Arnold Schwarzenegger
*Governor*

# ENERGY INNOVATIONS SMALL GRANT PROGRAM: 2001 INDEPENDENT ASSESSMENT REPORTS

PIER FINAL PROJECT REPORT

*Prepared For:*
**California Energy Commission**
Public Interest Energy Research Program

*Prepared By:*
San Diego State Research Foundation

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# Preface

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

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

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

- PIER funding efforts are focused on the following RD&D program areas:
- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

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For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

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# Table of Contents


Abstract ..... v

Executive Summary ..... 1

1.0 Introduction ..... 3

2.0 2001 Independent Assessment Reports ..... 7

2.1. Bio-Filtration Abatement of Landfill Gas Energy Exhaust Pollutants ..... 7

2.2. Flywheel Energy Storage Unit in Power Distribution Networks ..... 11

2.3. Prototype and Demonstration of a Light-emitting Diode Alternative to Screwbase Incandescent Lamps ..... 13

2.4. Materials for Fast-Response Solid Oxide Fuel Cells ..... 18

2.5. Gyroton Rotary Engine Project: A Controllably Variable Compression and Displacement Engine ..... 21

2.6. Low Emissions Atmospheric Metering Separator ..... 25

2.7. Use of Waste Fuel Gas to Reduce Biofouling of Power Plant Cooling Water Intakes 28

2.8. Real-Time Energy Meter Radio Frequency Communications System ..... 31

2.9. Field Feasibility Determination of a Novel Energy-Saving Refrigeration Controller 36

2.10. Development of an Effective Fire-Shield for Powerpoles by Custom Tailoring a Mineral Polymer Material ..... 40

2.11. Microturbine-Based Building Energy System ..... 45

2.12. Ultra Reduced Emissions Burner for Gas Turbine Combined Cycle and Combined Heat and Power Applications ..... 49

2.13. Flexible Low-Emissions Combustor for Renewable Fuels ..... 52

2.14. Multi-Spectral (Visible and Infrared) Imaging Camera ..... 57

2.15. Desiccant Enhanced Indirect/Direct Evaporative Cooling ..... 61

2.16. Solid-State Electrolytes for Dye-Sensitized Solar Cells ..... 64

2.17. Prototype and Demonstration of Vision Tuned Fluorescent Lamps ..... 67

2.18. Low-Cost, High-Efficiency Solar Cell Fabrication Using Inkjet Printing ..... 72

2.19. Development of Single Fan Multi-Stack Exhaust Systems ..... 76

# Abstract

The Energy Innovation Small Grants (EISG) program is specifically designed for higher risk, "proof-of-concept" ideas in which the Energy Commission explicitly tracks and expects a number of technical failures. As a "proof-of-concept" program, EISG seeks out concepts that are not yet proven and are very early in the research pipeline. These programs encourage technical innovation and risk taking. The Energy Commission awards up to $95,000 for EISG grants to test a new idea. After project completion, the PIER Program uses independent experts to evaluate the research results and assess the technical success compared to the original project objectives, as well as the likelihood the product will succeed in the market.

Independent assessment reports are written at the completion of every EISG grant projects. The report outlines the objectives of the project, highlights the successes and failures, and offers recommendations for potential future work. This summary report includes many of the Independent assessment reports for EISG grant projects awarded during 2001.

**Keywords:** EISG, independent assessment report, electricity, natural gas, research, project, market, objectives, summary, highlights, outcomes, conclusions, benefits

# Executive Summary

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

The Commission recognizes the need for a program to support the early development of promising new energy technology concepts, a niche not covered by PIER general solicitations that focus primarily on development of established concepts. The Commission established the EISG program to meet this need. In addition, to encourage participation in the program, the process for soliciting, evaluating and awarding grants has been simplified and streamlined.

This report includes project assessment reports for grant projects that were awarded in 2001 and have not been previously published.

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

# 1.0 Introduction

In 2001, the Energy Innovations Small Grant (EISG) program funded 25 grant projects for a total of $1.9 million. The Independent Assessment Reports (IAR) for six of these grant projects have already been published. (See Table 1.1 below.) This section contains the 19 IARs from 2001 EISG projects that have yet to be published. (See Table 1.2 below.)

**Table 1.1: 2001 EISG projects with published IARs**

| Project | Researcher | EISG Funding |
|---|---|---|
| Proof-of-Concept of a Dual-Fired (Solar and Natural Gas) Generator for use in a Space Cooling System for Residential and Light Commercial Buildings | Cooling Technologies, Inc. | $75 K |
| Spectrally Enhanced Ceramic Incandescent Emitter | Sonsight Inc. | $75 K |
| High-Volume Manufacturing for Low-Cost, Flexible Solar Cell | InterPhases Research | $75 K |
| Quantitative Cooling of Buildings by Infrared-Reflective Rooftile Coatings | American Rooftile Coatings | $75 K |
| Improvement of Thermal Stability of Lithium-Ion Batteries by Polymer Coating of Lithium Manganese Oxide | University of California, Davis | $75 K |
| Energy-Efficient Process for Using Membrane Technology to Treat and Recycle Agricultural Drainage Water | WaterTech Partners | $75 K |

**Table 1.2: 2001 EISG projects with IARs included in this section**

| Project | Researcher | EISG Funding |
|---|---|---|
| Bio-filtration Abatement of Landfill Gas Energy Exhaust Pollutants | Don Augenstein | $75 K |
| Flywheel Energy Storage Unit in Power Distribution Networks | Elcom, Inc | $75 K |
| Prototype and Demonstration of a Light Emitting Diode Alternative to Screwbase Incandescent Lamps | Conway & Silver, Energy Associates LLC | $75 K |

| Project | Researcher | EISG Funding |
|---|---|---|
| Materials for Fast-Response Solid Oxide Fuel Cells | University of California, Berkeley | $75 K |
| Gyroton Rotary Engine Project: A Controllably Variable Compression and Displacement Engine | Dehlsen Associates LL | $75 K |
| Low Emissions Atmospheric Metering Separator | Two-Phase Engineering & Research, Inc. | $75 K |
| Use of Waste Fuel Gas to Reduce Biofouling of Power Plant Cooling Water Intakes | University of California, Santa Cruz | $75 K |
| Real Time Energy Meter Radio Frequency Communications System | BCD Electronics, LLC. | $75 K |
| Field Feasibility Determination of a Novel Energy-Saving Refrigeration Controller | ADA Technologies, Inc. | $75 K |
| Development of an Effective Fire-Shield for Power Poles by Custom Tailoring a Mineral Polymer Material | BlazeBarrier, Inc. | $75 K |
| Microturbine-Based Building Energy System | Nissen A. Jaffe | $68 K |
| Ultra-Reduced Emissions Burner for GTCC and CHP Applications | Altex Technologies Corporation | $75 K |
| Flexible Low-Emissions Combustor for Renewable Fuels | Altex Technologies Corporation | $75 K |
| Multi-Spectral (Visible and Infrared) Imaging Camera | International Electronic Machines Corporation | $75 K |
| Desiccant Enhanced Indirect/Direct Evaporative Cooling | Innovative Research Enterprises | $75 K |
| Solid State Electrolytes for Dye-Sensitized Solar Cells | Konarka Technologies, Inc. | $75 K |

| Project | Researcher | EISG Funding |
|---|---|---|
| Prototype and Demonstration of Vision-Tuned Fluorescent Lamps | University of Nebraska, Lincoln | $75 K |
| Low-Cost, High-Efficiency Solar Cell Fabrication Using Inkjet Printing | Sunpower Corporation | $75 K |
| Development of Single-Fan Multi-Stack Exhaust Systems | University of Nebraska, Lincoln | $75 K |

# 2.0 2001 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 EISG projects. This section includes the IARs from grant projects that were awarded in 2001 that have yet to be published.

## 2.1. Bio-Filtration Abatement of Landfill Gas Energy Exhaust Pollutants

Awardee: Don Augenstein
Principal Investigator: Don Augenstein

### *Introduction*

Landfills in California and across the United States generate large amounts of methane-rich landfill gas (LFG). Methane makes up about 60 percent of LFG. Converting the methane emissions of landfills to equivalent tons of carbon dioxide ($CO_2$), the United States Environmental Protection Agency (U.S. EPA) has calculated that landfills in the United States produced 140.9 terra grams $CO_2$ equivalent (6,709 giga-grams methane) in the year 2004. This large amount of methane is both an environmental problem and a potential resource. Investors have installed LFG powered generators in California landfills to produce about 200 megawatt electrical (MWe). A dominant barrier to more landfill gas-fueled electricity in California is the level of exhaust gas pollutants (nitrogen oxides, [NOx] and carbon monoxide, [CO]) from the reciprocating engine and gas turbine prime movers. Exhaust catalysts of types used in automobiles are not economic solutions because trace amounts of harmful chemicals in landfill gases quickly inactivate the catalyst. There are only very limited solutions to the exhaust emission problem.

An additional 100 megawatts (MW) or more of LFG electric generation could be installed in California. One of the problems stalling the further development of LFG generators is the lack of a solution to the air quality problems. Until the generators are installed to consume the LFG, the available landfill gas is flared or otherwise lost.

Landfill gas is a mixture of about 60 percent methane ($CH_4$), 40 percent carbon dioxide ($CO_2$), and small amounts of other gases. The heating value of this gas mixture is considerably lower than that of pipeline natural gas. Because of the gas composition and lower heating value, LFG cannot be directly inserted into natural gas pipelines. With proper modifications, internal combustion engines can be fueled by LFG to produce electricity. Landfill gas must be used as it is recovered because storage is impractical. Electricity produced from landfill gas can be used locally at the landfill site or sold as renewable energy to a nearby load-serving utility. Because

of landfill proximity to population centers, landfill gas-fueled electricity is well-located generation that could reduce electric transmission line congestion.

Among LFG-fueled prime movers for electric generation, reciprocating internal combustion (IC) engines are most frequently used. Reciprocating engines have a higher tolerance to landfill gas impurities such as siloxanes (a class of organic or inorganic chemical compounds of silicon, oxygen, and usually carbon and hydrogen). These engines also exhibit high reliability, high efficiency, and relative ease of maintenance. These engines are used in the 0.5 to 5 megawatt electrical (MWe) power generation range, while gas turbine engines are most often employed above 5 MW. Gas turbine engines require less maintenance than reciprocating engines, but require more extensive fuel cleanup to preserve the life of the engine. Reciprocating engines have very desirable thermal efficiencies in the range of 32 to 40 percent, while gas turbines above 5 MW have efficiencies in the range of 30 to 38 percent. While reciprocating engines have higher thermal efficiency they also produce much higher levels of NOx and CO emissions than gas turbine engines.

In this project the researcher proposed to reduce the pollutants in engine exhaust gases using bacteria within a solid matrix. This process is known as "bio-filtration." Bio-filtration is used widely at large scales to remove gaseous organic compounds, and odorous pollutants from gas streams for processes such as sewage plants. Prior to this project bio-filtration had not been considered for treating landfill gas-fueled engine exhaust pollutants.

The researcher proposed to use the very large masses of waste already within the landfills as a bio-filter for exhaust gas cleanup. His reasons for selecting the in-situ waste as a bio-filter were: (a) the enormous volume available for in-landfill bio-filtration, which offers treatment retention times for exhaust gas of a day or more, (b) low-to-negligible incremental cost of landfills on a volume basis, and (c) the known ability of many organisms in nature to degrade pollutants of concern with favorable thermodynamics. The researcher speculated that good thermodynamics could result in high destruction rates of the NOx and CO.

This project examined feasibility of treating landfill gas energy exhaust gas pollutants, by bio-filtration of the exhaust gas in the landfilled waste. Testing was carried out by laboratory bio-filtration of the exhaust gas in actual waste lots sampled from landfills. Laboratory experiments were conducted at the University of California, Davis, Agricultural Engineering Department, using actual waste batches from core sampling of a landfill cell at Yolo County, California.

### *Objectives*

The purpose of this project was to prove the feasibility of a bio-filter composed of aged landfill material to reduce the levels of NOx and CO in the exhaust of engines fueled by landfill gas. The researcher established the following project objectives:

1. Assemble laboratory equipment/reactors.
2. Develop techniques to reduce carbon monoxide (CO) and nitrogen oxides (NOx) by at least 50 percent and possibly up to 90 percent.

3. Determine pollutant bio-filtration kinetics under various gas flow regimes. Limit engine thermal efficiency loss due to filter backpressure to less than 5 percent.
4. Project efficiency, engineering, and operational parameters of a full scale landfill bio-filter for internal combustion engine exhaust cleanup.

### *Outcomes*

1. The researcher constructed three laboratory reactors to perform tests.
2. The researcher reported that the bio-filter reduced NOx concentration from "over 100 parts per million (PPM)" to a level of three PPM of outlet NOx. The researcher claimed that 3 PPM of NOx was equivalent to 0.02 grams NOx per kilowatt-hour (kWh) of electricity produced. The residence time for this reduction was four to eight hours. The researcher also reported reduction in CO levels by over 90 percent. The residence time for this reduction was two to five days. Increasing the moisture content to 40 percent from the 23 percent used in all other experiments resulted in a faster reduction of CO levels.
3. No data or conclusions were presented in the report to indicate if this objective was met. The researcher stated that "…at these flow velocities any flow-induced pressure gradient was unmeasurable." The researcher stated that calculations were performed to show that the "engine power and efficiency reductions are negligible." The researcher omitted the calculations from the final report.

   The researcher designed a large-scale landfill bio-filter using in-situ landfill material, and evaluated likely operational features using conservative values for gas generation, energy exhaust flow and waste permeability. The values came from known energy equipment performance parameters and documented field measurements of landfill waste properties. One design with a detention time of over a day for exhaust gas detention appears practical. One subtask was estimation of the effect of back pressure from the bio-filter on engine performance. Because of scale factors, pressure drops were not measurable on laboratory scales and had to be estimated from large scale landfill permeabilities (the researcher used available data). Estimated back pressures are less than one foot water head. Such back pressures if attainable at large scale, could have negligible effects on internal combustion (IC) engine performance. Gas turbine engine performance is more rapidly degraded by exhaust back pressure. The researcher estimated the economics of landfill bio-filtration. The researcher's preliminary projections show capital costs for a 2.5 MWe generation facility in the range of $40 to $120 kilowatt electrical (kWe) capacity. The researcher did not provide any details of economic calculations. It is not clear if this number includes the cost of the equipment for exhaust gas cooling.

### *Conclusions*

This project proved the feasibility of using a bio-filter composed of existing, in-situ, landfill material to reduce exhaust gas emissions of NOx and CO.

1. The researcher constructed appropriate equipment for the planned experiments with one exception. The researcher was not able to measure flow-induced back pressure on the engine exhaust.
2. The researcher demonstrated that the bio-filter met the original objectives. The residence times to achieve the reduction in emissions, up to several days for CO, present an operational problem for the landfill/engine operator.
3. Back pressure on the exhaust of internal combustion engines can have a significant effect on the engine efficiency. The use of the landfill as a bio-filter could increase exhaust back pressure and thereby reduce engine efficiency.
4. In a letter to the California Energy Commission, Ridgewood Power stated that it was removing engines burning landfill gas from California to other states. The reason for this action, they reported, was the fact that they were not obtaining long-term power purchase agreements from load-serving utilities. Ridgewood Power claimed that their bid costs were not considered financially competitive under the rules of the auctions for renewable energy. They did not indicate that exhaust gas emissions were the problem. Thus, adding up to another $40 to $120 per kWe capacity for bio-filtration of exhaust gasses will only make them less competitive.

### *Recommendations*

In the final report the researcher made recommendations and presented extensive design projections and estimates for a larger scale test to advance development. The program administrator recommends that a large scale test of landfill bio-filtration should be accomplished using any one of a large number of present landfills having an onsite engine-generator, gas wells, and other features need to continue the development. In a large-scale test, the researcher should carefully monitor the operation of the reciprocating engine. Engine efficiency, operating temperature and other parameters should be measured with normal exhaust system back pressure and with landfill back pressure. The test could also include various separations of the injection and recovery wells. Residence times and back pressures could vary with separation. A parallel laboratory test program should be carried out to further optimize emission reduction by varying parameters such as moisture and temperature in the landfill. Tests of this type will require the cooperation of the local air pollution control authorities.

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

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

### *Benefits to California*

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

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

The primary benefit to the ratepayer from this research project is reduced environmental impacts of the electricity supply system. Reduced environmental impacts come from the increased use of landfill gases that would otherwise be vented to the atmosphere or burned in a flare. Greenhouse gases would be reduced as would NOx and CO. The California Energy Commission estimates that an additional 100 MW of landfill gas powered generation could be installed in California. While this is not a large additional capacity, it would be capacity that could contribute to the 20 percent renewable mandate for investor-owned utilities in this state. Additionally the 100 MW of landfill gas generation would displace capacity currently fueled by natural gas.

## 2.2. Flywheel Energy Storage Unit in Power Distribution Networks

Awardee: Elcom Inc.
Principal Investigator: Prof. John C. Balachandra

### *Introduction*

As California's businesses continue to improve their productivity, they rely ever more on microprocessor-based technology. That technology, while powerful, is extremely sensitive to electricity fluctuations as short as one cycle. To avoid catastrophic losses of data and expensive losses of work in progress, companies employing microprocessor-based machinery currently can install battery-based, uninterruptible power supply (UPS) systems. Unfortunately, these systems are large and relatively inefficient, employ hazardous chemicals, and require battery replacement at regular intervals. In addition, expensive venting is necessary to remove potentially dangerous gases. These drawbacks limit their use. Many companies that do not employ any UPS suffer economic losses when power quality is degraded or longer outages occur. According to The Electric Power Research Institute (EPRI), power-quality disturbances alone cost the nation approximately $6.7 billion per year, while all power outages and quality problems cost the nation approximately $119 billion per year. The EPRI study found that California has the highest costs for both outages and power-quality disturbances, ranging between $13.2 billion and $20.4 billion total. Obviously these large losses reduce the competitiveness of California's economy.

If a competitively priced UPSs were commercially available that did not have the drawbacks of battery-based technology, both businesses and the public in general would benefit. Flywheels that store energy in a cost-effective manner might provide such a system. Advances in material science have produced flywheels that require a relatively small amount of space. Their use requires no hazardous chemicals. Such a system could save companies money by ensuring the consistent delivery of high-quality power to their sensitive equipment. It would eliminate the replacement of batteries and the cost of venting systems. Flywheel systems can function at efficiencies as high as 98 percent, while battery-based UPS systems operate near 85 percent.

The flywheel-based alternative UPS system is compact, economical, and efficient, and it contains no hazardous chemicals. This system, if it were proven viable, could solve the problem of power quality for many California businesses. At the time this project was proposed, there were no definitive test results of the flywheel-based UPS in the public record. In order for this technology to be widely accepted in California, the tests had to be based on conditions within the state, and the data had to be publicly available. The controls of any flywheel-based UPS are a critical issue. Developments in systems-control technology indicated that flywheels could be integrated into a complete energy-storage system to provide uninterruptible power to critical loads. The testing of this hypothesis required the development of a workable prototype for a flywheel-based energy-storage system. It would need to provide stable power to critical loads during both upset voltage conditions and during power outages of up to 15 seconds.

### *Objectives*

The goal of this project was to determine the feasibility of employing a flywheel energy system to maintain power quality during voltage variations of greater than 15 percent and voltage perturbations of up to 15 seconds. The researchers established the following project objectives:

1. Determine the ability of the flywheel UPS system to respond to voltage variations of greater than plus or minus 15 percent within 150 milliseconds.
2. Determine the ability of the flywheel UPS system to respond to voltage perturbations on the supply side by carrying the load for a period greater than 15 seconds.

### *Outcomes*

The researcher sent the program administrator large data files with little or no interpretation. The principal investigator claims to have met 90 percent of their objectives. While the researcher supplied the raw data in the final report, the researcher did not specifically interpret data relative to the objectives. It is difficult to determine how close the researcher came to meeting his objectives.

### *Conclusions*

It appears that others have proven the feasibility of using flywheel energy storage to maintain both power quality during voltage variations and a stable power supply during outages of up to 15 seconds.

The following conclusions are based on an independent report not provided by the principal investigator.

1. A flywheel-based UPS system can sustain full rated output during a grid outage for up to 15 seconds.
2. Output voltage total harmonic distortion was 3.4 percent at full load.
3. Flywheel-based UPS systems can provide high-quality power output, even when input voltage variations are as high as 15 percent within 150 milliseconds.

### *Recommendations*

The program administrator agrees with the researcher that no further research should be funded in this area. Caterpillar Inc., with support from EPRI, was developing a line of flywheel energy-storage systems coupled to diesel engine/generator sets during the acceptance of this project. Units were marketed in the 250 to 900 kilowatt (kW) range. Active Power, Inc., of Austin, Texas, produced a flywheel that provided up to 15 seconds of energy with turn-around efficiencies of 97.5 percent. A diesel engine provided further continuity if the outage lasted longer than 15 seconds. Further development of this concept should be adequately covered by commercial organizations.

### *Benefits to California*

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

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

The primary benefit to the ratepayer from this research is increased reliability of the California electricity system. Specifically, companies or individuals employing a flywheel energy-storage system should benefit from markedly improved power quality and the ability to sustain voltage during power outages. Voltage will remain constant up to the capacity of the storage system, and longer if the system is connected to an engine/generator. EPRI has estimated that unplanned outages and poor power quality cost California between $13 billion and $20 billion per year. Improving power quality will benefit businesses and consumers alike. The use of flywheel energy-storage systems will reduce costs, and it will improve safety and the environment by eliminating the hazardous materials in batteries required by other uninterruptible systems.

## 2.3. Prototype and Demonstration of a Light-emitting Diode Alternative to Screwbase Incandescent Lamps

Awardee: Conway & Silver, Energy Associates LLC
Principal Investigator: Kathryn Conway

### *Introduction*

Lighting consumes a significant fraction of the nation's electric energy. Residential and commercial lighting account respectively for 8 to 15 percent and 20 to 40 percent of the nation's total electric output. California's usage fell at the lowest end of both ranges during a 1997 study (Heschong Mahone 1997). State and national agencies have directed considerable effort toward limiting the use of high-wattage lighting and encouraging the development of lower-wattage technologies.

United States Department of Energy (U.S. DOE) studies forecast that the use of solid-state lighting devices, including light-emitting diodes (LED), could save the United States $128.6 billion between 2010 and 2025, with the largest savings realized in commercial (72 percent) and residential (10 percent) buildings. Other sectors that have already benefited through the use of LED lighting include exit signs, traffic signals, and automotive exterior signals. Widespread commercial and residential application of this technology could produce greater savings nationwide and within the State of California.

LED technology has improved dramatically in recent years in terms of cost, efficiency, color quality, illuminance, and production. LED units are increasingly more viable as an alternative to incandescent lighting. The researcher proposed to create a prototype LED light that could effectively replace a screwbase incandescent light. The new light was projected to save 50 percent of the energy of the incandescent bulb it would replace.

### *Objectives*

The goal of this project was to determine the feasibility of producing an LED lamp, equivalent in light output to an incandescent lamp (plus/minus 20 percent), with an energy savings of 50 percent. The researcher established the following project objectives:

1. Specify and build one or two engineering prototypes of an LED lamp based on U.S. Patent 6,149,283.
2. Measure and analyze the performance of the prototype lamp(s) in comparison with published data for conventional incandescent lamps. Demonstrate that the light-output performance of the LED prototype falls within a plus/minus 20 percent range of a comparable incandescent lamp. Demonstrate that the required input power does not exceed 50 percent of the comparable incandescent lamp.
3. Develop specifications for mass production of the LED lamp, including components, performance parameters, quantities, and targeted costs of production.

### *Outcomes*

1. As part of prototype development, the researcher evaluated three lighting applications, including pendant down lights, task lights, and recessed down lights. The relatively low efficiency and high weight of LEDs and necessary components eliminated task lighting as a viable option for prototyping. For the two remaining applications, a single prototype was developed, along with two housings to simulate a pendant light and a recessed down light. Although the researcher did create a prototype, it fell short of the design requirements set forth in the patent application. Weight and size restrictions

2. Although budget restrictions prevented the researcher from contracting a qualified testing laboratory for standardized testing procedures, she was able to acquire instrumentation in order to benchmark the performance of the prototype against 25- and 40-watt A-lamps and a 30-watt R-lamp. The original prototype failed to meet the objective of 50 percent input power reduction. The prototype LED lamp actually required approximately the same input power as an equivalent incandescent lamp. Benchmarking tests showed that the prototype required 33 watts of input power and produced illuminance levels of 93 units of illuminance and luminous emittance (lux) directly beneath the lamp and 27 lux at the farthest measurement point. The 30-watt (nominal wattage) A-lamp provided the most equivalent output with a measured 25 watts of actual input power, 105 lux beneath the lamp and 38 lux at the farthest measurement point. A projection of the output results for this lamp to an input power of 33 watts, equivalent to the prototype, showed that the incandescent lamp would actually produce between 50 percent and 85 percent more illuminance than the prototype LED lamp at the same power, rather than 50 percent less illuminance as hypothesized.

   The researcher noted early equipment issues that may have compromised many of the LED lamps. As such, she provided a projection of the benchmark results using one string of four LEDs that produced the highest illuminance levels; then she multiplied by 4.5 to simulate the entire 18-LED assembly in a "fully functioning" prototype. These projections closely match those of the 30-watt A-lamp, but they also indicate that the incandescent lamp at an input power of 33 watts would produce between 10 percent and 35 percent more luminance than a fully functioning LED prototype.

   In order to achieve the illuminance goal, the researcher added a Fresnel focusing lens to the string of four LEDs and again multiplied the output by 4.5 to simulate a fully functioning prototype. With this design modification, projected input-power adjustments to the 30-watt A-lamp, and projected illuminance adjustments to simulate 18 LEDs, the fully functioning prototype operating at 33 watts would produce between 46 percent and 81 percent more luminescence than the incandescent A-lamp. These results suggest that the design-modified prototype could produce nearly the same or higher illuminance levels as an incandescent bulb, while requiring only 50 percent of the input power.

3. The objective of developing specifications for the lamp was not achieved. The prototype was not close enough in sophistication or performance to warrant this effort. Rather, the researcher presented a case study for lighting alternatives within a California restaurant chain with approximately 45 locations.

   The case study compared energy and operating costs for the restaurant using the following lamps: 1) 40-watt, soft white incandescent A-Lamp, 2) 40-watt, tinted incandescent A-lamp, 3) 30-watt, incandescent spot R20-Lamp, 4) current, 33-watt

prototype LED lamp, and 5) 16-watt LED lamp targeted for 2007 production, based on projected technological improvements. The cost analysis includes annual energy savings and operating cost savings per lamp and as a total for the restaurant chain, assuming that replacement of 1,800 lamps with LEDs could be reasonable. The researcher shows a total annual energy-cost savings of $11,000 and operational savings of $685,000 for the restaurant chain using currently available LED technology. Savings for LED technology projected for 2007 are $38,000 for energy use and $963,000 for operational costs.

### *Conclusions*

While the research did not prove the feasibility of a LED lamp for task lighting, she did demonstrate a prototype for an LED lamp that might serve as a replacement for low-wattage incandescent lighting in other applications.

1. The objective of creating a screwbase-style LED lamp prototype based on U.S. Patent 6,149,283 was not met. Weight and size restrictions prevented encapsulation of a stand-alone screwbase LED lamp that could effectively replace conventional incandescent lamps. Such a configuration requires more advanced LED technology and miniaturization of components. The researcher forecasts that technological advances would meet this goal by 2007. The prototype created did not include the color control and dimming features described in the patent, due to early market timing and equipment malfunction.

   An independent reviewer noted that commercial LED luminaire products are currently available in the marketplace. Some of these products feature the color controls originally included as a technical goal for this project.

2. The objective of demonstrating illuminance equivalent to an incandescent lamp with 50 percent input power was met by modifying the LED lamp design to include a Fresnel lens. Without that design modification, the incandescent lamp produced equivalent illuminance with a lower input power.

3. The objective of preparing manufacturing specifications for the LED lamp was not met. In place of this objective, the researcher prepared a case study showing energy use and operational costs for LED lamps compared with incandescent lamps for a California restaurant chain.

   Differential energy savings were based on the wattage used for the test cases listed previously. However, benchmark studies discussed under Objective 2 clearly show that the LED lamp is similar to the 30-watt incandescent A-lamp in illuminance levels. In fact, the 30-watt incandescent lamp produced more illuminance at all measuring points than the prototype LED lamp. Allowing for malfunctioning LEDs, a comparison of benchmark results reveals that a “fully functioning” prototype would provide higher illuminance in 9 of 16 test locations compared to the 30-watt A-lamp, and only 5 of the 16 locations compared to the 40-watt A-lamp. Either comparison demonstrates the fallacy of suggesting that the 40-watt incandescent lamps and prototype LED lamps are equivalent options. Use of a more comparable 30-watt A-lamp would have shown that the LED lamp replacement would have incurred a higher energy cost.

4. Although savings of energy remain unproven, operating cost savings are clearly evident. LED bulbs currently in production have lamp lives ranging from 10 to 25 times those of the incandescent bulbs considered in the case study. Further, technological advances promise to nearly double the currently rated lamp life. LED lamps have higher unit and replacement costs, but the greatly reduced frequency of replacement leads to significant savings in operational costs. LED lamps produce these savings over all incandescent types, both for current LEDs and for those projected for production in 2007.

   Outcomes and conclusions regarding this study based on benchmarking data are somewhat contrary to the generally understood advantages of LED-lamp technology. Nationwide, industrial applications, including traffic lighting, are moving away from traditional incandescent lighting to exploit the efficiency and operational savings inherent in LEDs. Although data presented herein support the operational savings based on manufacturer-specified data regarding lamp-life ratings, they do not validate the anticipated savings in energy costs. The inability to create a prototype based on U.S. Patent 6,149,283 was due at least in part to market timing and the availability of miniaturized components. However, issues related to malfunctioning dimming and color-control components appear to have been solved elsewhere within the market.

### *Recommendations*

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

1. Further investigation and prototype modification is required to more clearly demonstrate a savings in energy use with LED lamps as a replacement for screwbase incandescent lighting.
2. Research the current state-of-the-art in component technology to allow inclusion of dimming and color-control features.
3. Investigate alternative designs, such as inclusion of the Fresnel lens, that would make LED lamps a viable alternative for higher-wattage lamps, in the range of 60 to 100 watts. Alternatively, consider opportunities related to the use of low-wattage lamps in appliance applications (such as refrigerator and oven lights) where distributed lighting might be preferable to a single bulb.

### *Benefits to California*

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

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

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. This is due to a potential reduction in energy usage achieved by the use of LED lamps for ambient lighting. Actual cost savings are difficult to estimate due to the lack of sophistication of the prototype developed in this study. However, U.S. DOE studies forecast that the use of solid-state lighting devices, including light-emitting diodes (LED), could save the United States $128.6 billion dollars between 2010 and 2025, with the largest savings realized in the commercial (72 percent) and residential (10 percent) sectors.

The significantly longer life of LED lighting may also offer some advantage in terms of waste reduction and disposal costs. Although incandescent lamps are likely to be smaller, they need replacement 10 to 25 times more frequently than lamps using current LED technology.

## 2.4. Materials for Fast-Response Solid Oxide Fuel Cells

Awardee: University of California, Berkeley
Principal Investigator: Lutgard C. De Jonghe

### *Introduction*

Electrical energy production and distribution in California require constant innovation and improvement. This project explored material technology that could improve the response time of small, efficient generating facilities comprised of solid oxide fuel cells (SOFCs), while lowering the cost of the materials. If SOFC facilities of a few megawatts or less could produce power on short notice (minutes rather than up to an hour) they could reduce fluctuations in power demand and supply. For practical reasons they must be inexpensive, rugged, reliable, and have a small impact on the communities where they are installed. Thus the use of SOFCs poses many technical problems. The present project addressed two of the technical problems.

- Fast start-up of the generator produces large thermal transients as the interior temperature rises from room temperature to 800 degrees Celsius.
- Operation at high temperature (800 degrees Celsius) requires matching thermal coefficients of expansion for all parts of the fuel cell. This is a critical requirement during rapid thermal cycling.

Solving these problems should benefit California consumers in the following ways:

- SOFC-based sources are more efficient than small turbine plants, so operating costs can decrease. “Peaker” gas turbines may not be needed if fast responding SOFCs are available.
- Widespread use of SOFC-based sources could produce a more stable electricity supply and reduce or eliminate brownouts, rolling blackouts, and fluctuating voltage levels.
- Small, distributed resources can be installed in or near existing substations, thus reducing the need for siting large plants.

The researcher in this project proposed using moderately priced materials to achieve rapid response, high power density and low cost. Specifically the researcher proposed replacing the nickel/ yttria stabilized zirconia (YSZ) cermet anode with a less expensive chromium steel material coated with a thin layer of nickel/YSZ to match the coefficient of thermal expansion.

### *Objectives*

The goal of this project was to determine the feasibility of fabricating solid oxide fuel cells (SOFCs) from moderately priced materials, while designing for rapid response, good power density, and operation at temperatures below 850 degrees Celsius. The researchers established the following project objectives:

1. Demonstrate materials compatibility for alloy-supported membranes for at least 1,000 hours at 800 degrees Celsius.
2. Achieve a power density of at least 300 milliwatts per square centimeter ($mW/cm^2$) at 850 degrees Celsius for the membrane.
3. Demonstrate resistance to performance degradation following 20 rapid thermal cycles between room temperature and 850 degrees Celsius.
4. Provide detailed cost calculations based on the materials and processing procedures used that support projected membrane cost of less than $65 per square foot (SF).

### *Outcomes*

1. No specific longevity test was reported, but the thermal cycles (Outcomes 2 and 3) constitute hundreds of hours of operation at temperatures of 800 degrees Celsius or higher.
2. Power density of 350 $mW/cm^2$ was reported at 900 degrees Celsius; this value scales down to more than 300 $mW/cm^2$ at 850 degrees Celsius.
3. Steel-supported fuel-cell membranes were cycled 50 times between 200 degrees Celsius and 800 degrees Celsius with heating and cooling rates of approximately 50 degrees Celsius per minute. No cracking or delamination of the multilayered SOFC membranes was observed, and maximum power density in the 900 degrees Celsius tests dropped less than 8 percent.
4. Table I of the proposal indicates the costs for the system that proved successful. Those numbers fall within the $65/SF limit.

### *Conclusions*

1. The extended test for stable operation (1,000 hours) does not appear to have been done, but many shorter-cycle tests give evidence of robust behavior.
2. Power density testing is close to the original goal; devices have been operated at 800 degrees Celsius and sufficient power obtained at 900 degrees Celsius to allow extrapolation to the original 850 degrees Celsius goal.
3. Tests that ran to 50 cycles exceeded the goal of 20 thermal cycles. This is probably the most critical test of the device.

4. The final report contains no further cost calculations beyond those in the original proposal, but those do match the expected figure of $65/SF. Many more aspects of fabrication cost must be considered; some support for the predicted cost can be found in the previous reference.

The proposed program has achieved its major objectives, demonstrating the compatibility of a metal-ceramic-composite supporting layer in laboratory-scale configurations of solid oxide fuel cells, and its ability to withstand rapid thermal cycling.

### *Recommendations*

This project produced some important findings. The next steps in the evolution of SOFC generators include development of the following: materials that could further reduce costs and allow lower operating temperatures, studies of corrosion problems associated with hot gas flow; and the fabrication of larger-scale prototypes. Because Lawrence Berkeley National Laboratory cannot carry out the next step of making a commercial product another entity must be engaged to start manufacturability and commercialization work on the improved SOFC.

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

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

### *Benefits to California*

Public benefits derived from PIER research and development 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 will be reduced environmental impact of power generation. SOFCs are considerably cleaner than other fueled generation facilities. In addition the increased efficiency will result in reduced emissions. Local siting of megawatt-sized SOFC facilities leads to less environmental impact associated with the construction of large conventional generating and distribution facilities. Because the work in this project is still in the research stage, it is not possible to estimate when Californians could benefit from the findings. Nor is it possible to determine to what degree the electric utilities will adopt distributed SOFC generators for managing fluctuations in supply and demand.

## 2.5. Gyroton Rotary Engine Project: A Controllably Variable Compression and Displacement Engine

Awardee: Dehlsen Associates LLC
Principal Investigator: Matthew Brown

### *Introduction*

Distributed energy resources (DER) are standalone electric generation units located within the electric distribution system at or near the end user. California recognizes the need for DER because DER can be beneficial to both electricity consumers and the energy utility. Installing DER near the end user can benefit the user by avoiding the cost of an expensive tie-in to the grid and it can benefit the electric utility by avoiding or reducing the cost of transmission and distribution system upgrades. DER employs a variety of energy sources including wind and solar power and engines providing shaft power to generators. Two of the most common sources of shaft power for distributed generation (DG) for small consumers are rotary microturbines and internal combustion reciprocating engines. Microturbines operate with a thermodynamic cycle with low expansion ratios having less than desired electrical efficiencies, generally in the range of 20 to 30 percent even with recuperation. Microturbines operate at high shaft speeds, up to 96,000 revolutions per minute (rpm) with a high-pitched noise profiles that are sometimes found to be objectionable at the point of installation; however they do have the potential for very low emissions. Most reciprocating engines employ the Otto Cycle with symmetric thermodynamic cycle of equal expansion and compression ratio. These engines have high expansion ratios and efficiencies up to 45 percent, but with high compression ratios they require post-combustion treatment for emission products. They also have heavy crankshafts and engine blocks, which limit deployment. This project proposed a more efficient low-speed, light-weight rotary engine called the Gyroton Rotary Engine, with an asymmetric operating cycle having a high expansion ratio, but a lower compression ratio. By virtue of the high expansion ratio, the Gyroton would have higher thermodynamic efficiency, but because of the lower compression ratio the emission of pollutants, particularly nitrogen oxide (NOx), would be lower. Finally the projected capital cost for the Gyroton was estimated to be very competitive at $400 per kilowatt (kW) shaft output.

There are substantial benefits that could accrue to California from lower cost higher efficiency DG sources. Current estimates for total DG which is connected to the grid are 17.5 gigawatts (GW) for the United States as a whole, and 3.5 GW for California alone. The total power for DG including stand alone systems is much higher; the Electric Power Research Institute (EPRI) estimates a total DG of 147 GW for sizes up to 10 megawatts (MW) for the United States, and California's total DG capacity is estimated to be 30 GW. The 30 GW capacity for California is a mix of power sources including photovoltaic, wind power, as well as shaft powered energy such as microturbine and reciprocating engines. For the sake of discussion, it is assumed that 3 GW (10 percent of the 30 GW in California) is due to shaft-powered generation. This then represents a yearly electrical output (for 100 percent generator efficiency) of up to $2.6 \times 10^{10}$

kilowatt-hour (kWh), or $2.6 billion at $0.10 per kWh. An increase in engine efficiency of 10 percent then has a savings value of $260 million. Another form of savings can be viewed in terms of displaced central power plant demand or avoided cost of new transmission line service. New central utility power plant costs are in the range of $1 billion per GW capacity, while the costs of 155 kilovolt (kV) transmission lines are about $286,000 per mile. Thus electric utilities, and their customer base, can avoid substantial new costs with DG.

A key advancement of science needed for the successful demonstration of the Gyroton Rotary Engine in DG is the development of low-friction sliding seals internal to the engine. In the current Gyroton design there are six lobes with seals that move in and out of a rotor as it turns in circular motion in an oval-shaped cylindrical cavity. The six spaces between the seals comprise six combustion chambers, each with its own sparkplug. As the rotor turns, the combustion volume changes asymmetrically such that there is 8.5:1 compression ratio up to maximum compression and a 14:1 expansion ratio after maximum compression. The lobes are driven in and out of the rotor with positive "desmodromic" mechanical actuators.[1] The sliding seals at the ends and sides of the lobes are spring loaded to aid in keeping them against the oval cavity. The rotor is designed to operate at 2,000 rpm with six power pulses per revolution. The design criterion was to have less than 10 percent seal leakage when the rotor was passively driven (no combustion) at 250 rpm the design starting speed, which would then allow the engine to start and run under its own power.

### *Objectives*

The goal of this project was to determine the feasibility of producing a rotary engine that is competitive in both fuel efficiency and cost to conventional internal combustion engines and microturbines and may be applied to distributed electricity generation for the California grid.

The researchers established the following project objectives:

1. Complete the detailed design of the 10 horsepower (hp) prototype Gyroton Rotary Engine, including construction of computational solids models incorporating seal design and lubrication solutions for the prototype.
2. Fabricate and assemble a 10 hp prototype Gyroton Rotary Engine.
3. Test the prototype for sealing and compression without fuel addition or ignition, achieving less than 10 percent leakage during compression.
4. Test the prototype for sealing with fuel addition and ignition, monitoring the expansion to within 10 percent leakage.
5. Determine operating characteristics and identify elements needing further development.
6. Determine whether the Gyroton design can be commercially cost-competitive with current micro-scale gas turbines and four stroke reciprocating engines. Compare the design against commercially available equipment with capital costs as low as $400/kW. Apply this data to the long-term goal of combining the initial capital cost estimates with

1 Desmodromic refers to mechanisms that have different controls for their actuation in different directions.

fuel use/efficiency data and operations and maintenance (O&M) estimates to arrive at an early production cost estimate for electricity generated by the Gyroton engine.

### *Outcomes*

1. This objective was successfully met. A detailed design for a 10 hp prototype Gyroton Rotary Engine, including construction of computational solids models incorporating seal design and lubrication solutions for the prototype, was completed. The design called for a starting rotational rate of 250 rpm and an operating rate of 2,000 rpm.
2. This objective was successfully met. A prototype Gyroton Engine with 10 hp design output was fabricated and assembled. The prototype was run-in on a test stand under electric power.
3. This objective, to test the prototype for sealing and compression without fuel addition or ignition and achieve less than 10 percent leakage during compression, was not fully met. The internal seal leakage while driven on the test stand at 250 rpm was 18.3 percent, which is short of the 10 percent target goal. However, the test-stand Pressure versus Revolutions-Per-Minute Plot extrapolated to 290 rpm indicated that the leakage would fall below 10 percent at the higher rotational rate.
4. This objective, to test the prototype for sealing and compression with fuel addition and ignition and demonstrate less than 10 percent leakage, was not successful. Importantly, operation under internal combustion was not achieved. A redesign of the combustion chamber did not lead to successful operation.
5. The objective to determine operating characteristics was not successful because the engine was not made to operate. Elements requiring further development were identified and redesigned. In particular seal elements requiring high spring loading to function were redesigned, and the design of a new seal system that is gapless and able to accommodate thermal expansion was made.
6. The objective to determine whether or not the Gyroton design can be commercially cost-competitive with current micro-scale gas turbines and four stroke reciprocating engines was not met. This is because operation of the engine was not achieved. For the same reason it was not possible to make a realistic comparison of the design against commercially available equipment with capital costs as low as $400 per kW. Nor was it possible to apply this data to the long-term goal of combining the initial capital cost estimates with fuel use/efficiency data and O&M estimates to arrive at an early production cost estimate for electricity generated by the Gyroton engine. However no impediments to the development of a production engine with an installed cost below $400 per kW were uncovered by the researchers.

### *Conclusions*

1. The initial seal design for the prototype not adequate to meet the required degree of seal. The seal materials that were used were not specified. The redesign appears that it will work better. However, it seems likely that the entire issue of rotor seals will be a major technical issue and could require much more work (and much more funds) to bring about an effective low-friction, long-lived design.

2. Although a prototype Gyroton Engine with 10 hp design output was fabricated, assembled and run-in on a test stand under electric power, it did not support combustion and thus did not operate under its own power. Therefore, it is concluded that there are still not-understood problems with the design.
3. This objective, to test the prototype for sealing and compression without fuel addition or ignition and achieve less than 10 percent leakage during compression, was not met. It is concluded that more testing should be done to identify the location of the remaining leaks.
4. This objective, to test the prototype for sealing and compression with fuel addition and ignition and demonstrate less than 10 percent leakage during engine operation, was not successful since operation under internal combustion was not achieved. Evidently the gaseous fuels ether, propane, and butane were tried, but without success. It would have been useful to have real-time combustion chamber pressure data versus shaft angle during these attempts at starting the engine to aid in determining what went wrong.
5. The objective to determine operating characteristics was not successful because the engine was not made to operate. Once again it is concluded that real-time pressure data would be useful for analysis. Also the program administrator would like to see actual shaft torque–versus-angle data while driving the engine on the electric test stand to combine with the chamber pressure data for analysis.
6. The objective to determine whether or not the Gyroton design can be commercially cost-competitive with current micro-scale gas turbines and four stroke reciprocating engines was not met because of engine non-operation. Due to the mechanical complexity of the design as it stands, it is not known if a production engine with an installed cost below $400 per kW is realistic.

The main goal of this project was to determine the feasibility of producing a rotary engine that is competitive in both fuel efficiency and cost to conventional internal combustion engines and microturbines and could be applied to distributed electricity generation for the California grid. Because the engine could not be made to operate, the main goal could not be met.

### *Recommendations*

The program administrator would find it useful for the project to start more simply than with a six-chambered advanced rotor design. The costs would be lower, and more design iterations could be could be carried out for the same amount of funds. At the same time, much more data acquisition when attempting operation is needed to quantify what is actually happening in the engine. Certainly real-time combustion chamber pressure versus shaft angle data would be extremely valuable for analysis. Shaft torque data while passively driving the engine would reveal internal friction. Shaft torque data in addition to chamber pressure data while attempting to start the engine could show where there are problems with the design. Also operation with different fuels could be important for starting the engine and then defining the path to what is required for the fuels of choice.

### *Benefits to California*

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

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

The primary benefit to the ratepayer from this research is in "reduced environmental impacts of the California electricity supply or transmission or distribution system." Distributed generation (DG) reduces the demand on the grid and the need for new central power stations and transmission lines.

In the case of non-grid connected users, DG can also eliminate the need for costly new power line connections to the grid, and thus it aids in increased affordability of electricity in California for those consumers who would otherwise require connection to the grid.

## 2.6. Low Emissions Atmospheric Metering Separator

Awardee: Two-Phase Engineering & Research, Inc.
Principal Investigator: Doug Jung

### *Introduction*

Geothermal sources produce power by bringing hot water and steam to the surface under high pressure and temperature. The steam propels a turbine generator to produce electricity and then vents to the atmosphere. Pollutants within the steam must be separated from it before it can serve as a propellant in the turbine to generate electricity. Geothermal power can be both expensive and environmentally unfriendly because of the cost to remove pollutants from the steam and the noise associated with pollution-reducing gas separation.

California has an installed geothermal capacity of 1,900 megawatts (MW) and an estimated potential capacity of 4,000 MW. As the State of California moves toward the goal of 20 percent of its electricity derived from renewable sources, one can expect an increase in geothermal facilities. Local communities will accept these facilities more readily if the system can significantly reduce separator noise while it effectively removes the noxious gasses and solids.

Prior to this project the researcher developed a geothermal gas-separation device that he named the "Low-Emissions, Atmospheric, Metering Separator" (LEAMS). Its primary function is to safely capture and contain the solids, liquids, and noxious gasses associated with the vented steam from geothermal drilling and power plant operation. Unfortunately, the original LEAMS

created too much noise. This project proposed to reduce the noise level by 10 decibels (dB) to 20 dB, and additionally, to improve separator performance.

To reduce noise the researcher proposed to seal the equalizing inlet and recycle steam back to the inlet from the vessel body. The researcher predicted that the discharge from the inlet pipe at sonic velocity would behave as a two-phase inductor or, in other words, a self-induced vapor pump. Sealing off the air inlet and installing a conduit back to the body would recycle steam, free of oxygen. The researcher projected that this process would not only reduce noise by up to 20 dB, but also would significantly reduce oxygen-induced corrosion.

### *Objectives*

The goal of this project was to prove the feasibility of a noise-separation mechanism added to an existing LEAMS. Additional improvements to the LEAMS concept were included in the project objectives. The researcher established the following project objectives:

1. Reduce noise levels by 10 to 20 dB over present technology (Blooie Muffler).
2. Reduce air/steam condensation by 90 percent.
3. Reduce cost of transportation and setup.*
4. Reduce local atmospheric pollution.*
5. Increase flow capacity of existing LEAMS by 10 percent.
6. Design a secondary hydrogen sulfide abatement system.
7. Produce design for expansion cells for high-capacity wells to 350 kilo pounds per hour (kph).

* Indicates objectives not included in the project proposal but added during the project.

### *Outcomes*

1. Noise levels were 66 weighted decibel (dBA) versus 100 dBA for conventional technologies (the Blooie Muffler). However, mass flow rates were not identical.
2. The researcher did not provide data to indicate any reduction in condensation. The researcher did claim that the steam vapor plume extended to 300 feet above ground level.
3. The design reduced the number of components needed to construct the device on site to two modules instead of three, thus lowering the cost both of transportation and installation.
4. Increased exhaust-stack height mitigated local atmospheric pollution.
5. The researcher did not report on improvements in flow capacity.
6. A chemical-abatement spray system was designed for direct injection within the vessel. Secondary abatement may be desirable to further remove noxious or corrosive gasses.
7. The modular design allows larger units to be constructed for larger geothermal sites.

### *Conclusions*

The researcher proved feasibility of a geothermal separator with reduced noise characteristics.

1. Lower noise levels will make this device a more environmentally friendly geothermal separator. The LEAMS noise level may be understated since the flow rate for the LEAMS test was about 20 percent lower than that for the Blooie Muffler test.
2. Condensation reduction data were insufficient to draw a conclusion.
3. A smaller number of modules enables more cost effective transportation and construction.
4. The principal investigator reported only anecdotal evidence about the reduction of local atmospheric pollution through increased exhaust-stack height.
5. No data were presented to support progress in flow capacity.
6. While the researcher discussed the development of a secondary hydrogen sulfide ($H_2S$) abatement system, no design or operational details are presented in the final report.
7. Larger geothermal sites can benefit from this device because of its modular construction.

### *Recommendations*

The researcher claims that the improved LEAMS is now "commercially available in a limited way." Some additional research, development, and demonstration (RD&D) may be appropriate to extend the usefulness of the current technology to geothermal flows characterized by very high dissolved solids such as those found at the Salton Sea. Additional RD&D work should also focus on field performance of units.

### *Benefits to California*

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

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

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California systems that supply, transmit, or distribute electricity. The new geothermal separator improves noise abatement and air quality around geothermal electrical-generation sites. These characteristics are important, as the state relies more on geothermal power plants to provide needed renewable energy supplies. The improved separator has a lower noise signature and removes noxious components of the waste flow from geothermal well development and operation. The reduction in both noise and pollutants reduces environmental costs. Those, in turn, lower expenses for geothermal electricity generators in California and reduce costs to California ratepayers. The final report presented insufficient data to allow quantitative estimates of cost savings.

## 2.7. Use of Waste Fuel Gas to Reduce Biofouling of Power Plant Cooling Water Intakes

Awardee: Institute of Marine Sciences, UC Santa Cruz
Principal Investigator: Greg Rau, Ph.D.

### *Introduction*

Large Rankin cycle or combined cycle power plants use large quantities of water to condense spent steam. Most power plants located near a sea coast use once-through heat exchangers. Seawater flows on one side of the heat exchanger, and the pure power plant steam/water flows on the other side. Plant operators perform only minimal treatment to the incoming sea water. Usually this consists of two types of filters. The first is a device to prevent the ingestion of large fish. The second filter is a trash rack in the inlet to prevent driftwood or other large floating objects from entering the heat exchangers. What isn't removed is a vast number of biological organisms. These include mollusks such as mussels. These life forms enter the heat exchangers and colonize on the surfaces of the inlet or the heat exchangers. As they flourish on these surfaces, they reduce the flow of fresh water into the heat exchangers and reduce the heat transfer across the heat exchanger surfaces. This is called biofouling. The economic result is the reduction of capacity of the power plant because of insufficient cooling of the condensate. If not continuously treated, the growth becomes so thick that the organisms have to be removed mechanically. The removal process is expensive and can be environmentally unfriendly. Another approach to minimizing the growth is to apply chemicals, usually a form of chlorine, to the inlets. Obviously excessive amounts of chlorine can be discharged to the sea, causing environmental damage.

The operator of the Moss Landing power plants has reported that the economic effects of biofouling amount to approximately $9 million per year. Thus biofouling has a large economic burden on California ratepayers, while chemical treatment of biofouling can have a large negative effect on the California environment. According to the project proposal, a decrease in this operating cost by a half would reduce electricity costs statewide by $100 million a year.

The goal of the project was to test the hypothesis that marine biofouling of power plant heat exchangers could be significantly reduced by mixing flue gas from the power plant with water going to the heat exchangers. Physical testing was required because reduction of biofouling is a difficult problem with many variables. There are many conflicting observations about the causes and uncertainties about the methods that work to alleviate the effect. The researcher proposed to mix flue gas with the cooling water, an approach that could have unforeseen environmental effects. The objective of this project was to test efficacy of the flue gas mixing while keeping the scale of the experiment small enough to avoid environmental consequences.

### *Objectives*

The goal of this project was to determine the feasibility of using exhaust flue gas from a power plant as an anti-settling (prevents marine settlements) and anti-fouling agent in a power plant's cooling water intakes. The researchers established the following project objectives:

1. Design, construct, and operate *in situ* intake experiments on-shore that will determine the efficacy of using flue gas as an anti-biofouling agent. After project initiation this objective was modified to include "outdoor aquaria…" in addition to the "*in situ* intake" goal.
2. Determine the anti-fouling effect (per unit surface area) of a given flue gas dose rate. Quantify the impediment to settlement and growth of biofouling organisms imparted by a given flue gas dosing rate. (This objective was simplified to "Conduct experiments to quantify the effectiveness of flue gas applications and to determine optimum delivery and dosing requirements.")
3. Quantify the downstream effects on pH and dissolved oxygen caused by a given flue gas dose rate to determine if water quality requirements are met. The addition of carbon dioxide ($CO_2$) cannot cause
    a. The pH of the discharge water outside the zone of initial dilution to fall outside the range of 7.0 to 8.5.
    b. The pH to change by more than 0.2 units.
    c. The dissolved oxygen concentration outside the zone of dilution to fall below 5.0 milligrams per liter (mg/L) or to be depressed more than 10 percent from that which occurs naturally.
4. Determine the optimum flue gas delivery and dosing requirements.

### *Outcomes*

1. The in situ testing was not done. The logistics of performing realistic tests within the power plant heat exchangers were far too difficult for the funding available. The program administrator allowed the researcher to build a series of aquaria simulating the inlet environment. Eight aquaria, each containing two substrate surfaces (one concrete and one tile), were set up with different flue gas mixtures ranging from the normal sea water to 20 times as much carbon dioxide ($CO_2$) in the sea water. Many power plant shutdowns during the experimental phase of this project led to long periods of no flue gas. Thus, controlling the gas composition was difficult. Due to corrosion effects and variability of flue gas supply, there was no control over what kind of organism would grow on the substrates. (Only tunicates were observed.)
2. At a $CO_2$ concentration of 10 times normal sea water, the growth of tunicates appears to be nearly zero. Unfortunately, this is only one data point and does not lead to a scale for how much $CO_2$ is needed to achieve the result.
3. Quantify the downstream effects of:
    a. No effects on downstream water quality were reported.

b. No effects on downstream water quality were reported. There was no reporting of tests related to effects of $CO_2$ concentrations on downstream water quality.

c. No effects on downstream water quality were reported.

4. No outcomes were reported for this objective.

### *Conclusions*

While biofouling is a serious economic and environmental problem with power plants using sea water cooling, the outcomes of this project do not prove the feasibility of using flue gas as an anti-fouling agent.

1. The researchers built aquaria to simulate the power plant inlet. Insufficient data were recorded to determine if this project proved feasibility. Because of many site-related problems, there was little scientific control of the experiments.
2. In order to have some analytic results for how flue gas could control biofouling growth, there should have been some characterization of the flue gas as well as monitoring of the composition of the gas as the experiment progressed. A further disturbing result is that the growth of the tunicates was near zero for 227 days when there was no flue gas flowing. Such an observation does not instill confidence in the conclusion that the flue gas controls the growth. The researcher suggested a residual protection existed beyond the period of high $CO_2$. No scientific evidence was presented to validate this hypothesis.
3. The only water monitoring appears to be pH measurement. The researcher assumed that pH is a useful indicator of $CO_2$ concentration. Many gas components can affect pH and the flue gas may have contained some of those components. Even though the experiment was supposed to test the effect of flue gas, there does not appear to be any check of how much flue gas was being dissolved in the sea water. In addition there was a problem with choice of $CO_2$ concentrations for the aquaria. Only one aquarium had large concentrations of $CO_2$ where the effect this gas could be seen. The other aquaria were operating at a factor of ten lower concentrations of $CO_2$ and yielded only highly variable results.
4. Because of the problems described in Outcome 2, there may not be any way of using the results of this project to specify optimum flue gas flow or mixing in to control biofouling.

The researcher noted some degradation of the "concrete" samples used in the aquaria. These observations may have little import as the "concrete" samples were paving stones purchased at a local hardware store. The stones were never shown to be similar to the concrete walls of sea-water intakes of power plants.

Public officials in California are attempting to prohibit sea water cooling in new power plants and, where possible, to replace it with other cooling methods in older power plants. These actions will limit the potential benefits of this project.

### *Recommendations*

New experiments should be conducted using more rigorous scientific methods to establish a set of data that can be used by other researchers. With the new data, the researcher should compare this method of fouling prevention with other methods in a quantitative manner. To do this the researcher should assemble a group of experts with diverse expertise ranging from materials experts to marine organism experts. This recommendation is based on the complexity of the problem being addressed. The researcher should also look at other substrate materials to see if the anti-fouling effect can be observed with other substrates, especially those similar to power plant surfaces. The researcher should also evaluate the energy required to inject flue gas into the incoming water stream.

### *Benefits to California*

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

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

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. Reducing the cost of current method to remove marine organisms would reduce the cost of electricity in California. The researcher estimated that up to $100 million could be saved. In addition the environmental effects of the current cleaning methods could be drastically reduced by eliminating mechanical removal or large dosages of chlorine. Unfortunately this project did not deliver enough quantitative results to allow quantification of the potential benefits and costs of using flue gas as an anti-fouling agent.

## 2.8. Real-Time Energy Meter Radio Frequency Communications System

Awardee: Elsmore William Bush
Principal Investigator: Elsmore William Bush

### *Introduction*

California's residential electric consumers are unable to realize the cost savings and environmental benefits of time–of–use (TOU) pricing, which would provide appropriate price signals based on the real-time cost of energy. This is because there has been no widespread deployment of meters capable of this information to these consumers or their serving utility. The barriers to deployment have been: 1) public policy, which until recently had been

ambivalent about the merits and methods for residential deployment, and 2) the high cost of a residential meter compared to its projected benefits.

The public policy discussion has resolved in favor of deployment of TOU meters for all classes of customers on a phased schedule. California's investor-owned utilities (IOUs) are in the process of developing their implementation plans (Pacific Gas and Electric [PG&E] has received the required California Public Utilities Commission approvals, and Southern California Edison [SCE] and San Diego Gas & Electric [SDG&E] are nearing completion of their proposals). As this deployment proceeds, its success in the residential sector depends on availability of low-cost meters capable of accurately measuring and communicating with the customer and the serving utility over many years of service in the field. Progress has been made, with residential TOU meters and associated communications components now offered by various established vendors, although their price is still above that of conventional meters.

The element where the most potential for improvement remains is in the communications system used to transmit meter readings to the serving utility and to the customer. Commonly used radio-based approaches using the ultra-high-frequency (UHF) band can encounter difficulties in achieving full coverage of a utility's service area, especially in cases where the meter is inside a building or bordered by dense neighboring structures or moving sources. While these issues are being addressed through improvements in the UHF-based systems, there remains room for alternative communications approaches.

California's electric load varies considerably with the time of day, reaching peaks in the late afternoon or early evening. The cost of generated and imported power to meet these peaks is very high, compared to the average price during the day, because much of the peak is met with less efficient, higher cost units. Matching the price of energy to its real-time cost offers significant potential to reduce on-peak electric consumption. This has been proven in the commercial and industrial sectors, where TOU meters and pricing have already been available to customers. Extending this approach to the residential sector is expected to provide similar on-peak reduction potential, although there may be a smaller percentage of a home's total load that is suitable for time shifting (for example, an air conditioner).

Estimates of total residential savings from TOU pricing vary considerably, depending on the assumptions made about the impact of price signals on customer behavior and on the real-time cost of energy in the market; however, the IOUs are projecting break-even points for the costs of converting to residential TOU metering that are comparable to the payback periods for adding generation and associated transmission and distribution infrastructure to meet increased loads. These direct savings would be in addition to the land use and air/water quality benefits of reducing the generation, transmission, and distribution required to meet system peaks.

In response to the need for reliable, full communication coverage for all TOU meters in a utility's service territory, as an alternative to currently employed UHF band approaches, this research proposed using narrowband very–high-speed (VHS) communications with selectable relay control to transfer electric meter data.

### *Objectives*

The goal of this project was to determine the feasibility of using narrowband VHS communications with selectable relay control to transfer electric meter data. The researchers established the following project objectives:

1. Produce a residential TOU meter with integrated communications that can be sold in high volumes for less than $80 per meter.
2. Demonstrate meter data communications capability to provide remote read-out and flexible central control that:
   a. Eliminates the possibility of data corruption
   b. Has sufficient operational margin to overcome urban man-made noise
   c. Operates with a minimum of human intervention
   d. Includes redundancy and flexibility to insure system integrity in emergencies
   e. Insures cost effective operation in a residential environment.
3. Demonstrate a communications system that complies with the Federal Communications Commission (FCC) (Part 90) allowing 1 watt output power in a narrow UHF band and achieves a range of 5 miles under normal conditions, as well as under severe shadowing and man-made noise
4. Demonstrate automatic adaptability capability to circumvent shadowing and/or excessive man-made noise through allowing each meter to act as a relay point, such that a central control station can automatically select a new transmission path when needed.

### *Outcomes*

1. After producing several prototypes, two meters and a base station receiver/transmitter were assembled and bench-tested. The principal investigator provided a detailed cost breakdown, which showed that including material, assembly, and test labor, with a 10 percent profit markup the meter would cost $44.85, well below the $80 research objective. Based on prior experience in high-volume assembly of electronic circuit boards, the principal investigator believes that significant reductions in this cost will be possible in commercial production.
2. Objective Two in the grant application was not stated or addressed directly in the principal investigator's final report, although results were presented that were related to this objective. The final report contained different objectives, and those which most closely align with the original Objective Two are listed below in italics, followed by their results:
   a. *The Master Control Station will demonstrate the energy use acquisition by providing a real-time listing of the energy used by all the residential customers served by an electric utility.* The final report contains a meter download report resulting from operation of the designed meter and communications system and showing the data targeted for this objective under bench conditions.

b. *The demonstration listing will include the cumulated energy used plus the energy used in each 30-minute interval for the previous 40 days.*
The meter download report referenced above confirms compliance with these objectives, as well as showing how individual energy reading times were calculated and correlated with real time.

c. *An energy use listing will be produced that demonstrates:*

   1. *Thirty-minute interval energy data accumulation.*
   2. *Forty-day nonvolatile energy data storage.*
   3. *A transmission data rate of 1,200 baud.*

   A crystal-controlled clock oscillator in the meter meets the 30-minute time interval objective, with an accuracy of one part per million. Phase locking the clock to the line frequency to increase long-term accuracy was rejected as not cost-effective or necessary.

d. *Demonstrate a 40-day nonvolatile energy data storage capability.*
The 40-day, 30-minute interval nonvolatile energy data storage was doubled to accommodate data in the relay mode and did not conflict with locally generated profile data.

e. *Demonstrate that a 1,200-baud transmission data rate was incorporated.*
This objective was met.

3. Objective Three in the grant application was not stated or addressed directly in the principal investigator's final report, although results were presented that were related to this objective. The final report contained different objectives, and the objective which most closely aligned with the original Objective Three is listed below in italics, followed by its results:

   *Demonstrate, in the absence of man-made noise, a 10-mile line-of-sight transmission/reception range.*
   Because field testing was not conducted, this objective was not met. The principal investigator presented a calculation that indicated that such a range should be feasible, subject to actual testing for confirmation.

4. Objective Four in the grant application was not stated or addressed directly in the principal investigator's final report, although results were presented that were related to this objective. The final report contained different objectives, and the objective that most closely aligned with the original Objective Four is listed below in italics, followed by its results:

   *Achieving 100 percent data transfers will be demonstrated, where noise and/or shadow interferences would otherwise make communications impossible.*

   Because field testing was not conducted, this objective was not met. The design addressed this objective by incorporating two operational modes for each meter. One mode reads and records energy use, and the other mode interrogates, reads, and records

another meter's energy profile readings. Mode selection would be made by the system's master controller, wherein the second mode would be selected when necessary to overcome noise and/or shadow interference by using a second meter's relay function to provide a clear path.

### *Conclusions (related to original four research goals)*

1. The estimated cost of approximately $45 suggests the meter and included communications module could be price-competitive with offerings from other major meter manufacturers, assuming the package meets all required standards for accuracy, reliability, longevity, etc. At this stage, with the package existing only in bench-testing form, it is not possible to conclude that these criteria will be met in a production offering, and such investigations would be part of a logical next step.
2. The results of this research are encouraging with respect to the original goals for this item, in particular the tested units' ability to accurately store and transmit data in bench testing, resulting in a satisfactory meter download report. However, the lack of field tests preclude conclusions about the critical items of whether use of a narrowband VHF system can overcome communications problems in high noise/shadow areas and provide 5- to 10-mile transmission path length.
3. As stated above, this item was not met because field tests were not conducted.
4. As stated above, this item was not met because field tests were not conducted.

In summary, the principal investigator has made significant progress in integrating a VHF communications module into an existing, patented TOU meter. Unfortunately, the planned field testing was not conducted, which left several of the key objectives of the research unmet. This testing, as well as work to validate meter accuracy, reliability, longevity under field conditions, etc. would be required to move this research toward commercialization.

### *Recommendations*

1. Complete development of the field test plan and execute.
2. Consider concentrating any subsequent research on the communications package itself, rather than its inclusion in a specific meter. Given the availability of a number of proven residential TOU meters from established meter manufacturers, the meter developed as part of this research may not represent a viable commercialization alternative. In contrast, if the VHF communications package proves to meet the goals established in this research, it could be of interest to these manufacturers as an alternative for inclusion in their residential TOU meters, as an alternative to a UHF-based system.

### *Benefits to California*

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

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

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

The primary benefit to the ratepayer from this research would be increased affordability of electricity. Given California's daily and annual load shape, reducing the magnitude and timing of system peak should lead to better utilization of existing generation and transmission assets, reduced need for less efficient peaking generation and its associated fuel consumption and air and water impacts, and a lower overall cost of power. Since California's major utilities have already or are soon to select the TOU meters that they will deploy in their service areas, the technology developed in this project must be brought to the market quickly to have any impact or benefit. At the request of the researcher, the program administrator extended this project to 40 months from the original 12 month period of performance. Unfortunately the many extensions may result in an untimely market introduction.

## 2.9. Field Feasibility Determination of a Novel Energy-Saving Refrigeration Controller

Awardee: ADA Technologies, Inc.
Principal Investigator: Patrick D. French

### *Introduction*

Energy consumption for defrosting commercial/industrial refrigeration units' evaporative coils is typically not optimized with present methods. Ice removal is necessary to mitigate its impact on heat transfer efficiency caused by reduced airflow cross section between fins and thermal insulation of the coils. Each defrost cycle consumes significant power to melt the ice, re-cool the evaporative coil, and in some configurations re-cool the refrigerated space. Defrost cycles are typically initiated by a timer, whose interval is often set to ensure frost free operation during peak icing conditions, leading to excess cycles during most days of the year. Although operating personnel could reset intervals on a regular basis to more closely align them with the anticipated near-term icing conditions, this is unlikely in practice. A low-cost, automated system that would initiate defrosts only when needed could improve energy efficiency for commercial refrigeration units.

A 1993 study done for the New York State Energy Research and Development Authority demonstrated a savings of 6 to 15 percent of total refrigeration energy using a demand-defrost controller in grocery store settings. Results suggested that the number of defrost cycles could be reduced by 50 to 75 percent under normal operating conditions. With commercial refrigeration energy estimated at 4 percent of national electricity consumption, the potential benefits of such an improvement are significant, assuming a commercially viable demand-based controller can be developed.

Under a U.S. Department of Energy Small Business Innovations Grant, ADA Technologies, Inc. (ADA) had previously developed and successfully laboratory-tested a prototype demand defrost controller for use on commercial/industrial refrigeration systems. The frost sensor and associated control algorithm have been patented. The principal investigator believed that a commercial/industrial scale device can be built for less than $300, which is roughly the cost for a typical timer-based defrost controller. The advancement of science proposed for this EISG grant was to maximize energy savings through the refinement and field-testing of the prototype device and control algorithm.

The frost sensor is composed of four physical sensors (one heat flux and three temperature sensors). The heat flux sensor measures the heat flow from the air to the fin of the evaporative coil. One of the temperature sensors is located to provide the temperature of the fin where the heat flux sensor is located. The second temperature sensor is positioned to measure the temperature of the air immediately prior to entering the evaporative coil (effectively the air temperature at the point of the heat flux sensor). The third temperature sensor is used for defrost termination and is located separate from the heat flux sensor.

The installation technician locates the heat flux sensor in front of the fan and the defrost termination sensor in a region that is slow to defrost. The heat flux sensor is located in front of the fan to maximize the change in heat flux from the frost-free condition to the highly frosted condition. The frost sensor measures the thermal conductivity of the thermal path from the refrigerant to the air and can recognize the reduction in thermal conductivity due to the thermal insulation effect of the frost and due to the loss of airflow from excessive ice formation.

Using these inputs, the frost sensor provides two signals, which are used to control the defrosting of evaporative coils. The first signal is used to initiate the defrost cycle. The second signal is the temperature of the fin in a slow to defrost zone, which is used to terminate the defrost cycle once the coil has reached some predetermined temperature during defrost.

ADA used the time required to defrost the coil to calibrate the frost sensor as installed. It was necessary to learn the optimum point to initiate defrost on each system, since a given installation of the frost sensor may vary significantly.

The defrost controller shown is capable of working in either a stand-alone configuration (controlling a single-compressor, single-evaporative-coil unit such as the coolers in a convenience store), or it can be daisy-chained together to defrost several different evaporative coils that are all supplied from a single compressor skid (such as units in a supermarket).

Although the prototype device was extensively tested in the laboratory prior to this grant, it had not been tested in the field to validate anticipated cost, energy savings, and longevity under actual operating conditions. This important next step was the basis for the grant, which calls for performing the first field evaluation of the prototype device and associated algorithm and determining the actual energy savings under real-world conditions.

### *Objectives*

The goal of this project was to determine through a field trial the feasibility of using a prototype demand-defrost controller to improve industrial/commercial refrigerator performance and to reduce energy consumption. The researchers established the following project objectives:

1. Demonstrate that the demand-defrost controller can achieve an energy savings in the range of 6 to 12 percent of the compressor power used for the refrigeration system.
2. Develop a model to predict energy savings using the demand-defrost controller on various size refrigeration units in different climates by combining the documented energy savings from Objective 1 with information from the literature and from manufacturers.
3. Demonstrate that the prototype demand-defrost controller can operate continuously for 3 to 6 months without failure or false alarms.
4. Demonstrate that the prototype device can maintain the temperature within the refrigerated space within plus/minus 5 degrees Fahrenheit of the set point during normal refrigeration periods.
5. Demonstrate that the controller functions properly under various field conditions such as doors being left open, addition or subtraction of thermal loads, and dirt build up on the evaporative coil.

### *Outcomes*

1. After six months, it was clear that the initial test site (a freezer inside a supermarket in Susanville, California) was unsuitable for the demonstration, due to a low number of required defrosts, leaving little room to demonstrate a difference between conventional timer operation (2 defrosts/day) and prototype device operation. This resulted from a combination of low humidity inside the store and infrequent entries into the freezer.
2. The system was subsequently relocated and tested for six months at another site (a large refrigerated food-product warehouse in Wisconsin) with higher defrost requirements (5 to 10 per day) and significant day-to-day and seasonal humidity variations. Although the site offered a good range of defrost requirements, a combination of interface issues with the building's sophisticated industrial controller and lack of funds for required technical support from local personnel prevented operating and testing the system in control mode.
3. As a result of the limitations encountered at both sites, it was not possible to assess the prototype device's ability to deliver energy savings.
4. Since Objective 1 was not met, it was not possible to meet Objective 2.
5. The controller was able to control the refrigeration system in Susanville in Timer Mode for six months without any failures, demonstrating that both the sensor and controller were able to survive the environment for an extended period.
6. At the Wisconsin site, although the controller was not tested due to site limitations, the frost sensor survived continuous operation over a six month period. No drift in sensor calibration was observed in the test.

7. The Susanville tests showed the freezer temperature was maintained within plus/minus 5 degrees Fahrenheit in timer mode. The Wisconsin tests did not provide any additional data on temperature regulation as the large open warehouse uses 30 evaporative coils to control the temperature and ADA's sensor was only placed on one of these coils for this evaluation.
8. The controller was shown to function well in timer mode in Susanville. The Susanville site turned out to be unsuitable for demand-defrost applications so the unit was never tested in demand-defrost control mode. The prototype device was not tested in Timer or control mode at the Wisconsin site. Testing confirmed that the sensor output was stable over a six-month period and did not fluctuate for load changes or other circumstances.

### *Conclusions*

1. The full range of required testing was not conducted at either site, making it impossible to assess the prototype device's energy savings potential under field conditions. These barriers do not suggest that the prototype device cannot function as proposed, or that a successful testing protocol cannot be developed and implemented at other sites. The Susanville test suggested that some sites may not benefit from the proposed device.
2. No conclusions are possible at this point. This remains a valid objective for further work, assuming a successful control mode test can be conducted.
3. The prototype device's survival in timer mode at Susanville, and the frost sensor's performance at Wisconsin are encouraging, but without extended longevity data for the prototype device in full control mode, it is not possible to conclude that this objective was fully met.
4. This objective was not met, since the Susanville test validated temperature control only in timer mode, and the Wisconsin test did not include temperature control.
5. The limited control mode testing makes it impossible to conclude this objective was fully met. The Susanville site did not offer the robust set of challenges enumerated in the objective, and while the Wisconsin site did offer these, the full prototype device capability was not tested there.

Although the testing in the project was not sufficient to determine (or disprove) actual energy savings from the prototype device, progress was made on some objectives. The frost sensor worked over extended periods without any changes in calibration, as did the controller box. No equipment failed in the field testing. In addition, other related benefits were realized: The system is in a much more complete state than at the start of the project and incorporates several firmware upgrades necessary for use on real refrigeration systems, and field installation procedures have been worked out for future installations.

### *Recommendations*

The market still appears to be very interested in demand-defrost as an energy saving technology. Given the patent on this prototype device and the apparent scarcity of competing demand-defrost technologies in commercial operation, a new field test should be designed. Such testing should build upon the lessons learned in this grant, including the need for more

rigorous evaluation to ensure selection of a field test site that offers a challenging set of humidity/defrost scenarios, a refrigeration plant sized to allow full deployment/testing of the unit in controller mode, and a budget and supporting personnel from the grantee and test host site sufficient to see the project through to completion on schedule. The potential for the patent owner to work through an independent testing contractor, rather than undertaking project management and testing work in-house should also be considered. The program administrator also recommends that the principal investigator work with a consulting firm knowledgeable in the commercial refrigeration market. The consulting should be employed to determine the market size, market barriers, and market penetration strategy.

#### *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 potential benefit to the ratepayer from this research would be increased affordability of electricity in California for commercial/industrial refrigeration and freezing applications. Because the present grant did not successfully meet its objective of validating the projected energy savings of a demand-defrost controller, it is not possible to determine the potential energy savings in California.

A 1993 study done for the New York State Energy Research and Development Authority demonstrated a savings of 6 to 15 percent of total refrigeration energy using a demand-defrost controller in grocery store settings. Results suggested that the number of defrost cycles could be reduced by 50 to 75 percent under normal operating conditions. With commercial refrigeration energy estimated at 4 percent of national electricity consumption, the potential benefits of such an improvement are significant, assuming a commercially viable demand-based controller can be developed. Because of the large food industry in California, percentage savings should be at least as big as those for the nation as a whole.

Related potential benefits include reduced emissions as a result of less electricity being used in defrost cycles, as well as possibly less food temperature variation from multiple defrost cycles.

## 2.10. Development of an Effective Fire-Shield for Powerpoles by Custom Tailoring a Mineral Polymer Material

Awardee: BlazeBarrier, Inc.
Principal Investigator: Dr. Clement Hiel

### *Introduction*

Historically, California utilities used asbestos as fire insulation on wood poles, but asbestos is a hazardous material subject to environmental restrictions and is no longer used. The catastrophic California wildfires of October 2003 destroyed thousands of bare wood utility poles and dramatized the need to protect those wood poles with some sort of fire shield. Protection of the California electricity grid is vital to California ratepayers to prevent expensive outages.

Preventing wood utility pole fires could lead to the following benefits:

- Reduction of power outages due to brush fires by 50 percent.
- Reduction of system restoration time after a brush fire by 70 percent.
- Reduction of toxic exposure of workers from burning utility poles by 100 percent.
- Reduction of end-of-life disposal costs for wood poles by 90 percent.

The researchers proposed an inorganic polymer cement composite with several advantages over the common organic polymer cement. Reinforcing the polymer with glass fibers produces a composite material having desirable properties, especially fire protection. The inorganic cement composite coating proposed for this project has thermal as well as mechanical properties that protect poles against wild fires. The researchers estimated that a pole could be coated for about 15 percent of the cost of replacing it. When applied to utility poles, the inorganic cement would eliminate the environmental impact of chemicals used as wood preservatives. It also would eliminate the exposure of utility workers to toxic resin fumes.

### *Objectives*

The goal of this project was to determine the feasibility of an inorganic (mineral) polymer composite material to provide fire protection to wood distribution and transmission poles during wildfires. The researchers establish the following project objectives:

1. Create a material formulation that blends the fire-shield properties of mineral polymer cement with glass fibers to provide toughness. Toughness tests specified by utilities are: a) stabbing with standard lineman's climbing gaffs (200 pound [lb] person's weight); b) drilling with a three-eighth inch bit to make a pilot hole to hammer in a standard climbing step; and c) impact blows with an eight-pound sledgehammer. No significant chipping or cracking visible in the periphery of the hole or impact area is permitted in any of these tests.
2. Fabricate demo test samples to verify the effectiveness of the mineral polymer cement and glass fiber composite through fire testing. Apply the selected coating on the Douglas fir substrate, and direct an acetylene torch flame at 1,200 degrees Celsius on a one-square-inch area for a minimum of 10 minutes to verify that there is no flaming of the wood.
3. Quantify the efficiency improvements and benefits to California ratepayers, including the cost competitiveness of this composite and its environmental friendliness. Coat an actual distribution pole in the field using the application method developed and

perform a time study to establish labor and material costs targeted in the range of $600 to $1,000 per pole.

### *Outcomes*

1. The composite material system consisted of inorganic polymer cement (IPC) with a glass fiber mat. Its thermal properties and its toughness satisfied the test objectives. The researchers provided samples consisting of wood coated with IPC and glass fiber reinforcement. They verified the fire-resistance and thermal-insulation properties of the coatings used for the fire shield by exposing them to the direct flame of an acetylene torch, and by measuring temperatures on the flame and on the wood side of the samples. They verified the mechanical toughness of the fire shield by impacting the coated wood with a sledgehammer and a pickaxe and by drilling one-half inch diameter holes in the sample. Resulting cracks, chipping, and shattering fell within the test objectives.
2. For their demonstration, the researchers used realistic field samples with the coating applied to creosote and diesel/ insecticide-impregnated wood. They coated the first series of samples in-house to verify the effectiveness of the application techniques to creosoted wood. Subsequently they torch-tested two samples at 1,600 degrees Celsius for 15 minutes. Examination of the circular cross-section through the coated pole sample showed that the underlying wood did not sustain any damage from flaming. The U.S. Forest Service's wildfire research laboratory claims a forest fire of the highest fuel content reaches a maximum core flame temperature of 1,200 degrees Celsius for no more than three minutes.

   They coated a second series of two creosoted wood pole samples at Southern California Edison's Santa Ana service center with Edison engineers present. This gave the potential customer confidence that this new coating could be applied effectively in the field. They sent both samples to an independent thermal test laboratory, which subjected them to a modified ASTM E-108 test. Southern California Edison verified the test to be representative of the rigors of actual fire conditions in the field. The mineral polymer composite coating went through the fire test together with two competing products. It easily passed, whereas the two competing products failed.

   The researchers performed a third series of tests on three creosoted wood pole samples at Edison's Westminster Shop Services and Instrumentation Department. This again gave the potential customer a firsthand chance to evaluate the product. Testing consisted of impact, drilling, and climbing by a lineman, all in combination with torch testing. They found the following results: 1) The coating has enough mechanical integrity to carry the weight of a lineman climbing it with standard gaffs or spikes. 2) The toughness of the composite coating minimizes the structural damage imposed on the coating by the testing so well that a subsequent fire can be sustained without burning the pole. 3) The coated poles can sustain several fires because they maintain their basic structural integrity.

3. Cost-effectiveness of the fire retardant coating is a strong function of the location of the poles, the probability of fire in these locations, the investment cost of the circuit, the installation cost of replacement poles, and the cost of applying the coating. However, this does not account for the added costs of loss of power to ratepayers, individuals, and businesses over the period of several weeks that is required to set new poles.

   The researchers produced a composite coating through this project, and they have developed it to a level where they consider it to be the only technically and economically feasible replacement for asbestos in protecting utility wood poles. They estimate that they can apply their coating at an approximate cost of 10 to 15 percent of the average cost of replacing a burnt pole.

### *Conclusions*

The researcher have proven the feasibility of an effective fire-shield material, delivered it, and made it available for use. Innovative uses for this product in protecting structures from fire are additional benefits from the project.

1. Comparing the mineral cement that is referred to as IPC (Inorganic Polymer Cement) and the reinforced composite that is referred to as IPCC (Inorganic Polymer Cement Composite) shows that the composite material is dramatically better in both thermal and mechanical toughness. Mechanical tests were impact testing using a single hammer blow. Thermal testing used an acetylene torch to produce a high temperature and temperature gradient through the material as a coating. The reinforced material has a vastly different response to the mechanical and thermal shock, surviving the thermal and mechanical loading while the non-reinforced material does not.
2. The demonstration test samples, which are realistic field samples, passed the assigned tests as described in Outcome 2 above. It is particularly notable that this coating passed through the fire test that two competing products failed.
3. The project researchers have developed a composite coating formulation with the thermal and mechanical properties needed to function as a fire shield. They have demonstrated its performance on realistic field samples. The coating can be applied at an estimated cost of 10 to 15 percent the average cost of replacing a burnt pole.

### *Recommendations*

The company has been engaged with California utilities in interactive efforts to make use of the proposed pole coating for utility poles in the field. The program administrator encourages the company to continue working with the utilities. The utilities themselves ultimately will determine the feasibility and economic effectiveness of using this fire shield to protect wood utility poles.

The program administrator recommends that the researchers consider additional testing of the material under thermal and mechanical shock loading, particularly along lines that will convince potential users of its technical feasibility and value. One research area could be the potential interactive effects of combined thermal and mechanical loading; another, to find out

more about the coating's sustained performance over a period of time; and a third, the response of the material to thermal and mechanical loading of varying duration.

The researchers have suggested five tasks to continue their work on product development and commercialization. The program administrator recognizes that these tasks will expand the use of this material system as a fire shield.

1. Improve the field application methods and techniques for coating the poles.
2. Establish coating methods and techniques for bare poles, prior to installation in the field.
3. Investigate if the coating can eliminate the need for impregnating the poles with insecticides.
4. Investigate modifications based on the patented reinforcement techniques to enhance structural strength of the pole.
5. Apply to other utility products such as retaining walls, transformer firewalls, and trench covers.

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

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

### *Benefits to California*

Public benefits derived from PIER research and development 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 to increase the reliability of the California electricity system by providing a composite coating that can form a fire shield to protect wood utility poles from wildfires. The October 2003 wildfires in Southern California destroyed more than 5,000 poles. One California utility alone has over 7,000poles that need protection in areas known to be hazardous. As familiarity with the use of the coating increases, further applications should emerge to reduce the vulnerability of other structures to fire damage.

## 2.11. Microturbine-Based Building Energy System

Awardee: Nissen A. Jaffe
Principal Investigator: Nissen A. Jaffe

### *Introduction*

Microturbine-based systems that produce electricity and simultaneously recover waste heat to provide space heating, hot water, and cooling to buildings represent a promising application for California. It is generally recognized that the market for onsite power is still developing. While that segment grows, the economic benefits of combined heating and cooling enhance the viability of smaller systems in specific applications. Existing systems have focused primarily on the production of electricity and either heating or cooling; less attention has been directed to optimizing all three outputs of such a system: electricity, heat, and chilled-water production. In the past, combined heat-and-power systems have been programmed to output chilled water, hot water, or space heating as a function of seasonal demand. A newly configured system with more sophisticated controls could direct recovered heat optimally to meet real-time electric, heating, and cooling demands. An algorithm to optimize the combined output efficiency and improve the system economics could mitigate the impact of high initial capital costs. Such an application represents a significant market in California in certain commercial buildings with high, constant loads. In the recent past, the electric power system in California has been experiencing difficulties meeting peak summer demand. The researchers estimated that full deployment of combined heating, cooling, and power in distributed systems could result in a peak reduction of 4.4 gigawatts (GW).

The researchers proposed to analyze, quantify, and compare the benefits of a microturbine system that would optimize the space heating, hot water, chilled water, and electric power of such a system on a real-time basis, rather than maximizing it on an annual basis.

The variable-bypass recuperator, a new concept, was central to the increased benefits of this configuration. The researchers planned to improve economics by diverting various amounts of turbine exhaust through one or more heat exchangers in response to varying demands for heat, power, and chilled water.

Initial economic analyses indicated that, at maximum efficiencies, a 75 kilowatt (kW) system (based on costs associated with a Honeywell Parallon 75 microturbine) could demonstrate simple paybacks in 1.8 to 3.9 years. At the lower end of this range, and factoring in the intangible benefits of energy reliability and the environmental benefits of high-efficiency generation (on-site efficiency versus central-power-plant efficiencies), a development of this nature could launch a move towards significant market growth for distributed, combined, heat-and-power applications in this sector. Assuming constant system size, the researchers estimated that a reduction of up to 81 percent in electrical energy consumption was feasible.

### *Objectives*

The goal of this project was to determine the feasibility of configuring a microturbine system to respond to the real-time needs of commercial space for electricity, heating, and cooling. The

system was to produce these services at an average efficiency of not less than 55 percent. The key to this system was the diversion of hot exhaust gases to one or more heat exchangers as demand for services varies. To accomplish this goal the researchers established the following project objectives:

1. Establish the feasibility of operating a microturbine-based chilling, heating, and power (CHP) system using a variable-bypass recuperator. Examine various configurations for partial diversion of turbine exhaust gasses. Model the system and run design simulations with variable diversion strategies for the turbine exhaust. Model the system to operate within turbine manufacturer's back-pressure limits.
2. Achieve a system design capable of 85 percent peak and 55 percent average efficiency that yields a simple payback ranging from 1.8 to 3.9 years. Run design simulations of the system using actual building energy demand for electricity, heating, and cooling. In the simulations, achieve 90 percent efficient conversion of waste heat to hot water, 85 percent conversion to hot air, and a minimum coefficient of performance (COP) of 1 for absorption cooling.
3. Perform economic evaluations to compare the system's performance to standard configurations, to compare capital costs to those of standard systems, and to establish the payback based on actual costs.

### *Outcomes*

The researchers failed to prove feasibility of a microturbine system with a variable-bypass recuperator. They did not utilize the variable recuperator in their modeling.

1. The feasibility of employing a variable-bypass recuperator was not achieved. The investigators do not explain in great detail the process used to arrive at this conclusion. It appears that the researcher determined by engineering analysis that the thermal gains achieved by variable exhaust by-pass did not offset power and efficiency losses in the turbine. Thus the variable-bypass-recuperator configuration was discarded at the outset and not used in further analyses. The system used in the modeling consisted of a fully recuperated gas turbine with the exhaust gases directed to either an absorption chiller or to a hot water loop, depending on demand. The resulting cost and benefit values for three types of buildings in several climate zones in California are presented in the final report.
2. The economic analyses of the modeled system yielded paybacks ranging from 3.3 years to 6 years. These values do not meet the stated goals of 1.8 to 3.9 years. The building energy software tool VisualDOE 3.1 was deployed as the principal method of analysis. The comparisons were based on a building using utility power for all of its electricity, heating, and cooling. The results of the economic analysis are presented in a matrix that combines three different kinds of buildings: office, hotel, and hospital; and three regions: Central Coast, Central Valley, and South Coast. The researchers determined that commercial buildings do not use a hot-air loop for heating. Therefore they restricted their work to hot-water loops.

3. The researcher claims an improved efficiency of 10 to 15 percent for the proposed system over standard cogeneration systems which utilize waste heat for either absorption cooling or space heating, but not both. While it is clear that the proposed system is more efficient than conventional heating, ventilation, and air conditioning (HVAC) systems, the cost and performance comparison is not shown clearly.
4. By segregating the climate zones, the analysis shows an additional outcome of improved paybacks associated with facilities located in the Central Valley of California.

### *Conclusions*

1. The investigative effort quickly concluded that the thermal gains attributable to variable-recuperator bypass could not justify the associated power losses. No data are presented to support this assertion, although past experiences with combined-heat-and power systems indicate that this is true for current technology. The system used for the modeling study is only marginally unique for combined heat-and-power turbine installations.
2. Table 3 of the Final Report shows that efficiency profiles for the systems were slightly better (no more than 7 percent difference), and economic simple payback calculations were notably better (4.8 versus 5.9 years) in the climate zones that experience more ambient temperature extremes, such as the Central Valley.
3. The most significant impact of the proposed CHP system is the reduction of peak demand. This was achieved by combining the reduction in electric demand and the reduction in cooling resulting from the absorption-cooling component. Calculated peak demand reductions ranged from a low of 58 percent to a high of 84 percent, depending on the type of building and its climate zone.
4. The simulation produced a peak system efficiency approaching 70 percent, short of the objective of 85 percent. The second objective—to achieve an average efficiency of 55 percent—was achieved only in certain configurations. Further, the researchers observed that the average annual efficiency increases relative to building size. This is intuitively correct since the efficiency is related to an improved matching of system size to building size. However, for a fixed building size, the average annual efficiency decreases with increased plant size, as expected, because the increase in waste-heat utilization cannot keep up with increases in building thermal demand in a linear fashion. There is no one-to-one payoff in system efficiency. Thus, the need to engineer each system to closely match existing building size and loads appears to be a continuing and important requirement, since the results achieved show that the choice of system size is not immediately intuitive. The results do not support an off-the-shelf solution for building owners based on current technology and equipment costs.
5. The results indicate an increase in efficiency ranging from 10 to 15 percent for the proposed configuration relative to conventional CHP systems with heating or cooling only. It must be stressed that these are theoretical representations in efficiency gains only and do not compare the cost of a heating- or cooling-only cogeneration system versus the proposed configuration.

### *Recommendations*

While this effort focused mainly on theoretical parameters, future efforts should take into account improvements in unit/hardware costs, potential environmental issues, and potential utility incentives. Some consideration in any future analysis should also be given to the increased local emissions caused by widespread deployment of stationary gas turbines.

Another aspect that merits further investigation is a comparison of total investments required to deploy this sort of strategy, relative to other ways of reducing demand that are supported by the California Energy Commission, i.e.; load management controls, building design, and other traditional efficiency measures available in the market.

The increments in system efficiency projected by this study are based more on meeting building end-use demands than optimum component function. However, the figures need fine-tuning to account for specific effects in each component due to interactive effects. For example, the microturbine performance and efficiency is shown as constant. In theory this is feasible, but in practice it should be derated during the summer due to higher ambient temperature. In addition, the efficiency of gas turbines, even recuperated gas turbines, decreases with decreasing load. A life-cycle analysis also will show the impact on paybacks of longer run times and associated maintenance costs.

A refinement study of this nature, conducted on a theoretical level, is required even before embarking on a system demonstration based on a working model.

It would be beneficial to conduct further evaluations to assess the sensitivity of system paybacks as they relate to the cost of reducing peak demand for electricity, the value of power buyback, and the cost of natural gas. Any significant growth in distributed-energy generation is going to impact the demand for natural gas. Operators of distributed gas-turbine systems will have the added complexity of contracting for gas supplies and gas storage.

### *Benefits to California*

Public benefits derived from PIER research and developments 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 the increased affordability of electricity in California. The primary benefits accrue from the installation of on-site, distributed-cogeneration systems. The results of this project indicate that an additional 10 percent or more of saving may be realized by better control of the thermal energy. Quantitative benefits to ratepayers are difficult to analyze until the studied system is built and directly compared with a conventional CHP system based on a recuperated gas turbine. As the cost of electricity

increases, awareness and attention to the alternative explored in this project are valuable to California ratepayers.

## 2.12. Ultra Reduced Emissions Burner for Gas Turbine Combined Cycle and Combined Heat and Power Applications

Awardee: Altex Technologies Corporation
Principal Investigator: John Kelly

### *Introduction*

Gas turbine combined cycle plants (GTCC) and gas turbine combined heat and power (GTCHP) are the mainstay of future power capacity in California. Virtually all gas turbines sited in California today require selective catalytic reduction (SCR) to meet air emission requirements. Many gas turbines supplementary fire the exhaust with duct burners for incremental steam generation and improved economics but at the expense of yet higher exhaust emissions.

With support from the California Energy Commission and the U.S. Department of Energy, ultra-low nitrogen oxide (NOx) gas turbine combustors are under development and in the beginning stages of market introduction. Duct burners, however, have not advanced and SCR technology would still be required on all supplemental-fired gas turbine systems regardless of gas turbine exhaust emissions.

SCR adds considerably to gas turbine capital cost and operating costs. SCR systems also result in collateral air contaminants resulting from ammonia use and slip through the catalyst. A cost-effective non-SCR emissions solution for gas turbine combustors and duct burners will lower power costs to California ratepayers, will expedite the permitting process and will eliminate the environmental consequences of ammonia release in populated areas.

According to the California Energy Commission, California electricity demand will grow at a rate in excess of 1 gigawatt (GW) per year. Assuming that 50 percent of that demand will be met with base-load GTCC and GTCHP plants at an average capacity factor of 60 percent, the avoided cost potential of SCR elimination would be $750 million per year within10 years following SCR elimination. In addition, elimination of SCRs in new gas turbine plants would reduce the use and handling of toxic ammonia by 6,000 tons per year after ten years.

An Ultra Reduced Emissions Burner (UREB) was proposed that produces stable flames and very low NOx levels out of the duct burner. The innovative burner design divides the flame into several zones that are able to optimally balance flame stability, flame quality, carbon monoxide (CO) and NOx emissions. The UREB injects a premixed stabilizing air and fuel rich mixture into a reactor that serves as an oxidizer that lowers NOx in the gas turbine exhaust.

### *Objectives*

The goal of this project is to determine the feasibility of using a segmented duct burner design to reduce emissions in a GTCC system to a level that eliminates or significantly reduces the need for post combustion emission control equipment. The researchers established the following project objectives:

1. Show the ability of the UREB to reach a NOx level of less than 2 parts per million, volumetric dry (ppmvd) at 15 percent oxygen ($O_2$) (6 ppmvd at 3 percent $O_2$ or 0.152 pounds per megawatt-hour [lb/MWh]).
2. Show the ability of the UREB to reach a CO level of under 6 parts per million (ppm) at 15 percent $O_2$ (0.319 lb/MW-hr).
3. Show stable and low noise UREB combustion.
4. Show a UREB turndown of 4 to 1.
5. Show a UREB cost reduction of over 90 percent relative to SCR on a dollars per ton NOx removed basis.

### *Outcomes*

1. Subscale tests of a UREB showed that NOx can be reduced to the targeted 2 ppmvd at 15 percent $O_2$ by controlling burnout flame temperature with 30 percent simulated cooled exhaust gas dilution (nitrogen) and properly oriented injectors.
2. Results show that low levels of CO (6 ppmvd at 15 percent $O_2$) can be reached under low NOx conditions with modest amounts of dilution air. Low hydrocarbon (HC) results were also found for these same test conditions.
3. During all tests, the UREB fuel rich zone flame was stable and did not produce any noise above the background of the low-pressure blower. During normal operation, flames were well-attached to the injectors and did not exhibit any detachment or "floating" under any conditions. Likewise, the downstream fuel injector flames were stable. Unlike lean premixed combustors, the UREB burner could be operated over a broad load range (25 to 100 percent) and at less than optimal rich zone stoichiometric conditions without the flame becoming unstable.
4. With the proper amount of simulated cooled exhaust gas dilution, UREB NOx and CO targets could be met over a burner turndown of 4 to 1. In the case of 31 percent dilution, NOx levels of 2 ppmvd at 15 percent $O_2$ or lower were measured over the 25 to 100 percent load range. CO stays below the 6 ppmvd 15 percent $O_2$ target for loads greater than 40 percent.
5. According to the principal investigator, the UREB can save approximately 90 percent in total cost, per ton of NOx removed, relative to SCR. In contrast to combustion modification NOx control techniques, post-combustion control methods cost $2,000 per ton up to $16,000 per ton, over 10 times the cost of Dry Low NOx (DLN). The incremental cost per year for a UREB equipped 150 megawatt (MW) GTCC system is

determined to be $140,000 per year in contrast to the same system with an SCR that would be $1.4 million per year.

### *Conclusions*

1. The bench scale tests showed that the UREB can reduce NOx from the turbine exhaust. Target NOx levels can be achieved with the UREB technology primarily through optimization of turbine exhaust gas cooling (or cooled flue gas recirculation), duct burner dilution, and UREB tail end fuel/air premix.
2. Methods to lower CO and HC levels tend to push NOx levels higher. Principal techniques to lower CO and HC in the UREB are rich zone stoichiometry, duct burner dilution, gas turbine exhaust dilution and burn out temperature downstream of the UREB. Optimum UREB configuration tradeoffs have been identified that enable CO, HC and NOx targets to be achieved.
3. There are no issues with flame zone noise. Flame stability can be controlled and is important to flame stability and low emissions.
4. With proper dilution, flame stability and low emission performance can be maintained over a fairly wide load range.
5. Projected costs for the UREB are modest compared to an SCR system. The principal investigator estimates UREB capital and operating costs to be 10 percent of those for an SCR system.

This project showed that the UREB technology could sufficiently reduce emissions levels to eliminate the need for an SCR. The UREB can be integrated into GTCC and CHP applications in a similar way as conventional duct burners. The UREB system is relatively simple for base-load applications, requiring only one air and one fuel control valve. For variable duct burner load applications, an additional downstream fuel injector control valve would be needed, somewhat increasing complexity.

Burnout flame dilution and the associated flame temperature appear to be a major driver of NOx emissions. This suggests that the rearrangement of active cooling surface or cooled exhaust gas can be used to control NOx.

For variable load applications, tests showed that the UREB load could be varied over the targeted 4 to 1 load range, while maintaining flame stability and producing acceptable emissions.

### *Recommendations*

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

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

The UREB addresses an important need. The completed research has shown that low duct burner emissions can be realized through proper burner configuration and the use of cooled exhaust gas. To advance the UREB towards commercialization, a more refined prototype version of the burner should be developed and tested at a larger scale to verify scalability and repeatability. Also, actual cooled exhaust gases should replace the nitrogen dilution system used in bench scale tests; materials should be selected that would be used in a commercial prototype; and UREB cost estimates should be refined. As some air is added at the UREB, the duct burner fuel fraction is increase relative to the gas turbine combustor. The economic and market impact of this parameter should be weighed in the next phase of development. It is important that a HRSG provider and/or duct burner manufacturer be engaged in follow-up activity to properly stage exhaust gas cooling for optimal integration with the UREB.

### *Benefits to California*

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

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

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. If successful, the UREB technology would be applicable to all base-load GTCC plants and to larger GTCHP systems employing gas turbines. The resulting savings would be lower capital costs and lower operating costs. The electricity cost savings is estimated at $750 million annually within 10 years following initial commercial deployment of the UREB. The UREB would also eliminate significant amounts of ammonia use (6,000 tons annually) and slippage into the ambient air.

## 2.13. Flexible Low-Emissions Combustor for Renewable Fuels

Awardee: Altex Technologies Corporation
Principal Investigator: John Kelly

### *Introduction*

California produces over 60 million bone-dry tons per year of biomass materials. Some of these materials are taken to landfills (yard waste) or burned in the field (rice straw) or in incinerators (forest slash). While there are alternative disposal methods for each of these waste streams, all of these materials could produce about 2000 megawatts (MW) of electricity if they were converted to electricity. Two thousand megawatts is enough capacity to satisfy about half of the

peak demand for San Diego Gas & Electric. Electricity produced from these biomass materials could count toward California's goal of 20 percent renewable sources of electricity by 2010. The major technical issues facing the use of these fuels are: reducing air emissions, reducing boiler slag, and reducing the cost to transport, process, and combust biomass materials.

A resolution of these problems would make California less dependent on natural gas for electricity generation and increase the amount of domestic renewable energy. In addition, air quality would improve by the elimination of field burning of rice straw. Landfill utilization would benefit from the diversion of yard waste to energy uses. The ratepayers would benefit from lower-cost methods of converting the energy in biomass residues into electricity.

The proposed test combustion system incorporated features of both fluidized-bed and grate-type combustion systems to combust a variety of biomass residues. The researcher suggested that the proposed system would not only reduce nitrogen oxide (NOx) emissions, but also would overcome the problems of grate and fluidized-bed combustors by incorporating the following features:

- A sub-stoichiometric cyclone to trap all material particle sizes in an intensely stirred gasification zone.
- Intense stirring of the cyclone to promote positive ignition, even with high moisture content and low-energy-density fuels.
- A rabble system to prevent extensive scale deposits from forming in the combustor and to positively cool and then move ash out of the system.
- Sub-stoichiometric cyclone firing to minimize fuel-derived NOx formation.
- Air staging to burn up fuel gasses and fine particulates and further suppress NOx emissions.
- Cyclonic action to remove particles ahead of all heat-exchanger surfaces.

### *Objectives*

The goal of this project was to prove the feasibility of the proposed test combustion system for combusting biomass fuel, while reducing the NOx, carbon monoxide (CO), and particulate emissions. The specific objective was to determine the feasibility of the low-emissions biomass combustor in controlling ash deposition, handling moist biomass fuel of inconsistent size, and requiring minimal manpower for operation. Biomass was specified as rice straw and yard waste. The researchers established the following project objectives:

1. Demonstrate a NOx level of less than 30 parts per million, volume dry (ppmvd) at 3 percent oxygen ($O_2$).
2. Demonstrate a CO level of under 200 ppmvd at 3 percent $O_2$.
3. Demonstrate particulate emissions of less than 2.73 pounds per megawatt-hour (lb/MWh).
4. Demonstrate a turndown ratio of 3 to 1 (a 67 percent load reduction).
5. Demonstrate that the combustor will operate unmanned.

6. Show a cost benefit of up to 30 percent, relative to grate-based and fluidized-bed systems.

### *Outcomes*

1. The lowest NOx emissions from burning yard waste were 100 ppmvd corrected to 3 percent $O_2$. This failed to meet the project target of 30 ppmvd at 3 percent $O_2$. NOx emissions from burning rice straw were measured at 150 ppmvd, an even larger mismatch with the expected 30 ppmvd at 3 percent $O_2$.
2. CO emissions from burning yard waste were generally lower than the target of 200 ppmvd at 3 percent $O_2$ and maintained relatively low NOx levels. CO emissions from burning rice straw were at or below the target of 200 ppmvd at 3 percent $O_2$ under selected conditions. To maintain both NOx and CO under 200 ppmvd, the oxygen level had to be in the range of 2 to 4 percent.
3. The test combustor produced particulate emissions of less than 9.9 lb per MWh. The researcher determined this number from design and analysis and did not report direct measurements of particulates. This calculated value failed to meet the target particulate emission level of 2.73 lb per MWh.
4. The combustion system achieved load reductions (turn down) of 25 percent (rice straw) and 30 percent (yard waste) but fell short of the target of 67 percent.
5. The test combustion system required manual labor to clear the tube when yard waste agglomerated in the feed tube.
6. The researcher calculated a profit margin of 23 percent if the combustion system, in conjunction with an indirectly fired gas turbine, were to produce electricity and process heat. The internal rate of return (IRR) was calculated at 18 percent. The researcher concluded that the combustor would be economically viable for zero-net-cost biomass wastes such as yard waste. Relative to grate-based combustion systems, the test system showed a cost benefit of 39 percent. Relative to fluidized-bed combustion systems, the test system showed a cost benefit of 20 percent.

For both rice and yard waste, the following unanticipated outcome occurred:

1. Periodically, the biomass material would agglomerate in the feed tube, requiring manual labor to clear the tube.

### *Conclusions*

This project did not prove the feasibility of the proposed biomass combustor system.

1. The test combustor operated with NOx emissions of 100 ppm for yard waste and 150 ppm for rice straw, a much higher value than the target 30 ppmvd. The combustor did reduce the NOx by up to 87 percent compared to the researcher's baseline, but that baseline is not typical in practice. It would be helpful to the reader if the researcher compared his results to emissions of typical or best available combustion systems. The researcher suggested that fuel-bound nitrogen may have caused the NOx values to be higher than expected.

2. The test combustion system was able to operate and maintain CO emissions just under the 200 ppmvd target, provided the exit oxygen level was between 2 and 4 percent.
3. The test combustion system apparently failed to meet the project objective in controlling particulate matter. Actual test data would be helpful in this important area.
4. The test combustion unit did not meet the turndown objective. The researcher suggested that a variable eductor would maintain the airflow velocity and thereby increase the turndown range.
5. Problems in handling material that required manual labor to clear out feed tubes need attention in a future design. This includes the feed eductor, hammer mill, feed chipper, and ash handling systems. Material handling and size reduction are important cost drivers. The researcher did not break out the energy costs to perform these activities.
6. If the researcher's numbers are correct, the test combustion system provides significant economic advantages over conventional systems. However, the numbers are based on the use of an indirectly fired gas turbine. The program administrator is not aware of any indirectly heated gas turbine that currently is available commercially. The cost to bring an indirectly heated gas turbine to market is probably several hundred million dollars.
7. One of the objectives was to sustain gasification and combustion at temperatures below the ash fusion temperature, but wet-fuel stability problems thwarted this goal. The fuels required drying to sustain combustion. That caused the flame temperature to be higher than expected and resulted in molten ash.

The outcomes of this project indicate the need to substantially modify and/or redesign this system prior to beginning any future development program

### *Recommendations*

The recommendations for further study on the test combustion system are as follows:

1. The feeding and grinding systems need improvement to lessen labor requirements. The energy requirements for these processes must be clearly measured.
2. The further reduction of particulates, CO, and NOx is necessary. The researcher should perform a thorough analytical review of the combustor to determine what mechanisms are driving NOx production.
3. The researcher should measure sulphur oxide (SOx) emissions.
4. Higher turndown rates will require further work.
5. Because of the chemical composition of rice straw, its ash has a tendency to stick to boiler tubes (or heat exchanger surfaces) and rapidly clog any passageways. The researcher proposed a wet-ash removal system to solve this problem in future work.
6. The researcher should base his economic calculation on the use of available hardware. Specifically he should calculate the benefits using a steam turbine rather than an indirectly heated gas turbine. In addition, the researcher should pay more attention to the cost of fuel preparation and particle-size reduction.

### *Benefits to California*

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

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

The primary benefit to the ratepayer from this research is in the reduced environmental impact of the California electricity supply. If the proposed combustion system could convert plant wastes into energy at a cost similar to or only somewhat higher than traditional fuels, the use of greater amounts of these fuels for electricity generation would lessen California's dependency on natural gas. However, the cost of transporting the biomass fuels to the combustion system and the cost of preparing this fuel need full analysis to ascertain the total cost of electricity produced by this method. If this analysis proves beneficial, and emissions can be further reduced, California's vast quantities of biomass fuels could be converted to electricity in a relatively clean process. Because the researcher has not yet produced a system with proven feasibility, it is difficult to ascertain the costs and benefits.

## 2.14. Multi-Spectral (Visible and Infrared) Imaging Camera

Awardee: International Electronic Machines Corp.
Principal Investigator: Zach Mian

### *Introduction*

A significant amount of energy is presently wasted due to inefficiencies in insulation, leaking ducts, poorly sealed doors, and similar building deficiencies. Energy loss in forced-air heating/cooling systems has been shown to range between 25 and 40 percent. Although this waste is well-known and understood, it is difficult to remediate without an energy audit to pinpoint the deficiencies. Typically, such audits are performed using infrared-detecting (IR) cameras which can "see" areas of heat loss. However, state-of-the-art IR cameras are cost-prohibitive and often require training to interpret results. Consequently, audits using IR cameras have not become the state-of-practice for improving energy efficiency, particularly in the residential sector.

According to the U.S. Department of Energy's *Annual Energy Review* (2004), the nationwide residential consumption of energy in 2001 was 9,860 trillion British thermal units (btu) nationwide and 1,445.7 trillion btu in California. Over half of this consumption was used for heating and cooling. Conservatively estimating that widespread and affordable residential energy audits could result in a reduction of the loss to 15 percent of the heating and cooling energy consumption (or 3 percent of total residential consumption), California could realize a savings of 46.67 trillion btu, worth more than $460 million annually. Similar savings could be expected in commercial and industrial sectors, resulting in a total savings of well over $1 billion annually.

The researcher proposed a low-cost IR camera that combined visible images with IR images. To achieve a low price point the researcher proposed incorporation of low-cost micro-electro-mechanical machine (MEM) based IR sensors, as well as low-cost optics suitable for energy audits. Integration of both visible and IR images resulted in a composite image requiring no special training to interpret. At the time of project initiation, IR cameras retailed for approximately $12,000 and did not include visual indicators to assist in interpretation of IR images. At the time of this assessment, IR cameras could be found for approximately $4,000 to $8,000, and some have been enhanced with visual images. However, International Electronic Machines Corporation's (IEM) target price point of $2,500 allows widespread use in the residential sector.

### *Objectives*

The goal of this project was to determine the feasibility of building an IR/Visible camera appropriate for use in energy audits with a retail price of $2,500 or less. The researcher established the following project objectives:

Initial Objectives:

1. Finalize the IR camera design.
2. Fabricate a prototype.
3. Demonstrate 0.1 degrees Celsius accuracy in measurements.
4. Demonstrate an image resolution of 2 inches at 15 feet.
5. Achieve an image resolution of 128 X 128.
6. Show that the project findings support the $2,500 retail cost goal.

Added Objectives:

7. Determine emerging competition in the field.
8. Determine practical requirements for measurements in field conditions.
9. Determine if changes in technology warrant changes in design.

***Outcomes***

1. The researcher constructed two IR camera designs, one incorporating the originally proposed scanning mechanism, and the other with a fixed IR array. The scanning camera included two design approaches, one involving movement of the entire camera assembly, and one involving movement of mirrors within the camera. Although the rotation of internal mirrors proved superior to rotation of the camera assembly, the researcher found that the project objectives could be met without use of a scanning methodology in data capture. Consequently, most of the testing was conducted using the camera with a fixed IR array.
2. A prototype was constructed from the fixed IR array design and installed into a housing developed by IEM for its U.S Special Operations Command Rugged Camera, an existing product offering that had undergone usability testing. The prototype design was optimized for testing and commercialization by reducing the size and improving the form factor.
3. The original project objective (0.1 degrees Celsius accuracy in measurements) added significant cost. The researcher stated this requirement is not needed for most residential energy audits. The researcher also stated that accuracy within 1 degree Celsius was more appropriate for the intended use of the camera and for the price objective. (See Objective 8.)
4. Similar to findings for accuracy, the researcher found a 2-inch resolution at 15 feet would drive up the cost of the IR camera beyond the objective. The researcher chose a resolution of 1 to 2 feet at 10 feet. It was the view of the researcher that this resolution was more appropriate for the intended use of the camera. (See Objective 8)
5. An image resolution of 128 X 128 was achieved using both versions of the scanning camera prototype. The fixed IR array camera was designed using a 4 X 4 array but could achieve an effective resolution of 16 X 16 through interpolation.

6. The total cost for the component parts for the fixed IR array camera is $816. This number is consistent with a product price of $2,500.
7. The only extant competition in the field offering similar functionality, Gardco's Isquare 2, was more expensive at $4,000. This device did not offer significant improvements in performance.
8. The original accuracy and resolution objectives would have increased the price point of the IR camera. The researcher postulated that it is unlikely that temperature differences measured in tenths of degrees would be perceptible to people occupying the building being audited. Given the nature of heat transfer, and the settings in which the heat transfer are likely to occur, the researcher suggested that a resolution of 1 to 2 feet at 10 feet would be more than adequate to identify the source of heat loss.
9. The results of a technology survey to identify competitors revealed that a number of inexpensive medium- to high-resolution IR sensors are forthcoming in the near future. To accommodate these technological improvements, IEM designed their prototype to accept 8 X 8 or 16 X 16 IR arrays. IEM is working on design modifications to accommodate 16 X 16 or 32 X 32 arrays.

### *Conclusions*

1. This objective was met.
2. This objective met. The original prototype was optimized in anticipation of commercialization.
3. The researcher did not meet this objective. Experts in the energy audit business must determine if the revised objective of 1 degree Celsius is adequate.
4. The researcher did not meet this objective. Experts in the energy audit business must determine if the revised objective of 1to 2 feet at 10 feet is adequate for home energy audits. The revised objective of 1 to 2 feet at 10 feet was met using interpolation with a 4 X 4 fixed IR array.
5. The researcher met the objective of achieving an image resolution of 128 X 128 using either design for the scanning prototype, but not the fixed IR array prototype. Because the researcher chose to pursue a non-scanning methodology he did not meet this objective in his final design. The researcher sought to increase the effective resolution of his 4 X 4 IR array using interpolation. The result was a prototype capable of displaying 4 X 4 raw data, as well as an interpolated 16 X 16 grid. The researcher designed the camera to accept low-cost medium to high resolution sensors (8 X 8, 16 X 16 and 32 X 32) anticipated to be available in the future. Applying interpolation to a 32 X 32 array would approach the originally proposed 128 X 128 resolution with the fixed IR array camera.
6. The researcher met the $2,500 retail cost goal in theory. Component costs totaled $816 for the fixed IR array. This is consistent with a $2,500 sales price. Assembly, overhead, marketing, sales, warranty and profit must be added to the parts cost before a reasonable price can be determined.

7. The researcher met the objective of determining emerging competition. The researcher did not find significant competition at the targeted price point. The program administrator found numerous infrared imaging cameras on the market. Prices varied greatly depending on the features offered. Purchasers of these cameras may not make buying decisions on price alone. The program administrator recommends a detailed market assessment.
8. Meeting with industry representatives the researcher determined practical requirements for measurements in field conditions. This objective resulted in a revision to accuracy and resolution objectives. Revised accuracy and resolution objectives must be evaluated by the user community. Higher precision would have resulted in a higher unit cost.
9. The researcher designed the prototype to accept higher resolution IR arrays as they become available at lower costs. The anticipated availability of these arrays and their improvement in image resolution was the basis for the decision to use a fixed IR array camera rather than the scanning approach.

Overall the researcher met the goal of designing and demonstrating an IR/Visible camera that could be used for energy audits and would retail for $2,500 or less. A version of this camera is now offered for sale by International Electronic Machines (IEM). The market will decide if the features and price of this camera meet the needs of the energy audit professionals.

### *Recommendations*

The program administrator recommends a thorough market assessment to determine the specific needs of the energy audit market for infrared/visible cameras. The assessment should be performed by an independent organization to ensure that no bias is introduced into the study. Using the result of such a market assessment any researcher can target his/her product to the expressed needs.

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

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

### *Benefits to California*

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

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

The primary benefit to the ratepayer from this research is an increase in affordability of electricity in California as a result of improved energy efficiency. IEM's low-cost IR/visible camera should reduce the cost of residential energy audits resulting in a greater number of audits and corrective actions. According to the US Department of Energy's *Annual Energy Review 2004*, the nationwide residential consumption of energy in 2001 was 9,860 trillion British thermal units (btu) nationwide, and 1,445.7 trillion btu in California. Over half of this consumption was used for heating and cooling. Conservatively estimating that residential energy audits could result in a reduction of the loss to 15 percent of the heating and cooling energy consumption (or 3 percent of total residential consumption), California could realize a savings of 46.67 trillion btu, worth more than $460 million annually. Similar savings could be expected in commercial and industrial sectors, resulting in a total savings of well over $1 billion annually. Achieving these savings will not be easy. Almost every building must be audited using tools such as the infrared/visible camera, and building owners must invest in corrective actions for discovered deficiencies. The use of an inexpensive infrared/visible camera is just one part of a very large campaign to increase the energy efficiency of the built environment in California.

## 2.15. Desiccant Enhanced Indirect/Direct Evaporative Cooling

Awardee: Innovative Research Enterprises
Principal Investigator: William A. Belding

### *Introduction*

Residential and commercial air conditioning is a major contributor to the use of electricity and to peak electricity demand during hot weather in California. A cost-effective alternative to conventional electric-vapor-compression technology could provide much-needed demand-side relief on California's electricity grid. Direct evaporative-cooling technology is making market inroads in dry western climates, but it does not provide adequate comfort in most of California. Two-stage, indirect/direct evaporative coolers are effective in many California regions, but the large volumes of outside air they require to achieve adequate comfort levels render retrofits to conventional vapor-compression systems difficult and costly. The enhancement of indirect evaporative-cooling technology with desiccant dehumidification can achieve cooling comfort using ductwork designed for vapor-compression systems, even during severe California summers.

The project technology is intended for the retrofit air-conditioning market and could apply widely to residential households with central air conditioning and to commercial buildings employing rooftop air conditioning. Annual California energy usage is 11 billion kilowatt hours (kWh) for commercial rooftop air conditioning and 5 billion kWh for residential central air conditioning. A desiccant-based air-conditioning system with a seasonal energy efficiency ratio (SEER) of 25 could reduce energy use for air conditioning by 60 percent for

residential/commercial packaged air conditioning users whose existing systems have a collective average SEER less than 11.0. This equates to a potential annual savings of 9.6 billion kWh and $1.4 billion.

The proposed concept integrated desiccant dehumidification with indirect/direct evaporative cooling in a new configuration. The goal of using the enhanced desiccant-heat-exchanger (EDHX) technology was to boost the capability of a two-stage, indirect/direct evaporative-cooling system by providing colder supply air during the hottest days through existing building ductwork. The EDHX technology simultaneously dehumidifies the air and rejects the adsorption heat. The novel system is comprised of thin-wall impermeable partitions of high thermal conductivity coated with a layer of desiccant on one side. The modules are cycled through adsorption, regeneration, and pre-cooling modes by switching valves or through a wheel configuration.

The researcher described the benefits of this configuration over conventional desiccant/evaporative-cooling systems as:

- Ability to function as an indirect/direct evaporative-cooling system during most weather conditions when a gas-fired desiccant boost is not required.
- More efficient adsorption, and hence dehumidification, on the process air side during hot weather.
- Lower desiccant regeneration temperatures compatible with medium temperature collectors for a solar assist.

In the proposed system, sensible heat is rejected from the system by flowing adiabatically cooled secondary air along the bare sides of the partitions, while the latent heat is consumed by traditional direct evaporative (i.e., adiabatic) cooling of the process air as it exits the desiccant module. The process air leaves the desiccant module at an enthalpy level lower than that in a conventional desiccant/evaporative-cooling system.

### *Objectives*

The goal of this project was to determine the feasibility of an enhanced desiccant-heat-exchanger technology to enable cost-effective retrofits of conventional vapor-compression cooling systems. The researchers established the following project objectives:

1. Design and fabricate a prototype desiccant heat exchanger of 6,000 British thermal units per hour (btu/h) capacity.
2. Demonstrate that the prototype heat exchanger can achieve grain depression of 45 grains of moisture per pound of dry air (gr/lb) between the exiting and entering air streams.
3. Demonstrate that a heat-exchanger effectiveness of 60 percent can be achieved.
4. Confirm that the projected SEER rating for proposed indirect/direct evaporative-cooling system would be greater than 30.
5. Confirm that the projected manufacturing cost of the proposed system will be below $600 per ton capacity.

### *Outcomes*

1. The size of the heat exchanger module had to be increased from the original design in order to incorporate the intended amount of heat and mass transfer area. Even with the increase in module size, the prototype heat exchanger provided only 2,831 btu/h cooling capacity compared to the 6,000 btu/h design target.
2. Although the grain-depression goal of 45 gr/lb was achieved under process inlet conditions near saturation, it was not achieved at lower process air relative humidity conditions. For example, the results indicate a 37 gr/lb depression will be achieved at Sacramento's 1 percent design condition of 97 degrees Fahrenheit dry-bulb by 69 degrees Fahrenheit wet-bulb.
3. The heat-exchanger effectiveness of the EDHX module was calculated at 66 percent compared to the goal of 60 percent.
4. A Bin analysis for Sacramento for the prototype module indicates a seasonal SEER of 10.6 btu/h/watt for the system, compared to the goal of 30 btu/h/watt.
5. With improvements to mass-transfer effectiveness and/or a reduction in media thickness, a manufacturing cost of $500 per ton is projected. This cost is about 50 to 75 percent higher than the factory cost of vapor-compression systems and betters the target manufacturing cost of $600 per ton.

### *Conclusions*

1. Higher desiccant loadings and more heat and mass transfer surface are needed to provide a smaller, higher capacity, and more affordable package.
2. Measured grain-depression characteristics are inadequate for providing acceptable comfort in Sacramento and most other populated non-coastal areas in California. According to the researcher, increasing the thermal uptake without increasing thermal mass would likely fix this deficiency.
3. The heat-exchanger effectiveness of the EDHX module surpassed the design target.
4. A SEER of 10.6 is projected for current EDHX technology. With desiccant uptake improvements, the researcher projects the SEER to increase to 12.5. This still leaves a big performance gap to the target. Unless technology paths to bridge the SEER gap can be identified, this technology will not compete against conventional vapor-compression equipment.
5. The cost target appears to be reachable, but it is based on a high SEER for significant savings in energy cost to pay for the premium. Unless significant enhancements in energy efficiency emerge, the cost targets are of little consequence.

Concept feasibility was not demonstrated. The EDHX technology is still in an exploratory research stage. Substantial increases in energy efficiency are needed to motivate California market interest in the technology. The researcher stated that with further development, sufficient efficiency gains can be realized, making the system more acceptable for commercialization.

### *Recommendations*

Prior to further funding, the researcher should prepare a clear technology path to overcome current technology deficiencies. Furthermore, a manufacturing partner should be involved in any follow-on activity to ensure that efforts are targeting manufacturability, competitive pricing, and significant energy savings relative to traditional and alternative air-conditioning technologies.

### *Benefits to California*

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

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

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. If successfully developed and deployed, the desiccant-enhanced air-conditioning system would address the biggest contributor to California's peak electricity demand. Reducing peak demand would enable increased utilization of the generation, transmission, and distribution system and would delay new generating and transmission investments, lowering the cost of delivered electricity. Reducing peak demand also helps relieve congestion and improves the reliability of the power supply.

An economic, desiccant-based air conditioner would also help California adopters of the technology control their energy expenses. The light-commercial and residential sectors would best be able to utilize this technology. The electricity usage for air conditioning in California's addressable market (i.e. commercial rooftop and residential air conditioning) is 16 billion kWh per year. With energy savings of 60 percent projected, the displacement potential of desiccant air conditioning in these California sectors is estimated at 9.6 billion kWh annually, equating to residential and commercial sector cost savings of $1.4 billion per year.

## 2.16. Solid-State Electrolytes for Dye-Sensitized Solar Cells

Awardee: Konarka Technologies, Inc.
Principal Investigator: Dr. Russell Gaudiana

### *Introduction*

Solar energy is a major technology in California's goal to achieve 33 percent renewable energy. The California Solar Initiative (CSI) provides almost $3 billion to install existing solar products on houses and businesses. Other states and other countries also have large incentive programs to promote the installation of solar energy. Unfortunately, the net result of all these programs

has been to increase demand and thus increase the price for conventional solar energy panels. Prices of the panels (without installation) run about $3 per watt peak (Wp) when purchased in large quantities. While some price relief may occur when new silicon foundries come on-line in 2008 to 2010, no one is projecting large price reductions. When the CSI incentives are gone, prices of solar panels may not be significantly lower than today. Large scale installations will occur only when solar energy is priced, without incentives, near the price of conventionally produced electricity. This may require new technology for the production of solar panels.

Researchers and policy makers have long sought solar energy products priced near $1 per Wp. Numerous research programs have included this goal. Many project that any solar panel product with a market price at or below $1 per Wp would dramatically change the market dynamics. At that price homeowners and business would find it economical to install solar energy without the use of any state or utility incentive.

The objective of this project was to develop a low-cost, dye-sensitized titanium oxide ($TiO_2$) solar cell installed on a flexible plastic substrate. The researcher suggested that the use of low-cost materials and roll-to-roll manufacturing could reduce the cost of solar energy to approximately 50 cents per watt peak. Prior to this project, Konarka engineers developed an interconnection process that eliminated the need for soldering individual cells to one another. The cell-to-cell interconnection takes place during lamination and requires no additional materials or labor. Also prior to this project Konarka reported cell efficiencies approaching eight percent on glass substrates. These early units used liquid electrolytes that are harder to handle during manufacturing. The electrolyte is a key component of dye-sensitized solar cells that shuttles charge between one electrode and the dyed titanium oxide. The use of liquid electrolytes limits automated manufacturing and thus low-cost production. The primary goal of this project was to develop a solid-state electrolyte that would facilitate low-cost continuous manufacturing on a flexible substrate.

There were three major objectives in this project. The first objective was to develop high-performance, gelled electrolyte formulations. The second objective was to eliminate all volatile components including coating solvents and electro-active components. The third objective was to achieve solar cell performance using these new gelled electrolyte formulations that meets the cell performance observed using standard liquid electrolyte formulations.

### *Objectives*

The goal of this project was to determine the feasibility of developing low-cost, flexible, thin film solar cells based on dye-sensitized titanium dioxide ($TiO_2$). The specific goal of this project was to develop a solid-state electrolyte for the dye-sensitized solar cell mounted on a flexible plastic substrate. The researchers established the following project objectives:

1. Fabricate and test prototype dye-sensitized solar cells using the proposed solid state electrolyte formulations.
2. Develop a thermally reversible gel within a temperature range of 40 degrees to 90 degrees Centigrade.
3. Eliminate volatile components from the dye-sensitized solar cells (DSSC)

   a. Eliminate the volatile coating solvents.
   b. Develop stable, non-volatile active components.
4. Achieve cell performance exceeding that of liquid electrolyte cells (greater than 5 percent efficiency).
5. Show that a manufacturing cost of less than $1.12 per Wp for the DSSC material itself is possible with a long term cost goal of less than $1 per Wp.

### *Outcomes*

1. The researcher achieved this objective.
2. The researcher reported that he achieved a thermally reversible gel that allows the application of the gels at elevated temperatures with subsequent solidification upon cooling to ambient temperature. Temperatures were not reported. The gels were based on redox electrolytes that are nonvolatile, molten salts. The liquid electrolytes were gelled using lithium metal ions, which crosslink the polymers. The lithium ions caused a rapid gelling action.
3. The high viscosity gel electrolytes developed in this project were
   a. Nonvolatile.
   b. Chemically stable and do not compromise the photovoltaic characteristics of the cell.
4. Solar cells with ionic liquid based electrolytes achieved an efficiency of less than 4.5 percent, while solar cells with ion liquid/plasticizer based electrolytes achieved efficiencies of greater than 5.8 percent.
5. The researcher did not report any cost studies.

### *Conclusions*

1. The researcher met this objective.
2. It appears that the researcher met this objective, although critical data is missing from the final report.
3. The final report indicates that these objectives were met.
4. The researcher met his goal of greater than five percent efficiency from a dye-sensitized solar cell.
5. No conclusions are possible since no outcomes were reported.

### *Recommendations*

Konarka has abandoned the solid state electrolyte technology studied in this project in favor of another approach to dye-sensitized solar cells. No reasons have been offered for the change. Thus, the program administrator cannot recommend further activities based on this project.

### *Benefits to California*

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

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

The primary benefit to the ratepayer from this research reduced environmental impacts of the California electricity supply system. Solar energy is a high visibility technology in California. State policy, via the California Solar Initiative, strongly supports the installation of solar energy throughout the state. The technology of this project, had it progressed to a product, would have had the potential to greatly reduce the cost of solar cells while reducing the use of heavy metals inherent in the production of some solar cells. The initial cost goal for this project was 50 cents per Wp, a significant reduction from the 2007 market price of approximately three dollars per Wp. Since the final report did not discuss potential product cost, it is not possible to determine what the market price of the dye-sensitized solar cell could have been. Without those price projections it is not possible to determine the potential benefits to the California ratepayer.

Hopefully the work in this project had an influence on the development of the dye-sensitized solar cells that Konarka is now taking to market. Cost of those solar cells is not readily available either.

## 2.17. Prototype and Demonstration of Vision Tuned Fluorescent Lamps

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|---|---|
| Awardee: | University of Nebraska, Lincoln |
| Principal Investigator | Kevin W. Houser |

### *Introduction*

The consumption of electricity in California has grown steadily each year. An increase of 29 percent between 1980 and 1993 was due more to added population than to increases in energy intensity per square foot. The same source shows that lighting accounted for 10 to 14 percent of the electricity consumed in the residential sector and 42 percent within the commercial sector. The commercial and residential sectors account for 36.3 and 30.3 percent of electricity usage, respectively. According to estimates prepared by the California Energy Commission, electrical consumption for 2005 will total 268,099 gigawatt hours (GWh). Lighting accounts for almost 51,000 GWh of this total. Vision-tuned fluorescent lighting could produce significant savings in energy and costs for commercial building ratepayers and other end users of conventional fluorescent lighting technology.

Beginning in 1931 and continuing steadily into the 1990s, researchers have discovered and published detailed knowledge involving human visual performance as it relates to electric light

sources. This collective body of research indicates that the human visual system performs at its best level when a light source is augmented around the 450, 530, and 610 nanometer (nm) wavelengths. Unfortunately, designs of conventional electric light sources, especially fluorescent lighting systems, do not reflect this knowledge. Current designs spend excess radiant energy in adjacent wavelengths to produce the desired amount of light in the specified wavelengths. Existing fluorescent lamp design and manufacturing doctrines rely on color rendering index (CRI) and efficacy (expressed in lumens of light output per watt of power input) parameters. Neither measure reflects the effect of these most desirable wavelengths of light on known human visual performance characteristics. Despite many recent advances in the energy efficiency of fluorescent lighting systems, current designs based on CRI and efficacy values still result in wasted radiant energy in areas of the spectrum that are of minimal value to the human eye.

Lamps capable of maximizing light output at the desired 450, 530, and 610 nm wavelengths would be an attractive solution for enhancing the performance of fluorescent lighting systems. Limiting the lamp's radiant energy to these wavelengths would eliminate excess energy wasted on other areas of the spectrum, thus reducing the overall energy consumption of such a vision-tuned fluorescent lighting system.

### *Objectives*

The goal of this project was to prove the feasibility of a design for vision-tuned fluorescent lamps that are capable of maximizing light output at the 450, 530, and 610 nm wavelengths and reducing energy consumption by 20 percent. The researchers identified five main objectives:

1. Design and manufacture a set of prototype fluorescent lamps that maximize radiant energy in the three regions near 450, 530, and 610 nm while simultaneously minimizing it in the remaining portions of the spectrum. Make a minimum of four different types of prototype lamp.
2. Perform laboratory tests using both expert and naïve subjects to collect quantitative evidence that will determine if the vision-tuned lamps provide equivalent or superior visual performance. These tests will further determine if the requisite levels of visual performance are attainable with fewer radiant watts than standard fluorescent lamps.
3. Perform laboratory tests using both expert and naïve subjects to determine if the vision-tuned lamps exhibit measurably greater brightness per watt than standard fluorescent lamps.
4. Perform laboratory tests using both expert and naïve subjects to determine if the vision-tuned lamps exhibit greater color rendering than standard fluorescent lamps.
5. In conjunction with the laboratory tests of lighting quality, demonstrate that vision-tuned lamps are capable of delivering energy savings of 20 percent or greater compared to current fluorescent lamps. Once the actual energy savings value is identified in the laboratory tests, extrapolate this value to estimate the overall savings that could be realized in California's non-residential end use sector.

### *Outcomes*

1. The researchers satisfied their first objective. Eight prototype lamps were produced in conjunction with General Electric. One half of the lamps had the same phosphors as off-the-shelf tri-color lamps. These lamps were used for comparison and control. The primary factor in manufacturing the prototype lamps was the development of specialized phosphor configurations that would yield the desired light output. Unfortunately, none of the available phosphors enabled the creation of a truly optimized light source. All of the phosphor configurations generated undesirable levels of radiant power in areas outside the 450, 530, and 610 nm target regions. Nevertheless, the prototypes exhibited sufficient performance in these wavelengths to make the subsequent laboratory experiments possible.
2. The laboratory experiments yielded statistically significant data that demonstrated enhanced visual performance in test rooms illuminated with the vision-tuned lamps. Test subjects in both the expert and naïve categories reported that the test rooms with the vision-tuned lamps were brighter and more colorful.
3. The researchers demonstrated that their third objective was mostly satisfied. A statistical analysis of the test results involving both expert and naïve subjects determined that vision-tuned lamps exhibited equivalent levels of brightness (compared to broadband daylight fluorescent reference source) with 5 percent fewer radiant watts.
4. The researchers showed that both expert and naïve subjects strongly preferred the room illuminated with vision-tuned lamps. At the higher color temperature 94 percent of the expert subjects rated the vision-tuned environment as preferred, 100 percent as more colorful, and 83 percent as more natural. Similar trends (although not as strong) were found for the naïve subjects and at the lower color temperature.
5. The researchers failed to fulfill their fifth and final objective of demonstrating electrical energy savings of 20 percent or greater for the prototype vision-tuned lamps. Test results suggested energy savings estimates of 1.5 to 5 percent.

### *Conclusions*

The researchers did not prove the feasibility of using vision-tuned fluorescent lamps to reduce energy consumption by 20 percent, but improved productivity may well overshadow the energy savings of the lamps tested in this project.

1. While the prototype lamps demonstrated definitive performance improvements in the desired spectral regions near 450, 530, and 610 nm wavelengths, they did not sufficiently minimize the light from other portions of the spectrum. The researchers noted some disappointment with the actual spectral performance of the lamps. They ultimately determined that fluorescent lamp technology rendered it unsuitable for the selective targeting of wavelengths required for optimized vision-tuned lighting.
2. The researchers provided considerable qualitative and quantitative data with statistical validation based on the results from the various operational tests of the prototype lamps, as well as the experiments conducted with the panels of test subjects. These analyses, combined with the lamp test data, fundamentally reinforce the researchers' hypotheses regarding the enhanced visual performance enabled by the vision-tuned lamps. While

the researchers effectively quantified and validated the test results demonstrating the superior visual performance of the prototype lamps, they provided little information to clarify any differences in power consumption attributable to the lamps. A portion of this objective had been the stated intent of enabling enhanced visual performance with the use of fewer radiant watts than conventional fluorescent lamps. Unfortunately, the researchers' discourse was limited to the issues of visual performance and did not quantify any reductions in radiant watts achieved by the prototype lamps during this specific test.

3. Despite the range and depth of data provided by the researchers about the visual elements of the tests, they supplied no information for the input wattage values recorded for the test fixtures during the course of the experiments. As part of the assessment of how well the experiments fulfilled the project's objectives, the researchers estimated energy savings of 5 percent for the vision-tuned lamps, but they identified no electrical test data in support of this estimate. While the result confirms the researchers' hypothesis regarding a greater visual response to vision-tuned lamps, the differential power consumption was less than expected.

   Historical research cited by the researchers suggested that the use of vision-tuned lamps could produce a 30 percent reduction in power requirements (Thornton, IES 1980). While the researchers estimated a more conservative 20 percent reduction in power consumption for the experiment, the resulting 5 percent value represents a significant underperformance for the vision-tuned lamps. The spectral analyses and experiment designs addressed only the performance of the lamps and did not consider any influence of the ballasts and their impact on the stated goal of achieving energy savings. The lamp represents only a portion of a fluorescent lighting system, which depends critically upon the ballast for its function. Thus, the ability of the prototype lamps to yield energy savings requires further analysis in relation to the various ballasts currently operated in fluorescent systems (electro-magnetic, electronic, hybrid electronic, dimmable, digital addressable lighting interface (DALI) programmable, etc.).

4. The researchers met the objective of proving overwhelming preference of users for vision-tuned lighting.

5. The researchers supplied no power measurements or other standard electrical test data in support of the estimated 5 percent energy savings. One hypothesis put forward by the researchers suggests nearly 100 percent potential penetration of vision-tuned fluorescent lamps into the commercial building market. This statement fails to acknowledge the continuing resistance of some end users to modify their existing lighting systems to operate even the current generation of fluorescent lighting technology.

   The researchers suggest that the 5 percent energy savings achieved by the vision-tuned lamps would be applicable throughout the commercial building market. This 5 percent savings estimate was derived from the results of two of the researchers' experiments involving assessments of brightness-per-watt for the vision-tuned lamps. A description of these experiments provided by the researchers indicates how dimmable ballasts were used to modulate lighting levels for the vision-tuned lamps in order to match perceived

levels from adjacent reference lighting sources. Thus, the stated energy savings values depend upon the use of complex dimmable ballasts that are uncommon in most fluorescent lighting systems. Savings consistent with the researchers' results would require corresponding modifications to contemporary ballast characteristics as part of the conversion to vision-tuned lamps.

Fluorescent lamp technology inherently allows excess levels of undesirable radiant energy in portions of the spectrum that defeat the goal of vision-tuned lighting. Furthermore, the energy savings achieved by the prototype lamps was minimal and not well understood in the context of the most common types of fluorescent ballasts operated in the target market.

### *Recommendations*

Based on the test results for the prototype lamps in this project and the researchers' own conclusions, further efforts to derive energy savings from vision-tuned lighting should be directed toward LED technologies.

### *Benefits to California*

Public benefits derived from PIER research and developments 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 ratepayers from this research is increased affordability of electricity in California. The researchers claimed a 5 percent reduction in energy consumption for the vision-tuned fluorescent lamps. According to a report by Heschong Mahone Group in 1997, 22.4 percent of all the electricity used in California is used for lighting. The same source estimated that, assuming full theoretical penetration of compact fluorescent lighting in the residential and commercial sector, 10,603 GWh/year savings is possible by 2010. An incremental 5 percent savings based on the vision-tuned lamps tested in this project results in an additional 503 GWh saving. At $0.10 per kWh this saving is equivalent to $53 million per year. Unfortunately the energy savings is neither big enough nor well enough documented to lead to rapid commercialization and market penetration. It is not likely that the ratepayers will benefit soon from the vision-tunes fluorescent lamps tested in this project.

## 2.18. Low-Cost, High-Efficiency Solar Cell Fabrication Using Inkjet Printing

Awardee: SunPower Corporation
Principal Investigator: Neil Kaminar

### *Introduction*

Photovoltaic (PV) systems are environmentally preferred power generators, employed primarily in commercial and residential applications. Grid-tied PV systems are instrumental in peak load shaving, especially for facilities where the peak load occurs near the middle of the day when insolation levels are greatest. Currently PV systems are much more expensive than other types of generation – on average installed costs range from about $7 to $9 per watt for PV compared to $1 to $1.5 per watt for internal combustion reciprocating engine generators. Lowering the production cost of PV systems would benefit the California renewable energy market. A key area in solar cell fabrication where production costs can potentially be decreased involves the deposition of contact metallization on the silicon wafer (front and back). Currently, there are two proven methods of contact metallization – vacuum evaporation and screen-printing. Vacuum evaporation is effective but requires patterning and is capital-intensive. Screen-printing is less costly than vacuum evaporation, but there are process limitations related to resolution and production throughput. Additionally, screen-printing is an atmospheric printing method that does not require a controlled space.

This project investigated inkjet printing as a method of solar cell construction. Inkjet printing offers advantages over vacuum evaporation and screen-printing. First, inkjet printing is better suited for high-volume production of solar cells and modules. It should also result in better line resolution and improved aspect ratios, which could lead to better solar cell performance. Another advantage over screen-printing is that inkjet printing uses non-contact, conformal deposition. Also, inkjet printing offers lower capital investment than the other two methods. Industry currently uses inkjet printer technology for the fabrication of circuit boards, semiconductor polymers for light-emitting diode (LED) arrays, transistors, and smart labels.

Lastly, inkjet printing presents a no-waste approach to solar cell fabrication. Conceptually, the amount of material needed to cover a cell can be reduced by simply programming the inkjet printer to spray a fixed area.

The principal investigator proposed to determine the feasibility of using a commercially available inkjet printer technology to fabricate SunPower's high efficiency A-300 solar cell. The A-300 solar cell is 20 percent efficient. SunPower was attempting to enter the residential and commercial markets with this product in the timeframe of this project. The principal investigator modified an existing inkjet printer originally designed for printing on circuit boards. The researchers procured ink for this experiment from a company that designs inks specifically for inkjet printers. Using the modified printer and ink, the principal investigator tested the system to determine if minimum feature size of 100 microns (μm) was attainable.

### *Objectives*

The goal of this project was to develop low-cost, high resolution printing using current inkjet technology to fabricate SunPower's high-efficiency A-300 solar cells. Specifically, demonstrate the feasibility of using a modified commercial inkjet printer to deposit contacts on a 5-inch semi square silicon wafer. The researcher established the following project objectives:

1. Develop special inks that are useful in solar cell processing that can be printed by a piezoelectric type inkjet printer.
2. Modify a commercial inkjet printer to be able to print on standard 5-inch semi square silicon wafers.
3. Demonstrate printing an ink dot resolution of 100 μm on standard 5-inch semi square silicon wafers using the modified ink and printer.
4. Fabricate prototype solar cells using the proposed printing method and demonstrate a minimum cell efficiency of 20 percent at laboratory test conditions: 1.5 air mass, 100 milliwatts per square centimeter ($mW/cm^2$) insolation, and 20 degrees Celsius cell temperature.
5. Show from the research findings that the projected PV module manufacturing cost of $1.92 per watt, projected by SunPower for year 2005, can be achieved.
6. Determine feasibility of using the modified commercial inkjet printer obtained from Pattern Technologies Limited in England (PTL) for high-volume production of solar cells. This is a new objective adopted during the implementation of this project.

### *Outcomes*

1. SunPower procured an existing ink from England-based Avecia Limited used for inkjet printing that contained the desired properties for solar cell fabrication.
2. SunPower acquired from PTL a piezoelectric inkjet printer with ultraviolet (UV) curing capable of printing on silicon wafers. The investigator made modifications to the printer to allow for wafer loading and unloading. The investigator produced a vacuum platen system that was mounted on the printer to feed the silicon wafers through the printer. Additionally, the print heads had to be adjusted to obtain the required 720 dots per inch (dpi) pitch. The print heads in their existing configuration had a 360 dpi nozzle pitch. To achieve the desired resolution the two print heads were offset by 35.28 μm. Adjacent nozzles could not operate simultaneously, so two passes were required for a complete print. However, the print heads did not span the entire wafer, so a total of 4 passes were required for each print.
3. SunPower was able to demonstrate reliably a 300 μm resolution; however, the desired 100 μm resolution was not consistently achieved. Textured, metalized, and non-metalized silicon surfaces were tested.
4. Using the proposed inkjet printing technology, the researcher was not able to fabricate a prototype solar cell with the required specifications (minimum cell efficiency of 20 percent at 1.5 air mass, 100 $mW/cm^2$ insulation and 20 degrees Celsius cell temperature).
5. Researcher did not confirm or evaluate production cost of the A-300 solar cell.

6. Researcher developed a conceptual design of a high-volume production version of an inkjet printer used in the production of solar cells. The proposed printer is equipped with eight print heads and has a gross design rate of 1,600 wafers per hour. The total cost for the printer at commercialization is estimated to be $750,000.

### *Conclusions*

The researcher in this project provided a new approach to printing on silicon solar cells. The data, while promising, are not sufficient to prove the feasibility of the concept.

1. The researcher did not design a new ink for this project but used an existing ink that is compatible with inkjet printing. SunPower obtained the ink from a company that is involved in developing inks specifically for inkjet printers. According to SunPower, there are three printing steps in the fabrication of its high-efficiency solar cell. The composition and the required optical and electrical properties for the ink as applied in their solar cell design of the ink were not disclosed. Given that the researcher did not disclose this information, a conclusion cannot be made on whether or not the selected inks were appropriate for this study.
2. The researcher successfully modified an existing PTL inkjet printer to print on 5-inch semi-square silicon wafers. The researcher's selection makes good sense because this printer was originally designed for printing on 18-inch by 24-inch circuit boards. Initial testing and training were provided by PTL in England. Additional testing was performed at SunPower's facility in Sunnyvale, California. The researcher used a Design of Experiment approach to identify the optimum printing parameters.
3. The printer did not have the resolution required to manufacture the high efficiency A-300 solar cell. The researcher did not achieve reliably the required ink dot resolution of 100 μm. Although, the modified inkjet printer was able to demonstrate consistently a 300 μm dot resolution. According to the researcher, the inkjet printing did not reach the level of resolution obtained consistently with screen-printing. There were several reasons why the desired resolution could not be achieved:
    - Variation in flow among nozzles.
    - Randomness in trajectory of ink droplets.
    - Mismatch between printer resolution and required resolution for solar cell production.
    - Software corruptions when converting a Gerber plot file to a bitmap file. A bit location in the Gerber file did not result in the same bit location in the bitmap file.
    - Ink drying was a problem. Possibly, the ink viscosity and/or UV drying time was not optimal.
4. Since the researcher could not achieve the required ink dot resolution, they were not able to fabricate a complete high efficiency A-300 solar cell. The researcher speculates that within the next few years, inkjet technology will have improved to a level where solar cell fabrication is possible. This speculation cannot be supported based solely on

the results of this study. However, there are related published studies researching similar topics that show promise.

5. The researcher did not provide information to confirm or deny the estimated production cost for a SunPower PV module fabricated using inkjet printing. A product life cycle analysis along with a projected cost breakdown for each component would have been helpful in supporting researcher's claim. However, given that a finished solar cell was not completed and limited cost information was provided, the researcher's claim cannot be supported based on the results of this study.
6. The researcher developed a list of optimum design functions and parameters for future inkjet printers used in the fabrication of solar cells. Although not specifically detailed, the qualitative discussion did provide valuable information that can be used as a basis for future research. Future printer designs should have the following capabilities:
    - Equipped with a control mechanism for varying the curing time and UV light intensity.
    - The intensity and final cure time need to be optimized.
    - Nozzles should spray ink consistently and uniformly.
    - Print heads should be equipped with a control mechanism for varying droplet size and finer nozzle pitch.
    - Silicon wafer should sit as close as possible to the nozzles during spraying.
    - Individually programmable nozzles.

### *Recommendations*

Further optimization of the inkjet printing technology for solar cell fabrication is needed. The researcher should consider the following recommendations upon commencement of additional work in this area:

1. Improve ink characteristics to alleviate some of the known and published spraying and curing problems. Other studies performed on solar cell inkjet printing have reported using metal organic inks for fabricating contacts (i.e., silver [trifluoracetate] in ethylene glycol). SunPower should also investigate proper ink adhesion, contact resistance between the sprayed ink and the doped silicon layer, and ink electrical conductivity, as part of its quest for the optimum ink formulation and printer design.
2. With a reputable inkjet manufacturer, develop the inkjet printer technology further so that SunPower can meet the projected solar cell efficiency of 20 percent. The next step in the technology development process would be to implement the proposed design changes resulting from this study into the next generation prototype inkjet printer.
3. Specify optimal inks and further develop compatible printer performance to achieve the required ink dot resolution of 100 μm. Achieving this objective will further SunPower's goal of producing high efficiency solar cells at a lower cost. Processing parameters that should be investigated for optimum print resolution are substrate temperature, translation speed, the frequency, and the amplitude of the controlling impulses.

4. Develop an economic model that can estimate the production cost of the high efficiency PV module. Use this model to optimize the fabrication process and minimize production costs.

### *Benefits to California*

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

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

The availability of a lower cost, high efficiency PV module in the California market will directly benefit ratepayers by reducing environmental impacts of the California electricity supply and transmission and distribution system. Additionally, potential energy and cost savings to ratepayers would result from reducing transmission losses in electricity delivery and extending grid system equipment service life, as well as the period between grid system upgrades. Since the technology is still far from commercialization, it is difficult to estimate the rate at which these benefits would accrue to California ratepayers.

## 2.19. Development of Single Fan Multi-Stack Exhaust Systems

Awardee: University of Nebraska - Lincoln
Principal Investigator: Mingsheng Liu

### *Introduction*

California laboratory and processing building owners currently have fan exhaust systems that require 24 hours per day and 7 days per week operation to remove toxic fumes from the workers' environment. Even though the operations in these labs are not carried out continuously, the fans are in continuous operation, consuming considerable energy and adding to the overall electricity expense. This constant operation of the exhaust fan has been practiced so that safety margins can be maintained, and previous energy-saving fan strategies have resulted in reduced airflows that do not meet minimum safety requirements.

Current estimates indicate California laboratories with a conventional constant-speed, single-stack exhaust system with a 25 horsepower motor per exhaust fan consume 150 megawatt-hours (MWh) per year per laboratory. If the fan energy could be reduced by 55 percent, this would translate to annual savings of 82 MWh per fan worth over $8,000 per year. Further monetary savings are possible if the fan electrical peak demand can be reduced by 40 percent.

The innovation used in this project is the addition of a variable frequency drive (VFD) on the fan motor in combination with the use of a multiple stack system. By developing an optimization method of stack sizes and numbers, and the selection of sensors, actuators, dampers, and controllers, significant energy can be saved by reducing the electrical consumption of the exhaust fan. The VFD modulates the fan speed to maintain the required duct static pressure under partial loads. Low capacity stacks are selected to reduce the fan airflow and maintain required stack exit velocity. Noise is eliminated, and fan power is significantly reduced in the new system.

### *Objectives*

The goal of this project was to determine the feasibility of reducing fan power and energy by employing the combination of variable frequency drives and multiple stacks in building exhaust systems. The researchers established the following project objectives:

1. Design and construct a new energy-efficient, multi-stack variable speed fan exhaust system, one that is specifically suited for laboratory buildings.
2. Perform testing of the new system and demonstrate that it consumes 50 percent less fan electrical energy than conventional fan exhaust systems
3. Demonstrate that the fan electrical peak demand of the new system is reduced by 40 percent compared with conventional exhaust fan systems.
4. Demonstrate that the stack exit velocity of the new system can be continuously maintained at the required 3,000 feet per minute (FPM).
5. Perform an economic analysis and show that the projected payback period of the new system is four years or less.
6. Demonstrate that the new system will eliminate noise problems (new objective).

### *Outcomes*

1. An existing laboratory single-stack, constant-speed fan exhaust system with a 44-inch diameter single stack was chosen as the test site. The design fan airflow is 26,300 cubic feet per minute (CFM), and the design fan head is 3.9 inches of water. The building airflow was 11,000 CFM for normal operation and goes up to 14,000 CFM when all fume hood sashes are fully open. A 44-by-44-inch gravity damper was used to compensate for the airflow difference and maintain constant exit velocity.

   A new energy-efficient exhaust system was designed for the above system and included the following components:

   - A 24 horsepower VFD was installed on the exhaust fan.
   - A multi-stack assembly with a 26-inch diameter stack and a 12-inch diameter stack was installed atop the existing stack. A two-position switch damper was installed in the 12- inch stack.
   - A 6-by -4-inch modulation damper with an actuator replaced the gravity damper for accurate exit velocity control.
   - A static pressure sensor was used to measure the main duct static pressure.

- A static pressure sensor was used to measure the stack static pressure to obtain the fan airflow measurement.
- A static pressure sensor was used to measure the main duct pressure drop to obtain the building airflow measurement.

2. Testing was performed on the existing system before modifications to establish the following baseline conditions:
   - Actual fan airflow was from 28,000 CFM to 30,000 CFM.
   - Stack exit velocity was from 2,600 feet per minute (FPM) to 2,800 FPM.
   - The annual fan energy consumption is 103,400 kWh.
   - The fan electrical peak demand is 12.3 kW.
   - Negative duct static pressure changed from 2.6 to 1.8 inches of water, accompanied by high noise levels at 63.5 decibels with A scale weighting (dBA) in the building and 72.8 dBA in the lighting laboratory.

   The system modifications resulted in the following changes:

   - The fan airflow was reduced to 11,000 CFM for the single stack and 14,000 CFM for the double stack while maintaining the stack exit velocity at 3,000 FPM.
   - The annual fan energy consumption was reduced to 46,400 kWh, a 55 percent reduction from the baseline conditions.
3. Fan electrical peak demand was reduced by 49 percent to a value of 6.3 kW.
4. Actual stack exit velocity is maintained at 3,000 FPM at any exhaust airflow range.
5. The annual fan energy savings was $2,850 with an assumed electricity price of $0.05/kWh, which when compared with the retrofit cost is $10,290 resulted in a payback period of less than 4 years.
6. Duct pressure is reduced from 2.6 to 1.35 inches of water resulting in noise levels that were reduced from 63.5 dBA to 38.5 dBA. This last outcome is a new one that was unanticipated and is added to the original list.

### *Conclusions*

A multiple stack variable speed fan system was developed and tested on a full-scale building exhaust system. The following conclusions were arrived at as a result of this project:

1. A full-scale multiple-stack variable speed fan system was designed and installed on a typical laboratory building.
2. As a result of testing, the annual fan energy was reduced from 103,400 kWh to 46,400 kWh, which was a 55 percent reduction as compared to the original system.
3. During this same testing, the fan peak electrical power was reduced from 12.3 kW to 6.3 kW, which was a 49 percent reduction, compared to the original system.

4. As a result of using multiple stacks, exit exhaust air velocity was maintained at a continuous 3,000 FPM, regardless of the exhaust airflow range.
5. The payback time of the added cost of the improved system was found to be less than 4 years.
6. As a result of duct pressure reductions, the noise levels in the laboratories were dramatically reduced.

In summary this project achieved all of its objectives as shown above, and is a very good demonstration of the energy savings that are possible using intelligent design and operational principles in the use of a multi-stack variable speed fan exhaust system. Also impressive was the maintenance of the stack exit velocity at a constant safe value during airflow change. The energy savings translated into economic savings that allows the improvements to be paid off in a relatively short time. Moreover, the noise level was improved by controlling the duct static pressure using the VFD.

### *Recommendations*

This report answers most of the questions regarding the feasibility of this multi-stack, VFD fan exhaust system. A follow-on area of research could be the streamlining of the multi-stack structure to achieve further energy savings. Other than this, the concept has been proven in a full-scale experiment, and is recommended to transfer this technology to design firms and apply it in manifold variable air volume (VAV) fume hood exhaust system designs. The next step is to perform a market assessment.

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

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

### *Benefits to California*

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

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

The primary benefit to the ratepayer from this research is in increased affordability of electricity in California. The multi-stack, variable speed fan system can be widely applied in any manifold VAV fume hood constant speed fan exhaust systems in commercial or industrial buildings. The VAV fume hoods keep the building exhaust airflow much lower than the exhaust system capacity. Under partial exhaust airflows, the multi-stack system reduces the fan airflow; meanwhile the VFD reduces the fan power. For a typical laboratory exhaust system with an actual exhaust fan power of 25 hp, the annual electricity savings is 82 MWh and the peak demand reduction is 9.3 kW. The economic value of this energy savings is approximately $8,000 assuming $.10 per kWhr for electricity. The overall savings in California is not known since no estimate was made of the total number of laboratories that could use this technology.

# Glossary

| Acronym | Definition |
|---|---|
| µm | Microns |
| ADA | ADA Technologies, Inc. |
| btu | British thermal units |
| btu/h | British thermal units per hour |
| CFM | Cubic feet per minute |
| $CH_4$ | Methane |
| CHP | Chilling, heating, and power |
| CO | Carbon monoxide |
| $CO_2$ | Carbon dioxide |
| COP | Coefficient of performance |
| CRI | Color rendering index |
| CSI | California Solar Initiative |
| DALI | Digital addressable lighting interface |
| dB | Decibels |
| DER | Distributed energy resources |
| DG | Distributed generation |
| DLN | Dry Low NOx |
| dpi | Dots per inch |
| DSSC | Dye-sensitized solar cells |
| EDHX | Enhanced desiccant-heat-exchanger |
| EISG | Energy Innovations Small Grant program |
| EPRI | Electric Power Research Institute |
| FCC | Federal Communications Commission |
| FPM | Feet per minute |
| gr/lb | Grains of moisture per pound |
| GTCC | Gas turbine combined cycle |
| GTCHP | Gas turbine combined heat and power |
| GW | Gigawatts |
| $H_2S$ | Hydrogen sulfide |
| hp | Horsepower |

| Acronym | Definition |
|---|---|
| IAR | Independent assessment reports |
| IC | Internal combustion |
| IEM | International Electronic Machines |
| IOU | Investor-owned utility |
| IPC | Inorganic polymer cement |
| IPCC | Inorganic Polymer Cement Composite |
| IR | Infrared |
| IRR | Internal rate of return |
| kW | Kilowatt |
| kWe | Kilowatt electrical |
| kWh | Kilowatt-hour |
| lb | Pound |
| lb/MWh | Pounds per megawatt-hour |
| LEAMS | Low-Emissions, Atmospheric, Metering Separator |
| LED | Light-emitting diodes |
| LFG | Landfill gas |
| lux | Luminous emittance |
| MEM | Micro-electro-mechanical machine |
| MW | Megawatts |
| $mW/cm^2$ | Milliwatts per square centimeter |
| MWe | Megawatt electrical |
| nm | Nanometer |
| NOx | Nitrogen oxides |
| O&M | Operations and maintenance |
| PG&E | Pacific Gas and Electric |
| PIER | Public Interest Energy Research |
| PPM | Parts per million |
| ppmvd | Parts per million, volumetric dry |
| PTL | Pattern Technologies Limited |
| PV | Photovoltaic |
| RD&D | Research, development, and demonstration |
| rpm | Revolutions per minute |

| Acronym | Definition |
|---|---|
| SCE | Southern California Edison |
| SCR | Selective catalytic reduction |
| SDG&E | San Diego Gas & Electric |
| SEER | Seasonal energy efficiency ratio |
| SF | Square foot |
| SOFC | Solid oxide fuel cell |
| SOx | Sulphur oxide |
| $TiO_2$ | Titanium oxide |
| TOU | Time of use |
| U.S. DOE | United States Department of Energy |
| U.S. EPA | United States Environmental Protection Agency |
| UHF | Ultra high frequency |
| UPS | Uninterruptible power supply |
| UREB | Ultra-reduced emissions burner |
| UV | Ultraviolet |
| VAV | Variable air volume |
| VFD | Variable frequency drive |
| VHS | Very high speed |
| Wp | Watt peak |
| YSZ | Yttria stabilized zirconia |

## 4.0 Glossary

Independent Assessment Report – This is the report that San Diego State University Research Foundation is contractually required to provide the Energy Commission. It provides a summary of the grant projects and provides recommendations for future work.

Proof-of-concept Level Research – This is a basic research project that is seeking to prove the feasibility of a particular technological research project.