Energy Research and Development Division

FINAL PROJECT REPORT

Energy Innovations Small Grant Program:
2015 Independent Assessment Reports
Energy Innovations

California Energy Commission
Gavin Newsom, Governor

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The California Energy Commission Public Interest Energy Research (PIER) Program supported public interest energy research and development that would 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 conducted public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strove 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 were focused on the following RD&D program areas:

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

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

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

A key and unusual characteristic of the EISG program was the method program staff used to attract new ideas and nurture principal investigators. Principal investigators were encouraged to produce high quality proposals and high quality project outcomes. The staff worked with innovators and counseled them on writing clear objectives. Each proposal was reviewed by up to four technical reviewers from throughout the United States. Reviewers were chosen for their expertise from a list of more than 1,000 scientists. The EISG Directors thank all of these reviewers for their dedicated and thorough work.

EISG staff sent proposals passing technical review to a second review by a Policy Technical Review Board (PTRB). The PTRB consisted of approximately 12 highly respected energy experts from the private sector, academia, and the utility industry. EISG was fortunate to have many PTRB members serve for years. To these dedicated PTRB members the EISG Co-Directors extend their sincere appreciation.

Lastly, the EISG Program Co-Directors express their appreciation to the dedicated office staff who kept the wheels of this program on the track as it processed three solicitations and hundreds of proposals per year. Many of the staff served the EISG Program for more 10 years, providing valuable continuity.
ABSTRACT

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

The Energy Innovations Small Grant (EISG) program supported early phase development of promising new energy technology concepts. This category of projects was not covered by PIER general solicitations, which focused primarily on development of established concepts. Qualifying EISG projects addressed one of the defined PIER research, development, and demonstration areas. If feasibility of an innovative energy concept was proven through the EISG project work, then traditional research and development funding sometimes became available to further develop the project.

This report presents a collection of twenty-one independent assessment reports for EISG grant projects awarded in 2015. Each assessment outlines the objectives of the project, discusses the successes and failures, and offers recommendations for potential future work.

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

Please use the following citation for this report:

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EXECUTIVE SUMMARY

Not all research is carried out in large corporations or university setting – individuals can have a slice of research and development investment funds through the Energy Innovations Small Grant (EISG) Program. A component of the Public Interest Energy Research (PIER) Program, managed by the California Energy Commission, the EISG provided $75,000 -$150,000 in funding for hardware modeling projects to small businesses, non-profits, individuals and academic institutions for research that showed the practicability of new, innovative energy concepts. EISG projects targeted one of the PIER research and development areas, addressed California energy challenges and provided potential benefits to California electric and natural gas ratepayers.

This report is a compilation of Individual Assessment Reports (IARs) for grant projects that have not been previously published.

The Energy Innovations Small Grant (EISG) program awarded numerous grants for innovative energy research projects every year. Independent Assessment Reports (IARs) highlight the project outcomes for each of the EISG projects that have not been previously published. The reports in this document summarize the final projects of the EISG Program which ended in 2015.

The results of EISG had been lauded by Energy Commission Commissioners and in the media such as the Sacramento Bee, August 26, 2011, Viewpoints: Energy program generates ratepayer benefits. In addition to fostering technical successes, EISG provided guidance to many innovators in developing projects that could benefit ratepayers, innovators, and California for years to come. The EISG program clearly provided massive benefits to the ratepayers of California at a very low cost.

In its almost two decades, EISG funded more than 450 entrepreneurial projects. Projects received $75,000 to $150,000 to prove feasibility of the proposed concepts. Many of these projects were successful and were either awarded additional funding by government agencies or found venture/angel capital funding to take the concepts to market. Examples of EISG success stories are found on You Tube at http://youtu.be/pTnulBowas0.

The Projects

The EISG program awarded 21 projects totaling $2,925,410 in natural gas related energy research (Table ES-1). The awarded projects consist of 12 companies, eight academic institutions and one entrepreneur. The benefits California expect to receive after the research is completed and implemented are $1.65 billion in natural gas related annual cost reductions, 28 metric tons of CO₂ reductions per year, $10 million in new energy production, 70 percent increase in freight truck engine efficiency, 18 percent increase in in-state bio-power production and a knowledge base of manufacturing techniques for solar water heating and high temperature chiller applications.
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<td>$150,000</td>
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<td>On-Site Agricultural Biomass Gasification as a Natural Gas Substitute</td>
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<td>Enhancing Winter Solar Water Heating and High Temperature Chiller Operation</td>
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<td>The Building Occupant Mobile Gateway</td>
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<td>Advanced Prechamber Ignition For High EGR Dilute Burn Engine</td>
<td>North American Repower</td>
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Source: San Diego State Research Foundation

Projected Benefits to California

1. **Physical Sciences Inc.** - $100 million annual cost reductions from natural gas leak detections
2. **West Biofuels, LLC** – 7.5 million tons reduction in CO2 annually.
3. **Solar Stream Innovations** – Developing different manufacturing techniques for knowledge base.
4. **University of California Davis** – 10 percent energy savings and $3 million per year for Californians.
5. **University of California Davis** - $10 million annually of new energy (methane) production.
6. **Palios Corporation** - $90 million per year cost savings.
7. **University of California Berkeley** – Reduction of 2.4 million Metric tons CO2 equivalent annually.
8. **University of Southern California** – $192 million annually in energy savings for the commercial sector.
9. **Policy Consultants, LLC** – Save $1.5 million annually for multifamily buildings by efficiency monitoring.
10. **University of California San Diego** - Save California ratepayers about $245 million per year while producing 339 billion Btu of fuel gas.
11. **Stanford University** - $478,000 in savings for rate payers.
12. **Pyro-E LLC** – System was not built and tested so no quantifiable benefits.
13. **San Diego State University** – Increase in-state biopower to 18 percent of California annual energy demand.
14. **HI-Z Technology, Inc.** - Reduce 152,000 tons of CO2 annually. and save $22 million each year.
15. **California Polytechnic University** – Offset 11,430,000 megatons annually of CO2.
16. **Taylor Energy** - $2.13 billion annually economic benefits ($1.13 billion revenue and $1 billion cost savings)
17. **Cliff Edge Consulting, LLC.** – 70 percent increase in Class 8 freight truck energy efficiency.
18. **McMEM** – Reduce 18 tons of CO2 annually.
19. **Ken E. Pearson** – State emission standards now apply to this type of vehicle and manufacturers of utility vehicles may offer other solutions more cost effective.

20. **Otherlab** - A prototype was not created by the end of this project, no actual savings.

21. **North American Repower** - Testing showed the product was successful.
CHAPTER 1: 
Final Independent Assessment Reports

Independent Assessment Reports (IARs) highlight the project outcomes for the 21 Energy Innovations Small Grant (EISG) projects. This chapter includes the IARs from grant projects not previously published.

1.1 Natural Gas Leak Detection Sensor for Widely Deployable Networks (2014)

Awardee: Physical Sciences Inc.
Principal Investigator: Michael Frish

1.1.1 Abstract
Tunable diode laser absorption spectroscopy (TDLAS) is a robust, reliable, and configurable gas sensing technique with increasing usefulness for industrial process measurement and control. However, current TDLAS sensors are not yet suitable for mass deployment because of size, complexity, cost, and power use. To overcome these challenges, the project research team introduced a miniature low-cost, low-power TDLAS methane sensor initially intended for widely deployed methane detector networks. This sensor platform was enabled by two key innovations that eliminated thermal control and optical components that complicated and added cost to sensor fabrication. The research team assembled and tested a prototype sensor.

This miniature sensor maintained laser temperature by using a resistive heating technique such that its own waste heat contributed to temperature stabilization, resulting in power consumption lower than 100 milliwatts (mW). A lens-free assembly demonstrated spectral absorbance feature stability without sophisticated laser packaging that would inhibit high volume production. The sensor demonstrated spectral absorbance feature stability of less than 0.05 line width. Furthermore, the laser stability enabled attaining high sensitivities with standard deviations as low as 400 parts per million (ppm) to 500 ppm and 100 ppm to 150 ppm at acquisition rates of 10 hertz (Hz) and 0.1 Hz, respectively. These results held true over the ambient temperature range of 33.8°F to 75.2°F (1°C to 24°C) tested in this project. This compact TDLAS methane sensor achieved the basic performance for widely deployed methane detector networks with low power demand while being an inherently low cost product when mass produced.

Keywords: TDLAS, sensors, gas analysis, instrumentation, spectroscopy, diode laser, accuracy

1.1.2 Introduction
Leaks of natural gas from pipeline infrastructure are potential safety risks as well as greenhouse gas sources, possibly offsetting the climate benefits of natural gas over other fossil fuels. Thus, with increasing emphasis on natural gas as an abundant energy resource, there is concomitant emphasis on improving leak detection and prevention. Maintaining the pipeline system’s security and integrity is a continual process of monitoring pipeline parameters (such as pressure
and flow rate) to recognize abnormal events that may indicate leaks and ruptures. Scheduled
periodic walking, driving, or aerial surveys using methane detectors for locating and repairing
leaks supplement pressure and flow rate monitoring. However, routine but infrequent periodic
surveys may not capture leaks that are intermittent or develop abruptly. Continually operating
cost-effective methane detector networks could help identify these leak sources and provide
early warning of abnormal gas concentrations that may indicate potential safety or
environmental hazards.

The researchers envisioned a network of low-cost sensors to detect leaks in natural gas pipelines
and system components. If fully deployed, the proposed pipeline protection network would
benefit natural gas customers in California and elsewhere by helping early detection of pipeline
leaks that may result in human tragedies and costs. California’s costs are likely about 4 percent
of the national costs. For unaccounted gas leakage alone (not including incidents), California losses
are estimated to be approximately 100 billion cubic feet, worth about $800 million from 2000 to
2011. Continually operating cost-effective leak detector networks, when located judiciously,
could help identify and mitigate the sources of intermittent, yet significant, losses. Assuming that
one million sensors were installed in California at a cost of $500 per sensor, the one-time cost of
installation would be about $500 million, much of which would support product production and
installation jobs in California. The sensors could save California gas companies and consumers
about $100 million per year in costs of lost gas. Thus the sensors could have a five year simple
payback, not including unquantifiable costs of incidents and the environmental impact of gas
leakage.

The researchers planned to demonstrate the feasibility of developing miniature methane sensors
based on integrated optics and tunable diode laser absorption spectroscopy (TDLAS). Two
development goals were low-cost and low-power consumption in a package configured for
widespread deployment at gas meters and other key locations within the natural gas pipeline
infrastructure. This project supported the need for continually operating cost-effective methane
detector networks that can help identify natural gas leak sources and provide early warning of
abnormal gas concentrations that may indicate a potential safety hazard.

TDLAS is a configurable, robust, and reliable gas sensing technology that is commercially
successful in markets demanding sensitive detection of abnormal conditions with minimal false
positive occurrences and minimal down time. The technology is accepted for industrial process
monitoring and control, quality assurance, environmental sensing, plant safety, and
infrastructure security. Sensors incorporating well-packaged wavelength stabilized near-
infrared (1.2 micrograms [μm] to 2.0 μm) laser sources can sense trace concentrations of many
toxic or important industrial gases. Previous to this project the researchers had developed a
commercially available Remote Methane Leak Detector (RMLD™). The researchers developed
this instrument for natural gas pipeline leak surveying. More than 2,900 RMLD™ units are in
use worldwide.

Based on RMLD™ technology, the research team had previously developed a prototype
compact TDLAS sensor package comparable to a smoke detector that provides interfaces for
alarm communications devices. The 6” x 7” x 1.5” sensor consumed less than 1 watt (W) for
continuous operation at a 10 Hz data reporting rate. It sampled the ambient air along a 2” (5 cm) optical path. When configured to sense methane, its expected sensitivity was approximately 200 ppm. By increasing the path length to 10 cm, expected sensitivity improved to 100 ppm. Unlike electrochemical and broadband spectroscopic sensors (for example, LEDs and NDIR), this technology is insensitive to ambient gases other than methane.

Although the RMLD™ achieved the basic performance and data reporting goals for widely deployed methane detector networks (sensitivity of about 200 ppm methane, insignificant cross-sensitivity to other vapors, 60 second response to abnormal methane), its cost exceeded $5,000 per unit and a power demand of about 1 W. These factors diminished the usefulness of operating in large-scale natural gas leak detection systems. This project was intended to overcome technical obstacles to cost and power reduction. The high cost resulted from using laser packages designed in the early 1990s that cost about $1,000 each, bulk optical components which were often hand polished with sophisticated coatings, and control and data processing electronics built from commercial discrete components.

A typical laser package includes a thermo-electric cooler (TEC) platform, a thermistor, a micro lens to project laser light onto an optical fiber facet, an optical isolator to prevent optical fiber back-reflections from disrupting laser performance, and a monitor photodiode for measuring laser output. Because this laser package style enabled industrial quality TDLAS sensors, it has become the de facto TDLAS standard. However, for gas sensing applications the sophisticated laser packaging is unnecessary, detrimental to performance, and an inhibition to high volume production.

The power consumption results primarily from laser thermal control, wherein the laser temperature is maintained near 300 K (room temperature) with the ±10 millikelvin (mK) precision needed for sensitive gas detection. The laser’s efficiency is about 10 percent with about 90 percent of the power supplied to it discarded as waste heat. The TECs in the laser packages consume additional power and create additional waste heat to transport the laser’s waste heat to a heat sink external to the laser package. Since the TEC draws and wastes considerable power, its control electronics must withstand currents of about 1 amp (A), forcing use of discrete and inefficient electronic components.

Eliminating the laser TEC is a key to reducing sensor power consumption and cost.

For this project the research team created a simplified, potentially low cost TDLAS package concept (Figure 1) having no supplementary optics or TEC. The silicon substrate with deposited heater and electrodes for attaching laser and detector is shown in the left panel. The sensor package, including a porous window that allows gas exchange while blocking liquid and solid contaminants, is shown in the right panel. Ribbon cable attaches to an electronic control, processing, and communications circuit board.
1.1.3 Objectives

This project explored the feasibility of developing miniature methane sensors, based on integrated optics and tunable diode laser absorption spectroscopy (TDLAS), intended for low cost mass production and low power consumption in a package configured for widespread networked deployment at gas meters and other key locations within the natural gas pipeline infrastructure.

The researchers:

1. Assembled and documented the sensor and electronics by photographs.
2. Verified that the laser illuminates the detector.
3. Demonstrated detector output signal exceeds 20 millivolts (mV).
4. Demonstrated laser temperature stability with average heater power less than 100 mW.
5. Demonstrated power consumption less than 300 mW at reporting rate of 10 Hz, less than 100 mW at reporting rate of 0.1 Hz.
6. Set the laser temperature and current to identify methane absorbance at 6,046.95 cm⁻¹ at ambient room temperature and for ambient temperatures ranging from 32°F–104°F (0°C–40°C).
7. Achieved spectral absorbance feature stability to 0.1 line width.
8. Demonstrated sensor precision of about 200 ppm methane at reporting rate of 10 Hz, about 100 ppm at reporting rate of 0.1 Hz at room temperature.
9. Demonstrated average heater power less than 100 mW at ambient temperatures ranging from 32°F–104°F (0°C – 40°C).
10. Demonstrated sensor precision of about 200 ppm methane at reporting rate of 10 Hz, about 100 ppm at reporting rate of 0.1 Hz at ambient temperatures ranging from 32°F–104°F (0°C – 40°C).
12. Confirmed from the project findings that the projected manufacturing cost of less than $500 continues to be supported.

1.1.4 Outcomes

1. The researchers assembled the sensor and electronics and documented the equipment with photographs.

2. The sensor successfully detected the laser output.

3. The laser output signal detected by the sensor’s detector measured approximately 1.1 V with the laser tuned to 6,046.95 cm⁻¹.

4. The researchers measured the laser’s temperature stability at room temperature with stability within ±0.01 K. At an ambient temperature of about 75.2°F (about 24°C) and a laser set point of about 95°F (about 35°C), the heater power was approximately 5 mW.

5. At ambient temperature of 73.4°F (23°C), heater power was approximately 5 mW and laser power draw 30 mW. Thus the total power consumed by the laser and heater was ~35 mW, meeting the less than 200 mW objective.

6. The researchers demonstrated functionality at ambient room temperature by operating with the laser’s temperature set to 94°F (34.43°C) and current set to 41 mA to identify methane absorbance at 6,046.95 cm⁻¹. With the laser tuned to 6,046.95 cm⁻¹, heater power ranged from 0 mW to 120 mW, depending on ambient temperature. Over the ambient range of 33.8°F–75.2°F (1°C–24°C), laser power consumption was approximately 30 mW. Thus total power for laser and heater was 30 mW —150 mW at 10Hz.

7. The researchers demonstrated feasibility of lens-free optical innovation by achieving spectral absorbance feature stability of approximately 0.05 line width.

8. At the ambient temperature of about 75.2°F (about 24°C), the sensor demonstrated precisions of 400 ppm at 10 Hz acquisition rates and 100 ppm at 0.1 Hz acquisition rates.

9. Within the ambient temperature range of 33.8°F–75.2°F (1°C–24°C), the heater power was less than 100 mW. The specific laser evaluated tuned to the methane absorbance line only for ambient temperatures less than 27°C.

10. Over the ambient temperature range of 33.8°F–75.2°F (1°C–24°C), the sensor demonstrated precisions of 400 ppm—500 ppm at 10 Hz acquisition rates and 100 ppm—150 ppm at 0.1 Hz acquisition rates.

11. The researchers continued to predict manufacturing costs less than $500 per unit in high volume production (greater than 100,000 units/year) after investment of ~$10 million for integrating miniature electronics, packaging, advanced testing, and developing manufacturing processes.
1.1.5 Conclusions

Feasibility was demonstrated, although not every technical specification was met. In particular, the sensor can only be used at ambient temperatures of up to 75°F (24°C). The miniature sensor maintained laser temperature by utilizing a resistive heating technique, resulting in power consumption for thermal control lower than 100 mW. A lens-free assembly demonstrated spectral absorbance feature stability to less than 0.05 line width. The sensor was calibrated for temperature ranges between 33.8°F to 75.2°F (1°C—24°C) with precision of 400 ppm—500 ppm and 100 ppm—150 ppm at acquisition rates of 10 Hz and 0.1 Hz, respectively. In future work tests should be run at lower concentrations that one would find in the ambient in a leak situation. This compact TDLAS methane sensor achieved the basic performance requirements for widely deployed methane detector networks with low power demand. Of course the performance was achieved in a highly controlled laboratory environment. Extensive field and environmental testing must be completed before this instrument can be ready for mass deployment.

The cost estimates for the final deployed project depend on the production of one million units. The estimated cost of $500 per unit means the deployment of the technology would cost $500 million in sensor cost alone. Final unit costs will only be known when firm quotes are supplied by vendors of components such as the high temperature laser.

The installation, maintenance, and monitoring of the sensor array would substantially increase this cost. The expected payback of five years based on the cost of natural gas that would be saved by the detection and subsequent elimination of leaks seems optimistic.

However, the technology is sound and has a good likelihood of commercialization. Clearly, to be useful throughout California (and many parts of the United States), the upper temperature limit must be expanded. The researchers have a very clear path toward meeting this performance goal.

1.1.6 Recommendations

The Program Administrator recommends the researchers:

- Select an appropriate laser so that the sensor can function up to 104°F (40°C). The laser used in this project operated at ~93.2°F (~34°C) to maintain the desired wavelength. Thus, sensor operation was limited to ambient temperatures less than 74.2°F (24°C) to preclude overheating. Future implementations should specify laser diodes operating above 104°F (40°C).
- Implement dedicated electronics and firmware within the sensor. Sensor testing in this project used discrete electronic measuring components.
- Introduce an ambient temperature algorithm to auto-calibrate. The sensor in this project experienced small calibration variations with ambient temperature changes.
- Develop an algorithm to address ambient temperature changes for auto-calibration.
- Develop a roadmap for product commercialization. Include miniaturizing electronics in the form of application specific integrated circuits (ASIC), packaging, advanced testing, and production techniques.
- Design a field monitoring system that is compatible with utility practice.
• Develop a business plan that defines the product and markets, means for entering markets, and sources of financing to implement the development roadmap.
• Build early prototypes suitable for field testing.
• Work with gas utilities to create and execute a laboratory and field test plan.

After reviewing (1) research findings in the grant project, (2) overall development status, and (3) relevance of the technology to California and the PIER program, the Program Administrator determined the proposed technology should be considered for additional funding within the PIER program.

Receiving follow up funding ultimately depends on (1) availability of funds, (2) submission of a proposal in response to an invitation or solicitation, and (3) successful evaluation of the proposal.

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

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

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

The United States natural gas system comprises approximately 305,000 miles of transmission pipeline and roughly 1.2 million miles of gathering and distribution pipelines. California represents about 4 percent of this system with approximately 11,800 miles of transmission pipeline. Pipeline leakage poses safety hazards, contributes to greenhouse gas loads, and costs customers the price of lost gas. Maintaining the security and integrity of this system is a continual process of searching for, locating, and repairing leaks. The current pipeline leak inspection practice is via scheduled periodic walking, driving, or aerial surveys. These practices cannot rapidly detect pipeline failures that could potentially create explosive conditions.

When fully deployed, the envisioned pipeline protection network would benefit natural gas customers in California and elsewhere by helping early detection of pipeline leaks that may result in human tragedies and costs. California’s costs are likely about 4 percent of the national costs. For unaccounted gas leakage alone (that is, not including incidents), California losses are estimated to be approximately 100 billion cubic feet, worth about $800 million from 2000 to 2011. Continually operating cost-effective leak detector networks, when located judiciously, could help identify and mitigate the sources of intermittent yet significant losses. Assuming that one million sensors were installed in California at a cost of $500 per sensor, the one-time cost of installation would be approximately $500 million, much of which would support product production and installation jobs in California. The sensors could save California gas companies
and consumers approximately $100 million per year in costs of lost gas. Thus, the sensors could have a five-year simple payback, not including unquantifiable costs of incidents and the environmental impact of gas leakage.

1.1.8 Technology Transition Assessment

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

Marketing/Connection to the Market

Heath Consultants, the dominant provider of products for natural gas leak detection, had expressed interest in taking this technology to market. The researchers had not performed a market analysis at the conclusion of this project.

Engineering/Technical

The researchers estimated that they would need an additional three years and $4 million to $5 million to complete development and demonstration.

Legal/Contractual

At the conclusion of this project the researchers had neither performed a patent search nor applied for any patents. They claimed they had not disclosed the proprietary intellectual property.

Environmental, Safety, Risk Assessments/Quality Plans

Numerous environmental, safety, and risk assessments must be completed prior to taking this technology to market.

Production Readiness/Commercialization

The researchers are likely to use Heath Consultants to commercialize this technology once development is complete.
1.2 On-Site Agricultural Biomass Gasification as a Natural Gas Substitute (2014)

Awardee: West Biofuels, LLC
Principal Investigator: Chang-hsien Liao

1.2.1 Abstract
Organic waste feedstocks from agriculture, forestry, urban, and food processing operations can potentially be converted into sustainable and renewable synthetic natural gas (syngas) through gasification technology. Smaller, modular gasifier systems can be installed at the site of the waste production, allowing stranded wastes (potential biofuel feedstocks that may be difficult to access and transport) such as forestry thinning wastes to be processed. Researchers designed an improved the CircleDraft gasifier system to reduce syngas contaminants while also reducing problems caused by stones and other masses mixed in the feedstock. They evaluated a variety of organic wastes produced in California as a representative feedstock for application. They used shells and wood waste to evaluate the gasifier technology. Operational data revealed that the majority of the process parameters were met; however, feedstock loading required additional engineering. The quality of the syngas product was determined to have considerable contamination with tar and one, two, and greater than two ringed organics, thus eliminating its immediate use as a substitute for natural gas. Further problems with the process temperature control and the char removal system limited the operation of the gasifier to three runs. Researchers used validated process economic models to obtain a syngas cost of $3.41 per million British thermal units (Btu). They compared this calculated cost to the price of industrial natural gas and estimated the process payback period at 3.3 years. In addition, the use of organic waste feedstocks has the potential to reduce greenhouse gas emissions by an estimated 7.5 million tons of carbon dioxide per year.

Keywords: Gasification, biomass energy, natural gas

1.2.2 Introduction
California has mandated the use of renewable energy to provide 33 percent of the state’s energy demand by the year 2020. Waste biomass is considered an excellent feedstock for renewable energy technologies since it is relatively low cost and demonstrates few alternative uses. Furthermore, it risks releasing carbon dioxide during decomposition if not properly disposed. The researchers estimated that approximately 80 million bone dry tons of organic wastes are available for use annually. This feedstock includes agricultural wastes, municipal wastes, forestry residues, and food processing wastes.

An important issue is the location of these waste streams. While large centralized organic conversion systems have the potential to reduce the cost of capital and operating costs, they could also increase feedstock costs for transportation and increase roadway congestion and carbon emissions from transportation. Therefore, the researchers chose a modular conversion system that could be installed close to the biomass source and operated in an independent mode to produce electricity and heat. This may be an excellent approach to make use of specific
organic wastes. This is especially true for forestry waste that often represents a stranded resource because of its remote location.

Substantial development has demonstrated that gasification is appropriate for a range of organic feedstocks. Gasification can produce both process heat and syngas that may be converted directly to electricity or upgraded to pipeline quality natural gas (Figure 2). The researchers estimated that the application of gasification to the available waste organic biomass resource has the potential to produce 125 billion cubic feet of replacement natural gas, substantial process heat, and avoid 7.5 million tons of carbon dioxide emissions per year. An additional benefit is the distributed production of energy that may better meet local demand as well as modular application that would be more flexible to changes in organic feedstock supplies. Utility interconnections must also be developed for the gasifiers.

Figure 2: Gasification Process for Waste Organics to Fuel Gas

The specific technology proposed by the research team involved an advanced design for gasification using the CircleDraft system. The technology is an application of a fixed-bed draft-type gasifier. The innovation included improved filtering of tars and particulates in the syngas product as well as a grate system for removing stones and other materials that may otherwise accumulate and contaminate the system. The design was a collaboration of West Biofuels LLC and INSER S.P.A. from Italy.

1.2.3 Objectives

This project determined the feasibility of using a variety of organic waste feedstocks generated in California to produce energy and heat in an advanced gasification process. The researchers:

1. Selected three biomass residues that are suitable for gasification via the CircleDraft gasifier system.
2. Demonstrated a gasifier system that can measure specific feedstock and gas properties within specific criteria including feedstock mass flow and composition, gas flow and composition, and heating value of the feedstock and syngas.

3. Demonstrated gasifier parameters including efficiency and product syngas heating value, inert content, and impurities.

4. Confirmed the compatibility of the gasifier with natural gas devices, operating hours, capital costs, and product syngas costs and project the system payback duration.

1.2.4 Outcomes

The research team completed all identified project objectives. Specific outcomes include:

1. The researchers selected five prospective biomass sources for consideration, including almond and walnut shells, orchard pruning from almond production, and redwood and oak wood residues from thinning operations. The criteria for a prospective feedstock included statewide availability of one million tons per year, cost of less than $30 per ton, average moisture content of less than 25 percent, average ash content of less than 5.0 percent, average heating value greater than 7,000 Btu per pound, an ash melting temperature greater than 1,100° C, and delivered particle size of less than three inches. None of the biomass sources met all of the criteria. While almond and walnut shells and pruning waste met the cost, moisture, ash, Btu value, particle size and ash melting point, the annual availability was substantially less than one million tons. Biomass from wood thinning operations met all of the parameters with the exception of cost per ton. In the 2016 projection, transportation costs resulted in an overall biomass cost of $50 per ton. The researchers anticipated that location of a gasification plant closer to the wood waste source could provide a feedstock cost of less than the $30 per ton criteria. As such, the researchers projected that timber thinning operations could provide a feedstock for gasification that meets all of the important criteria.

2. The researchers operated and tested the CircleDraft gasifier to ensure that it could accurately measure feedstock flow rate, feedstock composition, feedstock heating value, process gas flow rate, gas composition, and syngas heating value. Measurement of the feedstock flow rate was difficult since the need for a sealed system ultimately resulted in the application of a double-dump feeder. This system for feedstock addition provides better accuracy when measured over a longer period of time. However the system demonstrated a relative standard deviation of almost 11 percent that was substantially higher than the anticipated accuracy of 5 percent. The researchers anticipated feedstock composition to be within 3 percent of moisture, fixed carbon, and volatile solids. These projections were met. However analysis of feedstock ash content was variable with a relative standard deviation of almost 12 percent. Process gas flow measurement was within the projected 10 percent and gas composition was determined to be within the 99 percent sum for all constituents. Researchers determined the heating value of the feedstock to be within less than 1 percent of true value and thereby within the anticipated 3 percent. Determination of the heating value for the product syngas
demonstrated a relative standard deviation of 4.6 percent that was slightly higher than the projected 3 percent.

3. The research team operated the CircleDraft gasifier using walnut shells and oak trimmings for three separate runs. Operational data were collected and analyzed and system performance was reviewed. Data indicated that the system met the efficiency parameter of greater than 70 percent, with the exception of periods during initial startup in which the system temperature was not optimum. Analysis of product syngas heating value was generally in the range of 150 to 300 Btu standard cubic foot of gas, as predicted. In addition, the syngas inert content was less than 60 percent for the majority of the process samples tested. That was within the specifications for the system. In general, the product syngas values were dependent on the gas flow rate and operating temperature of the system. Values outside of predicted were generally during startup or shutdown of the system when operating parameters were not optimal. Product syngas impurities did not meet performance specifications with substantial contaminants including tars and one, two, and greater than two ring organic components.

4. The researchers reviewed the compatibility of the product syngas for use in natural gas devices from the data collected during the operational runs with the biomass feedstocks. Data indicated that while the syngas product demonstrated the minimum energy content of 150 Btu per standard cubic foot of gas, the contaminant load was excessive and was not acceptable for use in natural gas devices. Additional system engineering is necessary to address the issue of syngas contaminant content. Consideration of the potential to operate the gasifier system at near 80 percent capacity, which is greater than 7,000 hours per year, could not be addressed due to engineering problems which reduced the actual operating time of the system. Issues with the feeder system, internal system operating temperature, and syngas contaminants restricted the operating time for the process. Researchers considered the economic analysis for system capital and syngas costs as well as investment payback period. They identified a capital cost of $125,000 per million Btu per hour plant size that was somewhat higher than the projected cost of $100,000 per million Btu per hour. However they calculated the cost of the syngas product to be approximately $3.41 per million Btu. That value was considerably less than the $6—$12 per million Btu projected. Finally, the system payback period was calculated to be 3.3 years based on a natural gas sale price of $6.35 per million Btu.

1.2.5 Conclusions
This project demonstrated an improved design of a traditional fixed-bed draft-type gasifier. The CircleDraft system employed improved engineering, providing better filtering of tars and particulates in the product gas and a grate system to reject stones and agglomerates that can accumulate in the bed in standard gasifier designs.

The following conclusions can be made:
1. Evaluating the timber waste from thinning operations and shells derived from almond and walnut operations demonstrated adequate values for moisture, ash, and heating value. However, some waste sources did not demonstrate the minimum statewide availability of greater than one million dry tons per year and, their use would need to be part of a combined feedstock to achieve this. For timber mill waste and forest thinning, researchers considered sufficient biomass to be available. However, the overall cost per ton was excessive based on transportation demand. Alternatively, the location of a gasifier close to the wood waste source could reduce the cost per ton for this feedstock, making it a viable biomass opportunity.

2. The ability to accurately measure and monitor the gasifier system is imperative if the process is to perform effectively and reliably. The engineering design of the feedstock addition system was problematic and required additional engineering to accomplish. The accuracy of measuring the feedstock addition to the process was outside of the envisioned accuracy of 5 percent. Accurate feedstock flow rates are important and variability may impair the process performance by changing the organic loading, temperature, and other parameters. In addition, analysis of ash content was less accurate. The process gas flow measurement met the performance of less than 10 percent relative standard deviation, allowing for acceptable accuracy in process flow monitoring and control. Gas flow measurement is an important operational parameter which controls the overall process rates and conversion of the organic biomass to the syngas product. Researchers determined analysis of the gas composition for major and trace gases was accurate to within 99 percent. That allowed for good monitoring of the process conversion within the gasifier. Researchers also determined feedstock heating value was accurate to within 1 percent, potentially allowing for good control of the process operation. They determined the accuracy in the analysis of the heating value of the product syngas was approximately 4.6 percent as compared to the anticipated relative standard deviation of 3 percent.

3. The researchers performed three runs with the CircleDraft gasifier using the biomass feedstocks. They measured a number of important process parameters and demonstrated that the system performed within specifications, including gasifier efficiency, product syngas heating value, and syngas inert content. The researchers noted that several of these parameters made excursions outside the normal ranges, specifically during startup but also during shutdown operations. However, researchers determined the most important parameter involving syngas impurities was well outside the required parameters for its use as a substitute for natural gas. Substantial levels of tar and one, two, and greater than two ring carbon were found to contaminate the syngas, resulting in contamination of the impingers and filters in the system. This indicated the improved CircleDraft gasifier design, anticipated to reduce or eliminate syngas contamination, did not perform as designed. While this data will be useful in re-evaluating the process, it is obvious that substantial engineering modifications will be necessary to circumvent this problem.
4. Using biomass feedstocks to operate the CircleDraft gasifier did not result in an acceptable syngas product, and therefore the process data could not be used directly to evaluate the process economics. In addition, since the gasifier suffered from a variety of mechanical problems, including the feedstock loading system and contamination of the syngas product, researchers did not perform collection of longer term operational data. Therefore no real analysis of potential capacity could be made and substantial engineering modifications must be implemented for longer term operations. Even without significant system performance data, the research team was able to conduct economic feasibility analysis using validated models for the process. The economic feasibility analysis indicated a slightly higher capital cost for the gasifier system than initially projected, while the syngas cost was about half of the projected cost. Ultimately, the researchers estimated the system payback period at 3.3 years based on the 2016 cost for natural gas in California. The researchers may not have accounted for all the elements of the syngas price. Cost of production of the syngas, while a major component of price, does not include all delivered costs such as profit, insurance, sales cost, management, and taxes. When all cost elements are included, the syngas may not be cost effective.

While the researchers made progress in this area, they did not prove feasibility. If proven feasible, this technology has the potential for California use, especially for stranded feedstocks such as forest thinning operations.

1.2.6 Recommendations
The Program Administrator recommends additional engineering to correct performance issues that were identified for the application of the CircleDraft gasifier for biomass waste feedstocks. The current project did not meet the most important criteria for syngas quality and stable operation. This indicates that the process is not ready for further demonstration or scale-up but requires a step back to evaluate the process at a more basic level. This effort will require substantial funding to improve the feedstock addition system and to improve process temperature control and syngas contaminant removal. In addition, the researchers should:

- Determine what permits would be required for modular gasifiers in different areas of California.
- Work with gas and electric utilities to determine what type of interfaces would be required for the distributed units and where the units could be located so the produced syngas and electricity can flow into the utility grids.
- Evaluate the level of training for operators of the distributed units.
- Develop a maintenance plan.

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

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

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California energy supply and distribution system. If this technology is proven feasible, the benefit will derive from the ability to convert organic waste to energy at smaller scale and in a modular format. Locating smaller waste-to-energy technologies at the waste source rather than encountering the transportation costs to move waste to a larger, centralized conversion facility would make economic sense if utility interconnections were feasible at those sites. A modular design would also allow for easier application of the technology to varying amounts of waste that may be seasonally impacted. In addition, a modular and mobile design may allow for the process to be used in a temporary setting and moved to locations as the need arises. Again, the permits and interconnections must be compatible at each of the temporary sites. Finally, using organic waste materials to generate energy reduces reliance on natural gas and provides for a sustainable energy source while reducing carbon dioxide emissions from natural decay of organic wastes. The research team estimated that application of the gasifier technology to eight million bone dry tons per year of organic waste could displace 125 billion cubic feet per year of natural gas and reduce greenhouse gas emissions by 7.5 million tons of carbon dioxide per year. At this time it is not possible to project when this technology might have an impact on California ratepayers.

1.2.8 Technology Transition Assessment

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

Marketing/Connection to the Market
The research team has a relationship with INSER-S.P.A. regarding the application of the CircleDraft gasifier to organic waste feedstocks. However the research team has not completed a market analysis for application of the technology nor determined potential partners for market penetration.

Engineering/Technical
The improved gasifier design was expected to reduce syngas contaminants while reducing problems with rocks and agglomerates by using an advanced grate system. However, substantial engineering problems surfaced during operation of the gasifier, including optimizing the feeding system and significant contamination of the syngas product. As such, substantial engineering improvements are necessary for the gasifier to operate as proposed using organic waste feedstocks.

Legal/Contractual
The research team’s partner, INSER-S.P.A. holds a patent on the CircleDraft gasifier design. The research team has not pursued any patents on the technology. However, important improvements are still required for the CircleDraft gasifier to function as anticipated and these improvements may be appropriate subject matter for further patents relating to the technology.
Environmental, Safety, Risk Assessments/ Quality Plans

Conventional gasifier technologies have been used for a substantial period of time with good environmental and safety records. Developing the CircleDraft gasifier for organic waste feedstocks requires improvements in engineering to meet operational expectations. Once the technology is proven, environmental, safety, and risk assessment should be undertaken.

Production Readiness/Commercialization

The technology is not yet ready to be considered for commercialization.


Awardee: Solar Stream Innovations
Principal Investigator: Jeffrey Lee

1.3.1 Abstract

Solar water heating is more efficient when operated at higher temperatures. One key to operating at higher temperature is to reduce heat losses. The higher temperature heat transfer fluid in the solar collector will improve the performance of a heat-driven chiller and also improve winter heating performance of solar water heaters. The researchers in this project proposed to use vacuum insulation as a means to decrease solar collector manifold heat loss compared to traditional fabric insulation.

The researchers used laser cutting of stainless steel tube, CNC milling of copper pipe, and vacuum furnace brazing processes to fabricate vacuum insulated manifolds. They retrofitted normal diameter, optical concentrating small diameter, and large single wall evacuated tubes, LN 58-1800, CPC 1515, and Seido 1-16 collectors, respectively, with vacuum insulated manifolds and tested them for thermal performance efficiency. Outgassing decreased the quality of the vacuum as researchers tested operating temperatures above ambient. While operating at approximately 68° C above ambient temperature, outgassing likely contributed to inferior retrofit performances of the collectors. During this project the researchers did not achieve their goals nor prove feasibility.

Fabrication process improvements during vacuum furnace brazing could be the only scalable remedy to self-seal high vacuum around prototype manifolds to achieve desired efficiency gains. High temperature oil testing, which was not accomplished during this project, is the best means to clearly differentiate before and after retrofit performance.

Keywords: Solar water heater, manifold, vacuum furnace, evacuated tube solar water heater

1.3.2 Introduction

Evacuated tube solar collectors are a low cost, mass-produced technology being widely deployed in many countries to provide residential space heating. Current evacuated tube solar
collectors are designed to only heat water and not to sustain peak temperatures to constantly supply high temperature heat for chiller operation. Moreover, evacuated tube collectors operate well in the winter; however they could operate even more efficiently and provide additional winter heating when heating is most required. Improving this type of thermal energy collection could increase solar thermal heating and cooling in California. By substituting more solar heating for natural gas heating, natural gas consumption during the winter should decrease. In addition, summer cooling load could be shifted from electricity to solar and natural gas, while simultaneously meeting water heating demand.

Solar water heating is more efficient when operated at higher temperatures. One key to operating at higher temperature is to reduce heat losses. The higher temperature heat transfer fluid in the solar collector will improve the performance of a heat-driven chiller and also improve winter heating performance of solar water heaters. The researchers proposed to use vacuum insulation as a means to decrease solar collector manifold heat loss compared to traditional fabric insulation.

Current evacuated tube solar collectors use glass wool to insulate the manifold at high operating temperature. The manifold is simply a copper pipe with a plurality of perpendicular intersecting sockets that receive the condenser bulbs of the evacuated tube heat pipes. Fluid is pumped into the copper pipe at one end and flows around the heated sockets until the fluid exits the copper pipe at a higher temperature. The current insulation does not provide adequate heat isolation. Vacuum insulation is the best form of insulation, eliminating convection and conduction of heat. The researchers proposed to develop a vacuum insulation system for the solar collector manifolds. Figure 3 illustrates a traditional system. The researchers proposed replacing the traditional thermal insulation with a vacuum housing.
Researchers proposed to replace the conventional insulation on the manifold with vacuum insulation.

1.3.3 Objectives

This project was to determine the feasibility of using an evacuated housing for tube solar collector manifolds to achieve improved thermal efficiency at operating temperature much higher than ambient temperature. Researchers:

1. Demonstrated fabrication and modular assembly can be performed using hand tools.
2. Confirmed chosen material thickness and composition can be brazed without leaks.
3. Confirmed internal assembly pressure tested to 160 psig and maintain pressure for 10 minutes without > 5 percent test pressure loss in accordance with SRCC Standard 100-5.3.
4. Confirmed joints do not leak with full length and pressure test.
5. Confirmed Seido 1-16 thermal performance increases by > 20 percent from 35 percent to > 42 percent at ΔT of 100°C.
6. Confirmed fabrication durability by confirming vacuum maintained and no fluid leakage.
7. Confirmed joints do not leak with full length and pressure test.
8. Confirmed LN 58-1800-20 thermal performance increases by > 20 percent from 31 percent to > 37 percent at ΔT of 100°C.
9. Confirmed CPC 1515 thermal performance increases by > 20 percent from 44 percent to > 53 percent at ΔT of 100°C.
10. Confirmed fabrication durability by confirming vacuum maintained and no fluid leakage.
11. Confirmed from the project findings that the projected manufacturing cost of $1,200 continues to be supported.

1.3.4 Outcomes
1. Researchers showed hand tool assembly was possible with both designs and full fabrication could be performed.
2. Prototypes could be brazed and were leak tight to helium.
3. Pressurized air and helium leak testing proved copper-copper joints could be leak tight brazed both by hand and by furnace, but stainless steel-copper joints could only reliably be leak tight brazed with a furnace.
4. Assembled full-length prototypes maintained pressure and were leak tight to helium.
5. Prototype performed 8.2 percent worse after retrofit at a $\Delta T$ of 70°C.
6. Prototypes did not leak during testing, withstanding all pressure loads applied at varying operating temperatures.
7. Assembled full-length prototypes maintained pressure and were leak tight to helium.
8. Prototype LN 58-1800-20 performed 2.9 percent worse after retrofit at a $\Delta T$ of 68°C.
9. Prototype CPC 1515 performed 1.9 percent worse after retrofit at a $\Delta T$ of 68°C.
10. Prototypes did not leak during testing, withstanding all pressure loads applied at varying operating temperatures.
11. The researchers projected a price premium over a traditional LN 58-1800 solar collector of about $442 or 2.7 percent.

1.3.5 Conclusions
The prototypes performed worse after retrofits. The researchers demonstrated that retrofitting commercial off-the-shelf collectors with vacuum insulated manifolds does not improve collector performance.

1.3.6 Recommendations
The Program Administrator recommends the researchers:
- Perform analysis to determine why the project hardware did not result in measurable benefits.
- Determine if an alternate design has a better chance of producing positive benefits.
- Seek advice and recommendations from heat transfer experts on possible paths for concept redesign.

1.3.7 Benefits to California
Public benefits derived from PIER research and development projects are assessed within the following context:
- Reduced environmental impacts of the California energy supply and distribution system
- Increased public safety of the California energy system
- Increased reliability of the California energy system
- Increased affordability of energy in California
The primary benefit to the ratepayer from this research would have been increased affordability of energy in California.
Since there was a lack of improvement in performance after retrofitting off-the-shelf solar collectors with vacuum insulated manifolds, there were no quantifiable benefits to California resulting from this project. The only benefit may be the developing a knowledge base of different manufacturing techniques for future technologies such as vacuum insulated pipelines for high temperature applications.

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

Marketing/Connection to the Market
A project subcontractor, SunEarth, expressed interest in taking the product to market if performance can be improved. Market assessment was not performed during this project.

Engineering/Technical
The researchers stated they planned to continue work on this project but were not clear on funding levels or time. Improving the vacuum is the primary engineering challenge.

Legal/Contractual
The researchers did not file for any patents during the period of performance.

Environmental, Safety, Risk Assessments/ Quality Plans
Any of these plans are premature until a functional prototype has been developed.

Production Readiness/Commercialization
Critical engineering tasks must be completed before the researchers spend effort on a commercialization readiness plan.


Awardee: University of California Davis
Principal Investigator: Theresa Pistochini

1.4.1 Abstract
This project developed an automatic clothes dryer cycle termination controller to accurately predict the end of the drying cycle. The technology promises to be more accurate and robust under different load and environmental conditions in comparison to existing technology. The researchers demonstrated the automatic controller in the laboratory to reduce energy use in gas clothes dryers by accurately terminating the drying cycle when the remaining moisture content of the load was 2 percent or less. In a standard United States Department of Energy (DOE) test conducted three times, the controller shut off the dryer when 2 percent remaining water content was predicted. Measured results showed remaining moisture content of 1.62 percent, 1.89 percent, and 1.93 percent for the three tests. For drying the DOE standard test load, the controller used 5—15 percent less total energy in comparison to three gas dryers tested by DOE. The researchers also demonstrated the accuracy of the controller for other load types under
other environmental conditions. An additional outcome of the project was determination of a method to use the information obtained in the drying cycle to predict real time energy efficiency metrics that can be used to track dryer performance with time as a means for fault detection and to provide information to the consumer.

**Keywords:** Clothes dryer controls, clothes dryer energy efficiency, automatic cycle termination, automatic shut-off, real time energy efficiency metrics

1.4.2 Introduction

According to the California Energy Commission’s 2009 Residential Appliance Saturation Survey, gas dryers consume 6 percent of total residential natural gas use. There is evidence that clothes dryers consume unnecessary energy by continuing to run well past the point where clothes are dry. Clothes dryers operate with two basic types of controls: timed dry and/or automatic termination. A timed dry shuts off the dryer after a pre-determined period of time set by the user, which is likely to result in under or over drying the contents. Automatic termination uses sensors and a controller to determine when the clothes are dry and automatically shuts off the dryer.

There has been a move toward automatic termination controllers that use some method of sensing to determine when the load is dry. Available test data; however, show these control systems do not fare well when their energy efficiency performance is measured. To gather data on the effectiveness of the automatic termination controls for dryers, the United States Department of Energy (DOE) tested numerous electric and gas dryers at an independent test laboratory (Table 2). For the eight dryer models tested, the automatic termination feature used 4—62 percent more energy than was required to dry the clothes to the remaining moisture content (RMC) standard of 2 percent. This means that in all cases tested the dryer ran the heat substantially longer than required to meet the standard. These tests were completed under DOE standard test conditions with new equipment, a specified test load, and inlet room air temperature modulated to be 75 ±3° F. However, performance may vary under different environmental conditions, load types, and as sensor accuracy drifts with time.
Table 2: Excess Energy Consumed by Automatic Termination of Dryer (DOE)

<table>
<thead>
<tr>
<th>Product Class</th>
<th>Sensor Technology</th>
<th>Energy Consumption (expressed as kWh)</th>
<th>Excess Energy Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>To Reach 2 percent RMC</td>
<td>End of Cycle Automatic Termination</td>
</tr>
<tr>
<td>Vented Electric Standard</td>
<td>Moisture + Temp</td>
<td>2.07</td>
<td>2.62</td>
</tr>
<tr>
<td></td>
<td>Temperature</td>
<td>2.23</td>
<td>3.12</td>
</tr>
<tr>
<td></td>
<td>Moisture + Temp</td>
<td>2.32</td>
<td>2.41</td>
</tr>
<tr>
<td></td>
<td>Moisture + Temp</td>
<td>2.28</td>
<td>3.14</td>
</tr>
<tr>
<td>Vented Electric Compact (240V)</td>
<td>Temperature</td>
<td>0.88</td>
<td>1.42</td>
</tr>
<tr>
<td>Vented Gas</td>
<td>Moisture + Temp</td>
<td>2.57</td>
<td>2.91</td>
</tr>
<tr>
<td></td>
<td>Moisture + Temp</td>
<td>2.53</td>
<td>3.16</td>
</tr>
<tr>
<td></td>
<td>Moisture + Temp</td>
<td>2.48</td>
<td>2.84</td>
</tr>
</tbody>
</table>

2 percent remaining moisture content (RMC) is considered “dry”

While dryer manufacturers do not publicize their control algorithms, the DOE testing categorizes dryers either as containing contact moisture or exhaust temperature sensors. A contact moisture sensor is a conductivity sensor that is shorted when moist clothes pass over the sensor. One limitation of this strategy is that the load may dry unevenly, so the clothes in contact with the sensor may not be representative of the entire load. Additionally, these sensors can malfunction when obstructed by lint or coated in fabric softener, and they can be damaged by dryer contents.

Another approach uses exhaust temperature measurements to determine dryness. There are two problems with this temperature measurement method: 1) the temperature of the exhaust will vary with inlet air temperature irrespective of content dryness (particularly if the dryer is located in unconditioned space such as a garage), and 2) the calibration of the temperature sensor may drift with time.

Some manufacturers use humidity sensors to measure moisture content. However, low cost relative humidity sensors have lower accuracy and stability compared to temperature sensors.

Historically, dryer manufacturers have not had significant motivation to develop accurate and reliable cycle termination controllers because dryer minimum efficiency standards do not require testing the automatic termination feature. In January 2015, Energy Star implemented a new clothes dryer certification that requires dryer manufacturers to meet an efficiency requirement with automatic termination controls. While the Energy Star program should move the competitive market in the right direction, low cost, reliable automatic termination technologies are necessary to achieve Energy Star goals.
Researchers developed and tested a relatively simple and inexpensive approach to improve automatic termination controls for clothes dryers. They developed an automatic control that measures the temperature of the air as it enters and exits the drum (Figure 4). As water is removed from the load, the temperature of the exhaust air is lower than the temperature of the heated inlet air from the cooling of the evaporated water. While the contents are drying, the differential temperature of the exhaust air plateaus in comparison to the inlet air. When the contents are almost dry, the differential temperature of the exhaust air decreases compared to the inlet air. The researchers developed control algorithms to detect these signal changes, determine remaining drying time, and shut off the gas heat and enter the cool-down cycle. The objective of the proposed research was to shut off the gas heat within two minutes of when the remaining moisture content reaches the DOE specification of 2 percent.

**Figure 4: Location of Sensors for Automatic Clothes Drying Sensing Technology**

Because accurate measurement of the temperature differential is critical, the researchers developed and tested a method to self-calibrate the signal periodically (for example, monthly) when the dryer is not in use. During calibration, the fan and heater will run for a short time and the exhaust sensor temperature value will be compared to the inlet temperature to re-calibrate the temperature differential endpoint. In the final system, the important measurement was the relative signal between the two resistive temperature detectors (RTD) (Figure 5) and not the actual temperature. This strategy resolves several problems with existing control systems:

1. The differential signal is not impacted by the inlet air condition, as is the case for a control system that attempts to determine dryness based on a single exhaust temperature value.

2. The RTD sensors are not subject to contact with dryer contents, as is the case for a moisture sensor that is in contact with (and likely damaged by) dryer contents.

3. The system will periodically self-calibrate to maintain sensor accuracy over the lifetime of the dryer. Existing state-of-the-art sensors do not assure accuracy over time.
1.4.3 Objectives

This project determined the feasibility of a low cost self-calibrating automatic controller to reduce energy use by 20 percent or more in gas clothes dryers and accurately terminate the drying cycle when the remaining moisture content of the load is 2 percent or less. The researchers looked to:

1. Confirm the hardware measures the differential temperature signal with an accuracy of 0.5° F.
2. Confirm the test stand is capable of testing a dyer to specifications of DOE Appendix D2.
3. Demonstrate the control shuts off gas heat within two minutes when remaining moisture content is 2 percent or less.
4. Demonstrate energy consumption using auto shut-off as measured by DOE Appendix D2 is 2.6 kWh or less.
5. Confirm sensors and controller can be manufactured at a cost not to exceed $25 to the dryer manufacturer.

1.4.4 Outcomes

1. The researchers designed and tested several control schemes, building and learning from the experimental results as the project progressed. The final control scheme design monitored the rate of change of the temperature difference between the inlet and outlet dryer temperatures. With this design, the researchers determined the actual accuracy of the measured temperature values were not critical. Therefore, demonstrating the 0.5° F signal accuracy was not a requirement for the controller based on the final design and was not further pursued.

2. The researchers constructed a test stand at the University of California, Davis, which largely satisfied the requirements of DOE Appendix D2. A few of the requirements were not satisfied because they were cost prohibitive and were not expected to significantly impact the test results. Researchers used utility-provided natural gas instead of laboratory grade natural gas. They accounted for this change by using the highest heating value of the fuel reported by the utility providing the gas service, which was 1.7
percent higher than the heating value specified by the test standard. Also, it was not possible to condition the tests cloths with the specific water temperature and hardness, and was not expected to impact the results.

3. The measured evaporation rate near the end of the cycle was 0.005 lbw/second, meaning the controller shut off the dryer within seven seconds of reaching remaining moisture content of 2 percent.

4. For the final controller design, researchers conducted three repeats of the DOE Appendix D2 test. For the DOE test load, a load with 2 percent remaining moisture content would weigh 8.6 pounds. For three repeats of the DOE Appendix D2 test, the final weight of the dry load when the controller shut off the dryer was 8.568 lb., 8.591 lb., and 8.595 pounds., which equates to remaining moisture content of 1.62 percent, 1.89 percent, and 1.93 percent, respectively. The total energy consumption (converted to kWh) for each load was 2.80 kWh, 2.69 kWh, and 2.61 kWh, or an average of 2.70 kWh. This was 4 percent higher than the target objective of 2.6 kWh. In addition to the DOE Appendix D2 tests, the researchers tested the controller with a variety of different load types with different room air conditions. The controller automatically shut off the dryer when the load was determined to be dry, and the measured remaining moisture content at the end of the test varied between 1.62—6.68 percent. All but one test had remaining moisture content between 1.62—5.0 percent, where 5.0 percent is higher than the DOE test standard of 2 percent. However, consumers would consider this moisture level dry. The energy consumed for the drying cycles varied between 1.4—4.13 kWh, where the energy consumption was a function of the size and composition of the load.

5. The researchers estimated parts cost for the controller if the components are purchased in large volume (10,000 units) at $24, less than the $25 target cost. The output relays and power supply may be redundant with components used in existing dryer controllers, so the incremental parts cost over existing controllers may be less.

1.4.5 Conclusions

1. This objective was not met. Although the researchers explained why this level of accuracy is not required, they should specify what adequate accuracy is required.

2. The researchers almost met this objective. They were constrained by budget to fully meet the DOE specifications. To some extent the researchers used a more realistic test than the DOE specifies.

3. The researchers met the performance objective of shutting off the dryer when obtaining 2 percent remaining moisture content.

4. The average energy consumption was 4 percent higher than the target of 2.6 kWh for the DOE standard test load.

5. The researchers estimated the parts cost for the developed termination controller at $24. This number could change when the controller is integrated into a complete clothes dryer control system. The researchers did not attempt to estimate the extra labor to
install this controller into a commercial dryer. A manufacturer would have to estimate the incremental cost and therefore consumer price. This objective was met.

The researchers essentially proved feasibility of an automatic dryer cycle termination controller. The data used to determine when to terminate the drying cycle could also be used to provide energy efficiency reporting metrics.

1.4.6 Recommendations
The Program Administrator recommends the researchers:

1. Develop additional data correlating the load size to the temperature response of the dryer when the burner fires.

2. Improve signal processing techniques to reduce errors in calculating the maximum temperature difference and associated drop of the temperature difference when the load is nearly dry.

3. Test the controller in different models and brands of dryers.

4. Compare test results of the project controller to other existing controllers under load and room conditions that vary from the DOE Appendix D2 standard.

5. Explore possible applications of real time energy efficiency tracking metrics.

6. Further develop the cost model with a manufacturer of clothes dryers.

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

Receiving additional funding 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.

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

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

The primary benefit to the California ratepayer from this research is increased efficiency and affordability of energy. The researchers demonstrated a cycle efficiency of 2.70 kWh per load using the DOE Appendix D2 test procedure. This compares to test data for three other cycle termination controllers tested by the DOE that had results of 2.91 kWh, 3.16 kWh, and 2.84 kWh.
(average 2.97 kWh). The controller design performance, compared to the three controllers tested by DOE, indicates a savings of 5—15 percent. Larger savings are possible under test conditions that vary from the DOE Appendix D2 test procedure. The researchers estimated a 10 percent energy savings when this controller is installed in California clothes dryers. This estimate is relative to today’s shut-off controllers. In a competitive market the other controller designs may improve, reducing the relative benefits.

According to the California Energy Commission’s 2009 Residential Appliance Saturation Survey, gas dryers consume 6.0 percent of total residential natural gas use. Residential natural gas use is 4,854 million therms in California per year. Based on this data, residential gas dryers consume 291 million therms per year. Saving 10 percent of dryer natural gas use with 10 percent penetration equates to approximately 3 million therms per year or $3 million per year savings to California residents, assuming an end-use natural gas price of $1 per therm. This equates to approximately 35,000 tons of carbon dioxide equivalent greenhouse gas emissions per year. Additional savings are expected over time in commercial environments with dryers such as hotels, laundromats, athletic clubs, and hospitals.

1.4.8 Technology Transition Assessment

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

Marketing/Connection to the Market

The researchers were talking with potential licensees of this technology.

Engineering/Technical

The researchers estimated less than $100,000 and two years to complete engineering development and demonstration.

Legal/Contractual

At the conclusion of this project, the researchers had filed a provisional patent application. They had obtained funding from a California utility to test the technology on electric clothes dryers.

Environmental, Safety, Risk Assessments/Quality Plans

Since the researchers plan to license the developed technology, the licensee is responsible for conducting these plans.

Production Readiness/Commercialization

The University of California plans to license the technology to a clothes dryer manufacturer.

1.5 Enrichment of Microbial Communities for Biogas Production in High Solids (2014)

Awardee: University of California Davis
Principal Investigator: Chris Simmons
1.5.1 Abstract

This research effort evaluated the potential to convert high solid tomato and grape wastes into biogas. The project team also used novel methods to evaluate the specific microbials (mesophilic and thermophilic) adapted to each feedstock and the best temperatures to grow these microbes. The team evaluated storage methods for the anaerobic microbial consortium to enhance operating this process intermittently, based on the seasonal nature of waste feedstocks.

Researchers prepared authentic tomato and grape pomace waste materials for all experiments. The high solids anaerobic digestion microbial consortium consisted of cow manure and green waste composting material, with about 30 percent solids. The researchers determined greater yields for mesophilic operation (30° C) as compared to thermophilic operation (55° C) for both pomace feedstocks.

Using new ribonucleic acid analysis techniques, the researchers identified that the principal microbial groups differed when the anaerobic system was operated under mesophilic as compared to thermophilic conditions. Bacteria of the *Methanoculleus* archaica were the major methane producers at thermophilic conditions (higher temperatures). Under mesophilic or lower temperatures both *Methanoculleus* and *Methanosarcina* archaica, and microbes in the miscellaneous Crenarchaeotal group, were present.

Methods to preserve the anaerobic consortium included freezing with and without a cryo-protectant and air drying. Following preservation, the researchers stored specimens for six weeks, then evaluated restarting the anaerobic bioconversion of the feedstock. Results indicated that freezing both with and without cryo-protectant was successful, while air drying substantially reduced the viability of the anaerobic microbes.

Finally, the researchers used methane yield data for pomace feedstocks to estimate the potential renewable energy that could be produced through high solids anaerobic digestion. They calculated that if all tomato and grape pomace in California were used as fuel for anaerobic digestion, a quadrillion cubic feet of methane (worth about $10 million) could be produced annually.

**Keywords:** Anaerobic digestion, high solids, microbial communities, biomethane, waste management

1.5.2 Introduction

Expanding anaerobic digestion to convert tomato and grape wastes to biomethane represents a renewable and sustainable energy source for California to help meet its Renewable Portfolio Standard goals. By 2020 California law calls for 33 percent of electrical energy in the state to be generated by renewable sources. To meet this goal, additional renewable energy sources must be established and expanded.

Using anaerobic digestion to organic waste conversion results in reducing volatile solids and pathogen volumes, stabilizes organics, mineralizes nutrients, reduces odors, and generates a biogas product containing methane. Anaerobic digestion is commonly used to treat municipal
sewage and animal manures and more recently has been demonstrated to be effective in treating food processing wastes. However, most anaerobic digestion systems involve low solids operation based on the high level of water in the waste streams treated. More recent applications have evaluated using organic feedstocks with low moisture content and operating at high solids levels. Anticipated advantages for high solids anaerobic digestion systems include reduced system volume and potentially capital costs, less space requirements, and reduced or eliminated dewatering process residues before use as a soil amendment. A generic process flow design is shown in Figure 6.

While using high solids may reduce costs associated with standard low solids anaerobic digestion systems, it is necessary to adapt the microbial community (consortium) to the level of low water content as well as the potential for higher concentrations of end products such as ammonia. Understanding the digestion system microbial group and changes with solids level and operating temperature may improve the stability and reliability of the microbial catalyst. Modern analysis of specific microbial groups present in a mixed culture is possible through analysis of ribosomal ribonucleic acid analysis. While highly technical and expensive, this analysis can help researchers understand the basic changes in the anaerobic digester consortium that may optimize or provide for a more robust process.

Food processing wastes may be generated seasonally. Therefore, a dedicated anaerobic digestion system may be required to experience start and stop cycles based on feedstock availability. Storing the microbial consortium for long periods of time followed by rapid restart is imperative and methods for reliably preserving the microbial consortium are essential. The research team evaluated several basic methods for preserving microbes and the dynamics to resume process operation.
1.5.3 Objectives
This project looked to determine the feasibility of developing a high solids anaerobic digestion process for tomato and grape pomace for producing a biomethane product. The researchers:

1. Developed sufficient quantities (25 kg) of representative tomato and grape pomace feedstocks for use in longer term studies to evaluate anaerobic conversion at high solids.

2. Developed a sludge microbial community active at 30 percent solids loading. Confirm biomethane production is greater than or equal to 200 ml of methane per gram volatile solids added with biogas quality of greater than or equal to 50 percent methane following optimization of the carbon to nitrogen ratio, biomass loading rate, and mass retention time.

3. Identified bacterial and archaeal species that account for greater than or equal to 95 percent of total community abundance for best performing sludge communities for both tomato and grape pomace. Determine species responsible for greater than or equal to 50 percent total dissimilarity between sludge communities with optimal activity and those from digesters with sub-optimal operating conditions.

4. Developed sludge community preservation methods that allow for greater than six weeks of storage. Confirm revived communities achieve biogas production rates of greater than or equal to 75 percent of maximum rate observed prior to preservation within 10 days of revival and greater than or equal to 90 percent of maximum biogas production within 20 days of revival.

5. Confirmed from project findings that 500 trillion Btu per year are offset from purchased natural gas in California if tomato and grape pomace supplies in the State are used for anaerobic digestion using sludge communities developed in this project.

1.5.4 Outcomes
The project team performed numerous individual tests and outcomes include:

1. The researchers sourced commercial tomato and grape pomace. They dried and ground the pomace to ensure a uniform feedstock for testing and a feedstock that could be stored for periods without spoiling. They generated 25 kg of each pomace for use in the study.

2. In evaluating high solids anaerobic digestion of pomace feedstocks, the researchers established a source for the microbial consortium. Desiccated cow manure and green waste compost resulted in a microbial consortium that was capable of high solids anaerobic digestion at 30 percent solids loading. Following acclimation of the microbial consortium, the researchers determined a biogas product with an approximate 50 percent methane content. They evaluated the high solids microbial consortium for optimum pomace loading levels and the effect of operational temperature. Tomato and grape pomace yielded 211 ml and 141 ml of methane per gram of volatile solids, respectively. The researchers determined the optimum loading rate was 5 percent on a
dry weight basis of pomace feedstock. Mesophilic temperature operation produced equivalent or superior methane productivity as compared to thermophilic operation.

3. Employing novel ribosomal ribonucleic acid analysis methods, the researchers identified bacterial populations from both mesophilic and thermophilic operation. Bacteria from the Firmicutes phylum comprised over 90 percent of the microbes in the thermophilic sludge, whereas Firmicutes, Bacteroidetes, and Fibrobacteres phyla represented over 90 percent of mesophilic communities. Microbes from the archaea group included the genus *Methanoculleus*, that constituted over 90 percent of the thermophilic microbes, while *Methanoculleum*, *Methanosarcina*, and miscellaneous Crenarchaeotal group represented 90 percent for the mesophilic consortium.

4. Analysis of preservation methods for anaerobic microbial consortia established that freezing methods both with and without cryo-protectant were superior to drying methods over a six-week period of storage. Air drying methods of microbial preservation were thought to inactivate oxygen-sensitive anaerobic bacteria. However, the researchers also found a lack of facultative and fermentative microbes. Microbial preservation by freezing resulted in significant revival over the initial 10 day period, generating 524 and 186 percent, respectively, of the cumulative methane production as compared to the untreated positive control for freezing with and without cryo-protectant. Extending the period of evaluation to 20 days established activity of 86 and 113 percent of the positive control for freezing with and without cryo-protectant. While the use of cryo-protectant (added glycerol) resulted in similar reactivation rates, the variability in revival was reduced. Therefore using cryo-protectant during freezing preservation of the anaerobic microbial consortium was preferred.

5. Using the preliminary methane yield data for high solids anaerobic digestion of tomato and grape pomace, the research team estimated a total of on quadrillion Btu of energy could be produced annually in California - worth about $10 million. Based on using the high solids digestion system to the low moisture pomace waste stream, the research team also calculated 800 million liters (211 million gallons) of process water conserved annually.

1.5.5 Conclusions
The research team reached a number of important conclusions. Developing high solids anaerobic microbes for organic waste conversion can be readily generated from desiccated mature cow manure and green waste compost. Furthermore, the microbial consortia may readily be adapted to either mesophilic or thermophilic conditions.

1. Tomato and grape pomace can serve as appropriate feedstocks for high solids anaerobic digestion. Five percent on a dry weight basis appear to be optimal for mesophilic process operation. It is unclear if additional acclimation of the high solids anaerobic consortium may lead to bigger methane yields or if the carbon to nitrogen ratio of the pomace feedstocks results in conditions such as ammonia accumulation which inhibit
production. Consider feedstock blending to increase carbon to nitrogen ratios, such as with a shredded paper component, may enhance overall process yields.

2. While using the novel ribosomal ribonucleic acid analysis of microbial populations can be informative, especially in relation to operational considerations such as temperature, it is still unclear how this information can best be used to optimize yields and increase the stability of the microbial consortium.

3. Considering appropriate methods for anaerobic microbes storage during longer periods of time is valuable when restarting digestion systems applied to seasonal feedstocks. The research team demonstrated that air drying, as anticipated for strict anaerobes such as methanogenic (methane gas producing) bacteria, did not allow for revival. Incorporating reduced iron compounds to protect strict anaerobes can improve air drying preservation methods. It is important to note, incorporating a cryo-protectant into the microbes reduced the inconstancy of reviving the anaerobic consortium on freezing and storage.

4. The current calculations regarding the impact of high solids anaerobic digestion to convert tomato and grape pomace for renewable energy generation in California are significant. Optimizing conversion rates and yields may further increase energy generation. Researchers should also evaluate reduced pomace waste transportation to landfills, avoiding carbon dioxide emissions from non-renewable methane use and generation, and use organic soil amendments to avoid mineral fertilizers.

The researchers made progress toward proving feasibility. Significant additional research is required before this technology can be commercialized.

1.5.6 Recommendations

The Program Administrator recommends the researchers:

1. Conduct additional testing to optimize rates and yields of high solids anaerobic digestion of tomato and grape pomace wastes.

2. Employ continuous high solids anaerobic digestion systems at bench or pilot scale to develop long term data for conversion to biomethane. Long term adaptation of the microbial consortium may further improve the rates, yields, and stability of the high solids anaerobic process. Potential accumulation of inhibitor components such as ammonia must be evaluated with strategies for overcoming the potentially low carbon to nitrogen ratio of pomace feedstocks through blending with low nitrogen waste materials.

3. Evaluate better low cost methods for preservation of anaerobic consortia. These can allow for long term storage with rapid revival. Improving preservation methods would allow for intermittent operation of anaerobic digestion systems and provide for safety in operation during digester system restarts such a catastrophic loss of microbial viability.

After considering (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 the proposed technology should be considered for additional funding within the PIER program. The research team has a unique opportunity to study improvements in the high-solids anaerobic digestion of food processing wastes based on their current experience and capabilities demonstrated in this study.

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.

1.5.7 Benefits to California

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

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

The primary benefit to the ratepayer from this research increasing the affordability of energy in California and increase renewable energy generation from food processing wastes in California. Demonstrating effective high solids anaerobic digestion systems that reduce system size, capital costs, footprint, and process water requirements could provide for affordable renewable energy opportunities throughout California.

The research team estimated the potential for high solids anaerobic digestion of tomato and grape pomace could produce as much as 1,000,000 million Btu, worth about $10 million, of energy annually. The increased methane generated from food processing wastes could increase the in-state energy currently derived from renewable sources. The potential economic benefits of this energy from additional food processing wastes include creating investment job opportunities and revenues.
1.5.8 Technology Transition Assessment
The Program Administrator reviewed the researchers’ overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market
Anaerobic digestion as a waste conversion technology is relatively well developed with established engineering systems for waste conversion and biogas use. The research team has not established market connections based on the preliminary nature of this study.

Engineering/Technical
Engineering and technical approaches to the anaerobic conversion system were not evaluated in this study. The researchers performed basic anaerobic high solids yield experiments.

Legal/Contractual
The research team did not develop any patent applications during the project.

Environmental, Safety, Risk Assessments/Quality Plans
The basic level of the research in this study did not warrant these assessments to be performed.

Production Readiness/Commercialization
While the researchers developed data that confirmed actively converting pomace to the biogas product, substantial additional research is necessary to establish optimized conversion rates and yields allowing for more reliable process economics. Without establishing the economic viability of the process for conversion of pomace wastes, commercialization may not be possible.

1.6 Apparatus for In-Situ Determination of Gas Pipeline Yield Strength (2014)

Awardee: Palios Corporation.
Principal Investigator: Phil Stephanou

1.6.1 Abstract
This project developed a measurement system to determine the in-place yield strength (the maximum stress the material can experience before being permanently deformed) of natural gas transmission pipelines. The measurement approach was based on converting ultrasonic resonances across the thickness of the pipeline walls.

The researchers demonstrated the yield strength measurement approach using a transducer assembly (a device that receives a signal as one form of energy and converts it in a signal to another form) comprising two to six stacked piezoelectric transducer rings, a monolithic ultrasonic horn and elastic sample, and an acoustic cap. They fabricated the combined elastic horn/sample component out of low, medium, and high strength stainless steels (alloys 304, 303, and 17-4 PH, respectively). The researchers deferred the complexity of coupling the transducer
assembly to a separate gas pipe wall to a later development stage. The transducer assembly operated in an axial mode of vibration between 40 kHz and 50 kHz with resonant quality factors of up to 1,400. The devices were driven and sensed using custom power amplifier and trans-impedance amplifier circuits.

The research team used finite element simulations to quantify the effects of material and geometric nonlinearities, validate analytical models, and design optimized sensor transducer assemblies.

The team developed a conceptual system design for field deployable implementation and a preliminary cost model. The limited dynamic range of the selected sintered piezoelectric transducer material prevented the achievement of the researchers’ ultimate goal of demonstrating equivalence with standard tensile testing.

**Keywords**: Yield strength, non-destructive test, non-destructive evaluation, maximum allowable operating pressure, specified minimum yield strength, ultrasonic, automated ball indentation, instrumented indentation testing, hydrostatic test

### 1.6.2 Introduction

Under current United States Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA) regulations, yield strength is a necessary variable to determine the design pressure for steel pipe (49 CFR 192.105). For pipe not manufactured with a listed specification or whose specification or tensile properties are unknown, regulations require tensile testing the pipe to determine its yield strength or a prohibitively low default value must be assumed (§192.107). The requirement for determining yield strength affects approximately 300,000 miles of pipeline in the United States. Currently, tensile testing with an extensometer (a device that measures changes in the length of an object) is the industry standard for measuring yield strength and requires removing a sample from the specimen and sending it to a lab for testing. Performing this procedure requires either disrupting gas service to remove a sample and patch the affected pipe. The process is slow, requires special tools and training, and is inherently expensive.

Measuring mechanical properties such as strength through nondestructive testing is desirable. Instrumented Indentation Testing (IIT) and Automated Ball Indentation (ABI) are two nondestructive testing technologies being investigated as alternatives to tensile extensometer testing to determine yield strength.

A non-destructive approach using ultrasonic resonances to determine yield strength could provide numerous benefits to natural gas customers, pipeline operators, and regulators. For example, the an in-the-field yield strength measurement apparatus would improve safety by decreasing the likelihood of pipes being operated above maximum safe pressure, reduce the cost of regulatory compliance for utilities and other operators, and improve audits for more statistically significant sampling.
1.6.3 Objectives
This project attempted to develop a measurement system to allow non-destructive in situ determination of the yield strength of natural gas transmission pipelines in the field. The researchers set a goal to:

1. Demonstrate geometric nonlinearity is less than 25 percent of sample material nonlinearity.
2. Demonstrate transducer material nonlinearity is less than 25 percent of sample material nonlinearity.
3. Confirm agreement between analytical and finite element analysis (FEA) models is within +/-5 percent for frequency and +/-10 percent for amplitude.
4. Demonstrate design with ratio of peak transducer stress to sample stress less than 1:5.
5. Demonstrate theoretical measurement accuracy is within +/-5.0 percent.
6. Demonstrate system is capable of operating at least 100 hours without failure.
7. Confirm agreement between measurements made using prototype and extensometer is within +/-5 percent for Young’s modulus and +/-10 percent for yield strength.
8. Demonstrate design with peak actuation voltage < 700 Vp-p and current < 200 mA.
9. Target unit weight of less than 10 kg and amenable to in-field use by a single operator.
10. Confirm cost target of less than $50,000 per unit for volumes of 1 to 10 units.
11. Demonstrate sensitivity of sensor resonant frequency to transducer stack preload < 10 Hz/Mpa.

1.6.4 Outcomes
1. The researchers found geometric nonlinearity to be less than 16 percent of sample material nonlinearity for the overall sensor system.
2. The researchers found the effect of transducer material nonlinearity to be less than 12 percent of effect of sample material nonlinearity on overall sensor performance.
3. The researchers found agreement between analytical and FEA models to be less than +/-1.0 percent for frequency and +/-7.0 percent for amplitude.
4. The designs yielded stress ratios of less than 1:100.
5. The theoretical measurement accuracy was under +/-1.0 percent for a sample having yield strength of 500 MPa and Young’s modulus of 200 Gpa.
6. The system logged more than 400 non-continuous hours of use during the project.
7. Researchers could not determine Young’s modulus and yield strength of the steel sample due to limited dynamic range of the piezoelectric transducer material.
8. The researchers demonstrated maximum operating voltage and current of 180 Vp-p and 100 mA, respectively.

9. Total design weight of the field-deployable sensor was approximately 44 kg, but the handheld portion weighed less than 8 kg.

10. Estimated per unit direct costs dropped below $50,000 for annual volume of eight or more units.

11. The sensitivity of sensor resonant frequency to transducer stack preload was less than 2 Hz/Mpa.

1.6.5 Conclusions

1. The researchers showed their design successfully demonstrated the yield strength measurement approach. They observed the expected relationship between drive amplitude and peak resonant frequency. The acoustic horn design exceeded the original goal for amplifying the stress within the sample by a factor of 10. The effects of geometric nonlinearities were negligible.

2. An intrinsic property of the piezoelectric transducer material prevented successful proof of concept. The sintered PZT piezoelectric transducer material exhibited virtually zero effective elastic linear response at the frequencies of interest. Overall nonlinear response was dominated by the elastic constitutive behavior of the transducer. The contribution of the steel sample could not be resolved. This behavior was shared by the four piezoelectric material formulations (from two vendors) that the researchers evaluated. The piezoelectric materials all exhibited more than adequate dielectric dynamic range.

3. The system benefitted from higher than expected resonant quality factors, allowing lower operating voltage and reducing potential loss of accuracy associated with self-heating.

4. In small quantities, the final device price is likely to be determined by fixed direct costs.

The Program Administrator concluded the researchers were on a path to prove feasibility of their concept. Unfortunately, the next phase of this work must be focused on transducer development. Materials-focused research necessitates highly specialized researchers and often long periods of time.
1.6.6 Recommendations
The Program Administrator recommends the researchers should proceed by:

- Evaluating alternative piezoelectric materials to replace the sintered PZT parts used in the existing prototypes. Single crystal piezoelectric materials such as lithium niobate and lithium tantalate are viable candidates. However, the change to such a material is likely to involve tradeoffs in operating voltage and transducer size that will require additional engineering resources to optimize. No other work should proceed until the proper transducer material has been identified.

- Investigating analog and digital signal processing techniques to compensate for intrinsic transducer nonlinearity. If this approach were successful, existing PZT transducers that are inexpensive, operate at relatively low voltage, and are easily manufactured in custom configurations could be used.

- Investigating the effect of preload on the performance of ultrasonic transducer assemblies. The research team should update its analytical and finite element models to simulate the effects of preload.

- Extending the concept to a field-deployable configuration once the measurement approach is successfully demonstrated with a benchtop prototype. This task requires replacing the monolithic horn/sample assembly with a transducer assembly that can be securely mounted to a target pipe in the field.

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

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

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

At this point in the research team’s yield strength measurement apparatus development there are no quantifiable monetary savings to natural gas ratepayers in California. However, successfully transitioning the proposed technology from a benchtop prototype to a field-deployable solution has the potential to enable substantial cost savings in mandatory safety and compliance testing while simultaneously enhancing public safety and reducing service interruptions. For example, replacing extensometer-based testing with the proposed non-destructive instrument could save public utilities more than $90 million in costs associated with determining the yield strength of transmission pipelines in just high consequence areas.
1.6.8 Technology Transition Assessment
As the basis for this assessment, the Program Administrator reviewed the researchers’ overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market
The researchers have retained an external consultant to provide market assessment. They claim Pacific Gas and Electric Company has expressed interest in the measuring device and has offered to help commercialize it.

Engineering/Technical
The researchers estimated they require about $400,000 and an additional 1.5 to two years of development to complete this project.

Legal/Contractual
At the completion of this project the researchers had applied for one provisional and one utility patent. They do not intend to form an alliance with any industrial company to take the product to market.

Environmental, Safety, Risk Assessments/Quality Plans
While these plans and assessments must be completed, they do not appear to be complex or to affect the introduction of the product. The biggest challenge will be to obtain regulatory approval of this technique. To do this, the researchers must prove that their measurement system is both accurate and provides repeatable data.

Production Readiness/Commercialization
The researchers plan to follow a fabless (outsourcing the fabrication of the device) model and market their products directly to customers. They have a commercialization plan.

1.7 Maximizing Efficiency of Natural Gas Engines through Argon Power Cycle (2014)
Awardee: University of California Berkeley
Principal Investigator: Jyh-Yuan Chen

1.7.1 Abstract
This project determined the feasibility of applying the argon power cycle (APC) concept to natural gas reciprocating engines for power generation. The research team investigated running a single cylinder engine modified to use compressed natural gas with an argon-oxygen mixture as the working fluid. The team compared engine performance operating under both air and argon-oxygen mixture conditions. As part of the comparison, the research team determined the most efficient points of operation by measuring operating factors such as temperature, pressure, emissions, fuel flow, power, and torque.
Internal combustion engine efficiency is a strong function of the ratio of specific heats ($\gamma$) of the working fluid. Replacing air with higher-$\gamma$ fluid enables dramatic efficiency improvement. Using argon ($\gamma = 1.67$) instead of air ($\gamma = 1.35–1.4$) theoretically allows an engine to reach cycle energy conversion efficiencies approaching 70 percent. The researchers call this thermodynamic cycle the argon power cycle.

Experimental results show that running the modified engine with an argon-oxygen mixture improves the efficiency up to 24 percent, and reduced carbon dioxide emissions. Additionally, nitric oxide emissions during operation are nearly eliminated. Results also show that using direct injection strategy allows for higher loads by preventing knock at higher compression ratios.

When used with compressed natural gas in a reciprocating engine, the APC could be a promising technology for improving the efficiency of large power generation systems while reducing the environmental impact. However, commercialization could take considerable time.

**Keywords:** Argon power cycle, electric generation, natural gas, internal combustion engine, air emissions, efficiency, gas separation

1.7.2 Introduction

The researchers proposed a solution to supplying backup power and balancing power to the California electricity grid as renewable energy content increases. Currently the electricity grid is backed up by large simple cycle gas turbines or large combined cycle gas turbine engines. These engines are kept operating at low output so they can rapidly ramp up to meet unexpected demand. While the combined cycle engines can be up to 61 percent efficient at full power, they have lower efficiencies, and fuel and emissions costs when operated in standby mode.

Although large (up to 100 MW) low speed diesel engines can be up to 55 percent efficient, and also ramp up quickly to meet unexpected demand, they also have comparatively high levels of air emissions. To improve emissions, the researchers suggested converting diesel engines to natural gas fuel and operating them either as spark ignited (SI) or compression ignited (CI) engines. This type of fuel conversion typically results in lower engine efficiency; however, to improve their efficiency, the researchers proposed and tested a new engine operating mode. They replaced the incoming air with a mixture of argon and oxygen. Using argon instead of air theoretically allows the engine to reach efficiencies approaching 70 percent.

This project explored the feasibility of applying the APC concept to natural gas reciprocating engines for power generation. The research team investigated running a single cylinder engine modified to use compressed methane (CH4) fuel with an argon-oxygen mixture as the working fluid. The team compared engine performance operating under both air and argon-oxygen mixture conditions.

Results from this project showed that running the modified engine with an argon-oxygen mixture improves efficiency up to 24 percent relative to the air cycle, with subsequently reduced carbon dioxide emissions. In the researchers’ tests, nitric oxide emissions during steady operation were nearly eliminated. In a commercial engine operating on pipeline natural gas,
nitric oxide emissions could be higher depending on the amount of nitric oxide in the fuel. The researchers used pure methane in their experiments. Results also showed that using direct injection strategies allowed for higher loads by preventing knock at higher compression ratios. Again, engine knock limits may vary due to other hydrocarbon species in pipeline natural gas.

The experimental apparatus is shown in Figure 7. The Cooperative Fuel Research (CFR) engine is a one cylinder standard research engine commonly used in fuel and engine research.

**Figure 7: Schematic of Experimental Apparatus**

1.7.3 Objectives

This project goal was to determine the feasibility of applying an argon power cycle to natural gas internal combustion engines for electric generation. The researchers looked to:

1. Demonstrate stable coefficient of variation (COV) < 5 percent, no-knock operation at low compression ratios (CR) between four and eight with torque equivalent to normal SI operation with methane.

2. Achieve thermal efficiency > 15 percent relative improvement over a spark ignited (SI) engine at respective peak efficiency compression ratios and ultra-low 90 percent reduction pre-catalyst NOx.

3. Demonstrate repeatability of direct injection event timing (< 100 μs standard deviation), duration (< 250 μs standard deviation), and mass flow (COV < 5.0 percent).

4. Demonstrated stable (COV < 5.0 percent) operation at moderate compression ratios (CR = 12–14).
5. Achieve thermal efficiency > 20 percent relative improvement over base case at respective peak efficiency compression ratios and 75 percent reduction in unburned hydrocarbons.

### 1.7.4 Outcomes

1. The researchers demonstrated stable no-knock operation at low compression ratio (CR = 6) with torque equivalent to normal SI operation with methane. Except for the case with 10 percent O₂+90 percent Ar, the COV levels for 15 percent O₂+85 percent Ar and 20 percent O₂+80 percent Ar cases fell within the 5.0 percent target.

2. For SI operation, the researchers achieved thermal efficiency improvement of 24 percent with 15 percent O₂+85 percent Ar relative to the air-breathing case with ultra-low pre-catalyst NOX (99 percent reduction).

3. Based on high-speed schlieren imaging from a constant volume device, the standard deviation of the injection duration for the experimental fuel injector was 133 μs for methane injected into argon atmospheres. The repeatability of injection event timing was 28 μs standard deviation and mass flow is < 5 percent COV at injection duration > 2.5ms.

4. The researchers achieved stable direct injected (DI) operation at CR =15 and CR=14 with COVIMEP < 5 percent in the CFR engine with the argon cycle.

5. For DI operation, the researchers achieved peak pressures of nearly 80 bar. However, thermal efficiency was only improved by 20 percent over the tested SI air operation mode. Unburned hydrocarbons were reduced up to 59 percent compared to the SI mode. The researchers observed less than 10 ppm of NOx, a 99 percent reduction relative to SI air operation.

### 1.7.5 Conclusions

The researchers proved feasibility of the argon power cycle for stable operation under spark ignition and compression ignition operation modes for internal combustion engines. When compared with a natural gas fueled and air breathing engine, the APC improved thermal efficiency using 15 percent O₂+85 percent Ar and 20 percent O₂+80 percent Ar. The improvements were 24 percent and 22 percent, respectively. For 10 percent O₂+90 percent Ar, the thermal efficiency was only slightly better than the spark ignition air case by 1 percent due to slow flame speed. For compression ignition with direct injection at a compression ratio of 15, the thermal efficiency was improved 14 percent over the SI air case. When the compression ratio was decreased to 14, stable combustion with assistance of spark was achieved with 20 percent relative improvement in efficiency.

The researchers found that argon power cycles produce less than 800 ppm unburned hydrocarbons. This corresponds to about a 50 percent reduction relative to air operation at 1,400 ppm. For NOx, argon power cycles achieved a 99 percent reduction relative to spark ignition air operation.
While the researchers achieved what they set out to prove, the APC is not close to commercial application. Significant barriers must be overcome in scaling the technology for large engines. Decisions and tradeoffs must be made regarding spark or compression ignition, compression ratios, efficiency, and cost. Once the development is completed, an industry organization must tool a factory to produce this engine, not an insignificant cost. In parallel, researchers must determine how to supply high purity oxygen safely to the engines and how to recycle the argon. Finally, testing with commercial pipeline gases nationally and internationally must be done to determine emission levels.

1.7.6 Recommendations

The Program Administrator recommends the researchers:

- Optimize compression ignition operation to fully realize the potential for higher thermal efficiency. Do this by fine-tuning the compression ratio, the injection timing, and the amount of methane injection.
- Develop and test a different size injection nozzle to allow higher fuel mass flow rates.
- Conduct more engine tests under both the SI and DI modes to develop a full load speed map of the engine.
- Establish a relationship with a manufacturer of large reciprocating engines to develop an engineering product specification.
- Estimate the cost to bring an APC reciprocating engine to market and the cost to produce such an engine.
- Evaluate the potential of other technologies, such as flow batteries, providing the same grid balancing function at lower costs.

After considering (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 the proposed technology should be considered for additional 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.

1.7.7 Benefits to California

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

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

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

The electricity system in California is experiencing significant changes. California has a goal to achieve up to 50 percent renewable content of its electricity by 2030. Although demand for electricity has been flat since 2008, numerous new and efficient power plants have been built, including approval of several more high efficiency combined cycle plants. These additional power plants have led to a surplus of electricity of up to 21 percent with more power plants due to come on line in the next two years.

This surplus had resulted in many, if not most, older power plants have been idled. Because of the large capital investment in new power plants, many of them owned by the investor-owned utilities and the push for renewable generation, it is unlikely that utilities will idle these new power plants in favor of a new type of engine in the foreseeable future. Especially for the investor-owned utilities whose power plants are supported by the ratepayers. Stranding these assets would drive up the cost of California electricity that is already much higher than the national average.

California supports the installing energy storage by electric utilities. Storage systems could reduce the necessity for spinning (standby) reserve.

In spite of this market situation, the new cycle should be pursued to determine if it could be useful to the California grid. If these engines prove to be superior, there is a possibility that they could be slowly inserted into the California power grid. The advantages of efficient and clean reserve could lead to lower natural gas use and reduction of air emissions.

1.7.8 Technology Transition Assessment

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

Marketing/Connection to the Market

The researchers had not performed a market assessment nor talked with any potential customers by the end of this project.

Engineering/Technical

The researchers estimated that they could complete development and demonstration on a small scale, with two additional years of work and about $300,000.

Legal/Contractual

The researchers had a patent search performed by a professional law firm. They did not find any infringement or conflict with any other patent. The researchers applied for a United States patent and planned to file in several other countries.
Environmental, Safety, Risk Assessments/Quality Plans

While these assessments are critical to a new engine cycle, they are premature at this stage of development.

Production Readiness/Commercialization

The researchers plan to seek licensing agreements or contract with partners such as MAN, Wartsila, or GE.

1.8 The Building Occupant Mobile Gateway (2014)

Awardee: University of Southern California
Principal Investigator: Kyle Konis

1.8.1 Abstract

This project explored the Occupant Mobile Gateway technology, a smartphone/server software application, to prove if appropriate information could be provided to building management personnel and allows them to adjust a building’s heating, ventilation, and air conditioning (HVAC) systems to reduce space heating energy while maintaining or enhancing occupant comfort. The researchers assessed the machine learning algorithms to generate useful personalized occupant comfort profiles using measured data from embedded sensors paired with subjective data collected in actual buildings. Analysis of data collected during a two-week period from four test sites in California climate zones 8 and 9 and 45 participants showed that, when sufficient occupant data were recorded to fit a personalized probabilistic model, the machine learning approach resulted in accurate models in nearly all cases. All 16 probabilistic heating set point models and 19 of 21 cooling set point models achieved an error rate less than 10 percent. For the remainder of individual cases it was not possible to generate a predictive model because a lack of discomfort response for either warm or cool sensations. However, when aggregated at the zone level, the heat response of each population could be predicted with an error rate of less than 10 percent. In two of the four test sites, the researchers found that heating set points could be extended to achieve a 30 percent or greater reduction in annual natural gas space heating energy consumption while maintaining thermal comfort. In addition, the researchers found the cooling set point could be extended at all four test sites for electricity savings.

Keywords: Mobile sensing, indoor environmental quality, occupant-aware energy management, space heating, natural gas

1.8.2 Introduction

The researchers developed and evaluated the feasibility of a prototype smartphone/server software application to collect and analyze real time occupant subjective feedback, indoor location, and objective thermal data from embedded sensors. This technology provided information to building management personnel allowing them to adjust building heating, ventilation, and air conditioning (HVAC) systems to meet space heating energy reduction goals.
and maintain occupant comfort and user acceptance. The specific innovations developed in this project include:

1. Extending participatory sensing to commercial buildings that do not have a building management system and to the many buildings where closed loop supervisory control of the building management system is not practical.

2. Developing machine learning algorithms to synthesize participatory and physical measurements into personalized and group level comfort models that can be interpreted to determine optimal temperature set point ranges based on energy and comfort goals.

3. Mapping spatially device user locations over time to calculate zone occupancies and to identify when and where discomfort conditions occurs.

This research targeted reducing commercial building on-site natural gas consumption for space heating. Temperature setbacks and schedule adjustments are two of the most practical and cost-effective strategies to reduce space heating. A temperature setback (for example from 71°F to 68°F) lessens heating loads by reducing heating hours and decreasing the difference between the set point and the outdoor temperature. Scheduling adjustments cut energy use by synchronizing HVAC equipment operation with daily and seasonal patterns of occupancy. Although field data is limited, feedback from commissioning agents (Landreth 2013) and available research (Mendell 2009) suggests that many buildings are unnecessarily overheated during the heating season, and spaces are heated when not in use. Even identifying where and when zones are being heated above recommended American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) practice has the potential to achieve savings before targeting additional savings through temperature setbacks.

Although temperature setbacks and schedule adjustments have significant potential for reducing energy if applied more broadly, applying these strategies to occupied spaces requires real time feedback on temperatures, comfort levels, and patterns of occupancy. Providing incentives for adopting beyond college campuses requires systems than can give evidence that occupant acceptance is routinely enhanced. The goal is to extend savings throughout the heating season by enabling building management personnel to adjust temperature setbacks in occupied spaces using optimized setbacks and schedules learned through continuous analysis of occupant subjective feedback paired with detailed thermal measurements.

Commercially available HVAC systems still rely on static proxies of occupant comfort that are applied throughout the year without feedback from building occupants. The OMG technology wants to apply mobile sensing as a low cost approach to implement personalized comfort models and explore the energy savings potential of set point extensions determined from analysis of data-driven individual and group level comfort models.

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1 For example: commercial buildings where concern for occupant comfort and productivity are paramount.
Existing approaches to mobile sensing are focused on closed loop control of existing building management systems with occupant detection and/or subjective feedback. The state-of-the-art is presently applicable to a small fraction of existing buildings due to several dependencies that limit widespread adoption. First, most approaches depend on sensor data from legacy HVAC systems for objective feedback, typically one thermostat per zone. In many buildings these data are often unreliable due to sensor calibration issues, indoor conditions that are not homogeneous, or data that are unavailable because of configuration problems that go unnoticed for months or years. Second, closed loop control of the building management system is not a practical option for many existing building management scenarios. Many small and medium-size commercial buildings do not have a building management, and few large commercial buildings have a fully connected control system at the zone level capable of local terminal unit control.

This project extended the state-of-the art for mobile sensing more broadly across the existing commercial building stock by developing a technology that does not require a parallel network of physical sensors and avoids the real world challenges of availability and usability of existing building management systems. A schematic of the researchers’ sensing and control system is presented in Figure 8.
1.8.3 Objectives

This project proved the feasibility of using smartphone-based sensing and server machine learning to inform building energy management and retune their practices with occupant feedback and physical measurements. The project:

1. Minimized interaction latency and data traffic between smartphone and server with the constraint of maintaining battery life greater than 50 percent and daily battery drain less than 10 percent. Maintaining battery life and limiting drain is important to avoid user dropout.

2. Achieved an intuitive and usable survey instrument and GUI as confirmed by a randomly selected panel of occupants.

3. Achieved a root-mean-square error (RMSE) of 1.0° F or less compared to concurrent reference temperature sensor (HOBO U-12 Temperature/RH data logger) measurements from onboard (Thermodo Temperature/RH) sensor data.

4. Resolved location of mobile device indoors with accuracy of < 4 meters.

5. Determined zone occupancy count with an error of < 10 percent.

6. Attempted to demonstrated high level (> 90 percent) of occupant satisfaction with user engagement module from a survey of participants after collection of two weeks of training data.

7. Predicted binary outcome (e.g., satisfied / dissatisfied) from training data with an overall error of < 10 percent for any given individual.
8. Predicted binary outcome from newly acquired data with an overall error of < 10 percent using models generated from training data.

9. Demonstrated high levels (> 80 percent) of occupant satisfaction with temperature set point range determined by the goal-seeking function.

10. Used energy simulation and apply set point adjustments learned from occupants, confirm 16.3 kBtu/ft²/y heating EUI as compared to California large office average EUI of 23.4 Btu/ft²/y for a thermal zone within a large office building.

1.8.4 Outcomes

1. Thermal sensing resulted in a 42 percent drop in battery drain over the 94-hour test, leading to a daily battery drain of 10.5 percent. This is very close to the performance objective of 10 percent and considered acceptable.

2. Analysis of an exit survey administered to the first two test site populations (N=25) resulted in a median satisfaction score of six out of seven, equating to an assessment of moderately satisfied on a seven point Likert scale ranging from: 1 = very dissatisfied, 2 = moderately dissatisfied, 3 = slightly dissatisfied, 4 = neutral, 5 = slightly satisfied, 6 = moderately satisfied, 7 = very satisfied.

3. The researchers achieved and surpassed this objective by applying a linear calibration to measurement data, leading to a RMSE error < 0.5° F.

4. Through a validation study on one floor of an academic building, the researchers confirmed that the location of a mobile device could be routinely predicted with the accuracy of desk-level spatial resolution. The researchers confirmed this with 216 individual desk trials.

5. The researchers determined that zone occupancy counts could be precisely calculated in software by counting the devices located within any arbitrary spatial boundary drawn with desk-level resolution on the floor plan used to validate the indoor location approach. This presented a benefit for identifying both when and where objective and subjective measures of discomfort were being reported.

6. The researchers found that 20 of the 25 participants surveyed at the end of the pilot study would continue to use the technology based on an energy savings motivation, for an 80 percent satisfaction rate. Similarly, 22 of the 25 participants would continue to use the technology based on a thermal comfort motivation, for an 88 percent satisfaction rate. The researchers did not meet the objective of > 90 percent satisfaction rate. However, the outcomes were close, within 10 percent and 2.0 percent respectively, and there were no negative responses.

7. Analysis of data collected over a two-week period from four test sites and 45 participants showed that, when sufficient occupant data were recorded to fit a personalized probabilistic model, the machine learning approach resulted in accurate models in nearly all cases. Sixteen of 16 probabilistic heating set point models and 19 of
21 cooling set point models achieved an error rate less than 10 percent. However, for the remainder of individual cases, it was not possible to generate a predictive model due to the lack of a discomfort response for either warm or cool sensations.

8. When applied to group level data sets, the machine learning approach was found to make predictions on new data with an error rate of 11 percent or lower, and in most cases with an error rate less than 3 percent. The researchers considered this a successful demonstration of the machine learning approach to predict the outcomes of new data.

9. The goal-seeking function interpreted annual simulation-based outcomes from an Energy-Plus model of a commercial office building to identify the heating set point adjustment required to achieve a 30 percent annual space heating energy reduction for a given California climate zone. Comparison between the target set point (Goal SP) and various learned set points showed that comfort could be maintained (> 80 percent probability) while achieving a 30 percent annual natural gas space heating energy reduction at two of the four test sites. At the other two test sites, group level models showed that extending the heating set point would result in a probability of discomfort greater than the 20 percent discomfort criterion and thus no natural gas savings were possible. Notably, all four sites indicated significant cooling energy savings while maintaining the comfort criteria.

10. Using EnergyPlus (2016) simulations of various vintages of commercial office building reference models, the researchers found that the learned heating set points for two of the four test sites, if applied annually, would lead to greater than a 30 percent NG space heating energy reduction in both the four warmest and the four coolest California climate zones. The set points learned for the other two test sites would lead to no reduction and an increase in space heating energy.

1.8.5 Conclusions
It is possible to model the thermal preferences of occupants at the individual and zone levels with data collected over a relatively short time period of two weeks. When it is learned that occupants are accepting of an extended temperature set point range, these models can be used to predict the optimal set point extension for both heating and cooling while maintaining a specified level of comfort. Indoor location adds additional value by allowing building management staff to identify where and when discomfort conditions occur. This can improve long term user acceptance of energy saving strategies.

1.8.6 Recommendations
The Program Administrator recommends the researchers:
1. Conduct additional field studies with larger user populations and more diverse thermal conditions.
2. Quantify energy savings at the zone or whole building level over the heating season using sub-metered energy data.
3. Quantify long term user acceptance of expanded temperature set points by conducting longer (such as seasonal or annual) field studies.

4. Further develop location-based mapping and HVAC adjustments (for example occupant-aware equipment scheduling and ventilation rate adjustments) enabled by the OMG.

5. Find a method to inform building managers of the energy savings potential for using this technology.

1.8.7 Benefits to California

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

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

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

The researchers estimated that in 2006, California had 361 million ft² of small office buildings (buildings with total floor area less than 30,000 ft²) with an average natural gas heating energy use intensity (EUI) of 8.62 kBtu/ft²/year. This is an annual natural gas space heating consumption of 3,111,820,000 kBtu, or 31 million therms. Within this sector, a 30 percent reduction in space heating could save 9.3 million therms per year. The State had 660 million ft² of large office buildings (buildings with total floor area greater than 30,000 ft²) with an average natural gas heating EUI of 17.22 kBtu/sqft/year or a space heating consumption of 11,365,200,000 kBtu, or 114 million therms. Within this sector, a 30 percent reduction in space heating could save 34.2 million therms per year.

Finally, in 2006, California had 4.9 billion ft² of existing commercial building stock with an average natural gas heating EUI of 9.46 kBtu/sqft/year - an annual natural gas space heating consumption of 46,354,000,000 kBtu, or 464 million therms. For all California commercial buildings, a 30 percent reduction in space heating could save 139 million therms per year.

Assuming a space heating cost of $1.381 per therm (U.S. Bureau of Labor Statistics, 2016), a 30 percent savings across the entire California commercial building sector could annually save $192 million to ratepayers. Given that the total square footage of commercial building space statewide and the price for utility gas are likely to increase over time, the future savings potential could be even greater. However, actual building-level outcomes will depend on local climate conditions, baseline equipment configurations, and end-user feedback. Because this technology leverages existing mobile devices and WiFi infrastructure which are present in a
large portion of existing commercial buildings, there is no technical limitation to scaling the application of the technology broadly across the existing building stock to achieve this potential.

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

Marketing/Connection to the Market
The researchers did not perform a market analysis. They did receive interest and positive feedback from some large architecture and engineering firms who provide services to owners and property managers of large building portfolios.

Engineering/Technical
The researchers estimate that they will require up to $500,000 and one to two years to complete this project.

Legal/Contractual
The researchers did not perform a patent search nor did they apply for a patent. It is the researchers’ goal to publicly disclose the concepts through publication.

Environmental, Safety, Risk Assessments/Quality Plans
Since this project was a process rather than a physical property most of these plans will not apply.

Production Readiness/Commercialization
The researchers plan to work with guidance from the University of Southern California (USC) Technology Transfer office, the USC Marshall School of Business, as well as the recently launched Los Angeles Clean Tech Incubator (LACI).
1.9 Multi-Family Residential Natural Gas Monitoring and Analysis Software (MFR-MAS) (2014)

Awardee: Policy Consultants, LLC  
Principal Investigator: Hal Nelson

1.9.1 Abstract
Researchers developed an analytical tool for identifying promising targets for natural gas efficiency enhancement programs and projects. The multi-family residential natural gas monitoring and analysis software was based on advanced techniques to aggregate parcel data and natural gas usage for multi-family residential properties. The researchers used natural gas consumption for all the multi-family residential properties in Los Angeles County extrapolated from consumption data from a 2009 residential appliance study and performed building energy modeling. They identified properties that used significantly more gas than average. The software provided a graphical interface useful for energy efficiency professionals and program administrators. The modeling predictions were validated with real utility data and showed a minimum of 86 percent accuracy in correctly identifying multi-family residential properties as single or multi-parcel developments. The main conclusion from the research was that it is possible to perform mass-scale benchmarking of multi-family residential properties.

Keywords: Multi-family residential, natural gas, demand side management, big data, energy efficiency, building energy simulation, Energy Star Portfolio Manager, cost effectiveness, targeted marketing

1.9.2 Introduction
Increasing the efficiency of energy use remains a high priority component of California’s energy policy. Residential and commercial buildings account for nearly 70 percent of statewide electricity use and 55 percent of natural gas use. California’s residential buildings use natural gas for space and water heating and for cooking. An estimated 50 percent of existing buildings in California were built before California building energy efficiency standards went into effect in 1978. One of the goals of the California Energy Efficiency Strategic Plan for the residential sector is to reduce energy consumption in existing homes by 20 percent by 2015 and 40 percent by 2020.

Much of the natural gas use is in multifamily residential units (MFR) such as apartments and condominiums. Efficiency programs to improve energy use in MFR can be difficult to implement. One barrier is tenants do not want to pay for new equipment since they are likely to move out before its benefits can be fully realized and landlords are hesitant to pay for expensive equipment when they don’t pay the energy bills. This landlord-tenant dynamic is at the heart of the barrier to an efficient MFR building sector. Legislation passed in 2015, AB 802, The California Energy Efficiency Plan, requires California utilities to provide benchmarked building energy consumption within four weeks of customers requesting the benchmark. MFR-monitoring analysis software can help utilities implement AB 802 and benefit the California Public Utility
Commission statewide efficiency marketing plan by automatically benchmarking properties on a mass scale.

Researchers tested software they previously developed to perform mass benchmarking of multi-family residential units. The researchers used Los Angeles and San Bernardino county parcel designations and property descriptors from multiple sources, including aerial maps, and undertook a series of data cleaning and aggregation steps to benchmark properties on a mass scale and calculating energy intensity scores for each. Figure 9 shows the data base scheme.

**Figure 9: Data Base Scheme for Multi-Family Residential Natural Gas Monitoring and Analysis Software (MFR-MAS)**

1.9.3 Objectives

This project tested the feasibility of developing prototype software for multi-family residential natural gas monitoring and demand analysis that uses spatial analysis and parcel mapping to aggregate natural gas use and square footage in MFR buildings. The researchers established the following objectives:

1. Demonstrate that 90 percent (+/- 10 percent) of the MFRs in the data fields contain the appropriate data.

2. Demonstrate that 85 percent (+/- 10 percent) of the spatial models’ predictions about single structure buildings and 70 percent (+/- 10 percent) of the spatial models’ predictions about multiple structure buildings are correct. Demonstrate that the building square footage (FT2) predictions are +/- 5.0 percent of actual from purposive and random samples obtained for validation.

3. Demonstrate that failure rates for monthly natural gas predictions for MFR accounts are < 20 percent.

4. Perform statistical analysis to estimate natural gas consumption that explains > 30 percent of the variation in MFR natural gas demand.
5. Demonstrate that 90 percent (+/- 5.0 percent) of all MFRs that are detected by the outlier detection algorithm as having high winter gas use are actually in the high winter natural gas usage distributions.

6. Develop a software user interface so that 75 percent of users would find the dashboard useful and intuitive to use.

7. Demonstrate a range of $1.1 million to $3 million per year savings for California ratepayers from widespread use of MFR-MAS.

1.9.4 Outcomes

1. The researchers completed statistical analysis of the data sets to determine the extent of missing data that was appropriate for multi-family residences in Los Angeles County. They used two data sets, one from the County Assessor’s Office and one from the Los Angeles County Apartment listing. They did the same for San Bernardino County, using different primary data sets. They looked at MFR with more than 15 units. The researchers manually validated that the same addresses in each dataset were being matched up. They validated the address matching by visual comparison of the columns for the street address of the utility service address with the columns for the street address in the county real estate database. They analyzed approximately 200 MFR complexes using this methodology. The manual validation showed text matching accuracy was greater than 95 percent for the sample of 200 MFR selected.

2. The researchers manually validated predictions about the type of MFR buildings in Los Angeles County. They used a stratified random sample of about 290 buildings split between MPDs, single parcel developments, and side-by-side single parcel developments. The validation was performed using MFR-MAS maps, Google Maps, apartments.com, and other internet-based real estate resources. They did not complete a square footage validation.

3. The researchers analyzed gas customer billing data for missing data and outliers. They found the total number of observations in the MFR natural gas database of 10,294,584 over twelve months had 2,117,363 missing observations, or 20.5 percent.

4. The researchers undertook a statistical analysis to explain differences in MFR natural gas consumption. They did not decisively determine the causes but did identify difficulties associated with the data sets, including combined gas and electric usage for some properties.

5. The researchers evaluated the accuracy of the software in identifying high users of natural gas, using a home energy intensity measure to check the correlation of predicted and metered data, corrected for weather and theft. The customer months identified as high use were correct at least 90 percent of the time.

6. The researchers developed a user interface that allowed for data extraction based on factors such as consumption or regional mapping. They used 21 people from different technical disciplines to evaluate the interface for functionality, speed, and aesthetics.
7. The research team quantified the benefits to California using the costs to benchmark MFR buildings. Table 3 shows the cost estimate of using each of three separate benchmarking methods.

<table>
<thead>
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<th>Method</th>
<th>Hours per Property per Fuel</th>
<th>Labor Rate</th>
<th>Cost/property</th>
</tr>
</thead>
<tbody>
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<td>1. Customer Data Entry</td>
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<td>$40</td>
<td>$5.93</td>
</tr>
<tr>
<td>2. Utility Program Staff</td>
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<td>$40</td>
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<td>3. MFR-MAS</td>
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<td>$118</td>
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</tbody>
</table>

1.9.5 Conclusions

1. Matching data from different data sets using parcel numbers and gas customers with good accuracy can be done, at least for properties with more than 15 units and in Los Angeles and San Bernardino Counties. The researchers completed this objective.

2. The software can accurately predict the type of MFR, but data was unavailable for predicting the square footage of each, regardless of type. The researchers only partly completed this objective.

3. The total number of observations in the MFR natural gas database was 10,294,584 over twelve months. The number of missing observations was 2,117,363, for a rate of 20.57 percent. The researchers completed this objective but narrowly missed completing it successfully.

4. Various data points, such as square footage, were unavailable, and others, such as electric and gas consumption, were homogenized. The researchers did not complete this objective.

5. The model correctly identified high use months for those MFR that were identified as outliers by the algorithm. The researchers completed this objective.

6. User-friendly interface can allow for quick extraction of data of interest to energy efficiency personnel. The researchers completed this objective.

7. Cost savings from modest to meaningful should be achievable using this software. The researchers found a savings in statewide administrative costs for demand side management (DSM) and AB802 compliance of $407,000 to $1,568,000. The researchers completed this objective but did not meet the performance metric of $1.1 M to $3.0 M per year savings.
8. The researchers demonstrated the technical functionality of the MFR-MAS software. Further work is required to make it more accurate in using disparate and/or homogenized data sets and inclusive of improved square footage data. The researchers have only partly demonstrated economic feasibility.

1.9.6 Recommendations
The Program Administrator recommends that the researchers:

1. Confirm that other county and gas utility data base structures are compatible with MFR-MAS software and develop application software to accommodate differences as necessary.

2. Consider extending the software’s capability to electricity and water for use by utilities serving such customers.

3. Consider extending the software to other customer classes such as commercial buildings.

4. Continue to develop the software, including improving the pre-processing steps and treatment of missing data points in county and utility billing data sets.

5. Consider development of a mobile device version for field personnel to do benchmarking on site.

6. Confirm that the software does not inadvertently identify properties as low consumption simply because they use electricity as an energy source for some uses like space heating.

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

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

The primary benefit to the ratepayer from this research is increased affordability of energy in California. This affordability is enhanced by lower utility cost of compliance with AB802 and accelerated adoption of demand side management techniques and equipment. The researchers estimated $1.38 per property cost to benchmark using the MFR-MSR software versus $3.33 to $5.93 using traditional approaches. Given four million MFR units and assuming seven units per property, benchmarking costs could be reduced by $1 million to $2.4 million. Larger and unquantified savings could be realized as additional measures are identified and implemented to aid the benchmarking. Rapid and comprehensive benchmarking should accelerate
1.9.8 Technology Transition Assessment
As the basis for this assessment, the Program Administrator reviewed the researchers’ overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market
The researchers have pilot tested their software with SoCalGas and Southern California Edison and must work with the other eight natural gas distribution utilities and multiple electric utilities to bring their software for statewide use. In particular, they must demonstrate properties benchmarked as high users actually are high users and that this information is used to achieve energy savings.

Engineering/Technical
The main technical issues needing resolution are data completeness in the separate data sets used. This may be a larger issue with data sets in geographical areas of California beyond those so far investigated. Expanding from natural gas to include electricity and water consumption and inclusion of commercial property would enlarge the usefulness and reach of the software.

Legal/Contractual
The researchers have not applied for patents or copyright protection.

Environmental, Safety, Risk Assessments/Quality Plans
There are no anticipated environmental or safety risks from the technology.

Production Readiness/Commercialization
The software is ready for initial commercialization and application.
1.10 Tar Reforming Catalyst for Producer Gas Cleaning for BioSNG Production (2014)

**Awardee:** University of California San Diego  
**Principal Investigator:** Robert Cattolica

1.10.1 Abstract

Converting available biomass to fuel gas by gasification has the potential to generate 339 billion Btu of energy annually in California. The initial phase of biomass gasification results in producer gas containing undesirable components including hydrocarbons, tars, and hydrogen sulfide which must be removed before upgrading to bio-synthetic natural gas. Conventional technology involving wet scrubbers and catalytic reforming are necessary and expensive.

The research team evaluated a solid support treated with a combination of low cost materials including nickel, iron, and calcium in a fixed bed reactor to reform producer gas and reduce process costs. Using a laboratory test system, the research team determined substantial conversion of representative tars including ethylene, toluene, and naphthalene. These data were used to calculate the catalyst necessary for 99 percent conversion of all tar components.

The researchers studied catalyst poisoning by hydrogen sulfide and tests determined that 100 parts per million of hydrogen sulfide rapidly reduced conversion of both ethylene and toluene. Removal of hydrogen sulfide from the process gas stream allowed for recovery of catalyst activity although very slowly.

Researchers performed economic projections based on a model from Black & Veatch for thermal gasification of biomass for the fuel gas production. They projected improvements in full-scale plant economics by incorporating the novel catalyst to reduce costs by 20.3 percent. However, using data derived from the project to convert representative tars, the actual cost savings were about 4.2 percent.

Additional research is required to overcome issues with hydrogen sulfide poisoning of the novel catalyst that reduces conversion rates. The researchers anticipate alternative catalyst components or engineered systems such as using a circulating bed reactor could improve performance and further reduce capital costs for the overall gasification process.

**Keywords:** Biomass, gasification, tars, reforming, catalyst

1.10.2 Introduction

California generates approximately 32 million bone dry tons of biomass annually, much of which is under-used for renewable energy production. Thermal gasification is a technology that converts organic matter to useful fuels and chemicals. Currently there are 272 operating gasification plants worldwide with the majority located in Asia and Australia. In addition, while coal is the major feedstock for many gasification plants, using biomass and waste as feedstock is expected to grow. To enhance the economics for thermal biomass gasification plants to produce synthetic natural gas, the research team evaluated a new low cost catalyst in a fixed
bed reactor for reforming hydrocarbons and tars before converting gas into methane (methanation) and final purification. A generic process flow design is shown in Figure 10.

**Figure 10: Thermal Gasification of Biomass for Production of Bio Synthetic Natural Gas (BioSNG)**

![Figure 10: Thermal Gasification of Biomass for Production of Bio Synthetic Natural Gas (BioSNG)](image)

Products from the thermal gasification of biomass include bio synthetic natural gas (BioSNG) and char. However, complex and expensive gas processing steps increase the overall costs for the process and reduce the economics for commercial plants. The research team projected reducing primary gas treatment costs by using the novel low cost catalysts could save California ratepayers about $245 million per year while producing 339 billion Btu of fuel gas.

The research team evaluated numerous potential catalysts for producer gas processing based on cost, availability, and activity and focused on a low cost catalyst with a mixture of nickel, iron, and calcium using a fixed bed reactor system (Figure 11).

**Figure 11: Fixed Bed Catalyst Flow Reactor**

![Figure 11: Fixed Bed Catalyst Flow Reactor](image)

The research team tested this new catalyst in the laboratory with careful analysis of all major and minor producer gas components. Determining the process rates and stability was important
and was the basis for deciding economic improvements for the overall gasification process at commercial scale.

1.10.3 Objectives
This project explored the feasibility of using low cost materials to catalyze the breakdown of hydrocarbons and tars from producer gas generated from the thermal conversion of biomass. The project team used a mixture of nickel, iron, and calcium oxide as catalyst on an inert ceramic bed material for laboratory studies to treat hydrocarbons and tars normally found in producer gas. The researchers established these objectives:

1. Develop a more accurate control system for operation of the fixed bed reactor to ensure precision within 2 percent for major and minor components in the process gas stream.

2. Develop procedures to generate a catalyst bed material with 1.6 weight percent of low cost material including 40 percent nickel, 20 percent iron, and 40 percent calcium. Use a Carbo HSP ceramic bed material as the support. The final catalyst product should have a precision of 2.0 percent.

3. Demonstrate the ability to evaluate deactivation of the catalyst by sulfur with a precision of 5 percent.

4. Demonstrate analytical capabilities to measure naphthalene, a primary tar component in the producer gas, with a precision of 5 percent.

5. Perform critical tests with the catalyst at a loading that reduces the tar component by 90 percent. Also determine the loading that is required for a reduction of the tar component by 99 percent.

6. Demonstrate that the tar reduction performance of the catalyst can reduce the capital costs for the BioSNG product gas by 15 percent of the levelized cost of $16.6 per MMBtu or $2.5 per MMBtu.

1.10.4 Outcomes
The project team performed numerous individual tests focused on addressing the objectives of the study. The study outcomes include:

1. The accuracy of mass flow controllers is imperative to precisely determine gas components in the producer gas from the thermal gasifier entering the fixed bed reactor. The research team performed calibrations for important producer gas constituents and surrogate tar components, including ethylene and toluene. All controllers provided a measured accuracy within 1.0 percent, exceeding the objective.

2. The procedures for reproducing the test catalyst required re-evaluation of the component solutions for the wet impregnation of the Carbo HSP ceramic bed support. Analysis of catalyst batches indicated a precision of 3 percent that was only slightly greater than the target objective of 2 percent.

3. The researchers studied deactivating the catalyst as a result of producer gas impurities such as hydrogen sulfide relative to converting toluene and ethylene. Data indicated
converting both compounds was substantially reduced with 100 parts per million of hydrogen sulfide. The reactivation of the catalyst occurred slowly once the hydrogen sulfide was removed. Increasing the amount of catalyst had only a minimal effect on deactivation by hydrogen sulfide. This data indicated that hydrogen sulfide must be removed from producer gas before the fixed bed reactor to maintain the activity of the catalyst or a regeneration procedure is required to maintain catalyst activity.

4. The researchers evaluated converting naphthalene, ethylene, and toluene in synthetic producer gas in the fixed bed catalyst reactor. Ethylene and toluene demonstrated a consistent conversion in the range of 67 to 69 percent while naphthalene demonstrated an average conversion of 43.6 percent. The accuracy of naphthalene measurements was determined within 2.5 percent - below the objective accuracy of 5 percent.

5. In a critical test for converting tar components in the fixed bed reactor, ethylene, toluene, and naphthalene were added to producer gas from the biomass gasification input. The conversion of ethylene was 23.2 percent, toluene was 52 percent, and naphthalene was 40 percent. Based on the experimental test runs, the amount of catalyst required to achieve 90 and 99 percent conversion for all tar components was 58 and 64 grams catalyst, respectively, based on a producer gas flow rate of 12 liters per hour.

6. Researchers calculated cost reductions for BioSNG production from biomass based on the incorporation of the low cost catalyst/fixed bed reactor using an economic model developed by Black & Veatch. Based on a plant size of 100 MW thermal, the projected cost savings for incorporation of the fixed bed catalyst as compared to the conventional tar reforming process was calculated at $0.724 per MMBtu as compared to the projected saving of $2.5 per MMBtu.

1.10.5 Conclusions
The research team reached a number of important conclusions. Additional conclusions have been considered and described.

1. Changes to the fixed bed reactor system and recalibration of the flow control system allowed for a high level of accuracy in measurement of the main constituents in producer gas at 1 percent. This precision provided an accurate evaluation of the conversion characteristics of the low cost catalyst employed in this study. This precision also improved the cost calculations employed for the full-scale plant.

2. The researchers developed protocols to generate accurately and reproducibly the desired catalyst utilizing a wet impregnation method. While they determined the accuracy for production of the catalyst to be within 3 percent, slightly above projections, small batch methods are fraught with minor variations. Commercial production should have greater accuracy.

3. Deactivating the fixed bed catalyst by hydrogen sulfide was rapid and resulted in reduced conversion of ethylene and toluene from the high 90 percent to 10 to 25 percent. In addition, once the hydrogen sulfide was removed, the regeneration of the catalyst
was slow. An alternative engineering design using a circulating bed rather than a fixed bed for the catalyst would allow for regeneration of the catalyst following poisoning with sulfur through treatment with oxygen followed by return to service.

4. The researchers determined conversion of the primary tar in producer gas naphthalene was, on average, 44 percent in the fixed bed catalyst reactor. The measurement accuracy was within 5 percent and was within the objective of the study.

5. Successful critical experimental tests employing the fixed bed reactor demonstrated degradation of producer gas tar components including ethylene, toluene, and naphthalene. Data from these experiments were used to calculate the catalyst necessary for 90 and 99 percent conversion of tar components as well as the impact on capital costs for a full-scale system. The confidence in the calculated catalyst loading for substantial conversion of component tars could have been enhanced by actual operational studies matching the catalyst and process flow rates to demonstrate conversion accuracy.

6. The projected improvement in capital costs by applying the low cost catalyst and fixed bed system in place of commercial tar reforming systems was substantially less than anticipated. Based on the economic model developed by Black & Veatch, the low cost catalyst system would provide a savings of only 4.2 percent as compared to the projected savings of 15 percent. While the cost savings are disappointing, the potential to use the low cost catalyst in a circulating bed configuration may improve the process economics. However, the research team did not evaluate this engineering design to improve the performance of the catalyst in the current application.

1.10.6 Recommendations
The Program Administrator recommends further testing of low cost catalysts with the objective of reducing the poisoning resulting from reduced sulfur present in the producer gas from thermal gasification of biomass. Alternative catalytic elements may be evaluated with less sensitivity or more rapid recovery profiles from sulfur poisoning than nickel and iron.

In addition, alternate engineering designs should be explored for rapid recovery of the catalyst conversion efficiency following sulfur poisoning. The researchers identified a circulating bed reactor; however, they performed no studies to improve catalyst use. Additional studies are warranted to evaluate using improved engineering designs for catalyst use. The research team has a unique opportunity to study improvements in thermal gasification of biomass based on their access to the West Biofuels Gasification power plant.

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 more PIER funding.

Receiving additional 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.
1.10.7 Benefits to California
Public benefits derived from PIER research and development projects are assessed within the following context:

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

The primary benefit to the California ratepayer from this research increases the affordability of gas from biomass by increasing the commercialization of thermal gasification as a conversion process for biomass. The research team estimated that using thermal gasification to convert the 32 million bone dry tons of biomass available per year in California could generate 339 billion Btu of fuel gas for energy use. The research team further estimated an annual savings of $245 million for California ratepayers if the low cost catalytic process evaluated in this study were realized by converting biomass to BioSNG.

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

Marketing/Connection to the Market
The Gasification & Syngas Technologies Council website identifies only a small installed gasification capacity in North America. In addition, few gasification plants focus on using biomass for feedstock - the majority use coal. Improvements for thermal gasification of biomass would enhance this small market. The research team has currently not made any connections to the existing market.

Engineering/Technical
One advantage for the research team was access to the West Biofuels thermal gasification system that allowed for direct use of producer gas for evaluation. This is important in considering integrating new and improved technologies as evaluated in this research effort. Additional testing of alternative catalyst and catalyst systems including the circulating bed reactor with direct process gas streams is imperative to validating data.

Legal/Contractual
The research team had not developed any patent applications at the end of the project. Additional efforts in evaluating catalyst and engineering systems may be fruitful for future patent applications.
Environmental, Safety, Risk Assessments/ Quality Plans

The research team focused on the basic evaluation of the novel catalyst in degrading hydrocarbons and tars. The early stage of the technology development did not allow for assessment of environmental aspects, safety, risk, or quality plans.

Production Readiness/Commercialization

The research effort identified additional studies necessary to achieve reducing capital costs for thermal gasification of biomass envisioned based on the low cost catalyst technology. This study did not result in a technology that is ready for production and commercialization.

1.11 In-Situ Sensors for the Control of Synthetic Natural Gas Production (2014)

Awardee: Stanford University
Principal Investigator: Ron Hanson

1.11.1 Abstract

This project demonstrated the performance of in place (in situ) laser absorption-based control sensors control production of synthetic natural gas from biomass gasification. The research team monitored the water (H₂O), methane (CH₄), carbon dioxide (CO₂) and carbon monoxide (CO) concentrations of a biomass gasifier, using ghost (spectral) simulations to select sensor wavelengths. They constructed and tested a prototype sensor to validate performance of these sensors, collaborating with researchers at the University of California, San Diego (UCSD), to conduct field measurements at West Biofuels in Woodland, California. The researchers designed these tests for a pilot-scale biomass gasifier, evaluating the performance of a prototype sensor for two sensor strategies; wavelength-scanned direct absorption and wavelength-scanned wavelength modulation spectroscopy, which could potentially reduce the costs of synthetic natural gas. The laser absorption sensor provided measurements with the sub-second time resolution required for gasifier control and, more importantly, provided precise measurements of H₂O in the product scheme, which is problematic for the typical gas chromatography sensors used by industry. The rapid measurement bandwidth and the sensitive determination make these sensors suitable to control the input streams for reactors producing synthetic natural gas from biomass gasification. Such control sensors could reduce the costs of synthetic natural gas made from gasification of agricultural waste biomass by 8.2 percent.

Keywords: Optical sensors, laser absorption, control sensors, gasifier, biomass gasification

1.11.2 Introduction

This project demonstrated an in situ laser absorption-based sensors to control synthetic natural gas production from biomass gasification. Producing synthetic natural gas provides potential renewable fuels; however, the declining costs of natural gas from fracking and increasing
production from existing petroleum wells have made it difficult for renewable synthetic gas to compete. Control and optimizing the biomass gasification and its conversion to synthetic natural gas could lower the cost of renewable energy to the California consumer. Successful control strategies require sensors to monitor control variables and provide the feedback to optimize the process. Producing synthetic natural gas injects steam into the syngas flow manufacturing methane.

To optimize methane production, the major composition of the syngas feed stream must be known. Especially important is the amount of water vapor in the syngas. Current sensors used by industry to monitor the syngas composition experience two challenges to produce synthetic natural gas: the standard gas chromatograph analysis does not provide the water vapor content, and the time resolution of the gas sampling and gas conditioning before the gas chromatograph (GC) or Fourier transform infrared (FTIR) analysis is not sufficient to provide the sub-second feedback required for gasifier control. Although GCs and FTIRs with sufficient time resolution are available, the necessary sampling and gas conditioning (filtering and drying) delay the time response. In situ laser absorption sensing may address both of these sensor shortcomings with the potential to also monitor other important major components of the syngas product flow and provide control of the input stream for synthetic natural gas manufacture. Such control sensors could reduce the costs of synthetic natural gas made from gasification of agricultural waste biomass by 8.2 percent. Because there are few commercial coal or biomass gasifiers in California and the United States, it is difficult to forecast how this technology could be best used in the near term.

In this project the researchers demonstrated \textit{in situ} laser absorption measurements of the product stream from gasification of biomass. They evaluated novel laser absorption sensing schemes developed by the researchers. A schematic of the test approach is shown in Figure 12.

The researchers selected the two most promising strategies in a pilot-scale biomass gasification facility to monitor H$_2$O, CH$_4$, CO$_2$, and CO. After these sensing schemes were validated in the principal investigator’s laboratory, the researchers conducted proof-of-concept measurements in the product gas stream of biomass gasification at West Biofuels in Woodland, California. This biomass gasifier was constructed and operated in collaboration with Professor Robert Cattolica of the University of California, San Diego (UCSD), who directs research to use biomass gasification to provide input to synthetic natural gas production.
Four lasers, one for each target species in the gas mixture, are combined on an optical fiber (wavelength division multiplexer) collimated into a free-space beam, and directed through a gas mixture. The transmitted light is collected and focused onto a detector. The laser controller time-multiplexes the four lasers so that only one laser is operating at a time, and sequential measurements are made at the rate of 50 Hz.

1.11.3 Objectives

This project determined the feasibility of in situ laser-absorption sensing for a real time monitor of composition of the products of biomass gasification before and after the reforming catalyst. In addition, the researchers sought to provide the fast time response necessary for process control to optimize synthetic natural gas production and lower the price to California consumers. The researchers established these objectives:

1. Demonstrate two sets of candidate laser wavelengths for interference-free absorption measurements with sensitivity and resolution better than 0.2 percent in molar concentration for detection of CH₄, CO, CO₂, and H₂O in the reactor gas flow.

2. Demonstrate prototype sensor for measurement of CH₄, CO, CO₂, and H₂O at better than 1 kHz measurement rate with less than 0.1 percent cross talk between channels in a gas cell in the laboratory.

3. Demonstrate CH₄, CO, CO₂, and H₂O to better than 0.2 percent in molar concentration using prototype sensor in a known gas mixture to simulate UCSD reactor gas composition with a one second time resolution in the laboratory.

4. Demonstrate sensor performance with:
   a) Sensitivity better than 1 percent molar concentration
   b) Time response target of less than 1 second for in situ sensor compared to sampled GC sensor times of multiple minutes
c) Projected 10 percent reduction of synthetic natural gas costs compared to current synthetic natural gas price of $16.6/MMBtu by optimization of efficiency and reduction of maintenance costs.

1.11.4 Outcomes

1. The researchers used design rules to select potential sensor wavelengths and compared these sensor wavelengths to lasers available either in the researchers’ inventory or for purchase without long lead times. This resulted in a list of two sets of selected wavelengths. The first choice (Set 1) would use a 1 meter optical path in the producer gas product stream of the biomass gasifier. Set 2 included alternative wavelengths that would be suitable for a 0.1 meter optical path. These two sets of wavelengths provided coverage of the short and long path absorption fixture possibilities for the field campaign.

2. Typical detection limits for practical laser absorption sensors is an absorbance of 0.05 percent of the transmitted laser light. From the simulation calculations, the researchers found that all the detection limits met the objective except for the Set 1 selection for CO₂, which has an estimated minimum detectable absorbance of a mole fraction of 0.3 percent of the producer gas stream. Because the predicted CO₂ mole fraction is 20 percent of the gas, a detection limit of 0.3 percent provides a signal to noise ratio of about 70, which was a value acceptable to the researchers for the demonstration experiments. In addition, this laser was readily available.

3. The researchers assembled a prototype sensor with the laser wavelengths from Set 1. They performed experiments to determine potential for modulation cross talk between the lasers at modulation frequencies ranging from 40 to 100 kHz and scan frequencies up to 10 kHz. Using the time-multiplexed approach, no cross talk (modulation of the detected laser power at frequencies used on laser other than the target, < 0.001 percent) was observed. The researchers measured the span of the communications system at two kilometers.

4. The researchers conducted wavelength-scanned WMS measurements in the static cell.

5. Both direct absorption and wavelength-scanned wavelength modulation spectroscopy (WMS) met the uncertainty target of 0.01 of mole fraction with averages of 12 up-scan line shapes (or 0.24 second averages), which was four times faster than the initial goal.

6. The performance of the sensor in field measurements shows that the laser absorption sensor with WMS modulation would be quite satisfactory for gasifier control. Using the model of Black and Veatch, the estimated cost of synthetic natural gas from biomass gasification was updated to $17.1/MMBtu consisting of $10.76/MMBtu for gasification and $6.34/MMBtu for methanation. West Biofuels agreed with this estimate. The estimated price was based on gasifier availability of 85 percent (15 percent maintenance time). The researchers estimated that a control sensor could increase this capacity to 90 percent for a 6.0 percent decrease in the gasification cost ($0.65/MMBtu). The second step of synthetic natural gas production is the conversion to CH₄ in the methanization
reactor. This methanation step could be optimized with real time monitoring of CO as a control variable to optimize the temperature of the methanation reactor.

7. With proper sensors it may be possible to improve the conversion efficiency of CO to CH₄ from the observed value of about 20 percent to 25 percent or more as is often achieved in coal gasification. In addition, real time monitoring of the H₂O content in the producer gas provides the opportunity to optimize the steam addition to the methanation reactor. Approximately half the savings would be lost to increase in rapid reactor heating costs, but this would still be a 12 percent reduction in methanization costs ($6.34/MMBtu) or a further reduction in the cost of synthetic natural gas of $0.76/MMBtu. The researchers estimated total reduction in synthetic natural gas costs at 1.41/MMBtu or 8.2 percent. This is slightly less than the of a 10 percent reduction in the cost of synthetic natural gas production from biomass gasification.

1.11.5 Conclusions
1. This objective was met except for the 0.3 percent versus 0.2 percent mole fraction detection limit for CO₂ for a 1 m path-absorption fixture.
2. The prototype met the goals.
3. The mole fraction targets and time resolution of Objective 3 were exceeded.
4. The researchers came close to their goal but did not meet the anticipated cost reduction. Cost numbers must be reevaluated before a sensor of this type is produced.

The researchers demonstrated that the scanned-wavelength WMS sensor was suitable to control a biomass gasifier and to identify any gasifier need for maintenance. This would optimize down time for maintenance as well as optimize gasifier performance for producing high quality producer gas. This real time monitor of producer gas composition could then be used to optimize the methanation reactor for producing synthetic natural gas. The researchers calculated a cost saving potential of $1.41/MMBtu in the price of synthetic natural gas from the adjusted $17.1/MMBtu benchmark price from the model of Black and Veatch. Because there are few commercial coal or biomass gasifiers in the United States, it is difficult to forecast how this technology could be best used in the near term.

1.11.6 Recommendations
The Program Administrator recommends that the researchers:
1. Identify a commercial partner and license the technology to that party.
2. With the aid of the commercialization partner, package the technology for installation, use, and maintenance by the industrial user.
3. Perform a market analysis to determine the largest potential markets for the technology.
4. Develop an engineering specification for the intended product.
5. Evaluate potential markets beyond the bio-gas reactor area. These could be combustion exhaust applications or natural gas leak detection applications.
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 additional funding within the PIER program.

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

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

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

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California energy supply and possible more affordable energy. According to the California Energy Commission roadmap for developing biomass there are 32 million bone dry tons of sustainable biomass feedstock available annually for gasification in California. This biomass feedstock could be gasified to drive synthetic natural gas methanation reactors to produce 339 billion Btu. Using the laser absorption sensor technology demonstrated in this project could save $1.41/MMBtu - a potential savings to California natural gas ratepayers could be $1.41 x 339,000 MMBtu or $478,000/year if this type of fuel were to be used. For comparison, natural gas prices were approximately $3.50/MMBtu in early 2017.

In addition, California is committed to reducing atmospheric greenhouse gas emissions. Using laser absorption sensing of CH₄ (50 times more potent as a greenhouse gas than CO₂) provides a method for natural gas leak detection that is more sensitive and applicable over a range of remote sensing applications. The added benefit is public safety in detecting leaks in the state’s gas pipeline system and oil field emissions.

Using available biomass material as a partial replacement for natural gas would decrease the net production of CO₂ from house heating and industrial processes. The benefit would be proportional to the amount of biomass-derived bio-gas to the total amount of natural gas consumed.

1.11.8 Technology Transition Assessment
As the basis for this assessment, the Program Administrator reviewed the researchers’ overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.
**Marketing/Connection to the Market**

The researchers did not conduct any market research. They deferred all market assessment activity to a commercializing partner. They had not identified the partner by the end of this project.

**Engineering/Technical**

The researchers stated that they had completed all basic engineering work. They deferred any product related engineering, including a product specification to the commercializing partner.

**Legal/Contractual**

The researchers filed for one patent through Stanford University related to work on this project.

**Environmental, Safety, Risk Assessments/ Quality Plans**

The researchers deferred this type of activity to the commercializing partner.

**Production Readiness/Commercialization**

The commercializing partner must be identified before any production readiness activities can begin.

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**Awardee:** Pyro-E LLC  
**Principal Investigator:** Kevin Lu  

**1.12.1 Abstract**

This project demonstrated heat (pyro-electric) assisted combined heat and power (CHP) system for single family houses. The researchers developed materials that exhibit strong pyro-electric effects to extract heat energy from the exhaust of a Stirling engine. Combining pyro-electric materials with the Stirling engine was expected to produce an efficient and low emission system providing all the electricity and heat energy required by a single family house. Testing of the pyro-electric materials demonstrated 10 times more power output than traditional thermo-electric materials. They estimated a manufacturing cost near $1.15/W however, without building a full prototype system it is difficult to estimate an installed price to homeowners

The researchers also estimated significant cost and water savings if the project system were installed throughout California. Since heating needs vary in California’s climate zones, the financial value of the heat energy will also vary. Additional market analysis and climate zone modeling are necessary to provide solid data for benefits analysis. Depending on the savings, the project systems could reduce CO2 emissions. The researchers claimed water savings derive from the assumed reduction of cooling water at large central power plants. Almost all water saved would be treated wastewater that is widely used for landscaping. It is unlikely that any existing large power plant would shut down during its planned lifetime due to this technology.

**Keywords:** Combined heat and power, Stirling system, pyro-electric device, heat recovery, heat
1.12.2 Introduction

Current California energy policy supports either zero net energy or significantly reduced energy consumption for residential buildings. Many houses now meet this goal for electricity by using rooftop solar. This project was to advance an alternate energy system for individual houses, powered by natural gas to provide all the heat energy and electricity necessary for that building. Each house would be equipped with a natural gas-fueled Stirling engine. Pyro-electric devices in the engine exhaust would produce additional electricity to increase the efficiency of the system. Exhaust heat would provide the energy for space and water heating.

The breakthrough aspect of the technology was using pyro-electric materials to improve commercial Stirling engine performance targeted for single family houses in California. The researchers choose the Stirling engine because there are few engine choices at the 1.0 kW electric output level and backup diesel generators are not designed for continuous duty. Other small-scale engines are only commercially available with outputs greater than 25 kW electric (kWe) or 10 times the average electrical load of a single family residence.

Stirling engines can be reasonably efficient and clean; however, they have not been accepted commercially for numerous reasons. First, it is difficult to deviate from the known internal combustion engine because of the heavy investment in that technology for more than a century. Second, Stirling engines are not particularly efficient at low loads and do not respond quickly to load changes, which is not a good feature if the engine is to follow residential loads. Electricity demand for a single house has sharp peaks and valleys as individual appliances are cycled on and off. A Stirling engine system for a single house must have some type of energy storage to meet the instantaneous demand of an air conditioner or refrigerator cycling on and off.

The researchers proposed to match the load profile of a residence with the Stirling engine system. They noted home generation systems could conform to existing gas infrastructure, regulatory policies, and renewable energy standards. The researchers envisioned a network of individual house units with sufficient capacity to sustain individual equipment failure. Efficiencies of combined heat and power system can reach about 85 percent for high thermal loads for space/water heating. The Stirling/pyro-electric system was expected to reach 21 to 23 percent efficiency; however, at the end of this project the researchers projected 25 percent efficiency for their system. This was a projected efficiency and not based on system tests.

The researchers purchased a NASA-developed Stirling engine from SunPower and intended to add their pyro-electric devices to that engine. The Stirling engine was not integrated or tested with the pyro-electric materials during this project. All development work in this project was focused on measuring efficiencies of pyro-electric materials and projecting the output of the proposed system (Figure 13).
Figure 13: Schematic of Experimental System

An electrical heat source is used to simulate the engine source to parameterize performance. The blue line indicates working fluid flow, green/yellow/red lines indicate positive, and black is ground signals.

1.12.3 Objectives
This project explored proving the feasibility of a pyro-electric assisted combined heat and power system for individual houses with these project objectives:

1. Acquire engine specifications for integration.
2. Acquire specifications for balance of system.
3. Schedule test bed delivery with SunPower/Ametek.
4. Design a system to demonstrate 1.0 kW capacity.
5. Monitor temperature, pressure, and gas flow rates.
6. Ensure temperature and pressure measurement errors are less than 5 percent.
7. Demonstrate baseline heat-toelectric efficiency of 15 percent under nominal conditions.
9. Demonstrate 100 W output for 500 hours of continuous operation.
10. Confirm the projected scale-up cost of $1/W continues to be supported.
11. Confirm 7.0—10 percent reduction in carbon emissions per California residence.

1.12.4 Outcomes
The project outcomes were:
1. The researchers acquired baseline engine speed, heat rate, and electrical power from the manufacturer of the Stirling engine.

2. The researchers obtained nominal heat source and sink temperatures as well as coolant fitting dimensions for retrofit.

3. The Stirling engine was delivered to the researchers from SunPower.

4. The researchers designed the combined cycle system for 1.0 kW electrical output.

5. The researchers installed thermocouples and pressure transducer in the apparatus test section.

6. The researchers calculated temperature measurement errors to be about 2.0 percent. Pressure measurement error was not calculated due to the slow response rate of commercial off-the-shelf transducers.

7. Device level conversion efficiency reached 14 percent (heat to electric).

8. The researchers projected, but did not demonstrate, system level conversion efficiency to exceed 25 percent.

9. The pyro-electric device output was about 125 W (peak) and exceeded 500 hours of total operation.

10. The researchers claimed to confirm scale-up costs by assuming 1 MW installed capacity.

11. The researchers claimed they achieved carbon reductions by assuming 25 percent residential market adoption.

1.12.5 Conclusions

1. The researchers achieved their goals for Objectives 1 through 5.

2. Objective 6 was partially completed.

3. Objective 7 was nearly achieved.

4. Objective 8 was not achieved since no system was built and tested.

5. Objective 9 was achieved.

6. For Objective 10, it is difficult to determine costs since the entire system was not fully defined.

7. There is little supporting data to determine that the researchers met Objective 11.

The researchers did not prove feasibility of the proposed concept. While they produced encouraging data, considerable work must still be accomplished to prove feasibility.

1.12.6 Recommendations

The Program Administrator recommends that the researchers:
1. Define a complete energy system. Identify key components of that system. Estimate total system cost, size, and performance.

2. Complete the integration of pyro-electric devices with the Stirling engine.

3. Test that system to obtain a performance map parameterized by power, efficiency, and various off-design specifications (i.e., load, turn down ratio or fractional output, coolant temperature, etc.).

4. Use these parametric relations as a blueprint to future technology demonstration, qualification, and deployment.

5. Develop a relationship with a systems manufacturer. Use that partner to optimize the system for low manufacturing cost.

6. Conduct market analysis to obtain customer interest in such a product.

7. Evaluate energy savings in each of California’s climate zones for various housing types and ages.

8. Evaluate building codes in California’s major cities to determine any roadblocks they may contain.

9. Analyze how the proposed system could be integrated into existing houses, condos, and apartment buildings.

10. Work with the California Building Industry Association (CBIA) to determine members’ interest in designing such energy systems into new houses.

1.12.7 Benefits to California

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

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

The primary benefit to the ratepayer from this research is increased affordability of energy in California. If the proposed concept came to market and reduced the cost of household energy it could benefit millions of California ratepayers, especially in areas of California with high space and water heating demand. While the researchers predicted that their concept could produce household electricity for about 8¢/kWh, that price could change when the full system is produced and priced for the market. One advantage to the proposed system is as a non-interruptible power source, benefitting areas of the state that are affected by frequent power interruptions from weather, fire, or other natural disasters. Although difficult to quantify this advantage, but it is easily understood.
Market adoption may be slow for various reasons. More Californians are living in apartments, condos, or rented houses and will not pay for a household energy source for buildings they don’t own or can’t control. Second, many families have limited financial resources that would prevent them from buying an expensive energy system. Finally, many families don’t consider their current electricity bills significant, especially as energy-efficient lighting and appliances reduce their bills.

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

**Marketing/Connection to the Market**
At the completion of this project the researchers had not performed a thorough market assessment nor talked with potential customers.

**Engineering/Technical**
The researchers stated that they required additional funding of $1.5 million and two years to complete the design, development, and testing of a prototype system.

**Legal/Contractual**
No patents had been sought or received during the performance of this project.

**Environmental, Safety, Risk Assessments/ Quality Plans**
Until a complete system is specified, none of these plans can be started. The researchers had not completed an engineering requirements specification for their system.

**Production Readiness/Commercialization**
The researchers planned to use United States-based contract manufacturers for parts supply and complete system assembly in-house.

### 1.13 Development of Next Generation Feedstock for Biomethane Production (2014)

**Awardee:** San Diego State University  
**Principal Investigator:** Temesgen Garoma

#### 1.13.1 Abstract
Converting extracted lipid and protein components from algae (algal) biomass through anaerobic digestion has the potential to generate substantial amounts of renewable and sustainable energy. From the lipid component alone, an estimated 1,157 giga-watt per hour (GWH) each year can be generated from algal biomass systems, improving California’s ability to meet its renewable energy goal of 33 percent by 2020.
The research team in this project evaluated established and newer methods to extract lipids and proteins from the algae *Chlorella vulgaris*. Key issues for recovery of lipid and protein components from algae focused on reducing chloroform levels in lipid-extracted algae product and the multiple wash steps required for protein-extracted algae.

The researchers evaluated anaerobic bioconversion of the lipid-extracted algae and protein-extracted algae products to optimize methane yields. They used organic loading rate of 2,000 milligrams dry feedstock per liter determining a one-to-one feedstock ratio for both the lipid and protein products. In addition, they determined optimum alkalinity for anaerobic conversion to be 3,000 milligrams per liter as calcium carbonate. The optimum process time was 20 days for both feedstocks at an operating temperature of 25° C. Anaerobic conversion yields were lower than anticipated, representing 58.5 percent for lipid-extracted algae and 37.2 percent for protein-extracted algae.

Additional research is required to overcome issues with low recovery and high energy costs for recovery of lipid and protein components from algae. In addition, further work is necessary to improve the anaerobic bioconversion rates and yields through further adaptation of the microbial consortium and to increase the carbon to nitrogen ratio through blending low nitrogen feedstocks such as paper. This would improve energy generation and process economics.

**Keywords:** Algae, lipid extraction, protein extraction, anaerobic digestion, methane

1.13.2 Introduction

Cultivating algal biomass and converting it to fuel gas represents a renewable and sustainable energy source for California to meet its goal of 33 percent of electrical energy generated by renewable sources by 2020. To meet this goal, additional renewable energy sources must be established and expanded. Currently, California has 12 biodiesel plants producing 41 million gallons per year with an anticipated demand for 200 million gallons by 2022. Expanding biodiesel production from algal sources could generate substantial amounts of waste streams containing lipid and protein components.

This research effort focused on evaluating methods for effective recovery of lipids or proteins from a identified algal source. The methods used were from established literature methods such as Bligh and Dyer method for lipids or conventional literature methods for proteins. Converting both products by anaerobic digestion required careful consideration of residual processing chemicals that may be considered toxic to the microbial consortium. A generic process flow design is shown in Figure 14.
This research effort focused on the individual methods for lipid and protein extraction, including yield, energy requirements, and residual chemical components. Evaluating the anaerobic conversion of lipid-extracted algae and protein-extracted algae is required to establish optimum operating conditions and determine yields and productivity for conversion of each feedstock.

1.13.3 Objectives
This project explored the feasibility of extracting lipid and protein fractions from algae to convert by anaerobic digestion to a methane energy product. Methods of extraction and recovery of lipid and protein fractions were from available published reports. The methods were not optimized for compatibility with anaerobic microbes, simplified process, low cost operation, or recovery of product. Therefore, the research project focused on optimizing methods for recovery of lipids and proteins from the algal biomass as well to determine anaerobic conversion rates and yields. The researchers established these objectives:

1. Using an established algae source, *Chlorella vulgaris*, determine the degree of treatment or purification required, in terms of energy consumed, for recovery of lipid-extracted algae and protein-extracted algae fractions.

2. Establish the values for process parameters that result in a methane yield of at least 180 ml at 25° C and 1.0 atm for 1.0 gram of lipid-extracted algae.

3. Establish the values for operational parameters that result in a methane yield of at least 180 ml at 25° C and 1.0 atm for 1.0 gram of lipid-extracted algae.
4. Demonstrate that anaerobic digestion will result in a methane yield of at least 180 ml per gram of lipid-extracted algae and a productivity of 9 ml of methane per day per gram of lipid-extracted algae at 25° C and 1.0 atm.

5. Establish the values for process parameters that result in a methane yield of at least 220 ml at 25° C and 1.0 atm for 1 gram of protein-extracted algae.

6. Establish the values for operational parameters that result in a methane yield of at least 220 ml at 25° C and 1.0 atm for 1 gram of protein-extracted algae.

7. Demonstrate that anaerobic digestion will result in a methane yield of at least 220 ml per gram of protein-extracted algae and a productivity of 11 ml of methane per day per gram of protein-extracted algae at 25° C and 1.0 atm.

1.13.4 Outcomes

The project team performed numerous individual tests focused on addressing the objectives of the study and include:

1. A validated culture of the algae *Chlorella vulgaris* was obtained from a commercial supplier and cultured in large-scale systems to generate algal biomass.

2. To generate the lipid-extracted algae fraction, the researchers used a standard method established by Bligh and Dyer. This method involved the use and recovery of chemicals, including chloroform and methanol. To prevent inhibition of the anaerobic microbial consortium, near complete removal of residual chloroform was necessary. While the researchers reviewed multiple methods, they used a process involving a rotary evaporator (rotovap) followed by oven drying. Results indicated a lipid yield of approximately 30 percent on a dry mass basis that was consistent with the lipid range reported in the literature. Combined use of the rotovap for 30 minutes followed by oven drying overnight at 100° C resulted in chloroform removal of 99.986 percent. The researchers determined the energy required for removal of chloroform was 6.52 KJ per gram dry lipid-extracted algae.

3. The researchers evaluated several extraction methods to generate the protein-extracted algae fraction, since no standardized method had been previously reported in the literature. Methods included the use of trichloroacetic acid, acetone, sodium dodecyl sulfate, phenol, and ammonium acetate. Following extraction and precipitation, the researchers evaluated re-solubilization of the purified protein extract using either phosphate buffer or 2-dimensional electrophoresis buffer. They determined the greatest yield of extracted protein used 80 percent acetone followed by solubilization with the 2-dimensional electrophoresis buffer. The researchers determined the overall yield was 3.17 percent, which was determined to be appropriate based on the recovery of only the soluble protein fraction. They determined the energy required for processing of the protein-extracted algae with the optimum conditions was 6.43 KJ per gram of dry protein-extracted algae.
4. Establishing the process parameters that result in greater methane yield, the researchers focused on analysis of the ratio of microbial inoculum to lipid-extracted algae feedstock. Maintaining a volatile solids loading of 2,000 milligrams per liter of volume, they determined an optimum ratio of 1.0 to 1.0 on a volatile solids basis for inoculum to the lipid-extracted algae feedstock.

5. Establishing the operational parameters that result in greater methane yield for the lipid-extracted algae, the researchers focused on evaluating the optimum alkalinity, digestion time, and operating temperature. Results indicated an optimum alkalinity of 3,000 milligrams per liter as calcium carbonate, a digestion time of 20 days, and greater methane yield for mesophilic temperature (37° C) as compared to thermophilic temperature (55° C). The researchers measured a methane yield of 105.3 ml per gram of dry lipid-extracted algae under optimum conditions. That was substantially lower than the anticipated yield of 180 or calculated theoretical yield of 300 ml per gram. In addition, they determined the volatile solids reduction by anaerobic conversion of the lipid-extracted algae feedstock to be 20 percent. That was significantly lower than the range of 40–45 percent volatile solids reductions for municipal sludge.

6. Analysis of the anaerobic conversion of lipid-extracted algae determined a methane productivity of 4.9 ml per day per gram as compared to the anticipated productivity of 9.0 ml per day per gram of feedstock.

7. Establishing the process parameters that result in greater methane yield focused on the analysis of the ratio of microbial inoculum to protein-extracted algae feedstock. Maintaining a volatile solids loading of 2,000 mg per liter of volume, the researchers determined an optimum ratio of one-to-one on a volatile solids basis for inoculum to the lipid-extracted algae feedstock.

8. Establishing the operational parameters that result in greater methane yield for the protein-extracted algae focused on evaluating the optimum alkalinity, digestion time, and operating temperature. Results indicated an optimum alkalinity of 3,000 milligrams per liter as calcium carbonate, a digestion time of 20 days, and greater methane yield for mesophilic temperature (37° C) as compared to thermophilic temperature (55° C). The researchers found a methane yield of 81.9 ml per gram of dry protein-extracted algae under optimum conditions. That was substantially lower than the anticipated yield of 220 or calculated theoretical yield of 360 ml per gram. In addition, the researchers found the volatile solids reduction of the protein-extracted algae feedstock to be 33 percent. That was significantly lower than the range of 40–45 percent volatile solids reductions for municipal sludge.

9. Analysis of the anaerobic conversion of lipid-extracted algae determined a methane productivity of 3.4 ml per day per gram as compared to the anticipated productivity of 11 ml per day per gram of feedstock.
1.13.5 Conclusions

The research team reached a number of important conclusions. Additional conclusions have been considered and are also described.

1. The researchers evaluated the methods for extracting lipids and proteins from the algae *Chlorella vulgaris* and evaluated them for optimized recovery of product, process energy requirements, and compatibility with the anaerobic microbial process.

2. The application of the Bligh and Dryer method with modification to include a rotovap removal of chloroform followed by oven drying produced lipid-extracted algae product with very low residual chloroform and presumably suitable for subsequent anaerobic conversion. However, evaluation of the energy required for processing was 6.52 KJ per gram of dry lipid-extracted algae as compared to the estimated energy content of the product identified as 10.81 KJ per gram. The small differential in the energy content of the product and that required for processing the lipid-extracted algae feedstock, limits the feasibility for its use.

3. While no established protocol was identified for algal protein extraction, the researchers evaluated several potential processes including buffers for re-solubilization of the product. The researchers found a method using 80 percent acetone followed by re-solubilization with a 2-dimensional electrophoresis buffer provided the best recovery of protein-extracted algae product. However, the process energy required for recovery of the algal protein product was 6.43 KJ per gram of dry protein-extracted algae as compared to the estimated energy content of the product of 15.5 KJ per dry gram. This relatively small difference in the product energy content as compared to the process energy required limits the feasibility for its use.

4. Anaerobic conversion of lipid-extracted algae product under optimum conditions of inoculum addition, operating temperature, alkalinity, and residence time was 105.3 ml of methane per gram dry feedstock and determined to be substantially below the anticipated yield of 180 ml of methane per gram dry feedstock. Potential issues resulting in low conversion include residual chloroform in the lipid feedstock, need for better acclimation of the microbial consortium, and low carbon to nitrogen ratio for the lipid feedstock.

5. Anaerobic conversion of the protein-extracted algae product under optimum conditions of inoculum addition, operating temperature, alkalinity, and residence time was 81.9 ml of methane per gram dry feedstock and determined to be substantially below the anticipated yield of 220 ml of methane per gram dry feedstock. Potential issues resulting in low conversion include better acclimation of the microbial consortium and low carbon to nitrogen ratio for the protein feedstock.

Technical information developed in this research effort has identified baseline values for recovery of lipids and protein from algae and the anaerobic conversion to methane. While initial results were disappointing, substantial research opportunities exist to improve the lipid and protein recovery as well as optimizing the anaerobic conversion. Collaborations with experts in
the existing biodiesel market may provide more informed development of processes for recovery of lipids and protein from algae. In addition, experts in the application of anaerobic digestion systems for municipal wastewater and applied systems for commercial wastes could also provide more directed methods to monitor and improve anaerobic conversion yields.

1.13.6 Recommendations
The Program Administrator recommends further testing to reduce the complexity and energy requirement for production of lipids and protein from algae and to improve the rates of anaerobic conversion of the lipid and protein products. The Program Administrator recommends the researchers:

1. Optimize the extraction of lipids and proteins from algae or algal waste streams.

2. Use the well-established method of Bligh and Dyer focusing on establishing methods for near complete removal of chloroform. Alternative methods employing less toxic solvents, less complex or costly materials, and less energy intensive methods must be researched. In addition, while recovery of process chemicals such as chloroform can be accomplished efficiently by rotovap (1.5 KJ per gram of dry lipid-extracted algae), additional chloroform removal by oven drying may not be necessary if the anaerobic microbial consortium is adapted to growth and conversion of low levels of chloroform in the feedstock.

3. Research additional methods for protein recovery. Unlike the established methods for lipid recovery from algae, proven methods for protein recovery from algae have not been published. The relatively low level of protein content extracted from the algae can be improved with better methods. The relatively high energy cost for producing the protein product must be improved. Reducing the complexity can go a long way to reducing both energy and real costs for recovering protein from algae.

4. Adjust a number of operational parameters for anaerobic conversion that were not evaluated in this study. Anaerobic conversion of algal-extracted lipid and protein were very low based on both volatile solids reduction and methane production.

5. Adaptation of the anaerobic microbial consortium to residual chemicals used in extraction of the lipid and protein products needs to be evaluated. Long term exposure of the feedstock to the microbial consortium allows specific microbes which are capable of specific compound degradation to proliferate and attain greater populations, improving conversion rates and reducing toxicity.

6. The research team identified that the carbon to nitrogen ratio may be substantially low in the anaerobic digestion system for algal lipids and protein products. This may be especially true for the algal protein product which allows for the breakdown of nitrogen-rich proteins to ammonia. At high concentration this can be toxic to the microbial community. The research team suggested evaluation of adding nitrogen-poor feedstocks such as paper to the digester to dilute the nitrogen component. While this approach has substantial merit and should be investigated, the researchers should first undertake
analysis of ammonia levels in the present anaerobic digestate to demonstrate this is the
issue.

After considering (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 additional funding
within the PIER program. The research team has a unique opportunity to study improvements
in recovery of lipids and proteins from algal biomass and their conversion to methane by
anaerobic digestion based on their current experience and capabilities demonstrated in this
study.

Receiving additional 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.

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

• Reduced environmental impacts of the California energy supply and distribution system

• Increased public safety of the California energy system

• Increased reliability of the California energy system

• Increased affordability of energy in California

The primary benefit to the ratepayer from this research involves increasing the affordability of
energy in California. This technology may improve market acceptance and use of renewable
algal biomass in energy generation in California. Demonstrating effective, low cost, and low
energy methods for lipid and protein waste recovery from algal biomass systems, coupled to an
optimized and high yield anaerobic digestion process for production of the methane energy
product, could provide affordable renewable energy opportunities in California. The research
team estimated the potential for only the lipid-extracted algae component as 1,157 GWH per
year, not including recovery and conversion of protein. The research team further determined
this potential for algal lipid recovery and anaerobic conversion could increase the in-state
energy currently derived from biopower to 18 percent of California’s demand. These energy
benefits did not take into account the energy input required to prepare (purification) the
feedstock. Accounting for that energy would result in no net benefit for this technology at this
time. Further research is necessary to reduce the entire energy input.

1.13.8 Technology Transition Assessment
As the basis for this assessment, the Program Administrator reviewed the researchers’ overall
development effort, which includes all activities related to a coordinated development effort,
not just the work performed with EISG grant funds.
Marketing/Connection to the Market
Currently, due to the preliminary nature of this technology, the research team has not developed a connection to the market.

Engineering/Technical
The researchers estimated that they require four to six years for maturation of the technology and about $700,000 to fund that work.

Legal/Contractual
The research team has not developed any patent applications at present.

Environmental, Safety, Risk Assessments/ Quality Plans
The research team focused on the more basic evaluation of lipid and protein recovery from algae and subsequent conversion by anaerobic digestion. The early stage of the technology development did not allow for assessment of environmental aspects, safety, risk, or quality plans. However, using 100°C oven heating of the product to drive off residual chloroform was identified as a potential and significant safety risk.

Production Readiness/Commercialization
This project did not result in a technology that is ready for production and commercialization.

1.14 Self Powered Thermoelectric Desalination System (2014)
Awardee: Hi-Z Technology, Inc.
Principal Investigator: Fred Leavitt

1.14.1 Abstract
Urban populations are demanding more potable water supplies. One answer is desalination of brackish or ocean water. While the market for water desalination is growing, the technology requires significant energy input 24 hours a day, making desalinated water more expensive than conventional sources. This projected explored the feasibility of using concentrated solar power and thermoelectrics to reduce or eliminate the cost of energy (usually natural gas) used for water desalination. Thermal storage is required to extend the source of heat beyond the normal solar day.

The researchers modeled a thermoelectric solar thermal desalination system that would provide affordable clean water for drinking water and cleanup of brackish water for agriculture. Five partners provided data for:

- A concentrated solar parabolic trough
- San Clemente Island, California, weather
- Thermoelectric generator electrical and thermal energy
- Two thermal desalination processes, forward osmosis and multi-effect distillation
• Thermal storage
• System performance and financial costs.

The researchers demonstrated a small (sub-scale) thermoelectric generator (TEG) that achieved greater than 90 percent electrical and thermal efficiency. The TEG’s conversion efficiency, while relatively low, supported all facility electric power requirements and achieved near 100 percent system energy efficiency since the balance of unused thermal power was provided to the desalination process. The prototype TEG performed as predicted.

The researchers projected the cost of water from their autonomous desalination system at $0.50/m³ for a mid-sized system producing 200m³/h. If this cost could be achieved in commercial practice, it would compare favorably with literature values for alternative technologies.

Keywords: Thermoelectric generator, desalination, forward osmosis, concentrated solar power, parabolic trough solar receiver, thermal storage

1.14.2 Introduction

Demand for water continues to increase while freshwater sources are becoming scarce because of increasing demand for natural resources and the impacts of climate change. Desalination of seawater and brackish water can be used to increase fresh water supplies; however, removing the salt from seawater or brackish inland ground water is an energy intensive process and consumes more energy per gallon than most other water supply and treatment options. On average, reverse osmosis (RO) desalination plants, the most common type of desalination technology, use about 15,000 kWh per million gallons of water produced) or 4 kWh per cubic meter.

The researchers proposed a system using energy from concentrating solar receivers. This concept seems particularly relevant in addressing the water-energy nexus in remote California communities where there is abundant solar energy and opportunities to desalinate brackish groundwater, agricultural runoff, or seawater especially in island/coastal communities. The researchers proposed using thermal storage to address solar inconsistency (intermittency) which extends the hours the system can operate.

The researchers selected thermal desalination powered by concentrated solar power (CSP) to address a range of salinity levels and to take advantage of the low cost of thermal storage to extend the hours the system can operate. Concentrated solar power (CSP) heats oil to 300° C. The oil is then used to heat a thermoelectric generator (TEG). Seawater is fed into a chamber with an osmotic membrane. A proprietary liquid polymer with a high affinity for water draws pure water from the seawater across the membrane into the draw solution. The cold diluted draw solution passes through the TEG where it simultaneously cools the TEG and is heated. As the diluted solution is heated, its solubility for water is reduced, separating the water from the draw. Pure water is pumped off the top of the separation tank and the concentrated draw is returned to collect more water.
The CSP and the forward osmosis units were considered to be developed commercial products. All research activity was focused on proving the TEG capable of handling the conditions imposed by the designed system.

1.14.3 Objectives
This project explored the feasibility of using a TEG to provide the electrical energy to fully power a thermally-based desalination system. The project included eight objectives to demonstrate the TEG:

1. Design, build, and instrument a prototype thermoelectric generator to demonstrate the possibility of >90 percent combined thermal/electrical efficiency when installed in a solar desalination system.

2. Demonstrate that the test stand is capable of measuring temperatures, flow rates, and power to an accuracy of ±5.0 percent and that the data can be extrapolated to a full-scale system.

3. Demonstrate total thermal/electrical efficiency >90 percent and 160 W_e power.

4. Show thermoelectric desalination is scalable from <100 m³/day to 5,000 m³/day to >500,000 m³/day.

5. Demonstrate that the prototype can operate at least 500 hours without failure.

6. Confirm that the projected manufacturing cost of $0.50/m³ capacity continues to be supported.

7. Confirm the cost of water produced with a thermal storage system is $0.10/m³ less than without a thermal storage system.

8. Determine that the life cycle cost of operating an autonomous desalination system (ADS) is less than alternative desalination methods. This objective was added after the proposal.

1.14.4 Outcomes
The outcomes for each of the objectives identified are summarized:

1. The researchers designed, built, and instrumented a prototype demonstration generator.

2. They measured the test stand overall accuracy at ±8.8 percent, exceeding the targeted ±5 percent objective. They claimed that most of that tolerance was due to the hot oil flow meter. Without the flow meter they measured the accuracy at ±4.6 percent. The researchers found no reasonable alternative to the flow meter used.

3. The researchers claimed a generator output of 170 W_e at the design operating temperatures.
4. The researchers showed that they could scale the generator from a few hundred watts to megawatts. This range would be suitable to power desalination systems from less than 100 m$^3$/day to 5,000 m$^3$/day to greater than 500,000 m$^3$/day.

5. The researchers operated the generator for 500 hours with no failure and no sign of degradation.

6. The researchers projected water cost at:
   - $1.52/m$^3$ at 100 m$^3$/day
   - $0.50/m$^3$ at 5,000 m$^3$/day
   - $0.42/m$^3$ at 500,000 m$^3$/day

7. The researchers calculated that thermal storage reduced the cost of water by $0.56/m3.

8. The researchers found life cycle cost of water produced by various desalination technologies to be:
   - MSF (multi-stage flash) $1.25/m^3$
   - VC (vapor compression) $0.95/m^3$
   - MED (multi-effect distillation) $0.85/m^3$
   - RO (reverse osmosis) $0.82/m^3$
   - ADS (autonomous desalination system) $0.50/m^3$

1.4.5 Conclusions

1. The researchers met this objective.

2. The researchers did not meet this objective.

3. The researchers met this objective.

4. The researchers met this objective although considerable work remains once a commercial system is designed at various sizes.

5. The researchers met this objective.

6. The researchers met this objective.

7. The researchers met this objective.

8. The researchers met this objective.

The researchers proved feasibility of the TEG component of the solar desalination system they designed with partners.
1.14.6 Recommendations
The Program Administrator recommends the researchers:

- Merge the three components into a fully functional demonstration system.
- Complete the design of and test a suitable thermal storage system.
- Design a small pre-packaged ADS that could be both a demonstration system and a commercial product. This system could fit entirely (not including the solar field) within a 40-foot shipping container capable of producing 20 m$^3$ (5,283 gallons) of water per hour.
- Refine the cost of produced potable water.
- Locate and secure a California test site.
- Operate a prototype system for at least one year to determine actual costs, maintenance issues, reliability, and other operational data.
- Working with vendor/partners, improve the cost model for a commercial system.
- Evaluate the possibility that heat engines that are more efficient than thermoelectric generators could be used to perform the same task with improved economics.
- Evaluate the brine disposal issue and potential solutions.

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 additional funding within the PIER program.

Receiving follow-up 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.

1.14.7 Benefits to California

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

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

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California energy supply and distribution system. If the proposed desalination system were put into commercial practice, it would eliminate the necessity for numerous power plants required to operate conventional reverse osmosis desalination plants. Reverse osmosis is the most accepted technology for seawater desalination. The Poseidon desalination plant in San Diego
County uses more than 28 MW of electricity with this cost accounting for the majority of the water cost. Replacing the 28 MW draw of the Poseidon plant could eliminate the consumption of 21.2 million therms of natural gas a year and the production of 152,000 tons of CO₂ per year. Additionally, the researchers estimated the cost of desalinated water from the proposed system to be significantly lower than reverse osmosis systems. An ADS system with an equivalent capacity (190,000 m³/day) of the Poseidon plant could use no grid electricity and produce water $0.32/m³ less than RO. The savings could be more than $22 million per year if the researchers’ calculations continue to be supported.

Since the proposed system can operate off grid, it could be used to recover brackish ground water and agricultural runoff. The reclaimed water could be used for agriculture and restoring water to the aquifers in California’s Central Valley. Because of California’s drought, aquifers are being drained at an alarming rate.

1.14.8 Technology Transition Assessment

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

Marketing/Connection to the Market

The researchers completed a market analysis. In addition, their partners have supported the market evaluation.

Engineering/Technical

The researchers estimated that they require about $2.5 million and two years to design, construct, and demonstrate a 10 m³/h system.

Legal/Contractual

Hi-Z has applied for three patents. The researchers claimed they completed a patent search and found no patents that would conflict with their intellectual property. The researchers received a $155,000 Phase I grant from United States Department of Energy to design a specific system for a United States Navy installation at San Clemente Island, with a potential $1 million follow-on Phase II grant.

Environmental, Safety, Risk Assessments/Quality Plans

The main regulatory barrier to the installation of seawater desalination systems is the return of the brine to the marine environment. Inland desalination plants face the issue of disposal of the concentrated brine. Other assessments must be completed before fielding a commercial product.

Production Readiness/Commercialization

At the completion of this project the researchers were working on a commercialization plan with the aid of a commercial investor.
1.15 Two-Phase Digestion for Enhanced Hydrogen Production and NOx Control (2014)

Awardee: California Polytechnic University.
Principal Investigator: Tryg Lundquist

1.15.1 Abstract

Anaerobic digestion of organic wastes represents an opportunity to generate substantial quantities of renewable energy. However, converting the biogas containing methane and carbon dioxide in cogeneration systems requires expensive catalytic technology to reduce NOx emissions. This study evaluated a novel two stage anaerobic system to convert organic wastes to generate an upgraded fuel gas, resulting in reduced NOx emissions when used in a cogeneration system. The anaerobic digestion system in this study contained a hydrogen-producing first phase and a methane-producing second phase, and recirculating gas from the second to first phase to achieve optimum mixtures of hydrogen to methane.

Researchers evaluated food waste and glycerol as low cost, high volume hydrogen producing feedstocks. Food waste produced a hydrogen yield greater than the optimal glucose yields achieved in previous experiments. Hydrogen production was about 1.26 and 1.01 liters of hydrogen per liter of digester volume for food waste and glucose, respectively. Glycerol produced 120 percent of the maximum yield of glucose after discounting the glucose yield to account for the reduced hydrogen production potential of glycerol.

The researchers constructed two lab-scale, two phase digestion systems and tested them to determine ideal organic loading rate and residence time for producing hydrogen.

The researchers developed a cost-benefit model comparing two phase digestion to conventional NOx control technologies. They estimated a $1.2 million savings over a 20-year lifetime. Compared to other NOx control technologies, they estimated two phase digestion could reduce NOx control costs by over 50 percent while meeting NOx emissions limits.

Keywords: Hydrogen, anaerobic digestion, two phase, glycerol, food waste, NOx

1.15.2 Introduction

Anaerobic digestion as a waste conversion and energy generation technology is relatively well developed and has been applied to a variety of organic feedstocks including municipal sewage, sorted refuse, agricultural manures, food processing wastes, and commercial wastes. California has set aggressive goals for greenhouse gas reductions with Senate Bill 1383 calling out reducing methane emissions from dairies and diverting organic wastes and food wastes from landfills to produce energy. Advantages to using anaerobic digestion include reduction of feedstock solids, odor, and pathogen load, while mineralizing nutrients as a soil amendment and generating a biogas product containing methane.

While a variety of biogas-to-electricity technologies are currently available, NOx emissions issues must be addressed. Technologies reducing NOx emissions increase capital and operating costs for anaerobic digestion systems making them less economically viable. Many of these systems may not be cost effective for small and medium-sized dairy operations. Current
methods for NO\textsubscript{x} reduction from biogas cogeneration systems have been demonstrated however they result in NO\textsubscript{x} emissions above the approved limit at least 5 percent of the time.

An alternative concept to control NO\textsubscript{x} emissions from biogas cogeneration systems is tailoring the hydrogen-to-methane content of the fuel gas to a ratio of 15:85 by operating the anaerobic digestion process as a two phase system. This concept was patented in 2009\textsuperscript{2} and focuses on a separate hydrogen production phase and a standard anaerobic digestion phase (Figure 15).

Figure 15: Flow Diagram for Two Stage Anaerobic Digestion for Enhanced Hydrogen Production for NO\textsubscript{x} Control

This study focuses on the feasibility of a laboratory-scale, two phase anaerobic digestion system to generate appropriate hydrogen to methane ratios for NO\textsubscript{x} reduction.

1.15.3 Objectives

The goal of this project was to determine the feasibility of developing a two phase anaerobic digestion system producing an optimized fuel gas product for reduced NO\textsubscript{x} emissions in cogeneration systems. The researchers developed laboratory-scale digesters to study and optimize the first and second phases and to generate gas products for evaluation. Objectives are:

1. Achieve a hydrogen production rate within 20 percent of the maximum hydrogen production rate of glucose, considered to be near the practical maximum.

\textsuperscript{2} United States patent number 7,575,907
2. Confirm the operation of the two vessel system which includes biogas and liquid pumping with gas balancing bags. The second phase is a fixed film design with a residence time of 1—10 days.

3. Demonstrate for each waste a model that describes the operational conditions within 75 percent confidence bands.

4. Reduce phosphate buffer by 75 percent, resulting in a maintenance cost reduction of 25 percent.

5. Achieve 20 percent of the ideal hydrogen to methane ratio 90 percent of the time.

6. Increase the volumetric productivity (based on liters per liter per day) by 50 percent over suspended growth digestion. Reduce the size and cost of the second phase vessel by 25 percent.

7. Confirm the NOx reduction potential will meet best available control technology reductions (9—60 parts per million) and emit less than 25 tons of NOx per year.

8. Confirm that operation of the proposed NOx control process will cost $0.80 per million Btu or less for a 1,000 cow dairy in California compared to NOx control for digesters with selective catalytic reduction costing $1.26 per million Btu.

1.15.4 Outcomes
The project team performed numerous individual tests focused on addressing the objectives of this study and include:

1. At similar organic loading as used for glucose in a previous study, food waste was able to produce 1.26 liters of hydrogen per liter of reactor volume. This was greater than the maximum of 1.01 liters of hydrogen per liter of reactor volume demonstrated with glucose. Glycerol achieved 120 percent of the maximum volumetric hydrogen production rate of glucose after discounting the glucose yield to account for the reduced hydrogen production potential of glycerol. Glycerol achieved 14 percent of the practical maximum molar yield for glycerol (0.5 moles of hydrogen per mole of glycerol).

2. The research team developed six additional anaerobic digester systems with biogas and liquid pumping and gas balancing bags. It operated these second stage systems as a fixed film design with plastic media to support microbial growth. The digesters were operated with a residence time of 30 days, as opposed to the projected 1–10 day residence time, to maintain a stable pH without adding base or buffer.

3. Laboratory data generated allowed the researchers to develop equations for the relationship between the volumetric yield of gas and the pH, organic loading rate, and hydraulic residence time of the reactors. For glycerol, the optimal conditions occurred at a pH of 6.5, a residence time of six hours and 20 grams of carbon oxygen demand per liter of reactor volume per day. For food waste, the optimal conditions occurred at 23.6 grams carbon oxygen demand per liter of reactor volume per day.
Data evaluation identified that a 95 percent confidence interval was able to capture the majority of the data.

4. To reduce operational costs, the researchers eliminated the use of phosphate buffer and replaced it with digested wastewater sludge. The pH was largely dependent on the organic loading rate, but it could be maintained with careful reactor operation.

5. The researchers determined the optimal ratio of hydrogen to methane of 15:85 in the product gas was within 20 percent of the ideal on average 70 percent of the time. Sparging the first stage with biogas from the second stage increased hydrogen yields from 0.11 liters of hydrogen per liter of digester volume per day to 0.28 liters of hydrogen per liter of digester volume per day, representing a 135 percent increase.

6. The volumetric productivity in liters of biogas per liter digester volume per day increased by slightly greater than 50 percent for the fixed film operation over suspended growth digestion when adjusted on a stoichiometric basis to account for differences in the methane potential of the substrate. The size and cost of the second stage vessel was not reduced by 25 percent to achieve the ideal hydrogen to methane ratio.

7. The researchers estimated NOx emissions based on project data and literature values for the two phase system. They determined NOx emissions were 6—36 parts per million, which meet the best available control technology standards. They calculated annual NOx emissions at 10 tons per year. Elimination or decreased dependence on a three-way catalyst could reduce the maintenance and complexity of the system.

8. Researchers estimated NOx control costs could be reduced by 63 percent by implementing the two phase system. Estimated capital and maintenance costs normalized over 20 years for both systems resulted in a total cost of $0.71 per million Btu for the two phase system and $1.90 per million Btu for the catalyst.

1.15.5 Conclusions

In performing the study, the research team reached a number of conclusions.

1. Food wastes and glycerol are promising substrates for hydrogen production in a two phase anaerobic digestion system. The impurities in crude glycerol do not appear to inhibit hydrogen production, and the high pH and alkalinity of the crude glycerol may reduce buffer requirements. Maximum gas yields are largely substrate dependent and limited by stoichiometry.

2. The fixed film anaerobic digester (second phase) did not allow the residence time to decrease without requiring buffer addition. Researchers concluded a larger reactor was likely more economical than ongoing buffer addition and maintenance costs for the life of the project.

3. Optimum operational parameters including pH and hydraulic residence times were similar, whereas the optimum organic loading rate was substrate dependent.
4. Alternative buffers such as municipal wastewater sludge and biodiesel wash water may be considered to maintain pH in the first stage reactor, reducing chemical costs.

5. Maintaining the optimal hydrogen to methane ratio of 15:85 within 20 percent was achieved 70 percent of the time for the two phase digester system using glycerol as a substrate. Feedback control systems could likely maintain tighter control of this ratio. Sparging the first stage with biogas from the second stage increased hydrogen yields by 135 percent.

6. While the fixed film operation of the second phase anaerobic digester increased the volumetric yield in proportion to the stoichiometric methane potential, a larger volume and longer residence time was required.

7. The two phase anaerobic digestion technology which produces optimum mixtures of hydrogen to methane to reduce NOx emissions is a promising technology. Reducing both capital and operating costs for the application of anaerobic digestion systems that meet stringent environmental emissions standards will result in increased application of the technology while helping California meet its renewable energy goals.

1.15.6 Recommendations
The Program Administrator recommends further testing to optimize the rates and yields of hydrogen/methane fuel gas with application to a broader range of feedstocks. The preliminary data generated in this project paves the way to further develop this technology. Important parameters for consideration are:

1. Evaluate developing precise fuel gas control systems to ensure appropriate hydrogen to methane ratios at nearly 100 percent of the time. These control systems may require periodic use of compressed hydrogen to augment the final fuel gas product. Ensuring accurate and reliable production of the optimum hydrogen to methane ratio is necessary to achieve permitting of the two phase digestion system as an emissions control technology.

2. Replicate experiments over a long time period to study the further adaptation of the microbial consortium in the first and second phase systems.

3. Evaluate low cost sources of alkalinity that can be used to buffer the first stage reactor. Evaluate the feasibility of using the second stage effluent to buffer the first stage reactor.

4. Conduct long term studies on how changes in food waste or crude glycerol quality and composition change hydrogen and/or methane production. Evaluate alternative feedstocks or blending of feedstocks to achieve improved conversion in the first stage.

5. Evaluate a pilot-scale system leading to installation of the first stage system on an existing dairy anaerobic digester for upgrading biogas with optimum hydrogen levels. In this way, adding a first stage hydrogen producing system to upgrade
conventional biogas could potentially rescue the economics of in-place digester systems from the negative economics in the use of catalyst systems for NOx control.

6. Operate a pilot-scale two phase system with combustion of the fuel gas and monitoring of the actual NOx emissions. This will be critical to obtaining permitting as a NOx control technology.

After considering (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 determined that the proposed technology should be considered for follow-up funding within the PIER program. The research team has a unique opportunity to study improvements in two-phase anaerobic digestion of glycerol and food wastes based upon their current experience and capabilities demonstrated in this study.

Receiving additional 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.

1.15.7 Benefits to California

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

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

The results of this research increase the affordability of energy in California by reducing costs for NOx control for anaerobic digestion systems. Reducing environmental impacts from anaerobic digestion systems, specifically NOx emissions during cogeneration of the biogas to electricity and heat is of prime concern. Enhancing the hydrogen content of the biogas produced from standard anaerobic digestion systems can serve to reduce NOx emissions without the capital and operating costs of conventional catalyst emission control systems.

The immediate value of this technology is to farmers and/or other waste producers since the cost of NOx control is a significant barrier to using anaerobic digesters. From this research NOx control costs could be reduced by 63 percent from $1.90 to $0.71 per million Btu. If this research is permitted as a NOx control device, it could significantly increase the amount of renewable heat and power produced while reducing the amount of carbon dioxide emitted. For example, digestion of California’s dairy waste alone could generate up to 180 megawatts electric to benefit farms. This would also offset nearly 11,430,000 megatons per year of carbon dioxide equivalents. In the longer term, food waste digestion facilities and biodiesel producers may also adopt two phase digestion with enhanced hydrogen production. In the coming years as more carbon emissions are regulated, cost effective NOx control technologies will be essential to the
implementation of anaerobic digestion to reduce carbon emissions and to produce heat and power.

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

Marketing/Connection to the Market
The research team has not established market connections based on the preliminary nature of the present study.

Engineering/Technical
Additional work is required to take the technology to pilot scale as well as to provide for more refined control over the final hydrogen to methane ratio in the product fuel gas.

Legal/Contractual
The researchers obtained a United States patent in 2009 that covers the two-stage anaerobic digestion process. Additional development of control systems to fine tune final hydrogen to methane ratios in the fuel gas may allow for future patent applications.

Environmental, Safety, Risk Assessments/Quality Plans
The novel first stage system for hydrogen production may need additional review for safety related to sparging of biogas and final control and possible blending with other hydrogen sources.

Production Readiness/Commercialization
Substantial additional research is necessary to establish optimized conversion rates and yields allowing for more reliable process economics to be performed. Without establishing the economic viability of the process for conversion of a wide variety of waste feedstocks, commercialization may not be possible.

1.16 Syngas Process Development for Renewable Methane Production (2014)
Awardee: Taylor Energy
Principal Investigator: Donald Taylor

1.16.1 Abstract
In this project the researchers produced a synthetic natural gas with energy content equivalent to 44 percent of the energy content using refuse-derived biomass from municipal solid waste (MSW). The researchers estimated a potential net annual economic benefit to California of $2.1 billion, including $1.1 billion in renewable methane revenue and $1 billion from MSW disposal cost savings.
California’s 39 million residents generate 4.7 pounds of municipal solid waste per person every day, which is disposed into 80 landfills across the state. About 64,000 tons of California MSW is available daily with energy content of 6,000 Btu/lb; equal to about 128,000 barrels of oil per day.

The researchers tested mild hydrogasification of refuse-derived biomass recovered from MSW that included 20 percent plastics which contribute hydrogen content to the process. Tests showed that mild hydrogasification reactions intensify using pulse compression waves that power a jet spouted bed.

Power output was confirmed to be greater than 60 kW (thermal) based on propane input. The firing frequency of the pulse deflagration prototype was 21 Hz; the firing frequency of the pulse detonation prototype was 3 Hz. The researchers found that approximately 1.0 percent of the bed materials (balls) were shattered or deformed after 48 hours of operation. At this time the researchers do not know if ball failure increases linearly with time, exponentially with time, or if the ball failure follows a classic bathtub curve. The researchers did not find “significant” cracks in the combustor after pulse operation. However, they did not specify the size of a significant crack.

If this process proves feasible and is commercialized, it could divert sizable quantities of MSW destined for landfill, depending on market penetration. In addition, the use of this process could reduce the use of natural gas. Because the process is not yet proven, it is difficult to quantify future benefits.

**Keywords:** Waste gasification, biomass gasification, pulse combustion, pulse deflagration, pulse detonation, refuse-derived biomass, hydrogasification, renewable methane

### 1.16.2 Introduction

California generates approximately 64,000 tons per day of refuse-derived biomass that is sent to landfills as municipal solid waste (MSW). The energy content is equal to about 128,000 barrels of oil daily.

Researchers explored producing methane from renewable sources using the organic fractions present in MSW. Competitive methods fall within two general categories: the biological paths that include anaerobic digestion (AD) and the thermal-chemical paths that include gasification-methanation and hydrogasification. Anaerobic digestion systems do not benefit from the presence of plastic fractions in MSW. In the proposed technology the researchers intended to use the plastic fractions in MSW as a source of \( \text{H}_2 \), contributing to the steam hydrogasification process to enable the rapid conversion of biomass into methane-rich fuel gases.

Refuse-derived biomass (RDB) fluff recovered from MSW was used as a feedstock. This material is created by shredding RDB in two stages using rotary less than two inch shear shredders and air stripped to remove glass, sand, grit, and debris. The RDB fluff contains most of the chemical energy available in MSW, including the plastic fractions. RDB is dried to 14–18 weight percent moisture content during storage, resulting in a homogeneous organic feed with low density and high surface area well suited for thermal-chemical processing methods.
The research team was aware of comparative production costs cited in the literature for AD systems available at commercial scale, including the AD biomass technology presently being deployed by CR&R in Riverside County, California. Sempra Energy estimated the AD cost for conditioned bio-methane at $9—$12/ million Btu.

Thermal-chemical processes are typically 100 times more time efficient when compared to biological paths. For example, AD requires seven days to complete the biological conversion of organic materials into methane, compared to the thermal-chemical paths typically completed in about three minutes. Commercial processes are available that employ solid carbon feeds for production of synthetic natural gas (SNG). Most prominent is gasification integrated with methanation. Carbon feeds are gasified via partial oxidation with oxygen to form synthesis gases (syngas) that are conditioned, cleaned, and then reacted over a methanation catalyst to produce SNG composed of 95 percent methane. The pertinent chemical reactions that describe methane production using syngas as the chemical intermediate are:

\[
\begin{align*}
\text{CO} + 3\text{H}_2 &= \text{CH}_4 + \text{H}_2\text{O} \\
2\text{CO} + 2\text{H}_2 &= \text{CH}_4 + \text{CO}_2 \\
\text{CO}_2 + 4\text{H}_2 &= \text{CH}_4 + 2\text{H}_2\text{O}.
\end{align*}
\]

The gasification-methanation path is available for large commercial applications. For example, Shell offers a coal gasification process for integration with the Haldor Topsoe TREPM methanation technology. The base-case cost estimates are for producing 78 billion ft³/yr of pipeline quality SNG. The Shell gasification process and similar SNG technologies, based on coal gasification integrated with methanation, are being deployed on a large scale in China where landed prices for LNG are greater than about $12/million Btu. The gasification-methanation path to SNG (using syngas as the intermediate) is applicable to any carbon source, including RDB. However, to date, the process complexity and the resulting high cost have prevented commercialization of small-scale RDB in California. The scale is 1,000 ton/day for California RDB compared to the 10,000—100,000 ton/day scale used for coal resources. The syngas intermediate product from carbon gasification must be cooled and cleaned using multiple processing steps prior to methanation to prevent catalyst contamination. The process complexity creates an overriding problem: the cost of syngas produced at large-scale from coal is about $0.06/lb based on syngas with 10,000 Btu/lb. The syngas cost is equal to about $6/million Btu. Purified syngas is a relatively costly chemical intermediate when used for production of CH₄ via methanation.

Between 2003 and 2006 the researchers developed a steam hydrogasification process at the Western Research Institute in Wyoming. The researchers planned to develop a coal to SNG process employing several counter-current stages of steam hydrogasification integrated with counter-current char-oxidation to generate process heat. The jointly sponsored research project was co-funded by the researchers and the United States Department of Energy. After testing at prototype scale, the process was selected by General Electric for commercial development. At this time shale gas production began to increase dramatically, lowering the cost of pipeline gas.
in the United States. This resulted in shutdown of the General Electric coal-to-SNG program at the Western Research Institute.

In this project the researchers focused on proof-of-concept testing of a steam hydrogasification method to prove that a pulse-POx combustor generating hot syngas can be used to drive a jet spouted bed and generate methane-rich fuel gases (Figure 16). The input to a pulse combustor includes fuel, oxygen, enriched air, and can include steam. The objective was to generate hot syngas products that were directed into the bottom of the jet spouted bed. The overall objective was to produce methane-rich fuel gas. The main focus was to operate the pulse-POx combustor discharging hot syngas into the jet spouted bed to produce methane.

The researchers optimized pulse-combustor prototypes for hot syngas production. The test program included plans for a short series of preliminary tests integrated with a jet spouted bed processing biomass feedstock to get some indication of the difference between operating with excess oxygen (autothermal gasification) and mild steam hydrogasification.

The test program looked at mild steam hydrogasification that offers many potential benefits. Hydrogasification typically requires operating pressure of 150 psig. The researchers expected to examine if the integrated pulse combustor/jet spouted bed could provide enough process intensification to enable hydrogasification under mild conditions, increasing the CH₄ content in the product gases. Sonic or ultrasonic compression waves were used to intensify thermal-chemical processes to enhance carbon use within the process, while performing proof-of-concept testing of mild steam hydrogasification. The researchers intended to show that pulse combustors integrated with a jet spouted bed offer special benefits. Essentially, the researchers used compression waves that pass through the process to increase thermal-chemical reactivity rather than compressing the entire contents within the process. The prototype pulse combustors served to increase the useful power output of the combustor exhaust and to discharge cyclic compression waves into the thermal-chemical process.

Figure 16: Process Flow Diagram of the Gasification System
1.16.3 Objectives
This project was to determine the feasibility of a new method for producing renewable methane using a high intensity thermal processing technology. The researchers tested a mild hydrogasification process using refuse-derived biomass (RDB) as the energy feed. They developed prototype pulse (POx) combustors and integrated them with a jet spouted bed to accomplish the process intensification. The objectives were:

1. Provide drawings showing key sub-components to be fabricated and installed on existing process development unit (PDU).
2. Demonstrate pulse-POx combustor with input greater than 60 kW per hour input capacity based on propane input.
3. Demonstrate the test system is capable of measuring performance parameters within an error of +/- 5 percent.
4. Demonstrate pulse-POx combustor has greater than 30 volume percent H₂ output.
5. Demonstrate pulse-POx combustor frequency is greater than 7 Hz.
6. Demonstrate durability of bed material, i.e., shattered or deformed balls are less than 10 percent after 48 hours of operation.
7. Demonstrate zero significant cracks that could result in failure of pulse combustor.
8. Demonstrate maximum expanded bed height greater than 24 inches during jet spouting using steel balls greater than 1 mm diameter.
9. Demonstrate maximum expanded bed height greater than 24 inches during jet spouting using ceramic balls less than 12 mm diameter.
10. Demonstrate RDB feed input of greater than 0.5 lb/min.
11. Demonstrate greater than 50 percent energy content as CH₄ in fuel gas products.
12. Demonstrate carbon-char product fractions are less than 25 weight percent of the dry feed input.
13. Confirm from the project findings that a production cost of $8 per million Btu renewable methane is supported.
14. Confirm from the project findings, using GREET analysis, that the projected carbon footprint of vehicles using renewal natural gas for vehicle fuel is less than 20g CO₂e/MJ or about 80 percent of the greenhouse gases generated by vehicles using gasoline as fuel.
1.16.4 Outcomes

1. The research team prepared drawings for fabrication of multiple prototypes, including three pulse deflagration prototypes and three pulse detonation prototypes.

2. Power output was greater than 60 kWt per hour based on propane input. The research team operated the pulse burner prototype with an average firing capacity of 137 kW (thermal) per hour based on a measured average flow of 3.1 scfm (186 scfh).

3. The test system was capable of measuring performance parameters within an error of +/- 5 percent. The best precision measured for methane under actual operating conditions, when the product gases included additional low molecular weight hydrocarbon gases, was +/- 6.46 percent and the worst was +/- 42 percent. The researchers observed the precision of the methane analysis decreased roughly in proportion with the increasing presence of other low molecular weight hydrocarbon gases. Real-time measurement of methane using an NDIR-type analyzer was somewhat more difficult than purported by the instrument supplier.

4. The research team demonstrated hot syngas output from the pulse deflagration prototype with 31 volume percent H₂ content with N₂ content removed from the gas composition.

5. The frequency of the pulse combustor was greater than 7 Hz. The pulse deflagration prototype operated at 21 Hz, whereas the pulse detonation prototype operated at 3 Hz.

6. The researchers observed 1.0 percent shattered or deformed balls after 48 hours of operation.

7. Researchers observed no significant cracks after operating the pulse combustor prototypes. They did not describe the size or significance of cracks which did appear.

8. The research team used an expanded bed height of 60 inches when operating with a bed composed of 0.5 mm stainless steel beads. When they used 1.0 mm steel beads, the fountain height was higher than 24 inches. The performance using the larger balls as a means of ablation was not as robust as that using smaller, lighter bed materials.

9. The research team confirmed that the expanded bed height was greater than 24 inches during jet spouting using ceramic balls with diameters of 2 mm and 5 mm. They observed a fountain height of 80 inches and 60 inches, respectively, when operating with ceramic beads with diameter of 2 mm and diameter of 5 mm.

10. The research team demonstrated refuse-derived biomass (RDB) feed input of 3 lbs/min.

11. The research team did not demonstrate conversion of > 50 percent of the embedded energy in the RDB to fuel energy in the synthetic natural gas. The maximum CH₄ content was 43.69 percent by volume when measured as a fraction of the total.
chemical energy content in the product gases. The project goal was 50 percent of gas-phase energy in the form of methane.

12. The research team did not demonstrate greater than 50 percent energy content as CH₄ in fuel-gas products. The data showed that the carbon-char fraction when measured on a dry-basis was 10.77 weight percent of the dry feed.

13. The research team did not demonstrate carbon-char products fractions were less than 25 weight percent of the dry feed input. This work was not completed because the methane content in the syngas product was not sufficient to warrant further analysis based on the project concept of a stand-alone renewable methane production facility.

14. The research team did not confirm from the project findings that the projected carbon footprint of vehicles using renewal natural gas for vehicle fuel would be less than 20 g CO₂e/MJ, about 80 percent of the greenhouse gases generated by vehicles using gasoline as a fuel. This work was not completed because the methane content in the syngas product was not sufficient to warrant further analysis. Based on the project concept of a stand-alone renewable methane production facility.

1.16.5 Conclusions
The researchers successfully accomplished 11 of the 14 project objectives. There are some indications that the process could be improved by a few percent.

Not enough favorable data was generated to support the key project goal, renewable methane with greater than 50 percent of the energy content in the form of CH₄. This new process cannot be commercialized without more substantive performance data.

However, the pulse deflagration and pulse detonation burner technology, integrated with jet spouted bed operation, have been reduced to practice. Further developments will constitute refinements of the technology approach and may lead to demonstration of a new co-production process that generates both hydrocarbon liquids and renewable methane.

1.16.6 Recommendations
The Program Administrator recommends the researchers:

1. Consider using propane as a reducing gas. Carbon-char used in a POx reaction with oxygen and steam may not be as good a source of reducing gases as propane.

2. Demonstrate that carbon-char reaches chemical equilibrium. The researchers can utilize a catalyzed means of increasing the rate of carbon conversion into carbon monoxide.

3. Conduct additional proof-of-concept testing to demonstrate 50 percent of the energy content can be produced as CH₄ content in fuel gas products. The present work shows the methane formation rate at 43.7 percent of the energy content.
4. Conduct additional proof-of-concept testing to show that steam hydrogasification reactions that produce renewable methane can be intensified using supersonic shockwaves that result from pulse detonations emanating from a high temperature syngas generator.

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

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

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California energy supply and distribution system. If this technology were to be proven feasible and commercialized, it could produce large amounts of synthetic methane while reducing the need to dispose of considerable amounts of refuse in landfills. It is difficult to estimate the benefits quantitatively until the process is proven feasible.

Based on the results of this research, the process was able to convert 44 percent of the energy content in the energy feed into methane. The potential annual economic benefits to California could be $2.13 billion per year. In California, the resource potential is 4.7 pounds of municipal solid waste (MSW) per person per day. Approximately 70 percent of MSW can be recoverable as refuse-derived biomass (RDB), which is a low density, high surface area feedstock well suited for thermal chemical conversion into renewable methane. Gasification typically converts 70 percent of RDB into synthetic gas. The results indicate that 44 percent of the net energy contained in RDB can be converted into 465 million scfd renewable methane.

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

Marketing/Connection to the Market
The researchers performed a market analysis and contacted potential customers. They considered the results of these activities confidential.

Engineering/Technical
The researchers estimated they would require another two years and approximately $1.5 million to complete development and demonstration of this concept.

Legal/Contractual
The researchers neither applied for nor secured any patents as a result of their work on this project. They did perform a professional patent search.
Environmental, Safety, Risk Assessments/ Quality Plans
These assessments are premature at this stage of technology development.

Production Readiness/Commercialization
The researchers intend to form a joint venture or license with commercial companies in the waste recycling business to commercialize this technology once it is proven feasible.

1.17 Exhaust Gas Heat Exchanger Model for Mobile ICEs (2014)

Awardee: Cliff Edge Consulting, LLC.
Principal Investigator: John Stewart

1.17.1 Abstract
California Air Resources Board has estimated about 60,000 Class 8, long-haul trucks are licensed in California. These trucks average 120,000 miles per year (not all in California) and consume 17,143 gallons of diesel fuel per year (seven miles per gallon). The annual value of this fuel is $48,343 for each truck at $2.82 per gallon\(^3\). While the truck engines are modern high-efficiency diesel cycle engines, more than half of the fuel energy rejected as waste heat. If this heat could be captured and reused to propel the vehicle, the annual fuel bill could be significantly reduced providing economic benefits to the truck owner, the economy and air quality.

Capturing this energy source however is a high cost and the weight on the truck of an effective heat exchanger for energy recovery. Current heat exchangers sized for a truck engine can weigh 5,280 lb. and occupy almost 17 cubic feet of space.

The researchers proposed to design and analyze a heat exchanger that was sufficiently light, compact, and inexpensive to make waste heat recovery practical for Class 8 truck engines. They envisioned the recovered heat energy could be used to drive a Rankine cycle engine turning an electric generator, resulting in a hybrid electric propulsion system. This engine would be fueled by liquefied natural gas rather than diesel fuel to prevent fouling of the heat exchanger.

The researchers developed a model for smaller and lighter heat exchangers that could be used in truck applications. Computer models predicted it would weigh 370 lb. and occupy less than seven cubic feet. The modeled heat exchanger was designed to extract the same amount of energy from the same heat source as would the Bowman model cited above.

Keywords: Exhaust gas heat exchanger, waste heat recovery system, natural gas, large mobile internal combustion engine, hybrid electric

1.17.2 Introduction
The researchers performed extensive modeling and presented detailed findings in their final report. All work related to the core heat exchanger that would be part of a larger waste heat energy recovery system. The larger waste heat energy recovery system was not designed as part of this project.

\(^3\) January 2017
The researchers developed a model for smaller and lighter heat exchanger cores that could be used in truck applications (Figure 17). Computer models predicted that the exchanger would weigh 370 lb. and occupy less than seven cubic feet. The modeled heat exchanger was designed to extract the same amount of energy from the same heat source as would the Bowman model cited.

![Figure 17: Heat Exchanger Core Assembly and Insert and Receiver Subassemblies](image)

### 1.17.3 Objectives

This project explored the feasibility of using radiation and conduction heat transfer to design, model, and simulate an exhaust gas heat exchanger that was sufficiently lightweight, compact, and cost effective to be used in a waste heat energy recovery system for large, mobile, natural gas-fueled, hybrid electric, internal combustion power systems such as those in heavy-duty trucks and locomotives. The researchers established these objectives:

1. Demonstrate that at 70 percent effectiveness the research heat exchanger size is less than 10.062 ft\(^3\), compared to the 16.77 ft\(^3\) of the Bowman model 12-60-3744-8.

2. Demonstrate that for inlet exhaust energy of 600 kW at 600° C and 45 kg/min flow rate the research heat exchanger will recover at least 425 kW and will weigh less than 2,112 lb. compared to the 5,280 lb. of the Bowman model.

3. Demonstrate that the price per kW of recovered energy is less than $32.16, which is 35 percent less than the $49.48 price per kW using the Bowman heat exchanger.
4. Select a manufacturer and refine the manufacturability of the detailed heat exchanger design.

5. Estimate the heat exchanger retail price per kW of recovered exhaust energy.

1.17.4 Outcomes

1. At 96 percent effectiveness, the research heat exchanger size was 7.02 ft\(^3\), which was 58 percent less than the Bowman size.

2. For an inlet exhaust energy of 600 kW at 600° C and 45 Kg/min flow rate, 421 kW was recovered while the research heat exchanger weight was 209 lb. This was 96 percent less than the Bowman.

3. The research heat exchanger energy price per kW of recovered energy was not estimated.

4. The researchers requested quotations and comments from three potential manufacturers of the stamped plates for the heat exchanger. Two responded with “no bid.” The third, Short-Run Metals, Inc., requested dimensioned CAD models and manufacturing instructions. They had not prepared their final response by the end of this project.

5. The researchers did not accomplish this objective.

1.17.5 Conclusions

1. The first outcome was successful. Effectiveness and size outcomes exceeded the objectives by 39 percent and 58 percent, respectively. The size outcome value was estimated because only the heat exchanger core was modeled, measured, and simulated during the research. The heat exchanger case and connecting plumbing were not. Those dimensions, which were used for comparison to the Bowman, extend beyond the core dimensions and were estimated.

2. The second outcome, while close, was 0.9 percent or 4 kW under the required 425 kW. The weight outcome was better than the objective. The research heat exchanger weight was 95 percent less than the Bowman and 93 percent less than the objective. The research heat exchanger weight included only the core. Additional equipment, such as case and plumbing, would increase the weight.

3. The third outcome was not successful because the work could not be done. To estimate the research heat exchanger price per kW of recovered energy, a complete research heat exchanger prototype model would be needed. Only the core was modeled in this project.

4. The researchers did not complete this objective.

5. The researchers did not accomplish this objective.
The researchers performed extensive analysis to develop a core heat exchanger that came close to meeting their objectives. There were some issues that were not addressed adequately in this project. First, the researchers assumed the exhaust energy would exit the heat exchanger at 65° C. Most designers require the exhaust temperature to be greater than 130° C to be above the acid dew point of sulfuric acid. Natural gas has very small amounts of sulfur dioxide that can combine with water vapor to produce sulfuric acid. This acid will corrode most heat exchangers. Using the higher exhaust temperature significantly reduces the effectiveness of the heat exchanger and thus the amount of heat recovered.

The researchers did not explain the Rankine cycle that would convert the heat energy to electricity. The Rankine components could be expensive and add weight to the vehicle.

Fuel prices have changed since this project was started. The cost of diesel fuel has decreased while the price of natural gas has increased. At January, 2017 prices, the large cost advantages of natural gas that obtained in 2013 had disappeared. In addition, natural gas engines are less efficient than diesel engines. Thus switching to natural gas at this time could increase fuel costs.

Decades ago Caterpillar, Inc. developed a primary surface recuperator for gas turbine engines. While not identical, the components of that recuperator resembled some of those in this research heat exchanger. Perhaps the researchers could speed development by striking a deal with Caterpillar to license their manufacturing process for these components.

1.17.6 Recommendations

The Program Administrator recommends that the researchers:

1. Talk with Class 8 truck manufacturers and investigate the possibility of including the research heat exchanger in their advanced truck designs.

2. Work to obtain funding for the construction and testing of a prototype heat exchanger core.

3. Characterize that prototype core.

4. Characterize the entire waste heat energy recovery system, including the Rankine cycle. Size the components of that system and estimate the overall cost and weight.

1.17.7 Benefits to California

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

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

The primary benefit to the ratepayer from this research is improved transportation energy efficiency.
During the past five years the United States Department of Energy has sponsored a Super Truck competition. The goal of this program is to double the average fuel efficiency of Class 8 tractor-trailers. Participants in this program have approached this challenge by looking at all vehicle factors that influence the energy efficiency of those trucks.

The truck developed by heavy-duty manufacturers Cummins and Peterbilt demonstrated a 20 percent increase in engine efficiency and a 70 percent increase in freight efficiency, reaching over 10 miles per gallon under real world driving conditions. In comparison, an average Class 8 truck typically gets 5.8 miles to the gallon.

The Daimler SuperTruck demonstrator ran a five day 300-mile route in Texas at a gross vehicle weight rating of 65,000 pounds at 65 mph. Under those conditions, the Daimler SuperTruck achieved a trip average of 12.2 mpg, more than doubling the average fuel efficiency of commercially available tractor-trailer rigs. In addition, it is working on an exhaust heat exchanger, but it does not anticipate market introduction of that component soon.

The benefits from this EISG project will only become available if the model heat exchanger is incorporated by one of the large truck builders. Obviously the truck manufacturers have an interest in improved efficiency.

1.17.8 Technology Transition Assessment

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

**Marketing/Connection to the Market**

The researchers had not performed a detailed market analysis nor had they surveyed potential customers by the end of this project.

**Engineering/Technical**

The researchers estimated that they would require a minimum of two and one-half years and $1.5 million in funds to build and test a prototype. They planned to seek funding to continue their work.

**Legal/Contractual**

The researchers applied for one patent as a result of the work done in this project.

**Environmental, Safety, Risk Assessments/ Quality Plans**

Normal product development plans must be followed once a waste heat energy recovery system has been specified.

**Production Readiness/Commercialization**

The research heat exchanger is not ready for commercialization. The researchers plan to license the technology. The researchers would like assistance in developing a business plan.
1.18 Low Cost High Performance NGV (2014)

Awardee: McMEM.
Principal Investigator: Jim Wong

1.18.1 Abstract
Transportation is the largest source of greenhouse gas emission in California, accounting for about 37 percent. Since passenger vehicles are a major contributor to these emissions, the California has a goal of reducing CO₂ emissions from this source by 40 percent. Electric vehicles, while having the lowest CO₂ emissions, may not gain enough market share because of the higher battery cost. An interim solution is to increase the number of natural gas-fueled vehicles. Until recently Honda Motor Co. offered a natural gas-fueled Civic. The company redrew it from the market due to low sales volume despite savings in fuel cost of up to 50 percent over gasoline-fueled vehicles. The main deficiencies of vehicles converted to burn natural gas are lack of power, higher initial cost, and limited natural gas filling stations.

The benefits of using natural gas vehicles are lower CO₂ emissions when compared with gasoline-fueled vehicles, lower operating costs, and domestic sourcing of natural gas. The researchers proposed a system they claimed would increase engine power, lower the additional cost of engine conversion to natural gas fuel, and lower the cost of operation.

They estimated that a gasoline engine could be modified to use natural gas fuel and use the proposed expander-compressor for approximately $6,000. If this technology were applied to 10,000 vehicles, the researchers estimated that it would displace 7.5 million gallons of gasoline and reduce CO₂ emissions by 18 tons.

Keywords: Natural gas vehicles, NGV, blow-down expanders, high pressure NG engines

1.18.2 Introduction
California has a goal of reducing CO₂ emissions from these sources by 40 percent below 1990 levels by 2030. Electric vehicles have the lowest CO₂ emissions yet have not gained a foothold because of the high cost of batteries. An interim solution is to increase the number of natural gas-fueled vehicles. The benefits of using natural gas vehicles are lower CO₂ emissions when compared with gasoline-fueled vehicles, lower operating costs, and domestic sourcing of natural gas. The main deficiencies of vehicles converted to burn natural gas are lack of power, higher initial cost, and limited natural gas filling stations.

Researchers explored a system they believed would increase the engine power, lower the additional cost of engine conversion to natural gas fuel, and lower the cost of operation. Natural gas is stored at high pressure (approximately 240 atmospheres) in natural gas vehicles and typically the high pressure gas is then expanded before being introduced into the engine. This compression energy is wasted in the expansion process.

The researchers proposed using a low cost expander-compressor to boost the engine intake air pressure and increase performance. The high pressure natural gas fuel would drive the expander,
The researchers identified a list of expanders and fabricated and tested many prototypes. On the compressor side, the researchers modified a turbocharger to compress ambient air to elevated pressure. They successfully demonstrated the use of high pressure, low flow natural gas to start and power two expanders. One expander spun at 15,000 RPM and generated 200 Watts.

The researchers evaluated six possible expander technologies and concluded that a Tesla drag turbine provided the best technical solution for the lowest cost. The Tesla drag turbine, named after Nikola Tesla, is not associated with Tesla Motors, a manufacturer of electric vehicles.

The researchers estimated that a gasoline engine could be modified to use natural gas fuel and the proposed expander-compressor for approximately $6,000. If this technology were applied to 10,000 vehicles, the researchers estimated that it would displace 7.5 million gallons of gasoline and reduce CO₂ emissions by 18 tons. It is not clear how much of these savings would be due to the expander-compressor addition to a natural gas vehicle or due to the fact that a gasoline engine had been converted to burn natural gas.

1.18.3 Objectives
This project explored the feasibility of using a device known as an expander-compressor to compress the inlet air of a NGV to increase the engine performance. The expander-compressor would be powered by high pressure CNG fuel. The researchers established the following objectives:

1. Generate an interface control document (ICD).
2. Generate a set of design parameters.
3. Demonstrate that the expander-compressor can increase engine intake pressure from 1 ATM to 1.1 ATM during the first set of prototype tests.
4. Demonstrate that the expander-compressor can increase engine intake pressure from 1 ATM to 1.3 ATM during a second set of prototype tests.
5. Confirm that the manufacturing cost of the installed retrofit kit can be reduced from $10,540 to $6,000.
6. Demonstrate that the modified Honda GX can decrease brake specific fuel consumption (BSFC) by 2 percent compared to a Honda GX with an unmodified engine.

1.18.4 Outcomes
1. The research team divided the fuel system into CNG fuel system, engine, expander, and compressor. On the expander side, the team identified a list of expanders that
could be used to extract power from high pressure gas and fabricated and tested many prototypes of these expanders. On the compressor side, the research team modified a Garrett turbocharger. The researchers wrote an ICD to identify the performance requirements and interrelationship between these four components.

2. The research team performed analyses to support sizing of the identified expanders and generated a set of design parameters.

3. During the first set of tests, the team wanted to show that high pressure gas can start and power the expanders. The expander prototypes were tested without loading. The research team measured the output of the Tesla drag turbine spun at 11,000 RPM at 250 SCFH. The research team performed a second set of tests, and the power output from the expander was used to drive the compressor. The researchers measured 15,000 RPM and 0.26 HP (200 W) at 250 SCFH flow rate. The researchers believed that the Tesla turbine achieved the objective of 1.1 ATM boost.

4. The research team constructed a new prototype based on the performance of the first set of prototypes and performed the second set of tests. They used the power output from the drag expander to drive the compressor. A rotary torque sensor was used to measure the torque sent to the compressor from the expander. The researchers measured 15,000 RPM and 0.26 HP (200 W) at 250 SCFH flow rate. The researchers believed that the Tesla turbine achieved the objective of a 1.1 ATM boost for the first set of tests but not the 1.3 ATM boost set for the second tests. The researchers believed the causes were related to the design of the turbine that was not optimal. In addition, they stated that the measurement system needed improvement.

5. The researchers performed a manufacturing cost analysis to identify potential suppliers and to determine the total cost of a new fuel subsystem. The researchers approached vendors to obtain volume pricing of major components. They summarized the total system cost and reached these conclusions:

- A commercial company can profitably modify a gasoline automobile to operate with either CNG or gasoline for less than $6,000.
- The parts for such a modification probably would need to be foreign-sourced to meet that cost target.
- The researchers were not sure if the prices they were given were based on future business or if the vendors were attempting to dump unsold parts due to the slump in the NGV market.

6. The researchers performed an engine efficiency analysis attempting to demonstrate that the modified Honda GX can decrease BSFC by 2.0 percent compared to a Honda GX with an unmodified engine using a full-size chassis dynamometer. When the research team attached the compressor to the air intake hose, the engine would start but quickly stalled. The problem was in the performance map stored in the Honda
ECU that was not programmed to work with high pressure inlet air. The program would need to be changed to operate with the compressor-expander.

1.18.5 Conclusions
1. The researchers met this objective.
2. The researchers met this objective.
3. The researchers achieved the 1.1 atmosphere boost and achieved this objective.
4. The researchers did not achieve the 1.3 atmosphere boost from the Tesla turbine. Designing such a turbine is a difficult task. If they are to proceed with this project, they should seek an expert Tesla turbine designer. This objective was not met.
5. The researchers put a lot of effort into this task. Within the constraints of the current market for NGV parts, they did an admirable job of attempting to cost out their proposed fuel system modifications. They met this objective.
6. Because of the problem with the ECU, the researchers could not operate and test the Honda GX engine. This objective was not met.

1.18.6 Recommendations
The program administrator recommends the researchers:
1. Evaluate the potential of applying this technology to commercial vehicles.
2. Seek a partner in the automotive component business to provide guidance and funding to continue the pursuit of this concept.
3. Develop a product specification with that partner.
4. Develop a lower cost expander.
5. Retain an expert Tesla turbine designer.
6. Investigate the feasibility of channeling waste heat from the engine exhaust manifold to warm the expanders or to pre-heat the fuel gas.
7. Continue to evaluate the entire system to enhance efficiency and reduce cost.

1.18.7 Benefits to California
Public benefits derived from PIER research and development projects are assessed within the following context:
- Improved transportation energy efficiency
- Reduced greenhouse gas emissions or reduced health and environmental impacts from transportation associated air pollution related to electricity and NG production and use
- Increased use of alternative fuels
The primary benefit to the ratepayer from this research is increased use of alternative fuels. The researchers’ goal was to make natural gas-fueled vehicles less expensive while offering a high level of performance. This, they expected, would increase the sales of natural gas-fueled vehicles and increase alternative fuels use.

Since this project was awarded, many changes have occurred in automotive technology. First, Tesla Motors has successfully introduced a credible long-range electric vehicle. The Tesla Model S is a mid to large sedan exhibiting high performance. Toyota has raised the fuel efficiency of the Prius to the high 50 miles per gallon range. Honda has introduced an affordable hybrid Accord sedan that achieves 47 to 49 miles per gallon. Almost all auto manufacturers now offer hybrids or plug-in hybrids. Most of these offerings are dependable and comfortable vehicles. With the exception of the Tesla Model S, they are all affordably priced. Almost all auto manufacturers are working on their next generation propulsion systems that will provide greater use of alternative fuels by providing high fuel efficiency combined with new safety and comfort accessories.

While the researchers in this project may have advanced the technology of natural gas vehicle propulsion, it is difficult to see how their technology will blend into the fast-moving commercial automobile market. The researchers suggested they could develop a reverse three-wheeled motorcycle with a natural gas engine. This may be possible, but it is a long, expensive path from the research lab to a commercial product that meets all regulatory and customer needs while providing an operating profit for the manufacturer. Tesla Motors has made no profit from the production of its highly successful Model S.

This technology, if aimed at passenger vehicles, may have little or no impact on either jobs in California or reduction in the use of carbon-based fuels. Electric vehicles have no carbon footprint, and high efficiency hybrids have an extremely low carbon footprint.

Perhaps the most promising area for this technology is to work with a manufacturer of natural gas-fueled commercial vehicles such as garbage trucks and school buses. This is now a large, well-established market. Natural gas-fueled commercial vehicles usually operate out of a home base that is equipped with a natural gas fueling station. The researchers must find a partner in this business and convince them that the project technology offers cost effective fuel savings for the operators of commercial vehicles. Usually operators of those vehicles look for simple payback times of less than three years.

1.18.8 Technology Transition Assessment

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

Marketing/Connection to the Market

The researchers performed a preliminary market assessment but had not talked with prospective users at the end of this project.
**Engineering/Technical**
The researchers are seeking up to $2 million to complete the design and demonstration of this technology. They were applying to the United States Department of Energy for a $1 million grant and expect investors to supply the balance of funding.

**Legal/Contractual**
The researchers have submitted provisional patents to the United States Patent Office. None had been granted by the end of this project.

**Environmental, Safety, Risk Assessments/ Quality Plans**
The type and scope of these assessments will depend on the specific market segment the researchers plan to enter first. Obviously they will must meet EPA standards and pursue an extensive safety analysis.

**Production Readiness/Commercialization**
The researchers prepared a preliminary commercialization plan. That plan will see many modifications as they select their business partners and focus on one particular market segment for technology introduction. To protect their proprietary information, they had not talked with potential business partners by the end of this project.
1.19 Direct Natural Gas Ceramic Fuel Cell Hybrid Vehicle Feasibility (2014)

Awardee: Ken E. Pearson
Principal Investigator: Ken E. Pearson

1.19.1 Abstract
This project looked at using a natural gas-fueled solid oxide fuel cell to recharge batteries on an electrically powered utility vehicle. The intent was to extend significantly the range while meeting recently enacted California Air Resources Board air emission standards for small utility vehicles.

The project was focused on integrating a solid oxide fuel cell that utilizes natural gas directly, using no fuel reformation, to generate electricity to recharge the on-board batteries of an electric all-terrain vehicle, resulting in extended range and reduced emissions. The researchers selected a Polaris Ranger electric vehicle and an Acumentrics 1 kilowatt solid oxide fuel cell, the Atrex Energy RP 1000, for testing. After mounting the solid oxide fuel cell and a compressed natural gas tank on the vehicle, the researchers measured range and emissions. They found range increased to 32.2 miles from 9.2 miles. In addition, emissions from the solid oxide fuel cell were very low. Certification values were much lower than California Environmental Protection Agency and California Air Resource Board standards.

Overall, this project provided proof of feasibility for integrating a natural gas-fueled solid oxide fuel cell on an electric utility vehicle to generate electricity for on-board battery charging. If commercialized, this concept could result in significant range and emissions improvements. However solid oxide fuel cell generators are currently very expensive and heavy. This may hinder implementation of this concept. Because the farm market for small utility vehicles is relatively large in California, and the California Air Resource Board emission standards now apply to this type of vehicle, manufacturers of utility vehicles may offer other solutions that may be more cost effective.

Keywords: Solid oxide fuel cell, electric, all-terrain vehicle, SOFC, emissions, natural gas

1.19.2 Introduction
The California Environmental Protection Agency and the California Air Resources Board vehicle emission regulations are changing the characteristics of the market for small (under 25 horsepower [hp]) utility vehicles often used on farms and ranches. These agencies want to reduce substantially off-road vehicle emissions generated by gasoline and diesel-powered all-terrain vehicles (ATVs) used on farms, ranches, and orchards. Off-road all-terrain vehicles are a substantial market with 11 million vehicles registered nationwide and over 1 million sold per year. Of these, the researchers estimated about 20 percent or 2.2 million are in California. Of that number, California ARB surveys indicate 60 percent are used for commercial activities, not as recreational vehicles.

Therefore, the existing fleet of commercial ATVs potentially affected by ARB’s strict new emission regulations is about 1.3 million vehicles. The new regulations have a greater
probability of affecting new vehicles, totaling about 100,000 per year. Powering these vehicles with electricity stored in batteries is probably the prime replacement technology. Unfortunately, batteries are heavy and generally provide limited vehicle range. For example, the electrically driven Polaris used in this project uses deep discharge lead acid batteries that provide about a nine-mile range. Electrically powered vehicles are being encouraged by the San Joaquin Valley Air Pollution Control District, as well as by other air districts in agricultural areas of California. ARB provided incentives in 2010-2011 to get farmers to buy electric utility vehicles to replace their diesel and gasoline units.

An electrically powered Polaris vehicle sells for about $11,000 in 2016. Energy is stored in four lead acid batteries (BB Battery HR33-12). These batteries are designed for a high discharge rate and have an expected life of up to five years. Typically they are recharged by plugging in a grid-supplied electric outlet. These batteries in the Polaris provide about nine miles of travel between charges. According to the researchers, this range is insufficient for many farmers and causes range anxiety. The researchers’ solution for the range issue was to add a solid oxide fuel cell (SOFC) and natural gas fuel tank to a standard battery-powered Polaris (Figure 18). They rejected using a proton exchange membrane (PEM) fuel cell because of its low efficiency and the necessity to use hydrogen as a fuel source.

Figure 18: Fuel Cell Mounted on Polaris without NG Tank

The type of Acumentrics SOFC used in this project was designed for mobile applications and has been sold to the military. (Since this project, Acumentrics has spun off its fuel cell business into a new company, Atrex Energy, Inc.) Because it was designed for tough use, the Atrex
Energy RP 1000 fuel cell was a good choice for this project. However, it weighs 351 pounds, and the dimensions of this unit are 25 x 28 x 39 inches. A 1-kilowatt (kW) SOFC of the type used in this project may cost $25,000 to $50,000 in its current configuration. It is not easy to ascertain a purchase price since the unit used in this project was leased. The researchers anticipated that manufacturers could optimize the system once feasibility had been shown.

After mounting the SOFC and a compressed natural gas tank on the vehicle, the researchers measured range and emissions. They found range increased from 9.2 miles to 32.2 miles. In addition, emissions from the SOFC were very low, with certification values much lower than EPA and ARB standards.

Another potential market for this concept is airport and port support equipment. Many airlines have already converted some of their ground support equipment, especially airplane tugs, to electricity. While the researchers did not identify any intellectual property for protection, they have not published their findings. Potential commercialization partners could be manufacturers of port and airport support equipment and off-road vehicle manufacturers such as Polaris, Toro, and John Deere. Longer term potential commercialization partners could include those involved with hybrid recreational vehicles, small trucks, and specialty vehicles.

1.19.3 Objectives
This project determined the feasibility of using a natural gas-fueled solid oxide fuel cell to power an electric vehicle and improve system efficiency at least 50 percent and significantly extending range. Researchers sought to:

1. Develop a detailed specification document (DSD) to provide the basis for design, fabrication, operability, maintainability, testing, and safety.

2. Document vehicle battery charge cycle from 50—55 percent to 95—100 percent of charge. Perform discharge/charging cycle three times, calculate mean charge time, and document run time.

3. Demonstrate 1 kW solid oxide fuel cell (SOFC) battery charging capability on four lead acid 12 volt (V) batteries from 50 percent to 100 percent, and record natural gas usage versus electrical output.

4. Design and build a printed circuit board (PCB) to control charging, and demonstrate that the fuel cell can fully charge the battery to within +/- 5.0 percent of its fully charged state.

5. Demonstrate modified vehicle operation on a test course for at least four hours.

6. Demonstrate SOFC efficiency increases vehicle range by at least 50 percent. Demonstrate that the system can be operated at least 100 hours without failure.

7. Demonstrate NOx emissions less than .05 pounds per megawatt-hour (lb/MWh) and confirm emissions meet or exceed CARB and EPA Tier 4 requirements.
1.19.4 Outcomes

1. The researchers developed a DSD and used it as a basis for design, fabrication, operability, maintainability, test, and safety.

2. The researchers performed testing of the on-board vehicle battery charge cycle for characterization of a typical charge from 50—55 percent to 95—100 percent state of charge to establish the baseline vehicle range without the SOFC-augmented charging capability. The results of these initial tests showed that the vehicle battery status gauge supplied by Polaris Industries after two runs with 30 minutes between, showed less than a 50 percent charge. The researchers determined that the factory state-of-charge gauge was inaccurate. Each rest period brought the battery status back to full. On the fourth loop batteries began to discharge rapidly, and the test was discontinued.

3. With four batteries, the SOFC system started charging the batteries in 55 minutes and had the four batteries charged within 42 minutes, using approximately 1.98 standard liters of natural gas.

4. The researchers designed and built a custom printed circuit board that controlled and monitored the on-board charging system and the vehicle-mounted SOFC as alternate charging sources for the vehicle battery system. Either charging source enabled the vehicle batteries to repeatedly charge to ± 5 percent of full capacity during the series of performance tests.

5. Researchers modified the Polaris EV to accept the SOFC. The first test ran for over 12 hours and allowed the Polaris to make 14 laps (32.2 miles) on the test course.

6. After more than 100 hours of testing, the researchers determined vehicle range increased by more than 280 percent, from 11.5 miles on batteries to more than 32 miles with the SOFC.

7. Sierra Research performed independent testing on the SOFC that showed NOx emissions to be less than .05 lb/MWh and confirmed emissions were better than CARB and EPA Tier 4 requirements.

1.19.5 Conclusions

The researchers proved they could integrate a SOFC with a small utility vehicle and achieve projected performance. The SOFC on the Polaris utility vehicle was fueled with on-board pressurized natural gas. However, the practicality of this vehicle has not been proven. There are significant cost issues remaining since SOFC generators are not yet in volume production and the type used in this project was designed for military applications. In addition, a SOFC is large and heavy in comparison with a small utility vehicle. Significant design work must be done to produce a practical vehicle that meets user needs while complying with ARB and safety regulations.

1.19.6 Recommendations

The Program Administrator recommends the researchers:
• Compare their concept to other technologies that could provide extended range at lower cost. One possibility is the replacement of the lead acid batteries with lithium ion batteries. This alone could add sufficient range so a fuel cell may not be needed. There could be other technology alternatives.

• Evaluate the manufacturing cost of a fuel cell-equipped utility vehicle. With a commercial partner, estimate selling price. Compare this to customer price expectations and affordability.

• Design a practical utility vehicle using a fuel cell/battery propulsion system that has useful tool storage that meets users intended purposes.

• Evaluate safety concerns of a utility vehicle equipped with a heavy fuel cell. Determine the effects of the extra weight on cornering and running on soft ground.

• Design affordable, farm-based refueling stations.

• Develop a maintenance protocol that would work in a farm environment.

1.19.7 Benefits to California

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

• Improved transportation energy efficiency

• Reduced greenhouse gas emissions or reduced health and environmental impacts from transportation associated air pollution related to electricity and NG production and use

• Increased use of alternative fuels

The primary benefit to the ratepayer from this research is reduced greenhouse gas emissions or reduced health and environmental impacts from transportation associated air pollution related to electricity and NG production and use.

By integrating existing SOFC fuel cell technology into a commercial electric utility vehicle, the researchers sought to extend the vehicle range with an on-board charger. Using natural gas directly, eliminated the necessity for on-board fuel reformation. This project should increase awareness to find low emission options for farm and utility vehicles. This category includes port and airport support vehicles and ranch and farm utility vehicles. If this technology is commercialized, it will give users greater choice in fuel types and vehicles to use.

Off-road all-terrain vehicles are a substantial market in California. The researchers estimated the existing fleet of commercial ATVs potentially affected by EPA emission standards at nearly 1.3 million vehicles plus sales of new equipment of about 100,000 per year. Assuming a 20 percent market penetration in California, there could be a significant reduction in emissions. NO\textsubscript{x} emissions were close to zero during testing with the SOFC operating.
1.19.8 Technology Transition Assessment
As the basis for this assessment, the program administrator reviewed the researchers’ overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market
The researchers interviewed six potential users who supported the concept of a long range, low emissions utility vehicle. The researchers stated that the market they were pursuing is a regulation-driven market. In 2012 ARB approved regulations for small off-road vehicles under 25 hp. ARB claimed this would result in a large demand for electrically driven utility vehicles with essentially zero emissions.

Engineering/Technical
The researchers estimated they could complete design and demonstration in two years with about $1.4 million of additional funding.

Legal/Contractual
At the completion of this project the researchers had not identified any potentially patentable intellectual property, nor had they filed for or received any patents.

Environmental, Safety, Risk Assessments/ Quality Plans
Because the researchers are pursuing a regulation-driven market, they face significant assessments to assure that their product meets all components of the regulations. In addition, they must address safety issues that may derive from utilizing a hot fuel cell in a small vehicle. Fuel cell weight and a high vehicle center of gravity may also lead to safety issues.

Production Readiness/Commercialization
The researchers have approached Polaris to be a commercialization partner. Polaris indicated some interest after observing a successful prototype.

1.20 TNG Spiral Tube Low Profile Natural Gas Tank (2014)
Awardee: Otherlab
Principal Investigator: Dan Recht

1.20.1 Abstract
This project investigated the feasibility of creating a low-profile natural gas tank for use in vehicles by developing a spiral-shaped pressure vessel made of a braided fiber. The goal was to design a tank no more than seven inches tall that could meet minimum burst pressures and lifecycle tests as defined in the American National Standards Institute for compressed natural gas vehicle fuel containers while also costing less than $5 per liter of volume. Engineers investigated numerous materials, developed tank designs, built and tested many small-scale prototypes, and manufactured a full-scale three-gasoline gallon equivalent prototype. This testing proved the feasibility of manufacturing a large-scale 180-foot-long tank and the
functional feasibility of a small-scale 0.6 gasoline gallon equivalent tank. In addition, cost analysis based on data gathered from vendors and research showed that a $5 per liter tank was realistic and achievable.

**Keywords:** Natural gas, conformable pressure vessel, compressed natural gas tank, natural gas vehicle, spiral pressure vessel

1.20.2 Introduction

Compressed natural gas (CNG) vehicles are an attractive alternative to gasoline and diesel vehicles due to substantially lower greenhouse gas emissions and fuel costs. However, adopting this technology in California has been limited. Two critical barriers to compressed natural gas vehicle adoption are fuel tank size and vehicle price. Because a gallon of natural gas compressed to the industry standard of 3,600 pounds per square inch (psi) is the fuel equivalent of 0.287 gallons of gasoline, a CNG vehicle would require an unworkable 350 percent increase in fuel tank volume to deliver a driving range comparable to a gasoline vehicle. In practice, CNG vehicles sacrifice valuable cargo space to accommodate a larger fuel tank, while accepting a shorter maximum range. When this reduced performance is combined with the vehicles high retail price, it is no surprise the sale of these vehicles has been slow.

In addition to being the main source of reduced performance, the fuel tank is also a major contributor to the high up-front cost of CNG vehicles. One example of this is the CNG-fueled 2010 Honda Civic GX, which retailed for $25,340, $6,935 more than the gasoline-powered (but otherwise equivalent) Civic LX that cost $18,405. Although exact data is hard to obtain, the fuel tank likely accounted for about one quarter of the price increase.

The Volute project at Otherlab, which was funded by a $3.45 million grant from the United States Department of Energy Advanced Research Projects Agency (ARPA-E), has been developing a conformable natural gas tank made of a collection of medium diameter cylinders joined by small diameter tubes at their caps, which addresses the tank size problem by fitting more internal tank volume into the same external space and taking advantage of locations that traditional tanks cannot occupy. However, Volute researchers projected that this tank would cost about the same as traditional cylindrical CNG fuel tanks. Although improved performance at equivalent cost is acceptable for the first generation product, these researchers began developing a second generation tank to outperform cylindrical tanks at much lower cost. The second generation tank is the subject of this project.

The research team believed a low-profile tank formed from a single continuous tube bent into a spiral could free cargo space by lying flat (in the bottom of a truck bed or in the undercarriage of a passenger car), while reducing production costs by taking advantage of continuous manufacturing techniques that cannot be used to form traditional cylindrical tanks or the first-generation product. Throughout the course of this project, engineers developed this spiral tube conformable natural gas tank using materials available from the development of the first generation tank and the existing design and testing infrastructure.

The current CNG vehicle fuel tank standard set by the American National Standards Institute for Compressed Natural Gas Vehicle Fuel Containers (ANSI NGV 2) admits four types of CNG...
tanks for vehicle use. Type 1 tanks are solid metal (typically steel), Type 2 tanks feature a metal
liner wrapped hoop-wise with a high strength fiber composite, Type 3 tanks have a metal liner
fully wrapped with a high strength fiber composite, and Type 4 tanks are similar to Type 3
tanks but with a polymer liner. Type 3 and Type 4 tanks provide the best strength-to-weight
ratio but at the highest cost. As discussed above, maximum range is a major concern for natural
gas vehicles, so it is expected that any successful mass market CNG vehicle will use either a
Type 3 or Type 4 tank because of the additional fuel economy (and thus driving range) the
lighter tank will afford.

Today, Type 3 and Type 4 tanks are manufactured in a series of time-consuming batch
processes. Liners are individually molded or machined to the desired geometry—a cylinder
with spherical or quasi-spherical end caps and a small diameter protrusion to connect with the
fuel system. Liners are then wrapped one at a time with high strength fiber, coated with resin,
and cured for hours. The challenge in this process comes primarily from winding fiber over the
spherical end caps and the diameter reduction to the end fitting.

The tank designed for this project did not require a molded liner. Instead, the researchers used a
continuously extruded liner that required minimal attention from skilled workers and allowed
for multiple tanks to be extruded with the same machine setup. The composite material was
also applied continuously. A braiding machine overlaid carbon fiber already impregnated
with resin directly onto the tank. With a continuous amount of liner, the braiding machine
could continuously cover tanks and would be limited by the finite amount of carbon that a
braiding machine could hold at one time.

In addition to improved manufacturing/processing, shape and location are also improved with
a spiral-shaped tank (Figure 19). Currently, all commercial CNG fuel tanks consist of a single
cylinder. This makes poor use of available vehicle space, which is typically either irregular or
rectangular. For example, a typical retrofitted CNG Ford F250 has its tank placed at the front-
end of the truck bed and, including the housing, shortens the bed by 25 inches and takes up 19
cubic feet of cargo space. Since cargo in a pickup truck often extends above the cargo bay walls,
the engineers believe that bed length is the key metric for storage space. The standard Ford F250
has a bed length of 98 inches; this CNG F250 has 26 percent less cargo space than its gasoline
counterpart. The engineers found through investigating existing CNG vehicles that a number of
potentially attractive locations for a CNG tank, such as a pickup truck bed, a spare tire
compartment, or the roof of a truck or bus, are broad and flat (as in, they have two long
dimensions and one short dimension). Cylindrical tanks are not ideal for this configuration
because they have two short dimensions (the cylinder’s radius) and one long dimension (the
cylinder’s length). A relatively small diameter spiral tank, however, would solve this cargo
space issue, and that is what the researchers focused on throughout this project.
1.20.3 Objectives

This project explored using spiral tubes made of a braided fiber composite to create a low profile natural gas tank for vehicles that is affordable and occupies little to no cargo space. This project is important because it has the ability make natural gas vehicles more accessible to consumers by lowering up-front and fuel costs as well as reducing emissions, while preserving the vehicle’s cargo space. The researchers established these project objectives:

1. Design a spiral tank that holds at least three GGE (gasoline gallon equivalents) and is no more than seven inches tall.

2. Confirm that at high volumes materials and manufacturing process can cost less than $5 per water liter of stored natural gas.

3. Demonstrate that material properties are consistent with the tank being able to sustain a pressure of at least 9,000 psi (Phase I testing).

4. Confirm that small-scale tank sections hold at least 0.25 water liters.

5. Verify that small-scale tank sections can burst above 9,000 psi, can survive 100 cycles to 4,000 psi, and can pass these tests at -40°F and 185°F (40°C and 85°C) (Phase II testing).

6. Build a prototype that holds at least three GGE.
7. Demonstrate that prototype meets the same requirements as tank section and has a height of no more than seven inches (Phase III testing).

8. Show a path to a low profile commercial tank costing less than $5 per water liter of gas storage.

1.20.4 Outcomes

1. The final prototype design held three GGE. However due to budgetary constraints as well as manufacturing and test equipment limitations, the shape of the tank exceeded seven inches in height. With more funds to develop custom tooling and differently sized manufacturing and test equipment, a low profile tank under seven inches could easily be designed and produced.

2. Based on a preliminary cost analysis, researchers chose nylon 6 for the liner and carbon fiber for the composite as the best candidates for testing and the most likely to achieve cost requirements at scale.

3. The materials the researchers chose have properties consistent with being able to sustain 9,000 psi. They developed a burst pressure calculator to provide an estimate of material performance given certain tank and braid parameters as well as fiber material properties.

4. All small-scale tank sections that the researchers tested held at least 0.25 water liters.

5. One sub-scale tank section (36 feet long, 2-layer spiral) burst above 9,600 psi. The researchers cycled one three-foot sample 66 times to 4,000 psi before it began to leak. They did not perform environmental cycle testing on any samples due to a lack of in-house testing capabilities. This had no impact on the outcome of the project.

6. The researchers produced a full-scale prototype designed to hold three GGEs (180-foot-long, 10-layer spiral).

7. Although the full-scale prototype tank was not less than seven inches high, the tank geometry that was used provided meaningful results. The full-scale prototype tank was pressurized to 3,700 psi before a test equipment failure occurred. The tank never achieved the goal pressure of 9,000 psi and was not able to be cycle tested either. The researchers did not perform environmental cycle testing on the full-scale prototype due to lack of in-house testing capabilities. This had no impact on the outcome of the project.

8. A path to $5 per water liter is achievable considering tank optimization of design, materials, manufacturing process improvement, and speeds, as well as cost reductions at scale.

1.20.5 Conclusions

The research team overcame significant challenges with respect to designing and manufacturing a spiral pressure vessel when the team produced a 180-foot-long, multi-layer spiral, three GGE prototype tank. Functional feasibility was indicated when a low profile, 36-foot-long, two layer spiral sub-scale tank burst above 9,000 psi. Several tanks of the same design
must be burst tested to determine the failure rate. The researchers made progress toward manufacturing and testing of sub-scale and full-scale tanks but did not prove feasibility.

1.20.6 Recommendations
The Program Administrator recommends the following:

- Construct and test multiple tanks of a common design. The test program should be set up to have statistical relevance.

- Design tanks to meet the seven-inch high goal or determine a new maximum height and explain the rationale for the new selection.

- Focus on a specific vehicle type for the first production tank. Work with the manufacturer(s) of that vehicle type to ensure integration with other vehicle systems.

- Form a partnership with at least one vehicle manufacturer and include that partner in further development and demonstration.

- Focus design efforts on tube end fittings and tank liner quality.

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

- Improved transportation energy efficiency

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

- Increased use of alternative fuels

Since 2000, advanced exploration and development technologies, including fracking and directional drilling, have made natural gas an abundant and cost-effective fuel in the United States. Now busses and local trucks (garbage haulers and others) routinely use it as fuel. Tanks for the natural gas are most often mounted on top of the bus or truck. The same is not true of passenger cars and pickup trucks because the tanks take up valuable trunk or load space. If the benefits of clean-burning natural gas could be applied to light-duty vehicles, owners and operators could save significant money. The researchers in this project addressed the size and shape of natural gas fuel tanks. If the tanks could be shaped to fit into remote spaces in light duty trucks, more purchasers might elect the natural gas option. The researchers also addressed creating a lower cost gas tank. The final problem inhibiting the widespread use of natural gas fuel is the availability of natural gas fueling stations. This problem was not addressed by this project.

Honda Motor Company offered a natural gas-fueled Civic for a number of years before withdrawing it from the market. The price was too high and fueling was not convenient. At the time of this project there were very few natural gas vehicles on the road. Benefits would accrue to vehicle owners in the form of lower fuel costs and less engine maintenance due to the clean burning nature of the fuel. The public would benefit from the reduction of certain air pollution species. Quantifying the benefits is difficult since the public probably has a negative view of
natural gas fueled vehicles at this time. In addition, the public has a wide choice in propulsion types—gasoline, diesel, hybrid gasoline, plug-in hybrid, battery electric, and fuel cell electric. The manufacturers of light duty vehicles will play a key role in helping the public decide the dominant technology for the future.

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

Marketing/Connection to the Market
The researchers claimed that a large company in the auto industry has expressed commercial interest in this product. The researchers had not surveyed potential customers for interest.

Engineering/Technical
The researchers estimated they would require about $2 million in additional funds and three years to complete engineering, development, and demonstration.

Legal/Contractual
The researchers had not performed a patent search by the end of this project.

Environmental, Safety, Risk Assessments/Quality Plans
Because the researchers had not created a prototype by the end of this project, they did not begin these assessments and plans.

Production Readiness/Commercialization
The researchers claimed that while they could take a subsequent product to market, they would probably seek an arrangement with a tier one supplier to the automotive industry.

1.21 Advanced Prechamber Ignition for High EGR Dilute Burn Engine (2014)

Awardee: North American Repower
Principal Investigator: Pete Petersen

1.21.1 Abstract
Recent emissions testing of in-use heavy-duty diesel engines has demonstrated that the legacy heavy-duty truck fleet contributes the most nitrogen oxides and particulate matter emissions in California’s nonattainment areas. To address this problem, the state has issued a timetable to remove all older engines from the road and replace them with new cleaner engines. Researchers proposed an engine technology for rapid introduction into the market for new and retrofit applications. This technology could potentially allow California to beat the mandated time schedule by two to three years.
Researchers converted diesel engines to spark-ignited natural gas-fueled engines with a high level of exhaust gas recirculation. The design features a new type of prechamber as an ignition energy multiplier to provide combustion stability at dilution levels in excess of those achieved with conventional ignition systems. The design places the spark igniter within the prechamber rather than at the rear of the prechamber and away from the chamber’s ejection port, as is commonly done. With spark initiation, the resulting combustion kernel develops such that any unreacted air-fuel mixture is trapped and cannot escape without being combusted, providing a robust ignition event. Furthermore, by controlling the prechamber volume-to-nozzle area ratio, researchers were able to control the burn duration and could greatly extend it beyond the typical one-to-two-millisecond spark ignition event. The prechamber, including the spark igniter, was designed to fit into the same engine port usually occupied by a fuel injector in a diesel engine.

Testing showed the prechamber provided a long and powerful ignition, resulting in rapid combustion. Additional design and development is required to optimize this concept before to commercialization.

**Keywords:** Prechamber, lean combustion, dilute low NOx, combustion stability, emissions, engine out

### 1.21.2 Introduction

Recent emissions testing of in-use heavy-duty diesel engines has demonstrated that the legacy heavy-duty truck fleet represents the largest contributor of oxides of nitrogen (NOx) and particulate matter (PM) emissions for California’s non-attainment areas (parts of the state considered by the US. EPA to have air quality below the National Ambient Air Quality Standards). To address this problem, the state has issued a timetable to take all older engines off the road and replace them with new cleaner engines. Project researchers proposed an engine technology that could be, in their opinion, rapidly introduced into the market for new and retrofit applications. This technology can potentially help the state achieve its emissions-reduction goals early.

The researchers proposed to convert diesel engines to spark-ignited natural gas-fueled engines with a high level of exhaust gas recirculation (EGR). To reduce emissions, these engines can be operated as lean (low fuel to air ratio) or dilute (high EGR) or both. By combining dilute burn with the appropriate after-treatment system (exhaust gas catalysts) emissions can be reduced 90 percent. However, these cleaner, efficient engines typically suffer poor ignition. Many such designs feature a conventional spark at the rear of the prechamber, away from the chamber’s ejection port. Upon spark initiation, the resulting combustion wave moves towards the port pushing un-combusted air-fuel mixture ahead of it into the main combustion chamber.

To resolve the ignition problem, the researchers designed a new type of prechamber as an ignition energy multiplier to provide combustion stability at dilution levels in excess of those achieved with conventional ignition systems. The design places the spark source within the prechamber; upon spark initiation, the resulting combustion kernel develops in such a manner that any unreacted air-fuel mixture is trapped and cannot escape without being combusted,
providing a robust ignition event. Furthermore, by controlling the prechamber volume-to-nozzle area ratio, the designer was able to control the burn duration and could greatly extend it beyond the typical one to two millisecond spark ignition event. The longer duration flame entering the main combustion chamber ensures complete and steady combustion. The prechamber, including the spark igniter, was designed to fit into the same engine port usually occupied by the fuel injector in a diesel engine.

Although testing was not completed in this project, data showed the prechamber provided a long and powerful ignition, resulting in rapid combustion. A picture of the prechamber during flame duration testing is shown in Figure 20. Additional design and development is required to optimize of this concept prior to commercialization.
1.21.3 Objectives

The goal of this project was to determine the feasibility of a new spark igniter prechamber for enhancing the stability of natural gas-fueled engines with high EGR. The researchers developed the following objectives:

1. Demonstrate that the engine provides baseline performance of 400 horsepower (hp) at 2,100 revolutions per minute (RPM) and 1,400 foot-pounds (ft∙lb) torque at 1,400 RPM.

2. Demonstrate expected NOx emissions of 1.4—1.6 grams per break horsepower-hour (g/bhp-hr) for baseline. This is the current NOx emission level before exhaust gas treatment for spark-ignited heavy-duty natural gas engines.

3. Demonstrate expected fuel consumption of 240 grams per kilowatt-hour (g/kWh) for baseline.

4. Demonstrate a NOx reduction of 50 percent from the baseline numbers with no increase in CO or THC numbers.

5. Demonstrate high stability at peak torque and power (coefficient of variation [COV] less than 5 percent).

6. Demonstrate an average 5 percent improvement in thermal efficiency over the 13 mode steady state test.
7. Demonstrate 10 percent reduction in fuel consumption (216g/kWh) from the baseline.

8. Demonstrate no thermal cracking or accelerated erosion of prechamber components.

9. Compare before and after microscope photos of the electrode and adjacent surfaces, looking for erosion.

10. Demonstrate prechamber life is 50,000 miles or 1,500 hours compared to standard compressed natural gas (CNG) engine plug life of 20,000 miles.

11. Demonstrate prechamber performance results are on par with plasma ignition performance of 0.04—0.055 g/bhp-hr NOₓ compared to 0.2 g/bhp-hr NOₓ for current car standards.

12. Confirm low volume prototype pricing below $2,400 per engine and high volume prototype pricing of $600 per engine.

1.21.4 Outcomes

1. The researchers successfully demonstrated baseline performance of 400 hp at 2,100 RPM and exceeded the 1,400 ft-lbs torque goal by 10 percent (1,550 for torque ft-lbs).

2. The researchers successfully demonstrated 1.6 g/bhp-h NOₓ for the baseline performance of the engine.

3. The researchers failed to demonstrate fuel consumption of 240 g/kWh (180g/bhp-hr) for baseline. The best number achieved was 209 g/bhp-hr.

4. The researchers failed to demonstrate a NOₓ reduction of 50 percent from the baseline numbers with no increase in CO or THC numbers. Due to speed limitations, the researchers were unable to run transient tests with the prechamber.

5. The researchers failed to demonstrate high stability at peak torque and power (COV less than 5 percent).

6. The researchers failed to demonstrate an average 5 percent improvement in thermal efficiency over the 13 mode steady state test.

7. The researchers failed to demonstrate 10 percent reduction in fuel consumption (168 g/bhp-hr) from the baseline.

8. The researchers successfully demonstrated no thermal cracking or accelerated erosion of prechamber components.

9. The researchers failed to compare before and after microscope photos of the electrode and adjacent surfaces looking for erosion.

10. The researchers failed to demonstrate prechamber life is 50,000 miles or 1,500 hours compared to standard CNG engine plug life of 20,000 miles.
11. The researchers failed to demonstrate prechamber performance results are on par with plasma ignition performance of 0.04—0.055 g/bhp-hr NOx compared to 0.2 g/bhp-hr NOx for current car standards.

12. The researchers successfully confirmed low volume prototype pricing below $2,400 per engine and high volume prototype pricing of $600 per engine.

1.21.5 ´Conclusions
The new prechamber was designed, prototyped, and tested on a natural gas version of the Detroit Diesel Series 60 engine. While the researchers did not achieve success on all goals, the overall performance offered compelling results. Dilute combustion engines require a long duration high energy ignition source, which the tested prechamber demonstrated. Unfortunately, it was over-sized for the application, and it overwhelmed the combustion chamber at higher speeds and loads. However, at light to medium loads the system could be controlled to provide near-instantaneous combustion of the main chamber with an 8-millisecond burn duration. The large size of the prechamber prevented the researchers from completing the entire test program as originally outlined. However, the data collected showed that the concept, with adequate application engineering and development testing, may provide a major solution for next-generation natural gas engines. Ignition timing could be adjusted from 0° to 4° at medium load. Combustion data showed that the combustion event was properly timed, meaning that the peak cylinder pressure occurred at the same location as an engine running with 28° of advance using conventional ignition.

1.21.6 Future Considerations
The Program Administrator recommends the researchers:
- Focus future prechamber work on development and application engineering.
- Continue engine testing of the existing design on the Series 60 engine to optimize the performance across the speed and load range of the engine.
- Create full engine maps. This is necessary if the technology is to be used in the transportation sector, i.e., on-road vehicles. If this cannot be achieved, the prechamber is not a viable product for on-road engines. As a second step, testing should focus on the performance map of stationary engines to see if a limited performance map can be achieved.
- Work with engine manufacturers to integrate the product design into the engine systems.

1.21.7 Benefits to California
Public benefits derived from PIER research and development projects are assessed within the following context:
- Improved transportation energy efficiency
- Reduced greenhouse gas emissions or reduced health and environmental impacts from transportation associated air pollution related to electricity and NG production and use
• Increased use of alternative fuels

The prechamber technology developed in this project has the potential to help Californians meet the state clean air mandates earlier than expected and at a lower cost. Depending on the success in completing development and demonstration, clean air goals could be achieved two to three years earlier than expected. For this to occur, the technology must be adopted by new engine manufacturers and/or by current engine owners who opt for a retrofit of their current engines.

1.21.8 Technology Transition Assessment

This assessment is based on the program administrator’s review of the researchers’ overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers operate a business, North American Repower, which converts truck engines to natural gas fuel. As such, they are close to the market and to individual buyers.

Engineering/Technical

The researchers estimated they could complete development and demonstration of this technology in one to two years with $1 to $1.5 million in additional funding.

Legal/Contractual

The researchers conducted a patent search and found no competing patents. They did not apply for patents during the period of this project.

Environmental, Safety, Risk Assessments/Quality Plans

Truck engine manufacturers should complete these assessments when they begin to use this technology.

Production Readiness/Commercialization

North American Repower has agreements with original equipment manufacturer heavy-duty engine manufacturers to build and distribute engines with its technology.