is typically required for engine calibration to achieve an optimum fuel to air equivalence ratio (Φ) and ultra low exhaust emissions.

The goal of this project was to evaluate the feasibility of utilizing a NO_x sensor installed downstream of the NSCR catalyst system along with a minimization control algorithm for feedback air/fuel ratio control. Such a system would enable precise control of the fuel to air equivalence ratio to ensure proper NSCR catalyst system operation and maintain emissions at acceptable levels over a wide spectrum of operating conditions. This innovation would be accomplished by:

- Development of an innovative control algorithm.
- Unique implementation of NOx sensors to control NSCR systems.

Natural gas is considered one of the most promising clean fuels able to meet strict engine emission regulations in many countries. Natural gas has relatively wide flammability limits, allowing engines to be operated in a large range of lean, stoichiometric, and rich burn conditions. The operating equivalence ratio and exhaust after treatment system employed generally characterizes engine exhaust emissions[32] such as NO_x, CO, and VOC. Other pollutants

32 Cho, Haeng Muk and Bang-Quan, He "Spark Ignition Natural Gas engines – A Review," Energy Conversion and Management (February, 2007) pages 608–618.

such as sulfuric oxides and particulate matter are not usually a concern for SI natural gas engines. NO_x emissions are primarily composed of nitric oxide (NO) and nitrogen dioxide (NO_2). NO_x is typically reported either as parts per million (ppm), as a mass flow rate (pounds/hr), or in reference to engine power (grams/brake-horsepower-hour or grams/brake kilowatt-hour). NO_x levels vary based on equivalence ratio and combustion temperature, which are interrelated. The lowest possible engine NO_x emissions in SI natural gas engines occur when operating under extreme lean burn conditions, that is, when the fuel air equivalence ratio is less than 1.0 ($\Phi < 1$).[33] Often this results in an increase in engine CO and total hydrocarbon (THC) emissions due to slower flame initiation and propagation at extreme lean burn conditions.

High CO and THC engine exhaust emissions are typically produced under rich burn conditions ($\Phi > 1$) due to insufficient oxygen that cannot fully oxidize the fuel. Exhaust residence time, reaction quenching in the exhaust process, and cooling at the combustion chamber walls also contribute to incomplete combustion and increased CO and THC concentration. Natural gas engines also produce less carbon dioxide (CO_2) emissions than diesel or gasoline fuels at equal power.

The overall goal for engine manufacturers and packagers is to achieve the highest possible thermal efficiency coupled with the most effective exhaust after-treatment system. Emissions technology has improved continuously over the last 10 years, particularly in combustion and catalyst systems. An exhaust after-treatment system is designed for the intended application, that is, whether the targeted engine is operating in lean burn or stoichiometric (slightly rich burn) mode.

For lean burn engines, a rather complex NO_x reduction after-treatment system is required such as selective catalyst reduction (SCR) or a NO_x trap. Lean burn operating limits are dependent on ignition timing and energy, combustion chamber geometry, and combustion turbulence. For stoichiometric (slightly rich burn) engines, NSCR catalytic converters are typically the preferred after-treatment method. This technique is designed to simultaneously reduce NO_x, CO, and THC concentrations and reduce VOC and hazardous air pollutants. NSCR is not typically used for compression ignition, two stroke, or other lean burn engines because the catalyst is required to operate at stoichiometric air/fuel ratio (AFR). Lean burn engines have an inherent advantage of higher power density, that is, lower brake specific fuel consumption.

This project focused on optimizing emission control systems for stoichiometric natural gas engines using a NSCR after-treatment device, a highly efficient catalyst, and precise control of the air/fuel ratio (AFR). The researchers used a heated oxygen (O_2) sensor as feedback to maintain precise AFR control, promoting high NSCR catalyst activity, and ultimately leading to effective reduction of NO_x, CO, and VOC emissions.

---

33 Korakianitis, T. "Natural Gas Fueled Spark Ignition (SI) and Compression Ignition (CI)Engine Performance and Emissions," Science Direct (August 21, 2009) http://www.sciencedirect.com/science/article/pii/S0360128510000377.

Proper NSCR catalyst system functionality requires that the fuel to air equivalence ratio be precisely controlled with a narrow range of tolerance at or near stoichiometric conditions.[34] The industry has had difficulty with long term stability of AFR control systems. Many control systems utilize lambda sensor feedback for equivalence ratio control. However research suggests that the lambda sensor calibration drifts outside of the narrow control range.[35] A recent study on the benefits of using additional instrumentation to improve feedback to the AFR control device, such as a NO_x sensor, led to the evolution of this project.[36]

NO_x sensor technology dates back to the late 1980s, with initial designs being constructed from various forms of ceramic type metal oxides including yttria stabilized zirconia. Material selection was adopted from lambda sensor technology which had been developed prior. Requirements of a robust NO_x sensor include a wide operating temperature range, sensitivity, accuracy, lifetime, and appropriate material selection to avoid degradation by gases such as CO_2 and SO_2.[37] Improved models such as the dual chamber zirconium dioxide have been developed and continue to be an area of active engineering research. For example, Continental Controls Corporation (CCC) developed a dual cavity NO_x sensor. Figure 25 describes the construction and operation of the CCC dual cavity NO_x sensor.

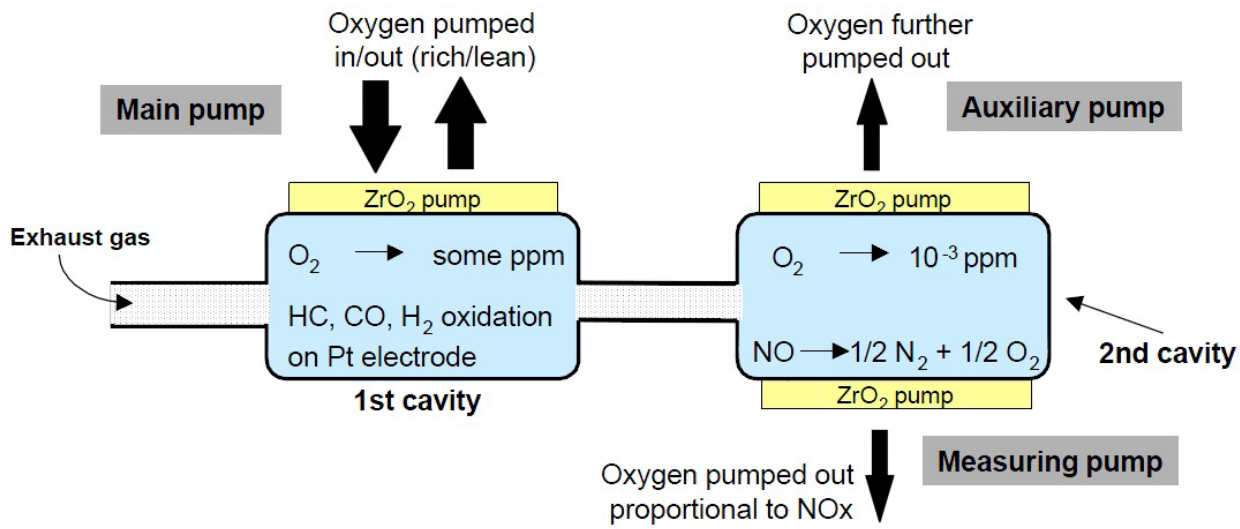
34 Amadu, Sule, and Olsen, Daniel Olsen "Operating Characteristics of an NSCR Catalyst on an 80 kW Cummins Onan Genset." (2008).

35 Nuss-Warren, Sarah, and Hohn, Keith "Final Report: Cost-Effective Reciprocating Engine Emissions Control and Monitoring for E&P Field and Gathering Engines" (2011).

36 Vronay, John; Roser, Ranson; Pratapas, John; Zelepouga, Serguei; and Grimes, Hilary "Task 2.4 - Sensor Screening Test Report, Task 5 - Emission System Test Plan & Emission System Development Report" (2010).

37 Woo, Leta "NOx Sensor Development" (June 10, 2010) Lawrence Livermore National Laboratory.

Figure 25: Construction and Operation of Continental Zirconium Dioxide Dual Cavity NOx Sensor



The zirconium dioxide dual cavity NO_x sensor operates in the following sequence:

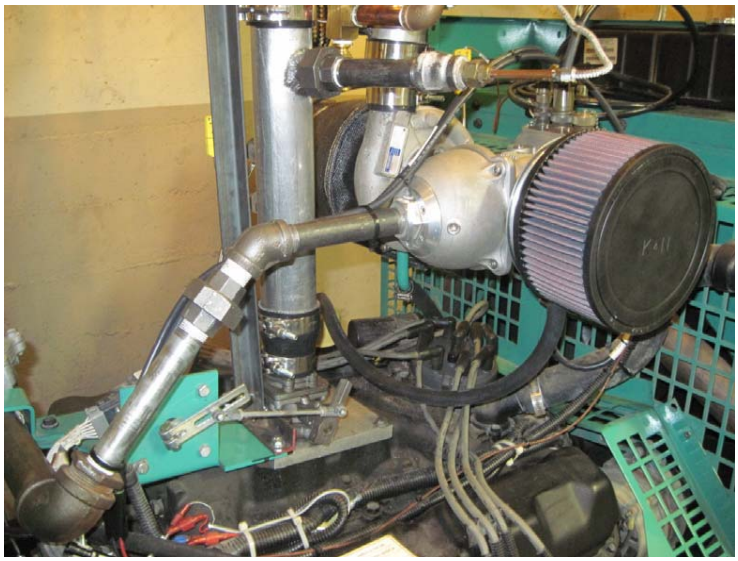
- Exhaust gases NO_x, HC, CO, O_2, H_2, etc. enter the first cavity of the sensor.
- O_2 concentration is maintained at a constant concentration within a few parts per million (ppm) of NO_x via the main O_2 pumping cell, and the rest is oxidized at the Pt pumping electrode.
- The new concentrated gas of NO_x and O_2 enter the second cavity.
- The auxiliary pump completely removes gaseous O_2 in the second cavity.
- The equilibrium of $2NO \rightarrow N_2 + O_2$ is changed at the measuring electrode by removing the generated oxygen from the reduction of NO.
- The measuring pump extracts and measures this generated oxygen which represents the NO_x concentration of the exhaust gas.

The zirconia electrolyte acquires an amperometric measurement. An electronic control unit is required to provide power control to heat and maintain the temperature of the sensor.[38]

For this project the research team selected an existing nominally rated 80 kW Cummins-Onan generator set assembled in 1999 as the engine platform to perform laboratory experiments and testing of its proposed NO_x sensor/minimization control algorithm. The engine was reconfigured to operate with a CCC electronic fuel controller with lambda feedback, exhaust after-treatment system, NO_x sensor system, instrumentation and appropriate data acquisition (DAQ) system. Figure 26 shows a photograph of the test engine reconfigured with a CCC fuel controller.

38 Siemens VDO Automotive AG (2008) "Continental NOx Sensor Technical," Continental Controls Corporation (2008). "Electronic Gas Carburetors EGC2/EGC4," (2010). "Catalyst Monitor and Datalogging," Inagaki, Hiroshi, Oshima, Takafumi, Miyata, Shigeru, and Kondo, Noriaki "NO_x Meter Utilizing ZrO_2 Pumping Cell" (1998) Warrendale, PA: SAE International http://papers.sae.org/980266.

Figure 26: CCC EGC2 Installed on Engine



The catalyst used for the project was a NSCR device designed to reduce exhaust emissions including CO, THC, NO_x, and formaldehydes. The NO_x sensor system was manufactured by CCC, and it included an electronic carburetor and catalyst monitor. The researchers developed propane blending and exhaust back pressure systems to introduce transients. They used propane blending to assess the ability to control exhaust emissions with variable fuel composition. They developed the exhaust back pressure transient to create an instantaneous change in back pressure.

The research team developed a test procedure to compare baseline testing with the NO_x sensor feedback control algorithm. It created various steady state and transient conditions to evaluate the system's ability to maintain high NSCR catalyst emissions reduction efficiencies. When the engine was operated at 100 percent load for only a short period of time, overheating occurred due to the generator set being located in an area of the facility with poor air circulation. It was decided that 80 percent load (64 kW electric power) would be established as the maximum load.

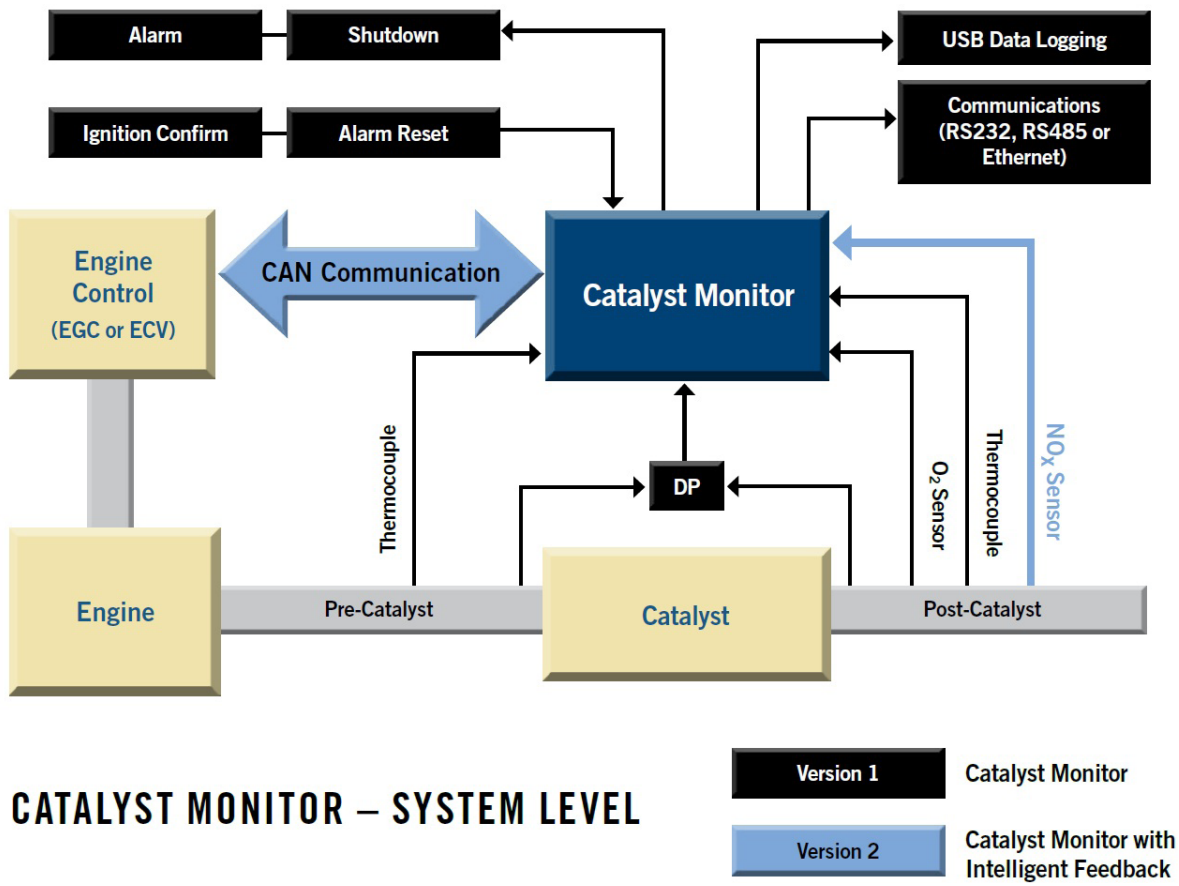
The researchers developed five test procedures for the study:

1. Equivalence ratio sweep steady state
2. Load sweep steady state
3. Load transient
4. Propane blending (steady state and transient)
5. Exhaust back pressure transient

The load sweep consisted of operating the engine at steady state generator load settings of 20, 40, 60, and 80 percent. The researchers evaluated the effects of catalyst temperature and its relation to the required AFR set point, as well as NO_x sensor correlations. They conducted the load transient test to evaluate the ability of the control system to maintain emissions compliance as load changed.

The research team developed and optimized the minimization control algorithm through multiple iterations. It performed a series of preliminary tests prior to integration with NO_x sensor feedback fuel control. It simulated various control variables to ensure that the algorithm behaved appropriately under various engine operating conditions. The researchers implemented NO_x sensor feedback fuel control utilizing a minimization control algorithm that was programmed into LabView. They were then able to measure percent simultaneous NO_x and CO reduction with NOx sensor/minimization control algorithm tied directly to LabView. Once the software was optimized on the LabView platform, they uploaded the final algorithm to a CCC onboard microprocessor, thus allowing lambda increment adjustments to take place without the use of LabView software. Figure 27 illustrates the test control schematic.

Figure 27: Test Engine Controls



Test results showed significant improvement in emissions reduction using NO_x feedback control in comparison to baseline testing using only lambda feedback control during steady state operation and even better results across the NSCR catalyst system at lower loads. The CCC microprocessor, embedded with the new minimization control algorithm, performed as expected. The new control algorithm was able to meet CARB 2007 emission requirements at 20 percent load for NO_x, CO, and VOC. At 60 and 80 percent load conditions, the new control algorithm was only able to meet NO_x and VOC emission targets. However CO emission levels exceeded CARB 2007 targets. The NO_x sensor minimization control algorithm behaved the same with both LabView and the on-board microprocessor. Both were able to drive the NO_x sensor output to a minimum and maintain it. THC and VOC emission reductions, however, were

measured to be greater using LabView compared to the on-board microprocessor. Further refinement of the software should eliminate this discrepancy.

Steady state testing at 20, 40, 60, and 80 percent engine loads revealed that the AFR needs to be shifted at each setting due to the change in catalyst temperature. The load transient showed significant improvement at lower loads using NO_x sensor minimization control by shifting the AFR, reducing NO_x concentration. Standard deviation during load and propane blending transient testing did not improve using NO_x sensor minimization control.

Researchers successfully demonstrated the concept of using a NO_x sensor minimization control technique in a laboratory environment. Initial test results were promising. Further development and optimization of the control algorithm and control parameter values over a wider range of engine operating conditions is recommended to demonstrate that the new concept can meet and maintain CARB 2007 emission targets. A field test is also recommended to evaluate phenomena not present during laboratory testing such as long term degradation of sensor, fuel quality variation, ambient air humidity and temperature changes, engine performance degradation, and catalyst degradation. For field implementation, NO_x sensor minimization control should be enabled only when catalyst temperature is within the catalyst operating range. During the warm-up period, standard lambda feedback control should be used.

The catalyst used for the project was over-sized by two to five times compared to typical field installations. Over-sizing of the catalyst is costly and may not be cost effective for commercial applications. A market assessment and cost analysis of the proposed system would help determine its viability and market potential. The research team is currently working with CCC on a commercialization plan.

2.3.3G Objectives

The primary goal for this project was to prove the feasibility of using a minimization algorithm with a NO_x sensor to control NSCR catalyst systems for industrial natural gas engines. The researchers established the following project objectives:

1. Reconfigure engine to operate with a Continental Controls electronic gas carburetor, NSCR catalyst, and NO_x sensor system. Measure percent simultaneous NO_x and CO reduction with standard lambda sensor feedback control. Measure standard deviation of emissions reductions for CO and NO_x during transient testing.

2. Develop control algorithm on LabView platform that controls engine fuel to air equivalence ratio by minimizing NO_x sensor signal. Perform bench tests to evaluate basic functionality of LabView program without running engine.

3. Perform experimental evaluation and refinement of proposed control system on a nominally rated 80 kW Cummins-Onan genset. Final test will include steady state test points and transient testing.

    - Measure percent simultaneous NO_x and CO reduction with NO_x sensor/minimization control algorithm.

    - Measure standard deviation of emissions reductions for CO and NO_x during transient testing with NO_x sensor/minimization control algorithm.

- Achieve CARB 2007 Distributed Generation pollutant emission levels (0.07 lb/MW-hr NO_x and 0.10 lb/MW-hr CO).
- Improve standard deviation by 5.0 percent (lower value is better).

4. Implement final algorithm on onboard CCC microprocessor.
5. Repeat experimental evaluation and testing on the 80 kW Cummins-Onan gen set. Final test will include steady state test points and transient testing.
   - Measure percent simultaneous NO_x and CO reduction with NO_x sensor/minimization control algorithm.
   - Measure standard deviation of emissions reductions for CO and NO_x during transient testing with NO_x sensor/minimization control algorithm.
   - Verify that the algorithm programmed in the engine microprocessor performs the same as LabView version (± 2.0 percent).
   - Improve standard deviation by 5.0 percent (lower value is better).

2.3.4G Outcomes

1. The researchers successfully configured the 80 kW Cummins-Onan gen set with the electronic gas carburetor, NSCR catalyst, and NO_x sensor system. Researchers also added a water/air turbocharger after-cooler and a National Instruments (NI) data acquisition (DAQ) system. The research team was then able to measure NO_x and CO emissions reduction using a standard lambda sensor feedback control and standard deviation of emission reductions during transient testing.
2. Researchers developed and optimized a new control algorithm on a LabView platform that controls engine fuel to air equivalence ratio by minimizing NO_x sensor signal and performed bench tests of the LabView program.
3. The researchers successfully performed testing and refinement of the control system using the 80 kW Cummins-Onan gen set platform and LabView software. The results showed significant improvements during steady state operation and increased emissions reduction efficiency across the NSCR catalyst system at lower loads.
4. The researchers programmed the final minimization control algorithm directly into the Continental Controls microprocessor, thus allowing lambda increment adjustments to take place without the use of LabView software.
5. The researchers completed final testing and refinement of the control system on the 80 kW Cummins-Onan gen set test engine platform. From a control standpoint, the CCC microprocessor embedded with the new minimization control algorithm performed appropriately. However the researchers measured reduction of THC and VOC emissions at higher loads to be less than that using the LabView algorithm control. The new control algorithm was able to meet CARB 2007 emission requirements at 20 percent load for NO_x, CO, and VOC. At 60 percent and 80 percent load conditions the new

control algorithm was able to meet NO_x and VOC emission targets. However CO emission levels exceeded CARB 2007 targets.

2.3.5G Conclusions

1. Integration of the new control algorithm and NO_x sensors on the 80 kW Cummins-Onan gen set platform was accomplished without much difficulty. This suggests that the proposed emission control technology, if proven to be successful and practical, could be integrated into a host of other engine platforms.

2. The use of LabView software for bench-scale work is a practical means of optimizing emissions control software prior to actual bench scale testing on an engine platform.

3. The new NO_x sensor minimization control technique produced promising results, albeit in a carefully controlled laboratory environment.

4. Software algorithms developed and optimized on a LabView platform can be easily uploaded into an on-board electronic carburetor.

5. Testing using NO_x sensor minimization control improved the reduction efficiency of NO_x and THC significantly at lower loads. Using the LabView platform for NOx sensor minimization control more consistently reduced CO and VOC emissions at higher loads compared to embedding the software into the onboard electronic carburetor. Control of NO_x emissions was identical for both the LabView and onboard microprocessor. Further optimization of the software would likely improve test results of the onboard electronic carburetor along with the potential of meeting CARB 2007 emission regulations under a wider range of operating conditions.

This work demonstrated the potential of a new emission control technique that could enable engine based DG and CHP systems to meet stringent CARB 2007 regulations in a more reliable and cost effective manner. Initial test results demonstrated compliance with CARB 2007 regulations for various engine load settings. Further system optimization is required to meet emission standards over a wider range of engine operating conditions. Steady state testing at 20, 40, 60, and 80 percent engine loads revealed that the AFR needs to be shifted at each setting due to the change in catalyst temperature. The load transient showed significant improvement at lower loads using NO_x sensor minimization control by shifting the AFR, thus reducing NO_x concentration. Standard deviation during load and propane blending transient testing was not improved using NO_x sensor minimization control. The NO_x sensor minimization control algorithm behaved the same with both LabView and the onboard microprocessor. Both were able to drive the NO_x sensor output to a minimum and maintain it.

2.3.6G Recommendations

Researchers successfully demonstrated the concept of using a NO_x sensor minimization control technique in a laboratory environment and demonstrated the potential of meeting CARB 2007 emission targets. The Program Administrator recommends the following:

- Field test to evaluate phenomena not present during laboratory testing, such as long term degradation of sensor, fuel quality variation, ambient air humidity and temperature changes, engine performance degradation, and catalyst degradation.
- Develop and optimize further the control algorithm and control parameter values. For field implementation, NO_x sensor minimization control should be enabled only when catalyst temperature is within the catalyst operating range. During the warm-up period standard lambda feedback control should be used.

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.

2.3.7G Benefits to California

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

- Reduced environmental impacts of the California energy supply and distribution system
- Increased public safety of the California energy system
- Increased reliability of the California energy system
- Increased affordability of energy in California

The primary benefit to the ratepayer from this research is increased affordability of energy in California.

California has adopted the most stringent emission controls in the country for DG and CHP related end use equipment based on mechanical drives such as spark ignited (SI) internal combustion engines, turbines, and microturbines. These systems typically require the use of complex post-combustion emission control systems to meet California's stringent CARB 2007 emission regulations (e.g., 0.07 lb/MW-hr for NO_x) which were established to improve air quality for the benefit of California citizens. A more reliable and cost effective NSCR control system would help to ensure that natural gas IC engines are able to maintain ultra-low NO_x, CO, and VOC emissions throughout their duty cycles and over the service life of the engines. A more reliable NSCR control system could also potentially reduce the need for costly emissions monitoring equipment. Reducing the cost of maintaining compliance lowers system operating costs and increases the overall cost effectiveness of DG/CHP systems. If regulatory requirements for emissions testing can be reduced from five to one per year, customers could save an average of $20,000/year per system (assuming an average cost of $5,000 per test). Assuming that there are 1000 rich burn engines in California, total savings to system operators could be approximately $20 million per year.

2.3.8G 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 proposed concept, if proven to be feasible and practical, could be purchased and/or licensed by engine manufacturers and system packagers who are currently active or interested in pursuing business opportunities in the California marketplace.

Engineering/Technical

The research team is partnering with Continental Controls Corporation to complete development and commercialize the proposed technology. It is anticipating funding by the Pipeline Research Council International (PRCI) for field demonstration.

Legal/Contractual

Researchers have not conducted a patent search nor filed for any new patents.

Environmental, Safety, Risk Assessments/ Quality Plans

There is no obvious safety or environmental risk associated with this system design. If additional research is pursued, the integrity of the system will need to be thoroughly tested to ensure it meets standard industry safety and permitting requirements.

Production Readiness/Commercialization

The research team is working with Continental Controls Corporation to complete development and commercialize the proposed technology. The concept is not yet sufficiently developed for commercialization. Field testing is needed to validate the performance and reliability of the technology in a real world working environment. Further optimization of the software and control algorithm will likely be needed. A cost analysis and business/marketing plan will help verify the market potential for this product and ensure that it compares favorably with other devices in the market.

2.4G The Development of a Prototype Natural Gas Fueled Homogeneous Charge Compression Ignition Engine for Hybrid Vehicles

Awardee: Rochester Institute of Technology

Principal Investigator: James H. Lee

2.4.1G Abstract

California policy encourages the use of transportation technologies that increase energy efficiency while reducing harmful air emissions. The goal of this project was to prove the feasibility of a compressed natural gas (CNG) fueled engine using advanced homogeneous charge compression ignition (HCCI) combustion technology to achieve those goals. The researchers proposed using this engine to power the battery charging system of a light duty plug-in hybrid electric vehicle (PHEV). They proposed using a modified Kohler model ECH-749, 750 cc, 90° V-Twin port fuel injected engine rated at 29 hp as a test engine. The researchers modified the engine by installing an exhaust gas recirculation (EGR) valve, replacing existing pistons with pistons capable of achieving a compression ratio of 14:1, and installing an intake air heater to provide start up energy for the engine. The design used exhaust gases to increase the energy content of the combustion chamber and to reduce oxides of nitrogen (NO_x) emissions from the engine. The research team also installed fuel injectors rated for CNG in the engine and an engine controller to enable the engine to be fueled with CNG.

The researchers demonstrated significant emission reductions. Most significantly, the research work determined that the conditions required to support HCCI combustion using a spark ignited engine could not be achieved because insufficient energy was recovered from the exhaust gases. To pursue additional HCCI research, the researchers stated that an engine block capable of a compression ratio greater than 14:1 is needed.

The work achieved considerable reduction (up to 80 percent depending on EGR) in engine NO_x emissions. The HC output more than tripled after 15 percent EGR was reached. Engine power and torque decreased significantly as a function of EGR. Further investigation could identify key parameters that will maximize the emissions benefit with little or no reduction in engine performance.

Keywords: HCCI, compressed natural gas, advanced combustion, emissions, PHEV, hybrid vehicles

2.4.2G Introduction

California policy encourages the development of new transportation technologies that increase energy efficiency while reducing harmful air emissions. Natural gas is a viable alternative to gasoline and diesel fuel because it is clean burning and available from large domestic reserves. However since it has a lower energy density than gasoline or diesel fuel, natural gas fuel requires very large storage containers on vehicles. If space for these storage tanks is not available, the vehicles have a reduced range. One way to overcome this shortcoming is to develop methods to increase the efficiency of engines burning natural gas fuel. In this project the researchers pursued HCCI engine technology. The potential for this technology is increased efficiency and lower emissions than current Otto or Diesel cycle engines using gasoline or diesel fuel. The potential benefit of this technology to California residents is yet unknown. The researchers estimated the potential emissions reduction of converting 5.0 percent of the 32 million vehicles registered in California to plug in hybrid electric vehicles (PHEV) using HCCI engines running on natural gas. They estimated that this could result in annual reductions of over 5 million tons of CO_2, 440 tons of CO, 15 tons of NO_x, and 35 million tons of hydrocarbon emissions. The savings would come from three changes. First, changing from a combustion engine as a prime mover to an all electric vehicle could result in significant emission reductions depending on the source of electricity. Second, changing from diesel fuel or gasoline to natural gas fuel in a traditional internal combustion engine would also result in considerable emission reductions. Finally, the subject of this project was to change the onboard engine from an Otto cycle or Diesel cycle engine to a homogeneous charge compression ignition (HCCI) engine which could also result in emissions reductions and energy efficiency gains.

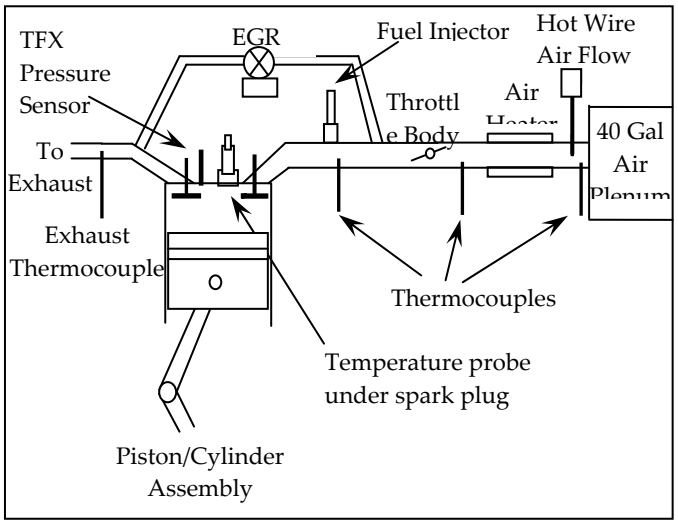
HCCI is a new and as yet not commercialized engine technology. According to Wikipedia: “HCCI has characteristics of the two most popular forms of combustion...spark ignition...and compression ignition. As in homogeneous charge spark ignition, the fuel and oxidizer are mixed together. However, rather than using an electric discharge to ignite a portion of the mixture, the density and temperature of the mixture are raised by compression until the entire mixture reacts spontaneously. Stratified charge compression ignition also relies on temperature and density increase resulting from compression, but combustion occurs at the boundary of fuel-air mixing, caused by an injection event, to initiate combustion. The defining characteristic of HCCI is that the ignition occurs at several places at a time which makes the fuel/air mixture burn nearly simultaneously. There is no direct initiator of combustion. This makes the process inherently challenging to control. However, with advances in microprocessors and a physical understanding of the ignition process, HCCI can be controlled to achieve gasoline engine-like emissions along with diesel engine-like efficiency."

Significantly more effort has been spent developing an understanding of HCCI combustion using liquid fuels as compared to natural gas and other gaseous fuels. In contrast, the research team in this project worked towards developing a prototype of a homogeneous charge compression ignition (HCCI) engine fueled by compressed natural gas (CNG) to power the battery charging system in light duty plug in hybrid electric vehicles (PHEV).

HCCI technology has been difficult to implement because the load variations associated with conventional engines cause the engine timing required to support HCCI combustion to vary greatly. The battery charging system on a plug-in hybrid electric vehicle (PHEV), however, does not exhibit such load variations and therefore is an ideal application for HCCI engine technology. A PHEV uses batteries as the prime energy source for propulsion and a small engine combined with a generator to recharge the batteries to extend vehicle range. The near constant load and engine speed required to charge batteries makes PHEV the ideal application for HCCI technology.

The first objective of this project was to identify and quantify the primary and secondary interactions of the engine design and operating parameters that enable HCCI combustion using natural gas fuel. The researchers attempted to achieve this goal through the use of commercially available software to model the fluid dynamics, heat transfer, and combustion in a piston and cylinder assembly. They modeled fluid dynamics and heat transfer using computational fluid dynamics software developed by ANSYS Fluent.

Figure 28: Schematic Diagram of the Test Engine



The second purpose was to design, build, and test a high efficiency, low emission engine and engine control system that meets the unique requirements of light duty PHEVs. The researchers modified a Kohler model ECH-749, 750 cc, 90° V-Twin port fuel injected engine rated at 29 hp in accordance with the results obtained from the computer simulations (Figure 28). Modifications included the addition of an engine control module, a port fuel injection system rated for natural gas, pistons designed to increase the compression ratio, and an exhaust gas recirculation system. The modifications were made to increase the probability of achieving conditions in the combustion chamber that would enable the spontaneous combustion required for HCCI.

2.4.3G Objectives

The goal of this project was to determine the feasibility of using a natural gas fueled homogeneous charge compression ignition engine operating at a single engine speed to

recharge the battery pack in a plug in hybrid electric vehicle. The researchers provided the following objectives to prove feasibility:

1. Start an engine at ambient temperature in HCCI mode within five seconds.
2. Start the engine at ambient temperature in HCCI mode using 12 Wh of battery energy or less.
3. Operate the engine in HCCI mode at an engine speed between 1,000 and 3,500 rpm, a range useful for a generator system.
4. Operate the engine in HCCI mode at an engine power of 25 hp.
5. Achieve a brake specific fuel consumption (BSFC) of 225 g/kWh or less with the engine operating in HCCI mode between 1,000 and 3,500 rpm.
6. Produce emissions (no catalytic treatment) with the engine operating in HCCI mode between 1,000 and 3,500 rpm lower than 5 g/kWh CO and 8 g/kWh of hydrocarbons and NO_x.

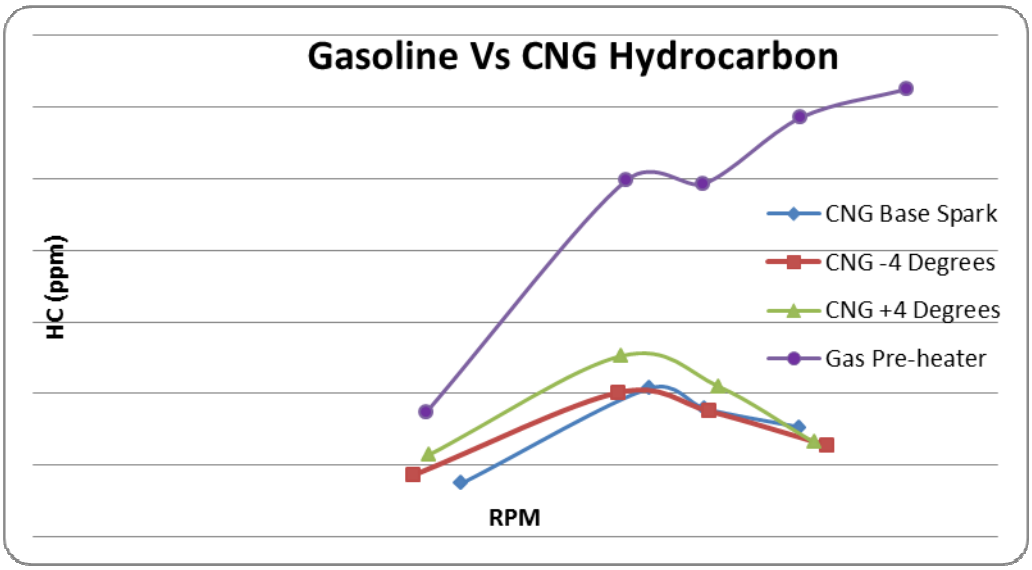
2.4.4G Outcomes

The research team was unable to demonstrate HCCI operations during the project period. Despite considerable effort, the modeling team was unable to achieve convergence (stable model operation) with the ANSYS Fluent® software. Many different strategies failed to eliminate the problem. In the absence of the modeling tool to guide the engine development effort, the research team resorted to the literature for guidance concerning the amount of energy required to achieve HCCI combustion.

However the research team did not find a means to transfer sufficient energy to the combustion chamber to reach the conditions required to achieve homogeneous ignition. In an attempt to achieve the required energy levels, the research team added heat tape to all of the accessible area of the intake air manifolds. Even though energy was added to soften the materials housing the fuel injectors, spontaneous combustion was not achieved. To achieve HCCI operations, higher compression ratios are required than can be achieved safely with a spark ignition internal combustion engine. The researchers suggested that compression ratios need to be greater than 14:1.

In relation to Objective 6, the research did produce substantial data documenting the benefits of using CNG and the benefits of using the inert exhaust gas during combustion to reduce emissions. For example, the hydrocarbon levels in the emissions measured from the Kohler model ECH-749 engine were as much as six times lower when fueled with CNG (Figure 29).

Figure 29: Comparison of Hydrocarbon Emissions from a Kohler Model ECH-749 Engine Fueled with Gasoline vs. CNG



Adding inert gas in the form of recirculated exhaust gas reduced NO_x emission nine times from the baseline engine. The effect recirculated exhaust has on NO_x production has long been known for larger engines.

2.4.5G Conclusions

The research team was unable to demonstrate HCCI operation by modifying the production spark ignition engine. The conditions required to support HCCI combustion using a spark ignited engine could not be achieved because insufficient energy was recovered from the exhaust gases. Therefore Objectives 1—5 could not be achieved.

In regard to Objective 6, the research team concluded that substantial benefit could be realized by the California consumer by utilizing CNG as a transportation fuel.

It may be possible to improve the performance of engines operating on CNG utilizing HCCI combustion. However it was not possible to verify the potential performance improvement from HCCI during this research project.

This project did not attain any of the proposed objectives and thus did not prove feasibility. The feasibility of the homogeneous charge compression ignition engine for plug in hybrid vehicles was not established.

2.4.6G Recommendations

The researchers committed to undertake their modeling effort beyond the conclusion of this project so the programming issue could be resolved and this tool could be used by the research team to guide future engine development. In addition, the researchers concluded that future research will need different engine technology to attain the proposed outcome.

The Program Administrator recommends that the researchers:

- Continue to investigate the interactions between exhaust gas concentration, spark timing, compression ratio, and fuel concentration and their effect on engine emissions, net power, and engine efficiency.
- Continue to pursue CNG fueled HCCI combustion and determine its effect on engine efficiency and emissions.
- Obtain an engine body capable of safely withstanding the higher pressures required to sustain HCCI combustion.
- Identify the range of constituents present in natural gas and determine the effects on engine performance and emissions with both traditional combustion methods and HCCI.
- Determine the performance effects of adding CNG storage tanks to a PHEV.

2.4.7G Benefits to California

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

- Reduced environmental impacts of the California energy supply and distribution system
- Increased public safety of the California energy system
- Increased reliability of the California energy system
- Increased affordability of energy in California

The primary benefits to the ratepayer from this research could be reduced environmental impacts. However no benefits will accrue to California ratepayers since this research failed to prove feasibility of using a natural gas fueled HCCI engine in a PHEV.

Benefits of using compressed or liquefied natural gas in the transportation sector are well known and are being implemented by others in the commercial world. These benefits are being developed for larger vehicles. Using CNG in a PHEV may not prove to be a useful idea since CNG tanks are usually large and heavy.

2.4.8G 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 research team has not developed a marketing plan since the technology is not yet at the demonstration stage.

Engineering/Technical

The key technical hurdle is to obtain an engine block that is capable of withstanding the higher compression ratios (greater than 14:1) required to operate in HCCI mode. With the proper equipment and a focused effort, the research team estimated a demonstration period of 18

months is needed. The team is committed to continue this work. The researchers have acquired a $46,000 grant from NYSERDA. A total cost to complete a demonstration is about $500,000.

Legal/Contractual

No work in this area has taken place since the EISG grant.

Environmental, Safety, Risk Assessments/ Quality Plans

Since the researchers did not prove feasibility with the engine chosen for this project, it is not relevant to pursue these plans.

Production Readiness/Commercialization

Due to the need to demonstrate the technology, there is no timeframe for production readiness and commercialization.

2.1T Metal Supported Solid Oxide Fuel Cells for APU Applications

Awardee: XCell Power, LLC

Principal Investigators: Quoc Pham

2.1.1T Abstract

The trucking industry is challenged by state and federal laws which require adequate rest between driving shifts and also minimize the time trucks are allowed to idle at rest stops. Truck drivers prefer to park their rigs for rest and relaxation at designated rest areas, truck stops, or other convenient locations after a road shift. Off the road, drivers typically maintain power in the cabin in order to operate the air conditioner/heater and to provide electricity for electronic devices and food preparation appliances. In most cases cabin power is enabled by truck engine idle. A clean, efficient, and cost effective auxiliary power unit (APU) attached to the cab would enable truck drivers to decouple power generation from the truck engine while providing the freedom to stop and rest at virtually any location. This project explored the feasibility of using robust solid oxide fuel cell (SOFC) technology for APU trucking applications.

Solid oxide fuel cell based APU technology has already been demonstrated on large trucks. However the technology is still far from being commercially viable because of cost. The industry needs low cost, robust, and reliable SOFC technology that can operate in the harsh environment of APU applications. The main objective of this project was to explore feasibility of a novel planar fuel cell design that could potentially overcome these material limitations.

Researchers designed a new support structure for the ceramic cells using thin films that use plasma spray coating technology. Testing showed reasonable performance for small cells but problems with larger cells. Further development work is needed to solve technical challenges and reduce manufacturing costs before this type of product can be successfully commercialized.

Keywords: Solid oxide fuel cells, SOFC, auxiliary power unit, APU, plasma spray, sheet metal substrates

2.1.2T Introduction

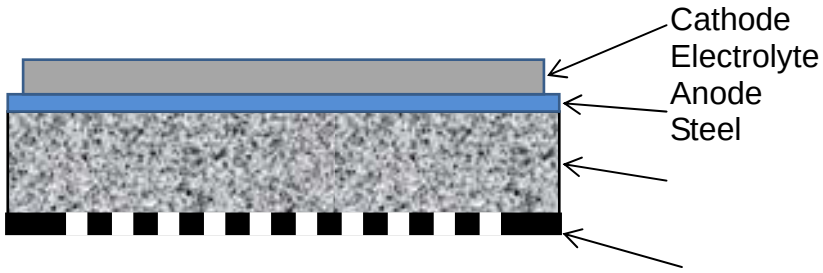
Truck drivers are faced with grueling work schedules. After several hours on the road they need rest, and they park their rigs at designated rest areas, truck stops, or other convenient locations. During rest periods drivers often maintain power in the cabin in order to operate the air conditioner/heater and provide electricity for electronic devices and food preparation appliances. For many years cabin power was enabled simply by truck engine idle. Recent changes in state and federal law, however, have produced new challenges to the trucking industry. State law limits truck idling to five minutes at a time in California. Federal law requires truck drivers to have at least ten hours of rest for every eleven hours of driving. Drivers are now at risk of receiving citations and paying substantial fines if caught for excessive engine idling. A solution is needed that enables truck drivers to maintain power in the cabin without the need for engine idle during rest stops and to provide the freedom to stop and rest at virtually any location.

Currently there are five major types of idling reduction technologies: cab and block heaters, automatic engine start/stop controls, battery powered air conditioning systems, on and off truck electrification (shore power), and auxiliary power units (APU). The current market penetration rate for all idle reduction technologies is estimated at 36 percent of the sleeper cab market, according to a report published by the American Transportation Research Institute in 2006. APUs constitute approximately 12 percent of the idle reduction technology market. Most of these APU devices are powered by internal combustion engines which suffer from efficiency, noise, weight, and emission issues.

SOFC technology appears to be the most promising candidate for APU applications because of its high efficiency, low emissions, and ability to use readily available fuels such as natural gas and diesel. To date, only a limited number of fuel cell APU units have been demonstrated on trucks. The technology is far from being commercially viable mostly because of cost issues. The industry needs a much more cost effective, robust, and reliable technology that enables fuel cell stacks to operate in harsh APU trucking conditions.

Researchers in this project identified two technical challenges which need to be addressed: the brittle nature of ceramic cells, and the need to seal ceramic cells to metal interconnects. Principal investigators explored the feasibility of using a novel planar fuel cell design that could potentially overcome both issues. They devised a new support system to mount thin film ceramic cells on a porous sheet metal plate to improve strength and reliability. See Figure 30 below. Unlike previous metal supported cells, the new cell design eliminated sealing problems while providing greater flexibility, simplicity, and reliability. The key to this approach was the use of plasma spray coating technology for the deposition of thick films without sintering issues. Testing showed reasonable performance for small cells. However for larger cells, heat generated during plasma spraying caused significant thermal stresses that resulted in buckling of the sheet metal substrates. Researchers will need to conduct further work to overcome this issue to fully take advantage of the proposed approach.

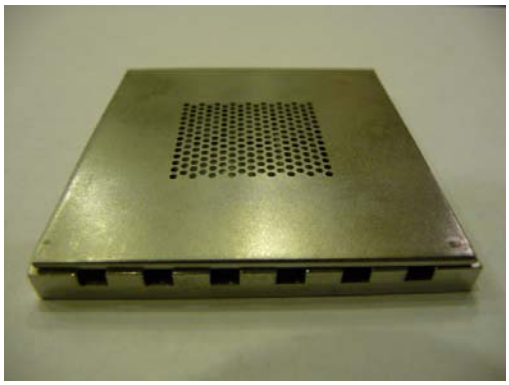
Figure 30: Ceramic Cells with Porous Sheet Metal Substrate



For commercialization purposes, the researchers developed a manufacturing cost model to estimate stack costs. At a production scale of 120,000 units per year, the cost of stack fabrication could be as low as $154 per kW, which is significantly lower than stacks fabricated using conventional manufacturing techniques.

This novel fuel cell fabrication concept has the potential to improve SOFC robustness, enhance reliability, and reduce stack manufacturing cost. Researchers demonstrated successful deposition of thick films using plasma spraying. See Figure 31. The research team demonstrated the potential viability of small button cell applications and the limited impact on fuel starvation of the sheet metal substrate. However, plasma spray coating of thick films on a thin porous sheet metal substrate caused buckling of the material due of excessive thermal stresses generated during film deposition. The development of this new approach is critically dependent on overcoming the thermal stress issue at the interface between the sheet metal substrate and the ceramic coatings.

Figure 31: Complete Metal Substrate with Perforated Sheet Metal and Interconnect



Compared to a truck without idling reduction capabilities, this technology has the potential of reducing diesel fuel consumption by 2,000 gallons per year. This translates to an annual emissions reduction benefit of 1,000 pounds of NO_x, 1,600 pounds of hydrocarbons, and more than 15 tons of CO_2 per truck per year.

2.1.3T Objectives

The goal of this project was to determine the feasibility of using robust solid oxide fuel cell (SOFC) technology for auxiliary power unit (APU) trucking applications. The researchers established the following project objectives:

1. Confirm that plasma spray techniques are suitable for use in thick film SOFC coating.
2. Obtain complete cells with a minimum area of 25 x 25 cm^2.
3. Demonstrate that proper sheet metal design does not cause more than a 10 percent drop in cell performance due to diffusion limitation through non-perforated parts.
4. Demonstrate interlocking mechanism between coating and substrate, with film penetration depth of 20 microns.
5. Obtain a cell power density of at least 0.1 W/cm^2 at 0.7 V.
6. Demonstrate that metal supported cells can withstand up to 80º C/minute heating rate.
7. Demonstrate that metal supported cells can withstand up to 300º C temperature gradient.
8. Demonstrate that stack cost can be less than $200 per kW.
9. Demonstrate that stack cost is less expensive than the conventional approach when realistic cell manufacturing yield is taken into account.

2.1.4T Outcomes

1. The researchers successfully demonstrated a plasma spray process for use in thick film SOFC coating for small cells. They did not observe any cracking or bending.
2. Researchers were not able to demonstrate the use of plasma spray on the larger surface area of 25 x 25 cm^2. Heat generated caused excessive buckling of the substrate.
3. The use of perforated sheet metal substrate caused less than 10 percent drop in cell performance due to diffusion limitation through non-perforated parts.
4. Plasma spray coating of 20 microns on a 25 x 25 cm^2 substrate was unsuccessful because of thermal stress build-up during the coating process.
5. Cell power density exceeded the minimum target of 0.1 W/cm^2 at 0.7 V. Actual power density recorded was 0.23 W/cm^2 at 0.7 V.
6. The researchers demonstrated that metal supported cells are able to withstand up to 80º C/minute heating rate without any sign of damage or degradation due to thermal shock.
7. Researchers were not able to demonstrate that metal supported cells can withstand up to 300º C temperature gradient since a larger substrate test sample was not available. It is not possible to create such a gradient across small button cells.
8. Researchers demonstrated that the stack cost can be less than $200 per kW. Actual cost estimates were $154 per kW.
9. Researchers demonstrated that the stack cost can be less expensive than the conventional approach when realistic cell manufacturing yield is taken into account. The actual cost

for the conventional approach can be as high as eight times the baseline cost for just 2 percent defect in the manufacturing line.

2.1.5T Conclusions

1. The use of a plasma spray process appears to be viable for thick film SOFC coating applications.
2. The issue of excessive heat generation causing buckling of a larger substrate surface area can likely be solved with further development work.
3. The introduction of the perforated steel substrate has no material impact on cell current voltage at low current densities. Furthermore, the impact of sheet metal on fuel starvation can be considered negligible.
4. The potential viability of using plasma spray coating on larger sheet metal substrates requires further development work to solve the problem of excessive heat generation during the coating process.
5. Metal supported cells appear to have market potential since power density performance measured on the initial prototypes was excellent.
6. Metal supported cells appear to be durable in terms of withstanding significant thermal stress and cycling.
7. Additional testing of larger substrates is needed to determine whether metal supported cells can withstand large temperature gradients.
8. Estimated stack cost is well below the typical $800 per kW or higher for traditional SOFC fabrication techniques if manufacturing yield is taken into account.
9. Conclusion is identical to Conclusion 8 above.

In summary, the research team developed a novel metal supported cell design and manufacturing process that could potentially improve the cost effectiveness and robustness of SOFCs. The team successfully deposited coatings on small ceramic and metal substrates. Actual cell performance exceeded targets with no detection of fuel starving issues. However, coating on larger size samples encountered unexpected difficulty with thermal stress build up during the plasma spray process. Additional development work will be needed to solve this problem. Researchers can then test the viability of a unique interlocking mechanism on a larger metal substrate.

The commercial viability of this innovative concept for the trucking market hinges on whether remaining technical issues can be resolved. Drivers need a clean, robust, cost effective solution that would enable them to park their trucks anywhere and get rest in a fully powered cabin in accordance to state and federal laws. The APU market potential in California is more than $1.0 billion. Other potential markets include portable power applications such as recreational vehicles and emergency power generators.

2.1.6T Recommendations

The proposed concept appears to be technically feasible but needs additional work before any conclusions can be reached concerning its feasibility and commercial viability. Researchers discovered that plasma spray deposition on thin porous sheet metals does not have sufficient mechanical strength to withstand significant thermal stress.

The development of this new approach is critically dependent on overcoming the thermal stress issue at the interface between the sheet metal substrate and the ceramic coatings. Further research is needed as described below:

- Evaluate the impact of pre-heating the substrate on thermal stress.
- Optimize sheet metal substrate. Thicker sheet metal (more than 100 microns) should be evaluated as substrates because they have greater mechanical strength and can better resist buckling.
- Measure and quantify thermal stress.
- Evaluate low pressure plasma spray technique. The problem encountered with atmospheric plasma spray may not be as severe in low pressure conditions since the coating plume is much wider.
- Compare the feasibility of plasma spray concept to other SOFC manufacturing techniques.
- Verify interlocking mechanism design.

Once the coating issue has been resolved and the viability of a unique interlocking mechanism has been verified, the next step would be demonstration of a 1 kW SOFC stack operating on hydrogen. The research team should then seek a strategic partner specializing in fuel processing to test fully the novel stack using processed natural gas and diesel fuels. The research team should also consider the assistance of a strategic trucking company for on road testing prior to early market penetration.

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.

2.1.7T Benefits to California

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

- Improved transportation energy efficiency

- Reduced greenhouse gas emissions or reduced health and environmental impacts from transportation associated air pollution related to electricity and NG production and use
- Increased the use of alternative fuels

The primary benefit to the ratepayer from this research is improved transportation energy efficiency.

Long-haul trucks typically burn about 2000 gallons of diesel a year during idling. Efficiency during idling is extremely low at less than 10 percent.[39] Using a high efficiency SOFC APU developed in this project would enable truckers to cut fuel consumption by 74 percent to 86 percent, corresponding to a fuel saving of 1400 to 1600 gallons a year or at least $5,950 per year at a diesel fuel price of $4.25 per gallon. Once costs associated with engine wear and maintenance are factored in, total savings could easily exceed $7,000 per year. The environmental benefit is also significant. The fuel saving using a SOFC APU would enable trucks to cut CO_2 greenhouse gas emissions by more than 15 tons per truck per year. According to the U.S. Environmental Protection Agency, one gallon of diesel generates 22 pounds of CO2.[40] SOFC APUs have negligible NOx emissions, compared to 10 grams per hour for engine based APUs and as much as 80.7grams per hour in the case of truck idling. This corresponds to an emissions reduction of 600 to 1,000 pounds of NO_x and about 1,600 pounds of hydrocarbons per year per truck.

The transportation sector is the largest source for global warming pollution in California, accounting for as much as 43 percent of total emissions. Heavy duty trucks and buses are responsible for 20 percent of all transportation sector greenhouse gas emissions, second only to passenger cars. There are about 150,000 heavy heavy duty vehicles (gross vehicle weight rating GVWR greater than 33,000 pounds) and as many as 200,000 medium heavy duty vehicles (GVWR greater than 14,000 pounds) registered in California, according to the California Environmental Protection Agency. If only 50 percent of the heavy heavy duty vehicles were equipped with a SOFC APU device, the emission reduction benefits to California would translate to more than one million tons of CO2, 22,500 tons of NO_x, and 60,000 tons of hydrocarbons per year.

Successful development and commercialization of SOFC APUs will provide truck drivers with the freedom to stop for rest at virtually any location, enable significant operation cost savings, increase the energy efficient of trucks, and reduce greenhouse gas emissions and other criteria pollutants in California.

2.1.8T 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.

---

39 Brodrick, C.J., M. Farshchi, H. A. Dwyer, S. W. Gouse, M. Mayenburg, and J. Martin, *Demonstration of a Proton Exchange Membrane Fuel Cell as an Auxiliary Power Source for Heavy Trucks,* Society of Automotive Engineers, Paper 2000-01-3488.

40 EPA420-F-05-0010

Marketing/Connection to the Market

The current market penetration rate for all idle reduction technologies is estimated at 36 percent of the sleeper cab market, according to the American Transportation Research Institute. Approximately 12 percent of drivers with idle reduction technologies are estimated to use APUs. The market potential for the SOFC product in California is approximately 300,000 APU units sized at three kW each. A successful SOFC APU product would provide the trucking industry with environmental benefits and lower operating costs due to a reduction in petroleum fuel use. Keys to market success are further technology development and validation, product reliability and durability, and reduction of manufacturing costs.

Engineering/Technical

The researchers estimate four years are required to complete engineering and technical work. Approximately $3 million dollars of funding is required for this work.

Legal/Contractual

The researchers have applied for patents related to development work completed to date.

Environmental, Safety, Risk Assessments/ Quality Plans

Once working prototypes are built, researchers will need to test the systems for safety and ultimately meet all industry certification requirements. A development or manufacturing partner can help with this phase of work.

Production Readiness/Commercialization

The concept is not yet sufficiently developed for commercialization. Additional funding is needed to complete development work, optimize design, build, and test prototypes. In addition, an economic analysis is required to ensure viability of the concept compared to other engine idling reduction techniques and products.

2.2T Lower Cost and Higher Density PHEV Battery

Awardee: University of Missouri

Principal Investigators: Galen Suppes

2.2.1T Abstract

This project addressed key parameters necessary to fabricate and demonstrate a 2 kWh convection battery. This battery, which is a new type of flow battery, has the potential to reduce charge times and battery costs given its unique characteristics. Principal advances that occurred during this project include:

- Demonstration and development in a laboratory of a convection battery with lithium iron phosphate (Li│FePO4) and lithium sulfur (Li│S) battery chemistries.
- Improvement of materials to overcome permeability issues with many of the materials that otherwise work with diffusion-based batteries.
- Demonstration of cycling on a laboratory scale.

The project's goal of demonstrating a convection battery at a 2 kWh scale was not attained, based on the proposed approach. Convection batteries are not ready to commercialize. Future research should include alternative approaches with revised experimental plans to attain the proposed scale.

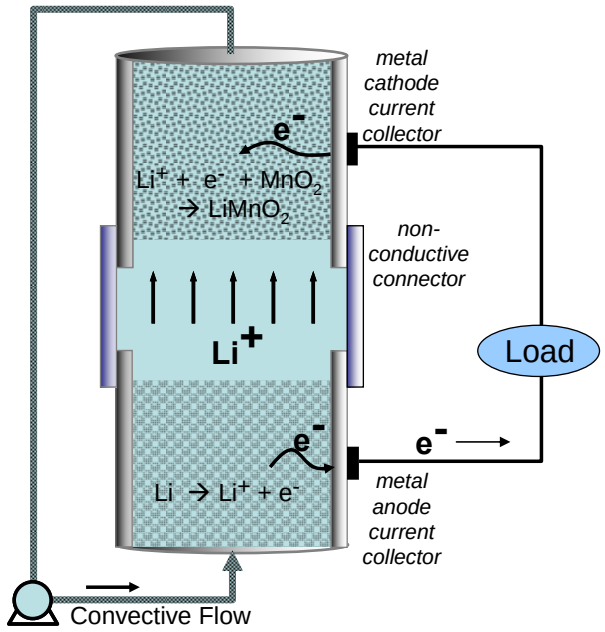
Keywords: Flow battery, lithium, sulfur, electric car

2.2.2T Introduction

The 2003 Joint Agency Report (California Energy Commission, California Air Resources Board) entitled "Reducing California's Petroleum Dependence" identified plug-in hybrid electric vehicles (PHEV) as the best petroleum substitution option for California. PHEVs are able to use electricity to replace petroleum in a manner that can lead to direct benefit to California's economy of up to $4.5 billion. The advantage to California's grid-connected electric consumers is that PHEVs can charge during the overnight hours. Realization of these benefits is hindered by existing battery technology and/or cost. Current lead acid battery technology has limited deep discharge cycling, while other battery options have high initial and replacement costs. The researchers in this project estimated that the savings per capita through the use of a convection battery would be $656 per year over the use of gasoline and $816 per year over the use of traditional (diffusion) batteries.

In this project researchers focused on the screening, testing, and proof of concept of a new convection battery at a 2 kWh scale that has the potential for significantly reducing both the cost and weight of PHEV batteries. As designed, the convection battery (Figure 32) would be a lower cost, higher energy density power source. The research was also intended to lead to an improved understanding of fundamental processes in lithium batteries.

Figure 32: Illustration of Convection Battery



An important aspect of the convection battery is the absence of polymer separators between the electrodes, a critical component of most batteries. This is possible because the electrodes are separated by distances too great for dendrite-modes of failure. The convection battery pumps a liquid electrolyte from the anode to the cathode through a permeable membrane. As a result, diffusion over potential limitations of typical batteries are overcome. In essence this allows for a more efficient functioning of a convection battery. This directly leads to the opportunity to design batteries using thicker electrodes and less membrane, which can substantially reduce

battery costs. Also this directly leads to the opportunity to operate at higher limiting currents, thus reducing charging times.

2.2.3T Objectives

The research team proposed to determine the feasibility of a new battery design known as the convection battery. The specific objectives were:

1. Synthesize and demonstrate electrode materials.
    a. Achieve the battery performance target of power output per surface of separator between electrodes based on power needed to achieve Task 3 demonstration. Submit a design specifying this power output. Design should meet $100/kWh criteria.
    b. Demonstrate a laboratory flow battery at the targeted power output with less than 30 percent over potential losses.
    c. Improve battery performance to demonstrate a laboratory flow battery at the targeted power output with less than 20 percent over potential losses.
2. Fabricate and demonstrate a 2 kWh flow battery that achieves less than 20 percent over potential loss.
3. Demonstrate the 2 kWh convection battery for 100 cycles with a voltage amplification system to provide a 48 volt (V) power output.
    a. Assemble a prototype 2 kWh flow battery fitted with voltage amplification to provide 48 volt power output.
    b. Demonstrate the prototype can operate at 100 cycles with less than 40 percent reduction in capacity.

2.2.4T Outcomes

1. Synthesize and demonstrate electrode materials.
    a. The researchers successfully demonstrated laboratory convection batteries for both lithium iron phosphate ($Li|FePO_4$) and lithium sulfur ($Li|S$) battery chemistries. They met the cost objectives of $100/kWh for the sulfur anode. However they did not meet the cost objectives for the lithium cathode.
    b. The researchers attained overpotential losses of less than 30 percent for both $Li|FePO_4$ and $Li|S$ battery chemistries. Based on a V_0 of 3.2 V for $Li|FePO_4$ chemistry, about 70 percent of the discharge was at overpotential losses between 5 percent and 20 percent with an average of about 18 percent for the entire discharge. They realized a similar low overpotential for the sulfur battery, but it was more difficult to quantify since V_0 was not constant.
    c. The researchers attained overpotential losses of less than 20 percent for both $Li|FePO_4$ and $Li|S$ battery chemistries for the initial part of the battery discharges. Based on a V_0 of 3.2 V for $Li|FePO_4$ chemistry, about 70 percent of the discharge was at overpotential losses between 5 percent and 20 percent with an average of about 18

percent for the entire discharge. They realized a similar low overpotential for the sulfur battery, but it was more difficult to quantify since V_0 was not constant. The researchers demonstrated the flow batteries on a laboratory scale of 0.01 Wh (Watt-hour). This included development of electrode materials with high permeabilities.

2. The researchers synthesized the flow cell and obtained materials to test the cell. All needed development was performed on a smaller laboratory scale prior to this task because of the costs of assembling and testing the 2 kWh test cell. Due to the cost of performing testing at the 2 kWh cell in the laboratory, the researchers performed an intermediate scale-up at 0.5 kWh. Based on the laboratory results, the researchers designed, fabricated, and assembled a scaled up convection battery. Figure 33 provides a schematic diagram of the scaled-up test cell. Prior to evaluating in this test cell, the researchers needed targeted performances in the laboratory cell, and the test circuit needed to be modified to operate at higher currents.

3. Demonstration of the 2 kWh convection battery for 100 cycles with a voltage amplification system to provide a 48 V power output.

    a. The researchers postponed demonstration of the flow battery with voltage amplification until better lithium utilization was attained. No results are available.

    b. The researchers conducted cycling studies on the laboratory scale for 10 cycles with about a 32 percent loss in stored energy. Testing for 100 cycles was postponed until the desired lithium utilization efficiency was attained.

2.2.5T Conclusions

The following presents the research conclusions for each outcome:

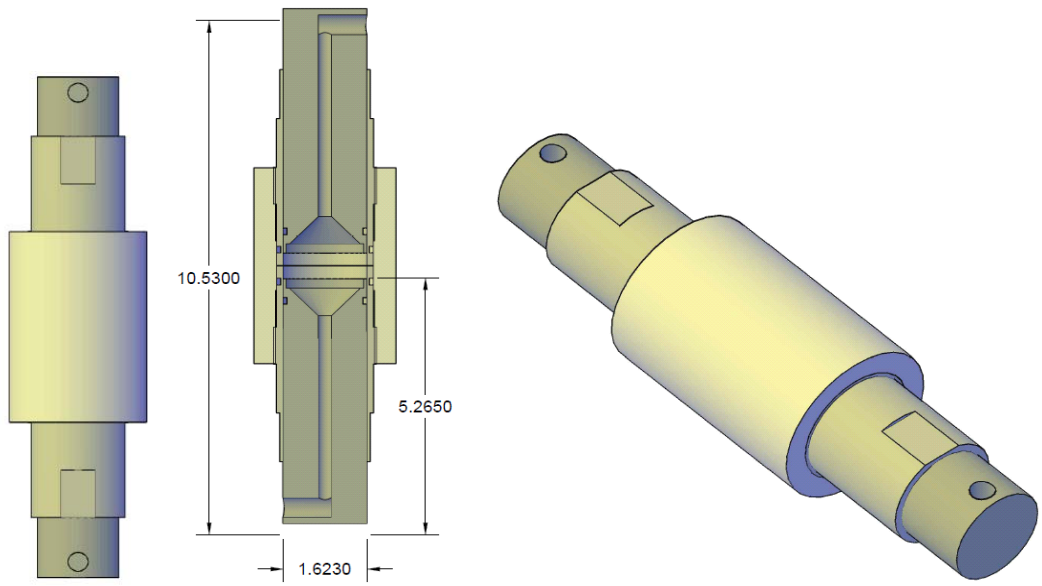
1. Synthesize and demonstrate electrode materials.

    a. The convection battery worked with lithium chemistry batteries being advanced for use with traditional diffusion-based battery designs.

    b. The researchers obtained overpotential losses of about 18 percent with the convection battery. This met the objective of attaining overpotential losses less than 30 percent.

    c. Overpotential losses of about 18 percent were obtained with the convection battery. This met the objective of attaining overpotential losses less than 20 percent.

Figure 33: Scaled Fabricated Convection Cell



2. The project objectives of attaining a 2 kWh demonstration were overly ambitious for this project's timeline. According to the researchers, a key factor that led to that decision was the inefficient use of lithium by the battery design.

3. Demonstrate the 2 kWh convection battery for 100 cycles with a voltage amplification system to provide a 48 V power output.

    a. No conclusions were possible on the voltage amplification since the project did not proceed to that point.

    b. Cycling of the laboratory test cell was successful and performed up to 10 cycles. The researchers evaluated only 10 cycles rather than 100 cycles since the equipment was needed to attain Objective 1 benefits. It would take many weeks to evaluate 100 cycles. After the first cycle the reduction in capacity during the next nine cycles was about 5 percent. A larger drop during the first cycle (about 25 percent) was attributed to the active components being physically loaded onto unstable sites initially.

The research project did not attain all the proposed outcomes and thus did not prove feasibility.

2.2.6T Recommendations

The feasibility of the convection battery for use in the PHEV market has not yet been established. Convection batteries are not ready to commercialize. While having some positive initial results, the research undertaken did not meet the proposed objectives. Substantial additional research is needed.

The researchers concluded that future research will need alternative approaches with revised experimental plans to attain the proposed scale.

Such an alternative approach should include:

- A modeling study to estimate rate capabilities of this technology when ohmic, kinetic, and mass transfer limitations are coupled.
- The availability and sufficiency of:
    1. Electrode materials with good permeabilities and good surface qualities that stabilize ions and maintain accessibility of the active materials.
    2. Membrane/separator materials with good permeabilities and good surface qualities that stabilize ions.
- Battery modeling that includes modeling of diffusion and convection. This modeling should include side by side modeling comparisons with diffusion batteries as a control and with other flow batteries. The goal should be to advance understanding to the point where alternative and/or new chemistries can be used as drop-in upgrades with a streamlined path to commercialization.
- Evaluation of the spiral wound convection battery as an optimal design to take advantages of the convection battery.

2.2.7T Benefits to California

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

- Improved transportation energy efficiency
- Reduced greenhouse gas emissions or reduced health and environmental impacts from transportation associated air pollution related to electricity and NG production and use
- Increased the use of alternative fuels

The primary benefit to the ratepayer from this research is the potential increased use of alternative fuels. In particular, this project would advance the implementation of plug-in hybrid vehicle technology. This benefit is noted in the 2003 Joint Agency Report (California Energy Commission, California Air Resources Board) entitled "Reducing California's Petroleum Dependence" which identifies plug in hybrid electric vehicles (PHEVs) as the best petroleum substitution option for California. Significant improvements in battery technologies that reduce costs and improve efficiencies could produce greater vehicle acceptance and thereby purchases by consumers.

With the added impetus to PHEV technology, domestic electricity could replace petroleum in a manner that can directly benefit California's economy. The 2003 Joint Agency Report also identified plug-in hybrid electric vehicles (PHEVs) as having a positive impact in California of up to $4.5 billion. As proposed, this project could contribute to this impact. Potential savings were based on the following assumptions:

- 8,000 vehicle miles traveled annually per capita in California
- $0.20 / mile costs for gasoline ($3.50 / gallon and 17.5 miles per gallon)
- $0.05 / mile for electricity costs to charge batteries (10.7 ¢/kWh, 80 percent efficient)
- $0.17 / mile for traditional batteries (1000 cycles per battery, 0.34 kWh/mile, $500/kWh for traditional battery system)
- $0.068 / mile for convection batteries (1000 cycles per battery, 0.34 kWh/mile, $200/kWh for convection battery system installed, $100/kWh for battery alone)

Using these assumptions, the savings per capita could be $656 per year over the use of gasoline only vehicles and $816 per year over the use of traditional (diffusion) batteries. These cost savings are based on 100 percent operation on electricity. Another benefit not quantified is the potential job creation by displacing the purchase of imported oil with the purchase of domestic electricity and by using batteries produced in California. Large scale savings would not materialize for at least 10 years depending on the adoption rate of PHEV technology.

The federal CAFE standard of 54.5 miles per gallon by 2025 could severely reduce or eliminate the public benefits of PHEV technology relative to gasoline fueled vehicles. Based on the assumptions listed above, consumer savings would decrease to zero when operating a gasoline fueled vehicle (non-hybrid) averaging 30 miles per gallon.

2.2.8T 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 have not indicated when they will undertake a market analysis or survey potential customers for interest in the product. However they proposed to have a validating prototype operational by 2015. Thereafter, working with a commercial battery manufacturer is their pathway to commercialization.

Engineering/Technical

Researchers plan to develop a convection battery design that operates with an electrode thickness of two to three millimeters. Engineering efforts will focus upon the improved use of active materials in the laboratory test cell. Finally, the engineering effort will address new options/approaches to the technology scale-up.

Legal/Contractual

The researchers have filed a patent application: CONVECTION BATTERY CONFIGURATION FOR CONNECTIVE CARBON MATRIX ELECTRODE. Inventor: Galen J. Suppes (Columbia, MO, US).

Environmental, Safety, Risk Assessments/ Quality Plans

At the present level of assessment the researchers have not identified issues nor proposed any environmental, safety, risk assessment, or quality plans.

Production Readiness/Commercialization

This convection battery is not ready for commercialization. The researchers propose to have a validating prototype operational by 2015. Thereafter, working with a commercial battery manufacturer is the pathway to commercialization.

2.3T Validated Multi-scale Analysis Tool for Mechanical Response of Aluminum Foams

Awardee: University of California, Los Angeles

Principal Investigators: Ertugrul Taciroglu

2.3.1T Abstract

This project developed key mathematical modeling and computer simulation capabilities for predicting the mechanical response of open cell aluminum foams using only bulk material properties and basic geometry information. Such models and simulation tools enable the design of structural components that contain metallic foam elements and the prediction of their performance under service conditions for vehicle application. The project developed two major components of such models, ligament and contact mechanics. Future work will focus on experimental validation of the simulation tools developed herein and on multi-scale analysis techniques. The goal is to validate these tools and bring them up to a maturity level allowing real world engineering use in the design of lightweight and fuel efficient vehicles.

Keywords: Metallic foams, lightweight structures, lightweight vehicles, finite element method

2.3.2T Introduction

In 2007 Californians consumed over 19.5 billion gallons of gasoline and diesel fuel.[41] This large consumption has associated economic, environmental, and security issues that have long put transportation fuel consumption near the top of state energy policy. Numerous programs, including standards, R&D, incentives, and land use planning, are aimed at reducing California's consumption of transportation fuels. One of the long term and promising areas for improvement is reducing the weight of vehicles through the use of composite and alternative materials, in addition to downsizing vehicles and engine technology advancements.

Aluminum foams (Figure 34) have favorable thermal and mechanical properties and are being used in a variety of applications. However they are not commonly used as load bearing structural members in vehicles due to the lack of adequate engineering methods. Predictive tools for their thermal and mechanical properties must be developed before they can have widespread application in vehicle design. Existing methods and design and analysis tools are limited in scope and capability and work only in very limited cases.

Figure 34: Aluminum Foam

In this project researchers developed and validated advanced computational algorithms to predict the properties of aluminum foams. The goal was to predict the response of aluminum foams under complex and arbitrary loading conditions, using only fundamental input parameters. This should enable design engineers to accurately predict physical response of foams and foam constructed parts under real world design conditions.

41 http://www.energyalmanac.ca.gov/transportation/summary.html#fuel

2.3.3T Objectives

The goal of this project was to determine the feasibility of developing mathematical models to predict the response of aluminum foams from first principles under complex/arbitrary loading conditions using only physical and directly measurable parameters, including foam topology, foam density, bulk aluminum Young's modulus, and yield stress. Quantifiable objectives for this project were as follows:

1. Generate multiple representative volume element (RVE) geometries, and subject each RVE to a unit axial load and compute the average RVE displacements. Attain a relative error that is 5 percent or less.

2. Apply moment to a cantilever beam and compute the tip deflection and rotation. Compare those values to a benchmark solution. Attain a relative error that is 5 percent or less.

3. Using the finite element analysis software ANSYS or equivalent, apply various loading cases to an aluminum cantilever ligament up to capacity (i.e., full section plasticity) and unload. Use J2 continuum plasticity with no hardening for modeling aluminum. Perform the same analysis with the resultant based plasticity formulation developed in this project and compare the results. Attain a relative error that is 5 percent or less.

4. Model two vibrating unit length beams with orthogonal axial orientations. Separate the beams with a gap of size 2/10. Prescribe an initial mid span displacement that is slightly larger than 2/10 to one of the beams, and then let go. Observe the beams vibrating for 100 times their natural period. Compare the total kinetic + potential energy at the beginning of the motion to that at the end. Attain a relative error that is 5.0 percent or less.

5. Validate simulation framework. Perform loading simulations on different RVEs and compare the results to published data. Compare the yield and plateau stress values. Attain a relative error that is 5.0 percent or less.

2.3.4T Outcomes

1. The researchers generated multiple RVE geometries. They subjected each RVE to a unit axial load and computed the average RVE displacement. They compared the mean values to a benchmark solution by Gibson and Ashby.[42] The relative error was 0.06 percent. The researchers compared their calculated displacement to published data to arrive at the relative error. An example of the use of an RVE is shown in Figure 35.

2. Using a cantilever beam, the researchers applied a tip moment and measured the deflection. The relative error between the tip deflection magnitude given by Bathe and Bolourchi[43] and that calculated was 74/100 percent.

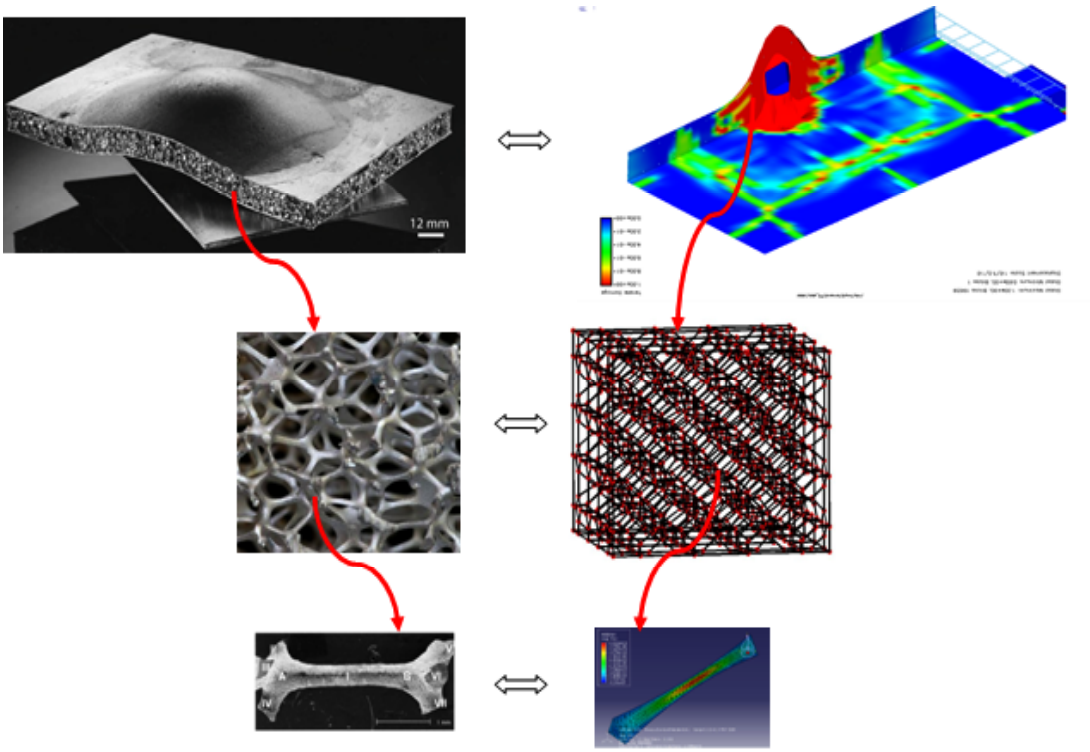
---

42 L. J. Gibson and M. F. Ashby, (1999), *Cellular Solids: Structure and Properties, 2nd Edition,* Cambridge University Press.

43 K. J. Bathe and S. Bolourchi, (1979), "Large Displacement Analysis of Three-Dimensional Beam Structures," *International Journal for Numerical Methods in Engineering*, 14(7), pp.961-986.

3. Using detailed fiber-based implementation, the researchers simulated loading an aluminum cantilever ligament in six separate loading cases at its tip (1 axial and 2 shear loads, 1 torque and 2 bending moments) up to full section plasticity and unloaded. They performed the same analysis with the developed resultant based plasticity formulation. Researchers calculated the relative error between results obtained in Steps 1 and 2 to be 11.1 percent or less. The researchers modeled two vibrating unit length beams aligned at right angles. The beams were separated with a small gap, forming a cross. One of the beams was given an initial mid span displacement and then let go, causing it to vibrate. The researchers observed both beams vibrating for 100 times their natural period. They compared the total kinetic + potential energy at the beginning of the motion to that at the end. The researchers calculated the relative error between the two quantities to be 2.2 percent.

Figure 35: Conceptual Multi-Scale Modeling of a Sandwich Plate with an Aluminum Foam Core which Sustains an Impact



The impacts where deformations are largest are interrogated through the use of a sub-simulation using a high fidelity RVE developed through the present project.

4. The researchers simulated loading conditions on different RVEs and compared the results to data published in Jang and Kyriakides.[44] The relative error between the two sets of calculated results for yield and plateau stresses were 6.6 percent and 4.7 percent, respectively.

44 W. Jang, A. M. Kraynik, and S. Kyriakides, (2008),"On the Microstructure of Open Cell Foams and its Effect on Elastic Properties," *International Journal of Solids and Structures*, 45 (7-8), pp.1845 – 1875.

2.3.5T Conclusions

1. The researchers showed that the RVE model generation tool created a random model that reflected the statistical distribution of ligament sizes, ligament lengths, and nodal connections. The relative error was 0.06 percent when compared to literature data. This outcome was significantly better than the objective of 5.0 percent relative error.

2. The researchers developed a geometrically exact beam that successfully represented the mechanical response of foam ligaments. The relative error was 0.74 percent when compared to literature values. This outcome was significantly better than the objective of 5.0 percent relative error.

3. The plasticity formulation developed for aluminum foam ligaments accurately predicted the inelastic response of a ligament from bulk material (i.e., aluminum) properties and physical principles. The relative errors ranged from 0.02 percent for monotonic loading up to 11 percent for multi-axial loading. This compared to the goal of 5.0 percent relative error.

4. The incorporation of new algorithms that detected the contact of ligaments generated the correct forces that occur between ligaments under contact. This is important for deformation and crushing predictions. Relative error was 2.2 percent. This outcome was significantly better than the goal of 5.0 percent relative error.

5. The researchers completed basic work on combining the various methods/computer codes under a single framework. This unified framework was capable of simulating the response of an RVE. The researchers successfully compared experimental data with simulations carried out using the developed framework. Comparison with experimental data yielded a relative error of 2.0 percent for yield stress and approximately 4.5 percent for the Young's Modulus. This satisfied the stated goal of 5 percent relative error.

The researchers showed that it is possible to create a computational framework/tool that can simulate open cell foam behavior from first principles, with the input being bulk material properties and other geometric data that can be measured directly.

2.3.6T Recommendations

The researchers should continue development of these engineering tools. They should:

- Create a user-friendly software package for engineering practitioners.
- Determine the needs for foam air space homogeneity in size and space as quality needs dictate.
- Document the method's accuracy in light of homogeneity issues associated with the production and manufacture of foam components.
- Investigate the impact on structural integrity of the aluminum foam from common manufacturing techniques such as milling, drilling, welding, and forming, and incorporate the findings in their design algorithms.
- Expand the computational methods to account for impact and crushing limits.

- Compare economics and performance of rigid foam materials with carbon fiber composite materials for identical applications.
- Measure strength impacts of fabrication techniques such as milling, drilling, welding, and forming.

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.

2.3.7T Benefits to California

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

- Improved transportation energy efficiency
- Reduced greenhouse gas emissions or reduced health and environmental impacts from transportation associated air pollution related to electricity and NG production and use
- Increased use of alternative fuels

The primary benefit to the ratepayer from this research is improved transportation energy efficiency through the application of lighter weight vehicle components, including use in electric vehicles.

As noted, Californians consume over 19.5 billion gallons of gasoline and diesel fuel every year for transportation. Cheah et al.[45] conclude, "For every 10 percent percent percent weight reduction, a typical vehicle's fuel consumption reduces by 6 percent percent to 7 percent." They also estimate that today's vehicles can be made lighter by 35 percent through the use of lightweight materials such as aluminum foams. This could result in a total reduction in fuel consumption per lightweight vehicle of 21 percent to 24.5 percent. Assuming a modest penetration of light-weight vehicles[46] of 5.0 percent over 10 years, this could represent a total saving per year of 209 million to 240 million gallons. At a gasoline price of $3.50 per gallon this could be a cost savings of over $800 million. This project also provided benefit in electric vehicle application, potentially extending vehicle range a significant amount.

---

45 L. Cheah, A. Evans, A. Bandivadekar, and J. B. Heywood, (2007), *Factor of Two: Halving the Fuel Consumption of New U.S. Automobiles by 2035.* Report by MIT Laboratory for Energy and the Environment, Cambridge, Massachusetts.

46 The term "light-weight vehicles" refers to vehicles that incorporate lighter weight materials such as aluminum foams, not the general distinction between light duty vehicles and heavy duty vehicles. Aluminum foam may be used in heavy duty vehicles with similar savings as for light duty vehicles.

2.3.8T 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 developed computational methods will be freely distributed by the researchers. The researchers plan to seek help from UCLA Engineering Institute for Technological Advancement (UCLA-ITA, www.ita.ucla.edu) to provide connections to the market. They anticipate interest in the software product from automobile and aircraft manufacturers.

Engineering/Technical

The researchers estimate that it will take another 15 months to complete the system integration, conduct further verification, and conduct predictive simulations of component scale tests. To do this work will require funding of up to $50,000. At the conclusion of this project the researchers received funding from the National Science Foundation in the amount of $33,393.09. The researchers plan to use UCLA internal resources to complete the work.

Legal/Contractual

The researchers do not intend to patent their computational methods. They will work contractually with software developers to bring the development to commercial use. The software product may be protected via copyright.

Environmental, Safety, Risk Assessments/ Quality Plans

The main safety risk from the use of lightweight fabrication materials occurs during vehicular collision. The extent of this risk is dependent on the particular load bearing members that are constructed of aluminum foam.

Production Readiness/Commercialization

The researchers plan to use the UCLA Engineering Institute for Technological Advancement (UCLA-ITA, www.ita.ucla.edu) to provide commercialization expertise.