DEVELOPMENT OF A PEM ELECTROLYZER: ENABLING SEASONAL STORAGE OF RENEWABLE ENERGY

Prepared For:
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Prepared By:
Schatz Energy Research Center
Humboldt State Univesity

FEASIBILITY ANALYSIS AND FINAL EISG REPORT

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ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

FEASIBILITY ANALYSIS REPORT (FAR)

DEVELOPMENT OF A PEM ELECTROLYZER: ENABLING SEASONAL STORAGE OF RENEWABLE ENERGY

EISG AWARDEE

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LEGAL NOTICE

PREFACE

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

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million of which $3 million/year is allocated to the Energy Innovation Small Grant (EISG) Program for grants. The EISG Program is administered by the San Diego State University Foundation under contract to the California State University, which is under contract to the Commission.

The EISG Program conducts four solicitations a year and awards grants up to $75,000 for promising proof-of-concept energy research.

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

- Residential and Commercial Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration

The EISG Program Administrator is required by contract to generate and deliver to the Commission a Feasibility Analysis Report (FAR) on all completed grant projects. The purpose of the FAR is to provide a concise summary and independent assessment of the grant project using the Stages and Gates methodology in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions (as presented in the Independent Assessment section).

The FAR is organized into the following sections:

- Executive Summary
- Stages and Gates Methodology
- Independent Assessment
- Appendices
    - Appendix A: Final Report (under separate cover)
    - Appendix B: Awardee Rebuttal to Independent Assessment (Awardee option)

For more information on the EISG Program or to download a copy of the FAR, please visit the EISG program page on the Commission's Web site at:
http://www.energy.ca.gov/research/innovations

or contact the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the Commission's Web site at http://www.energy.ca.gov/research/index.html.

Development Of A PEM Electrololyzer: Enabling Seasonal Storage of Renewable Energy

EISG Grant # 00-25

Awardee:	Schatz Energy Research Center
Principal Investigator:	Peter Lehman
PI Contact Info:	(707) 826-4345: pal1@humblodt.edu
Grant Funding:	$74,478.26
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Introduction

Many renewable energy sources are intermittent. Because of this characteristic, it is difficult to sell the electricity generated by those renewable sources into a forward market. The result is less revenue to the owner of the generator. One solution is to generate hydrogen with the renewable energy, store it, and consume the hydrogen in a fuel cell to provide electricity when needed. While holding hydrogen gas at high-pressure is the lowest cost method of hydrogen storage, it is not inexpensive. Compressing hydrogen is a major cost and thus is a deterrent to converting electricity generated from renewable sources to hydrogen to be stored for future use. Current technology hydrogen generators produce hydrogen at up to 375 psig. Mechanical compression of the hydrogen, a highly energy intensive process, is used to achieve storage pressures. In addition, most current generation high-pressure electrolyzers incorporate caustic liquid alkaline electrolytes and other hazardous materials. To solve the compression cost problem, one needs a non-caustic electrolyzer that produces hydrogen at storage pressure, eliminating the need for mechanical compression. An electrolyzer of this type is not currently available.

If the hydrogen storage cost problem were solved, renewable energy generators could provide more predictable power, allowing Californians to rely on more renewable energy. Generators would be able to utilize the forward markets and realize higher net revenues. With economical storage investors could develop more wind and solar electricity generators throughout the state. By adding predictable renewable energy into the California grid, grid operators might have less need to dispatch energy-inefficient "peaker" generators. In addition, if renewable generator output were more predictable, grid operators would not need to maintain fossil fueled plants at ready for system backup.

The researcher in this project proposed to produce high-pressure (2000 psig) hydrogen with a proton exchange membrane (PEM) electrolyzer. PEM electrolysis uses a solid electrolyte identical to that used in PEM fuel cells. PEM solid electrolyte is free of toxics and cannot spill or leak. In comparison with the more established alkaline electrolyzer technology, PEM electrolyzers are safer by virtue of their solid, inert electrolyte. They are capable of being operated at much higher pressures, and they can sustain high current densities. Other researchers have developed the concept of a PEM electrolyzer. Several PEM electrolyzers are available in the market today. The advancement of science in this project was to design the electrolyzer to withstand high pressures. The researcher in this project developed a design and selected appropriate materials to produce hydrogen at pressures of 2000 psig. The design had to solve the problem of hydrogen cross-over (to the anode) as the pressure increased. Safe handling of the oxygen developed in the electrolyzer was another key design challenge.

Objectives

The goal of this project was to determine the feasibility of designing a proton exchange membrane (PEM) electrolyzer to produce at least three standard liters per minute (slm) of hydrogen at 2000 pounds per square inch gauge pressure (psig). The researchers established the following project objectives:

1. Develop a PEM electrolyzer to generate three standard liters per minute of hydrogen.
2. Develop a PEM electrolyzer to generate hydrogen at 2000 psig without the use of mechanical pumps.
3. Achieve voltage efficiency of the electrolyzer > 90%.

Outcomes

1. The one-cell electrolyzer developed in this project produced 0.22 slm of hydrogen per minute. To achieve the desired 3 slm of hydrogen per minute the researcher proposed building a stack of 14 cells.
2. The researcher achieved the 2000 psig pressure objective in one-cell and two-cell electrolyzers.
3. The researcher measured the voltage efficiency at 92% and 95% in two different tests.

Conclusions

1. While showing a path to achieve the objective of 3 slm, the researcher should evaluate the costs associated with combining multiple cells to achieve the desired hydrogen output.
2. The researcher achieved a major pressure objective. This is a notable achievement and should reduce the cost of storing hydrogen produced by renewable energy generators or regenerative fuel cells.
3. The researcher met the voltage efficiency goal. Electrolyzers with higher voltage efficiency numbers are more energy efficient.
4. The researcher considers the specific materials used to prove feasibility confidential. The researcher also considers his solution to the hydrogen cross-over problem confidential.

Benefits to California

If the technology developed in this project were to be deployed commercially, Californians could enjoy the benefits of more renewable energy in the supply mix. A major benefit would be reduced air emissions because grid operators would not dispatch fossil fuel burning power plants for energy nor have them run as backup to support the grid if a renewable energy generator were suddenly to reduce output. Emissions from the standby generators reduce the air quality benefits of renewable energy generators. A second advantage would be greater grid stability due to the distributed nature of the renewable generators and the capability to produce electricity from the stored hydrogen when needed.

Recommendations

1. The researcher should calculate the “round trip” efficiency of converting renewable electricity to stored hydrogen and back to electricity. The U.S. DOE has established a goal of 70% for round trip efficiency. To achieve 70% one would need a hydrogen fuel cell operating near 80% efficiency and an electrolyzer operating at nearly 90% efficiency.
2. The researcher should calculate the expected cost of the PEM electrolyzer. The researcher should express cost in dollars per megawatt hour ($/MWh). Research to reduce electrolyzer cost will be needed before a commercial product can be produced.

The researcher should identify less costly but suitable diffuser materials for use in the module.

3. Efforts should continue to increase the working pressure of the electrolyzer.
4. Long-term bench tests should be conducted to determine the durability and reliability of the module design.

Stages and Gates Methodology

The California Energy Commission utilizes a stages and gates methodology for assessing a project's level of development and for making project management decisions. For research and development projects to be successful they need to address several key activities in a coordinated fashion as they progress through the various stages of development. The activities of the stages and gates process are typically tailored to fit a specific industry and in the case of PIER the activities were tailored to be appropriate for a publicly funded energy research and development program. In total there are seven types of activities that are tracked across eight stages of development as represented in the matrix below.

Development Stage/Activity Matrix

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Activity 1								
Activity 2								
Activity 3								
Activity 4								
Activity 5								
Activity 6								
Activity 7								

A description the PIER Stages and Gates approach may be found under "Active Award Document Resources" at: http://www.energy.ca.gov/research/innovations and are summarized here.

As the matrix implies, as a project progresses through the stages of development, the work activities associated with each stage needs to be advanced in a coordinated fashion. The EISG program primarily targets projects that seek to complete Stage 3 activities with the highest priority given to establishing technical feasibility. Shaded cells in the matrix above require no activity, assuming prior stage activity has been completed. The development stages and development activities are identified below.

Development Stages:	Development Activities:
Stage 1: Idea Generation & Work Statement Development	Activity 1: Marketing / Connection to Market
Stage 2: Technical and Market Analysis	Activity 2: Engineering / Technical
Stage 3: Research & Bench Scale Testing	Activity 3: Legal / Contractual
Stage 4: Technology Development and Field Experiments	Activity 4: Environmental, Safety, and Other Risk Assessments / Quality Plans
Stage 5: Product Development and Field Testing	Activity 5: Strategic Planning / PIER Fit - Critical Path Analysis
Stage 6: Demonstration and Full-Scale Testing	Activity 6: Production Readiness / Commercialization
Stage 7: Market Transformation	Activity 7: Public Benefits / Cost
Stage 8: Commercialization	

Independent Assessment

For the research under evaluation, the Program Administrator assessed the level of development for each activity tracked by the Stages and Gates methodology. This assessment is summarized in the Development Assessment Matrix below. Shaded bars are used to represent the assessed level of development for each activity as related to the development stages. Our assessment is based entirely on the information provided in the course of this project, and the final report. Hence it is only accurate to the extent that all current and past work related to the development activities are reported.

Development Assessment Matrix

Stages / Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop-ment	5 Product Develop-ment	6 Demon-stration	7 Market Transfor-mation	8 Commer-cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/								
Public Benefits/ Cost								

The Program Administrator's assessment was based on the following supporting details:

Marketing/Connection to the Market

The researcher has communicated with potential commercialization partners. The researcher has prepared a non-disclosure agreement to advance the discussions with one of the potential partners.

Engineering/Technical

This project proved the feasibility of producing hydrogen at 2000 psig using a PEM electrolyzer. Additional testing is needed to prove the durability and reliability of the high-pressure electrolyzer. Once the design and materials prove to be reliable and durable, the researcher should evaluate potential partners to complete the development of the electrolyzer and to commercialize the technology developed in this project.

Legal/Contractual

The researcher is pursuing patent protection for the technology developed in this project. There are no known legal issues.

Environmental, Safety, Risk Assessments/ Quality Plans

Quality Plans include Reliability Analysis, Failure Mode Analysis, Manufacturability, Cost and Maintainability Analyses, Hazard Analysis, Coordinated Test Plan, and Product Safety and Environmental**.** The researcher has not yet developed any of these plans. Product safety plans are critical due to the presence of high-pressure hydrogen in close proximity to oxygen. The researcher developed laboratory procedures to handle these materials safely.

Strategic

This product has no known critical dependencies on other projects under development by PIER or elsewhere

Production Readiness/Commercialization

The researcher has discussed commercialization with potential manufacturers of the PEM electrolyzer. Once an agreement has been reached the partner can begin the process of developing production readiness plans.

Public Benefits

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

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

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply, transmission system, or distribution system. When operators of renewable resource power plants can schedule the output of their equipment and sell into the forward markets, they will build more generators based on renewable resource. In addition, the grid operators will not need to maintain conventional power plants in spinning reserve to back up potentially unreliable renewable energy generators. Air quality benefits of renewable energy are greatly reduced when grid operators maintain power plants in a spinning reserve mode or, worse, dispatch "peaker" power plants to provide backup power. Producing and storing hydrogen for consumption in fuel cells at the needed point in time greatly reduces the need for backup power plants and the use of "peaker" power plants

Program Administrator Assessment

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

Appendix A: Final Report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment (none submitted)

ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

EISG FINAL REPORT

DEVELOPMENT OF A PEM ELECTROLYZER: ENABLING SEASONAL STORAGE OF RENEWABLE ENERGY

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Legal Notice

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Hal Clark and Steve Russell, EISG Program Staff

EISG Awardee

This project was awarded to Schatz Energy Research Center/Humboldt State University Foundation of Arcata, CA, a California 501(c)3 nonprofit corporation

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Abstract

The purpose of this project was to develop a proton exchange membrane (PEM) electrolyzer capable of generating hydrogen at high pressure in useful quantities for small-scale power systems. Specifically, our objective was to design, build, and bench test a PEM electrolyzer capable of generating a minimum of three standard liters per minute (slm) of hydrogen at 2,000 pounds per square inch gauge pressure (psig). We tested a wide variety of materials and components and made numerous iterative improvements to our original electrolyzer module in the course of the project. As of the conclusion of this project's funding cycle, we have achieved our 2,000 psig objective with an average hydrogen delivery rate of 0.22 slm per cell in modules with 1 and 2 cells at a current density of $700mA/cm^2$. This electrolyzer design would achieve our 3 slm delivery objective if expanded to a 14-cell stack format. However, given the numerous iterations in material selection required to arrive at a satisfactory single-cell design, project funding proved insufficient to construct a multi-cell stack of this size.

Key Words: Electrolyzer, Electrolysis, Hydrogen, Energy, High Pressure, Proton Exchange Membrane

Executive Summary

Introduction

Hydrogen and fuel cells are becoming widely recognized as clean, efficient energy storage and conversion technologies. The emerging hydrogen energy economy will require a safe, efficient means for generating hydrogen. There is also an unmet need for an equally safe and efficient means of storing hydrogen at the greatest feasible density, particularly for transportation applications, where minimizing fuel storage volume is critical.

High pressure proton exchange membrane (PEM) electrolysis can address both of these needs. The vast majority of commercial hydrogen is currently generated by reformation of fossil fuels. The small percentage of hydrogen generated electrolytically is produced using primarily alkaline electrolyzers that contain caustic liquid electrolytes and other hazardous materials. PEM electrolysis uses a solid electrolyte similar to that used in PEM fuel cells. It is free of toxics and cannot spill or leak. Existing hydrogen generation technologies also produce hydrogen gas at low pressures, typically 100 psig or less. A PEM electrolyzer can be engineered to safely produce high-pressure hydrogen without mechanical compression.

The Schatz Energy Research Center (SERC), part of the Humboldt State University Foundation (HSUF), embarked on the development of a high pressure PEM electrolyzer as a natural extension of more than a decade of our work in research and development of PEM fuel cell systems. Our efforts to develop an efficient, high performance PEM electrolyzer support our mission to promote the use of sustainable energy in our society.

Project Objectives

The original project objective was to design, build, and bench test a proton-exchange membrane electrolyzer capable of generating a minimum of three (3) standard liters per minute (slm) of hydrogen at 2,000 pounds per square inch gauge pressure (psig).

Project Outcomes

1. Despite initial challenges in identifying suitable materials for our electrolyzer module, we were able to construct a multi-cell module that ultimately delivered hydrogen at a rate of 0.22 standard liters per minute per cell. Extrapolating this performance to a 14-cell module would allow us to meet our performance goal of 3 slm hydrogen generation. In our best single- and two-cell tests, we were able to generate hydrogen at pressures in excess of 2,000 pounds per square inch gauge (psig).
2. Observed voltage efficiency for our PEM module is markedly better than that of a Teledyne Altus 20 alkaline electrolyzer, based on performance measurements made using both devices at the Schatz Energy Research Center. Conversely, current density (and thus hydrogen generation rate) at a given cell voltage is significantly better in our unit than in the Altus 20. Clearly, our PEM electrolyzer design offers greater efficiency than a typical commercial electrolyzer. This translates to more hydrogen generated per unit cell area, which in turn could result in more compact and economical electrolyzer designs.

Conclusions

1. We were able to identify a combination of materials, develop a module design, and fabricate electrolyzer module components that form the basis of a high-performance hydrogen generator with great commercial potential.
2. Based on electrolyzer cell efficiency, our design appears to offer a significant total energy efficiency advantage over an alkaline electrolyzer/mechanical compressor combination.

Recommendations

1. Laboratory research should continue, using a larger number of cells to increase gas output to commercially useful volumes.
2. Efforts should continue to increase the working pressure of the electrolyzer.
3. Longer term bench tests should be conducted to determine the ultimate longevity of the module design.
4. Research should continue to identify less costly but suitable diffuser materials for use in the module.

Public Benefits to California

Our work supports the PIER program's goal to "provide public value for the benefit of California and its citizens through the development of technologies which will improve environmental quality, enhance system reliability, increase efficiency of energy-using technologies, lower system costs, or provide other tangible benefits." The project can improve environmental quality by helping to displace more polluting existing energy technologies with clean hydrogen energy. It will enhance system reliability by allowing energy users to generate hydrogen for on-site use as a distributed generation and backup power fuel. Two important applications of high pressure PEM electrolyzer technology will be 1) home refueling of hydrogen vehicles and 2) seasonal storage of renewable energy for remote power, as in telecommunications repeater or environmental monitoring sites. The project also offers a business opportunity to California companies in manufacturing and marketing SERC's PEM electrolyzer technology.

Introduction

Background and Overview

Hydrogen and fuel cells are becoming widely recognized as clean, efficient energy storage and conversion technologies. The federal government and the State of California have greatly increased funding for research and development of these technologies and have entered into partnerships with industry and academic institutions to accelerate the deployment of a hydrogen-based energy economy.

The emergence of this hydrogen economy will depend upon the development of safe, efficient, and environmentally responsible means for generating hydrogen. At present, hydrogen is mainly used for industrial applications. Worldwide, 96% of hydrogen generated today is derived directly from natural gas, oil, and coal[i]. An alternative to fossil fuels reformation is the synthesis of hydrogen by the electrolysis of water. This technology lends itself well to small-scale, decentralized hydrogen generation and, if powered by electricity from renewable energy, produces hydrogen without depleting nonrenewable fuels or emitting air pollutants and greenhouse gases. Many commercial electrolyzers are available. However, electrolyzer technology is costly, and most current generation electrolyzers incorporate caustic liquid alkaline electrolytes and other hazardous materials.

In order to serve as a practical fuel for transportation, remote, and portable power applications, hydrogen must be highly compressed to minimize fuel storage volume. Typical hydrogen storage pressures for these uses are 2,000 to 5,000 pounds per square inch gauge (psig). Existing hydrogen generation technologies produce hydrogen gas at much lower pressures, typically atmospheric pressure to 375 psig.[1] Mechanical compression is needed to raise gas pressure to levels needed for almost all applications. Unfortunately, this compression process carries with it a significant energy penalty, requires large capital expenditures for the compression equipment, and incurs ongoing operation and maintenance costs.

Two alternatives to pressurized gaseous hydrogen storage are available: liquefied hydrogen and metal hydrides. However, liquefying hydrogen calls for expensive, elaborate equipment to cool the gas to -253°C and carries a high energy penalty. Metal hydrides are expensive, heavy, and have a limited lifespan, showing a decay in energy storage capacity after repeated cycling.

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[1] Example hydrogen delivery pressures: Vandenborre's H_2IGen unit = 375 psig; Norsk's high pressure electrolyzer = 232 psig; Proton Energy Systems' Hogen = 200 psig; Teledyne's Titan and Medusa = 100 psig; Hamilton Sundstrand's ES Series = 100 psig; Stuart Energy's Electrolyser ≈ atmospheric pressure.

Proton exchange membrane (PEM) electrolysis offers a clean, safe, and potentially cost-effective means of producing hydrogen at high pressures ready for storage or immediate use, without mechanical compression. PEM electrolysis uses a solid electrolyte identical to that used in PEM fuel cells. PEM assemblies are already widely available from a number of manufacturers for fuel cell applications. PEM solid electrolyte is free of toxics and cannot spill or leak. In comparison with the more established alkaline electrolyzer technology, Millet et al. point out that PEM electrolyzers are safer by virtue of their solid, inert electrolyte; are capable of being operated at much higher pressures; and can sustain high current densities.[ii]

The Schatz Energy Research Center (SERC), part of the Humboldt State University Foundation (HSUF), embarked on the development of a high pressure PEM electrolyzer as a natural extension of more than a decade of research and development of PEM fuel cell systems. SERC specializes in the design, construction, and demonstration of solar hydrogen systems, in which we combine our own fuel cells with off-the-shelf photovoltaic modules and electrolyzers to create totally clean and self-sufficient hydrogen energy systems that operate on sunlight and water. Our effort to develop an efficient, high performance PEM electrolyzer supports our mission to promote the use of sustainable energy in our society.

The California Energy Commission is supporting this project through its Energy Innovations Small Grants program under the Public Interest Energy Research program's Environmentally Preferred Advanced Generation category.

Report Organization

Following this introductory section, we discuss the project's objectives and specific tasks that were carried out to achieve these objectives. The report continues with a section that presents our project approach, from background research to preliminary designs, component fabrication, bench testing, and successive iterations that were needed to achieve performance objectives. A section on project outcomes describes our test results and significant design concepts that emerged from the project. We next provide conclusions summarizing the project, a list of recommendations for continued development of the PEM electrolyzer, a discussion of how this project can provide public benefits to California, and a development stage assessment that places our work in the context of the Commission's Stages and Gates Process. The report concludes with endnotes and a glossary. Photos and graphs are included where appropriate.

Project Objective

The original project objective was to design, build, and bench test a proton-exchange membrane electrolyzer capable of generating a minimum of three (3) standard liters per minute (slm) of hydrogen at 2,000 pounds per square inch gauge pressure (psig).

Project Tasks

Project tasks and subtasks identified in the proposal were as follows:

Task 1: Perform literature search and patent search to determine the state-of-the-art in PEM electrolysis.

Task 2: Prepare single PEM electrolysis cells for testing.

Subtask 2.1: Based on the results of Task 1, design a single PEM electrolysis cell, including choice of membrane material and thickness, catalyst, electrode material, and containment vessel.

Subtask 2.2: Prepare CAD drawings for experimental cell.

Subtask 2.3: Fabricate and assemble experimental cell.

Task 3: Bench test single cell design.

Subtask 3.1: Prepare test bench for single cell experiments. Procure necessary equipment, calibrate instruments, and program software.

Subtask 3.2: Test single electrolysis cell, gradually increasing the operating pressure. Collect and analyze data to determine cell efficiency, optimum current density and temperature, maximum operating pressure, and durability of materials.

Task 4: Redesign and retest single PEM electrolysis cell.

Subtask 4.1: Based on the results of Task 3, redesign the cell as necessary to improve performance.

Subtask 4.2: Repeat Subtask 3.2 on redesigned cell.

Subtask 4.3: Repeat Subtasks 4.1 and 4.2 until performance targets are met or as time and funding permit. Performance targets are: 75% voltage efficiency (HHV) at 2,000 psig output hydrogen pressure.

Task 5: Design, fabricate, and test a multi-cell PEM electrolysis stack.

Subtask 5.1: Utilizing the cell design developed in Task 4, design a multi-cell electrolysis stack capable of furnishing 3 slm hydrogen at 2,000 psig.

Subtask 5.2: Prepare CAD drawings for the electrolysis stack.

Subtask 5.3: Fabricate and assemble experimental stack.

Subtask 5.4: Test multi-cell electrolysis stack, gradually increasing the operating pressure. Collect and analyze data to determine cell efficiency, optimum current density and temperature, maximum operating pressure, and durability of materials. Make changes as necessary to meet design targets.

Task 6: Prepare and submit final project report.

Project Approach

Task 1: Perform literature search and patent search to determine the state-of-the-art in PEM electrolysis

Most of the literature review and patent search activity for this project was completed in the course of preparing our funding proposal. Our literature review and patent search are described below.

A number of authors have described the basic operation and economics of PEM electrolyzers. Knobbe[iii] provides an overview of PEM electrolyzer technology, comparing efficiency and other performance characteristics of high and low pressure PEM electrolyzers. This study found the mechanical simplicity of high pressure PEM electrolysis to be its main advantage. Ogden and Nitsch[iv] describe a hypothetical solar hydrogen economy and the important role that PEM electrolyzers could play in such an economy, assuming decreases in membrane and catalyst costs. Thomas and Kuhn[v] present a comparison of PEM and alkaline electrolyzers in which PEM electrolyzers show comparable efficiency at lower cost over a wide range of plant sizes.

There are also numerous articles describing techniques and materials for making PEM electrolyzers. Millet et al.[vi] provide details on the physical form and assembly of electrode membrane electrode (EME) composites. They also describe and provide a schematic of a PEM electrolyzer test station that was used for testing electrolyzers at up to 100 bars (approximately 1450 psig) pressure. Ledjeff et al.[vii] describe suitable materials for use in PEM electrolyzers, such as sintered titanium electrodes and platinum, ruthenium and iridium membrane catalysts. These authors also discuss the tradeoffs and performance achieved by using hydrophilic and hydrophobic electrode materials.

Several companies have developed PEM electrolyzers, including Proton Energy Systems, Hamilton Standard (now Hamilton Sundstrand), General Electric, Peak Scientific, Packard Instrument Company, and Vandenborre Technologies. So far, however, none of these commercialized products has offered high pressure hydrogen output. The highest available output pressure is 375 psig, from Vandenborre's H_2IGen unit[viii].

Proton Energy Systems continues to announce advances in development of a high pressure unit[ix], but has not yet publicly demonstrated the device or announced a date by which this product will come to market.

On the other hand, manufacturers such as Peak Scientific[x] and Packard Instrument Company[xi] have made PEM electrolyzers commercially available for several years. These products are touted as superior to electrolyzers employing liquid alkaline electrolytes, based on their low maintenance requirements and lack of hazardous materials. However, these electrolyzers produce hydrogen only on a small scale (0.2-1.2 slm) and at moderate pressures for laboratory applications such as gas chromatography.

SERC has identified numerous patents that pertain to PEM electrolysis, including (in reverse chronological order):

- U.S. Patent #6,383,361: Fluids Management System for Water Electrolysis. Uses a catalyst bed to react dissolved oxygen and hydrogen carried in water streams exiting electrolyzer.
- U.S. Patent #6,365,032: Method for Operating a High Pressure Electrochemical Cell. Focuses on design of pressure pad that supports MEA – combines metal and elastomeric materials for optimal combination of elasticity and conductivity.
- U.S. Patent #5,480,518: High Purity Hydrogen and Oxygen Production Using an Ion Exchange Membrane Having Catalysts Electrically Isolated Throughout. Ion exchange membrane has internal catalyst sites react without contaminating oxygen and hydrogen streams in anode and cathode chambers.
- U.S. Patent #5,350,496: Solid State High Pressure Oxygen Generator and Method of Generating Oxygen. Early high-pressure PEM design capable of delivering oxygen at up to 6,000 psig.
- U.S. Patent #5,271,813: Apparatus and Method for the Electrolysis of Water Employing a Sulfonated Solid Polymer Electrolyte. System for heating electrolyte to accelerate reaction without losing structural integrity, claims high ionic

conductivity and high energy efficiency. Electrolytes are sulfonated polymers including SPEEK, SPES, SPBI, SPPQ, SFPI.

- U.S. Patent #5,037,518: Apparatus and Method for Generating Hydrogen and Oxygen by Electrolytic Dissociation of Water. Features include separation of water and hydrogen, recycling water collected at cathode side for re-use at anode side, hydrogen pressure relief device, automated shutdowns based on sensing of water level and water quality.
- U.S. Patent #3,992,271: Method for Gas Generation. Focuses on use of platinum-iridium catalyst in place of pure platinum to avoid CO poisoning of electrode.
- U.S. Patent #3,870,616: Current Controlled Regulation of Gas Evolution in a Solid Polymer Electrolyte Electrolysis Unit. Emphasizes how gas output pressure from the electrolyzer is monitored and controls current fed to electrolytic cells, which in turn determines gas output rate.

A very recent patent of interest was U.S. Patent #6,554,978: High Pressure Electrolyzer Module. The electrolyzer described in this patent is not a PEM unit, instead using a liquid electrolyte. However, high pressure electrolyzers need to address many of the same design issues, regardless of what electrolyte is used. This design makes use of convection to circulate electrolyte without pumping. The pressure of the exiting gas is used to drive makeup water into the electrolyzer.

These and other patents offer insights to the state-of-the-art in PEM and other types of high-pressure electrolyzers, such as materials being used and component configurations. Most patents we found that specifically describe high-pressure and/or PEM electrolysis were issued in the past two years, corroborating our perception that the technology remains in the early stages of commercialization in the hands of other developers. The main conclusion of SERC's literature review, patent search, and extensive internet research is that no one has yet developed a market-ready high-pressure PEM electrolyzer.

In the course of our literature search, we identified safe handling of oxygen under pressure as a key issue in the design of the electrolyzer. We acquired and reviewed oxygen safety documents from NASA, the National Fire Protection Association, the American Society for Testing and Materials, and other agencies. We registered a Schatz engineer to attend an ASTM oxygen safety seminar, but the course was canceled in the aftermath of the September 11 attacks due to lack of enrollment. We acquired all of the printed training materials used for the course and reviewed them carefully until we became confident in our ability to select and use oxygen-compatible materials safely.

Task 2: Prepare single PEM electrolysis cells for testing

Task 2 began with the development of preliminary cell and multi-cell stack designs. Stainless steel was used for the endplates. Required thickness of the endplates, number and thickness of tie rods, and other component specifications were determined according to the stress associated with our target pressure of 2,000 psig. Other design factors included selecting oxygen-compatible materials; selecting a catalyst formula for the membrane electrode assemblies (MEAs); and selecting orientations for water, oxygen, and hydrogen ports in the end plates that would be feasible to machine using SERC's shop equipment.

A design decision made early in the project was to maintain low pressure on the anode (water/oxygen) side of the MEAs. This decision was made for safety reasons in order to avoid working with high pressure oxygen, a very hazardous material in any setting. The presence of pressurized hydrogen in close proximity was all the more reason to avoid high pressure oxygen. However, we recognized that by making this choice we would need to solve resulting design issues. The high pressure differential across the MEA would require a means of supporting the membrane as well as a mechanism for preventing significant crossover of hydrogen to the anode side of the MEA. Such crossover could result in a combustible mixture of hydrogen and oxygen, as well as reducing module efficiency due to the loss of recoverable hydrogen.

Our final single-cell electrolyzer module design consists of two stainless steel end plates, each having a machined circular pocket on its inner surface. This pocket accommodates a permeable metal diffuser disc. The anode-side pocket has two orifices, one for the introduction of water, and the other for the removal of water and oxygen. The cathode-side pocket has a single orifice for the removal of hydrogen. The MEA is held between the two end plates, which are compressed together using tie rods that pass through bolt holes arranged around the outsides of the circular pockets. The active areas on both sides of the MEA are in direct contact with the diffuser discs in the pockets. O-rings are set into machined grooves concentric to and just outside the pockets on the inner faces of the end plates.

Once our single cell electrolyzer module design was complete, we ordered MEAs, O-rings, diffuser materials, and stainless steel for end plates.

Given that we were developing a new, somewhat unfamiliar technology for use at high pressure in this project, we decided it would be prudent to operate the module within a containment vessel during tests. After investigating several containment options, we decided to modify an existing blast containment vessel used in the past at the lab for high pressure component and system testing. Before conducting any "live" electrolysis, we assembled a mock electrolysis cell with the stainless steel end plates, an O-ring, and the MEA and pressure-tested this assembly inside the containment vessel using helium.

Task 3: Bench test single cell design
After specifying and acquiring the needed components, we built the electrolyzer test station. The test station computer is an IBM NetVista work station equipped with two data acquisition cards: a PCI-6031E analog card and a PCI-DIO-32HS digital card. The analog card is connected to two Analog Devices 5B backplanes, carrying 25 input modules and two output modules. The digital card is connected to a single Opto 22 backplane, which carries seven outputs and two inputs. Parameters monitored include module current and voltage, hydrogen flow, hydrogen pressure, water flow, water conductivity, oxygen pressure, temperature of water entering and exiting the module, and ambient air temperature. The module is powered by a Sorensen 60-45B 2500-watt power

supply. The test station control and data acquisition programming is done in-house using National Instruments LabVIEW version 6i software.

We completed the containment vessel modifications, adding a removable front cover equipped with viewing ports. These ports and an illumination port in the roof of the vessel were covered with bulletproof glass. See Figure 1.

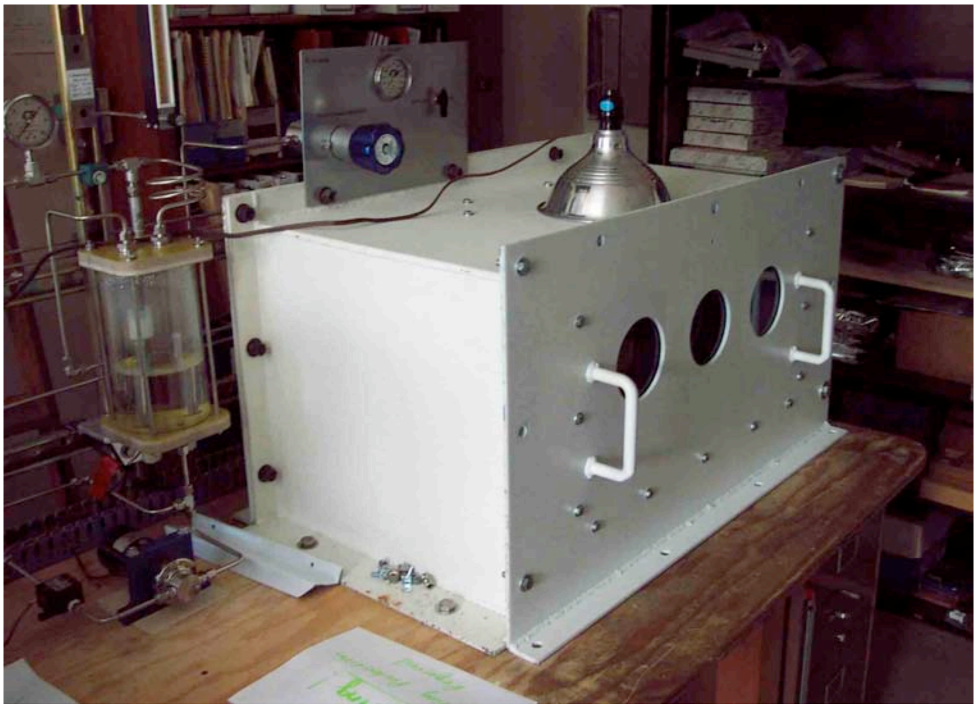

Figure 1. Pressure containment vessel and test station for electrolyzer testing

At this point, we were ready to begin our first single cell electrolyzer tests. In our first test, we were able to generate hydrogen. However, we found high contact resistance, corrosion of the diffuser, and undesired electrolysis reactions occurring in the cell away from the active area that resulted in rapid oxidation of cell components.

Task 4: Redesign and retest single PEM electrolysis cell

After making several modifications to the electrolysis cell to address the problems encountered while performing Task 3, we repeated the single cell tests. The results were encouraging. Comparing the cell efficiency to that of a Teledyne Energy Systems Altus 20 electrolyzer, we found that our cell had a markedly higher efficiency, as indicated by a lower cell voltage at a given temperature and current density.

Task 5: Design, fabricate, and test a multi-cell PEM electrolysis stack

Our only significant departure from the originally planned task sequence was the decision to proceed to the fabrication and testing of the multi-cell stack (Task 5) before reaching the single-cell target pressure of 2,000 psig (Task 4). We made this decision at a point when we had reached 1,000 psig with a single-cell module and exceeded our 75% voltage efficiency goal. We decided that our time and resources would be best spent proceeding with development of the multi-cell module, while simultaneously continuing to resolve some of the design problems encountered in reaching our target pressure of 2,000 psig.

Once we received and fabricated additional needed components, we assembled the two-cell stack and performed pressure tests, obtaining satisfactory results. We then proceeded to perform electrolysis and were able to generate hydrogen with the two-cell stack at pressures up to 2,000 psig. Results of our two-cell tests were very encouraging, showing high current density and balanced voltages between the two cells.

Task 6: Prepare and submit final project report
Work on the final report began in April 2003 with the preparation of an outline and first draft. These were submitted to the EISG program manager for review on May 15, 2003. Following receipt of comments from the EISG program manager, a second draft final report was prepared for submission by July 15, 2003.

Project Outcomes

1. Despite initial challenges in identifying suitable materials for our electrolyzer module, we were finally able to construct a single-cell module that operated at 2,000 pounds per square inch gauge (psig) at a current density of 700 mA/cm^2, producing on average approximately 0.22 standard liters per minute of hydrogen. Figure 2 shows hydrogen production rate, current density, and hydrogen pressure recorded over more than six hours of continuous operation during a recent test of the single cell electrolyzer. Our best sustained performance to date with a two-cell module has achieved hydrogen production at a rate averaging approximately 0.44 standard liters per minute and 2,000 psig, again with a current density of approximately 700 mA/cm^2 (see Figure 3). Extrapolating this performance to a 14-cell module will allow us to meet our performance goal of 3 slm total hydrogen generation. (*Note:* Figures 2 and 3 show cyclic fluctuations in hydrogen flow. This is an effect caused by the gas pressure regulator and is not a performance characteristic of the electrolyzer module itself. Also note that the single-cell test shown in Figure 2 was conducted at constant pressure after an initial ramp-up, while pressure was increased in stages throughout the two-cell test shown in Figure 3.)
2. Observed voltage efficiency for our PEM module is markedly better than that of a Teledyne Altus 20 alkaline electrolyzer, based on performance measurements made using both devices at the Schatz Energy Research Center. Similarly, current density (and thus hydrogen generation rate) at a given cell voltage is significantly better in our unit than in the Altus 20. Figure 4 shows a comparative cell voltage-current density graph of the two electrolyzers, each operating at a hydrogen output pressure of 100 psig. At 200 mA/cm^2, our electrolyzer has a voltage efficiency of 95%, compared to 87% per cell for the Teledyne electrolyzer. At a higher current density of 350 mA/cm^2, the relative efficiency difference is even greater: 92% for the SERC electrolyzer and 81% for the Altus 20. Clearly, our PEM electrolyzer design offers greater efficiency than a typical commercial electrolyzer. This translates to more hydrogen generated per unit cell area, which in turn could result in more compact and economical electrolyzer designs.

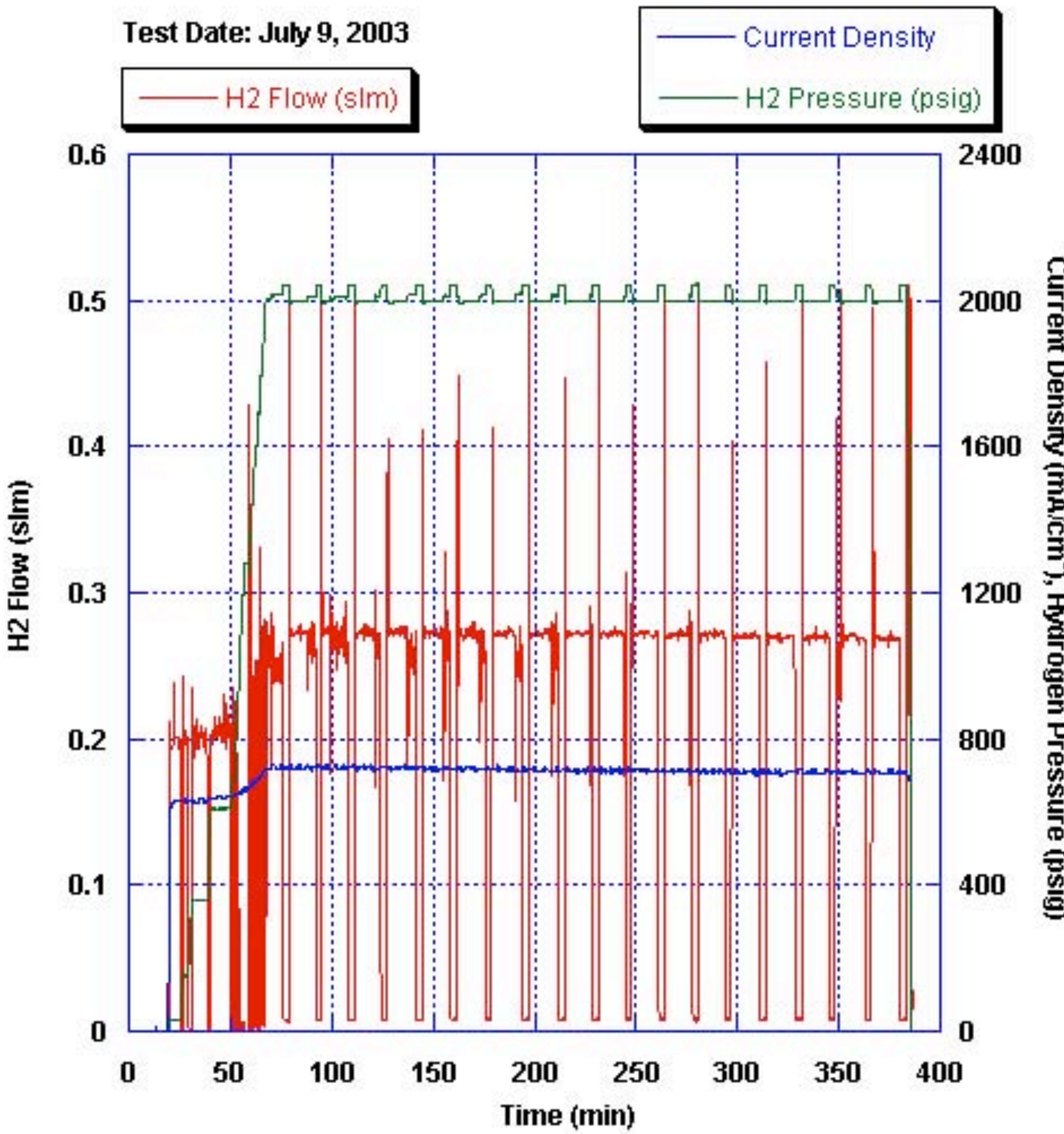

Figure 2. Single-cell electrolyzer module performance

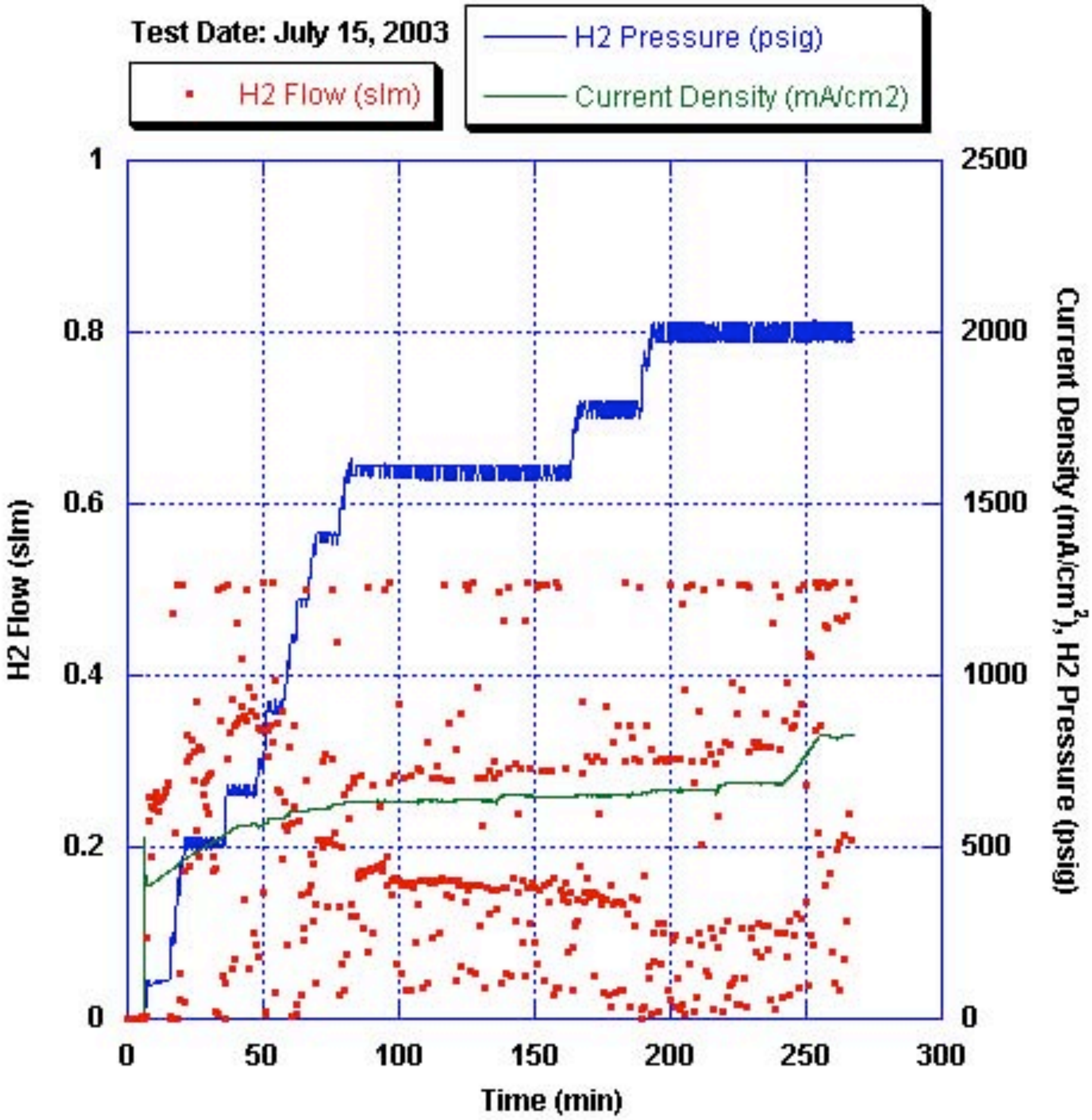

Figure 3. Two-cell electrolyzer module performance

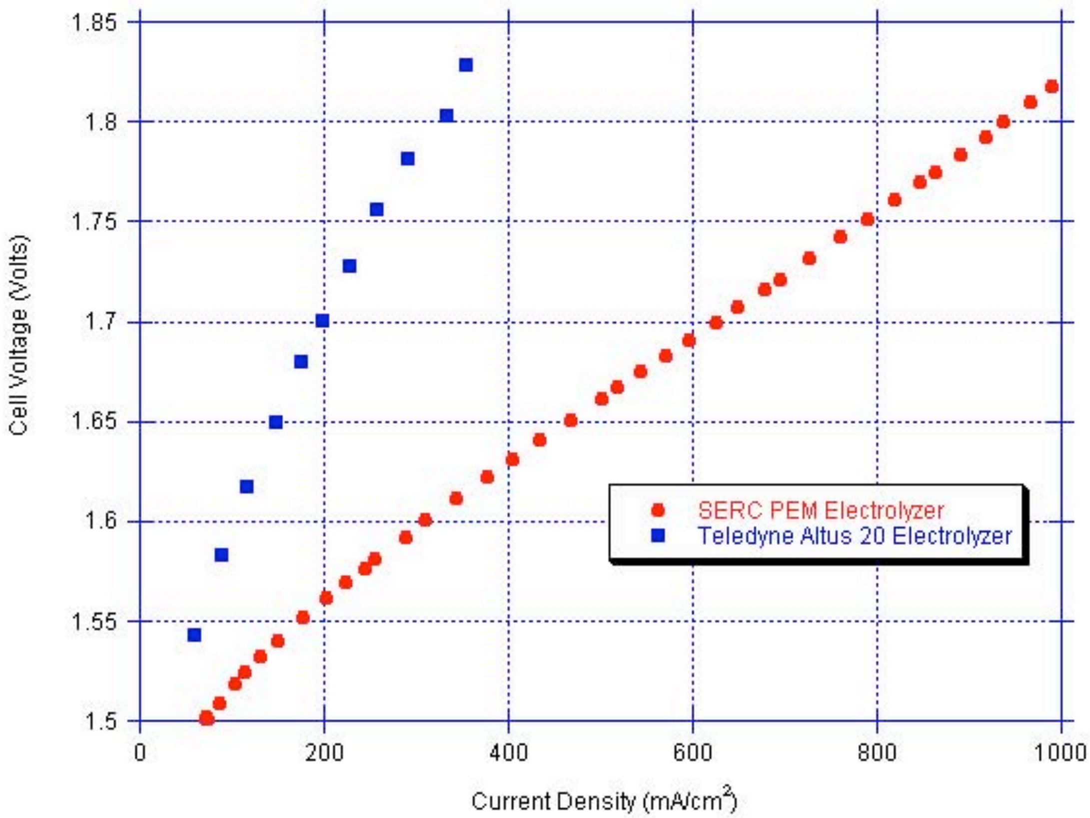

Figure 4. Comparison of SERC PEM electrolyzer and Teledyne electrolyzer

3. We addressed the problem of hydrogen crossover into the oxygen stream by installing a platinum catalyst bed in the oxygen stream downstream of the module's oxygen outlet.
4. Increased torquing of the module allows operation at higher pressures.
5. As of the conclusion of this project's funding cycle, we have achieved our 2,000 psig objective and a maximum hydrogen delivery rate of 0.3 slm per cell. This electrolyzer design would achieve our 3 slm delivery objective if expanded to a 10-cell stack format. However, given the numerous iterations in material selection required to arrive at a satisfactory single-cell design, project funding proved insufficient to construct a multi-cell stack of this size.

Conclusions

Through this Commission-funded project, we were able to identify a combination of materials and fabricate electrolyzer module components that form the basis of a high-performance hydrogen generator with great commercial potential. We were able to meet our output pressure goal of 2,000 psig in sustained single-cell tests. While time and cost constraints did not allow us to meet our goal of 3 slm hydrogen output using a multi-cell module, our results indicate that this goal is achievable simply by fabricating additional cells, increasing the total number of cells in the module to fourteen (based on current per-cell performance). With expected improvements in cell performance, we anticipate achieving 3 slm output with a 10-cell module.

Based on electrolyzer cell efficiency, our design appears to offer a significant total energy efficiency advantage over an alkaline electrolyzer/mechanical compressor combination. This performance advantage could help to make small, decentralized hydrogen generation systems for vehicular fueling and stationary and portable fuel cell power plants economically feasible.

Recommendations

In completing this project, we would like to make the following recommendations to the Commission regarding continuation of research and development in this area:

1. Laboratory research should continue, using a larger number of cells to increase gas output to commercially useful volumes.
2. Efforts should continue to increase the working pressure of the electrolyzer.
3. Longer term bench tests should be conducted to determine the ultimate longevity of the module design.
4. Research should continue to identify less costly but suitable diffuser materials for use in the module.

Public Benefits to California

Our work supports the PIER program's goal to "provide public value for the benefit of California and its citizens through the development of technologies which will improve environmental quality, enhance system reliability, increase efficiency of energy-using technologies, lower system costs, or provide other tangible benefits." The project can improve environmental quality by helping clean hydrogen energy to displace more polluting existing energy technologies. It will enhance system reliability by allowing energy users to generate hydrogen for on-site use as a distributed generation and backup power fuel. The project also offers a business opportunity to California companies in manufacturing and marketing SERC's PEM electrolyzer technology.

Development Stage Assessment

The EISG document "Stages and Gates Process" defines eight stage-gate pairs that make up the process of an EISG-funded research and development project, from concept to commercialization. Theoretically, a project will have completed stages 1 and 2 (idea generation, technical and market analysis) before being awarded EISG funds.

Table 1 is a matrix illustrating SERC's progress in completing activities within each of the eight stages of our PEM electrolyzer project as of the end of our EISG funding period. We largely dedicated our time and funding to the resolution of engineering and technical challenges during our EISG-funded work phase. Market research, establishment of intellectual property rights, and pursuit of commercialization opportunities have mainly been deferred to a later date, when we hope to have proven the durability and practicality of our design worthy of commercialization.

Table 1. Stages and Gates Matrix

Stages / Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop-ment	5 Product Develop-ment	6 Demon-stration	7 Market Transfor-mation	8 Commer-cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/								
Public Benefits/ Cost								

Each of the seven activity areas now stands at stage 3, with the exception of Technology Development, which has advanced to stage 4. The status of each activity area is summarized briefly below.

Marketing: No formal market study has been performed. Through our longstanding involvement in the hydrogen and renewable energy technical communities, we are aware of a general need for a safe, energy-efficient means of producing high pressure hydrogen. No manufacturer has yet brought such a product to market. In the U.S., Proton Energy Systems has developed and tested prototypes, registered patents, and issued news releases stating their intention to commercialize their high pressure PEM electrolyzer product. Belgian company Vandenborre Technologies has likewise had a high pressure non-PEM (liquid electrolyte) electrolyzer patent recently issued in the U.S. and already offers for sale an intermediate pressure (375 psig) unit. A market study and preliminary business plan are justified at this stage of the project.

Engineering/Technical: This has been our chief area of advance under EISG funding. We have progressed from concept through detailed design; materials testing, specification and acquisition; fabrication of a test station and single-cell and multi-cell electrolyzer modules; and extended laboratory testing. We have undergone multiple iterations of redesign and retesting to approach our project goal of generating 3 slm of hydrogen at a pressure of 2,000 psig. This activity area should continue progressing in stage 4 (technology development).

Risk Assessment/Quality Plans: Direct environmental risks associated with generation of high-pressure hydrogen as a fuel are probably negligible. Indirect environmental risks may exist depending on the primary energy sources used to provide the electricity needed to power the electrolyzer. If the electrolyzer is powered using renewable energy resources, it is likely the environmental impact per unit of energy generated and stored will be substantially less than the impacts associated with conventional energy production.

Safety hazards associated with operation of a high pressure PEM electrolyzer include high pressure gas accidents, fire, and electric shock. SERC has safety policies and procedures and an in-house training program in collaboration with Humboldt State University's Environmental Health and Safety department to manage these risks. There have been no serious accidents or safety mishaps in SERC's 14-year history. Component design and materials selection are carried out with safety in mind and in accord with codes and standards promulgated by the Compressed Gas Association, the National Fire Protection Agency, and other institutions in order to ensure that the prototype electrolyzer and any commercial version subsequently developed are as safe as possible to operate. As SERC advances this project from laboratory benchtop testing to our first field trials, we will develop a product quality plan that will include product-specific analyses of reliability, failure mode, manufacturability, cost, maintainability, and hazards.

Strategic: This project has the potential to support the objectives of three PIER program areas: Renewable Energy Technologies, Environmentally-Preferred Advanced Generation (EPAG), and Energy Systems Integration (ESI). No other project being supported at this time by PIER or EISG conflicts with or is redundant with SERC's electrolyzer development project.

- Cost-effective hydrogen generation would support PIER's Renewable Energy Technologies program area by enabling storage of intermittently available renewable energy.
- Hydrogen generated using the high pressure PEM electrolyzer could be used in fuel cells, a technology emphasized in PIER's EPAG program area. PIER's current online list of contracted projects includes several fuel cell-related projects that could benefit from integration with the efficient, high performance electrolyzer being developed by SERC. Full development and subsequent commercialization of this technology could boost the long-term economic and technical feasibility of any hydrogen-using technologies being developed with PIER support.
- Hydrogen generation has great potential as an energy storage technology for grid applications, identified as a topic of interest within PIER's ESI program area.

Production Readiness: Schatz Energy Research Center administration have communicated with corporate vendors of electrolyzers who have expressed interested in licensing our design.

Public Benefits/Cost: Our work supports the PIER program's goal to "provide public value for the benefit of California and its citizens through the development of technologies which will improve environmental quality, enhance system reliability, increase efficiency of energy-using technologies, lower system costs, or provide other tangible benefits." The project can improve environmental quality by helping clean hydrogen energy to displace more polluting existing energy technologies. It will enhance system reliability by allowing energy users to generate hydrogen for on-site use as a distributed generation and backup power fuel. The project also offers a business opportunity to California companies in manufacturing and marketing SERC's PEM electrolyzer technology.

Endnotes

Glossary

Cell: Individual electrolysis unit, consisting of membrane electrode assembly, diffuser discs, gaskets, and containment of these components in the form of end plates and/or bipolar separator plates, equipped with channels for reactants and products to enter and leave the cell.
Diffuser: Material in contact with proton exchange membrane, used to simultaneously deliver and distribute reactants to membrane surface, remove products, conduct electricity to reaction site, and physically support the membrane against a high pressure differential.
Electrolyzer: Device used to electrochemically divide water into its constituent elements, oxygen and hydrogen.
HSUF: Humboldt State University Foundation, the Schatz Energy Research Center's parent organization and a 501(c)3 non-profit corporation affiliated with Humboldt State University in Arcata, CA.
MEA: membrane electrode assembly, consisting of the proton exchange membrane, a catalyst coating, and in many cases an inactive gasket material on which the active membrane material is mounted.
Module: A complete electrolysis unit, which may consist of a single cell or a stack of cells.
PEM: proton exchange membrane, a transparent membrane material made from DuPont Nafion or a like material, impervious to water, hydrogen and oxygen and electrically nonconductive, but capable of transporting hydrogen protons.
psig: pounds per square inch gauge, a unit of pressure used to indicate the differential between measured pressure and atmospheric (ambient) pressure.
SERC: Schatz Energy Research Center.
slm: standard liters per minute, a unit of gas flow normalized for pressure and temperature.
Stack: A group of adjacent electrolysis cells, arranged in electrical series such that the sum of electrical potentials across each cell is equal to the total electrical potential applied to the stack.

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