Alkaline Electrolysis
Final Technical Report

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General Electric Global Research Center
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Contents

Executive Summary 3

Project Goals and Technical Barriers 4

Technical Target and Results Summary 5

Summary of Products 6

Project Results 7

- Task 1: Quantify Market Requirements 7
- Task 2: Preliminary System Design and Lab Development 8
- Task 3: Electrochemical Cell Engineering Analysis 11
- Task 4: Bench Scale System Engineering 16
- Task 5: Bench Scale System Testing 17
- Task 6: Education and Outreach 19
- Task 7: Sensor Development 19
- Task 8: Conceptual Development of a Power Park Installation 20

Scaleup for Project Continuation 22

Appendix 1: Conceptual Design Report (Task 8)
Appendix 2: Sensor Development Publications (Task 7)

Executive Summary

Hydrogen is an attractive fuel for mobile and stationary applications because it generates only water when reacted. However, many methods of producing hydrogen generate CO_2 and other emissions. One way to produce hydrogen with no emissions is to electrolyze water. If the electricity source used to power the electrolyzer does not generate CO_2, then the entire cycle of energy production and consumption can be free of greenhouse gas generation.

To date, electrolysis has not been the preferred method for large scale hydrogen production because it is more costly than reforming. Costs for electrolysis hydrogen are typically over $8 per kilogram, while hydrogen made by large scale steam methane reformers may cost less than $2 per kilogram. A key aspect of the Department of Energy’s HFCIT (Hydrogen Fuel Cell Infrastructure Technology) program is to make the environmental benefits of electrolysis hydrogen possible by reducing the price of electrolysis hydrogen to under $3 per kg.

In this project, GE developed electrolyzer stack technologies to meet DOE’s goals for low cost electrolysis hydrogen. The main barrier to meeting the targets for electrolyzer cost was in stack assembly and construction. GE’s invention of a single piece or “monolithic” plastic electrolyzer stack reduces these costs considerably. In addition, GE developed low cost cell electrodes using a novel application of metal spray coating technology. Bench scale stack testing and cost modeling indicates that the DOE targets for stack capital cost and efficiency can be met by full-scale production of industrial electrolyzers incorporating GE’s stack technology innovations. A multicell monolithic plastic stack was demonstrated to DOE HFCIT Production Team leader Peter Devlin on 15 April 2005. This 5-cell operating stack and system exceeds the specified project goal of a 3-cell bench scale stack.

Utility customers, for whom capital cost is the primary driver of hydrogen cost, have been identified as early adopters of the technology. The GE research team quantified the performance targets necessary to meet the needs of these customers and developed a strategy to meet these needs at capital cost targets consistent with the hydrogen cost goals set by DOE. Achieving these capital cost targets is also critical for meeting the needs of the distributed and central hydrogen production scenarios detailed by the H2A program.

Project Goals

The overall goal of the DOE HFCIT program is to accelerate the development and successful market introduction of hydrogen production, delivery and storage technologies.

The main goal of GE's Alkaline Electrolysis project was to develop a technology concept with entitlement to meet DOE cost targets for hydrogen production. At the beginning of the project this target was a projected cost of $2 per kilogram of hydrogen: in 2005 the target was revised to $2.85 per kilogram.

Technical Barriers

This project addresses the following technical barriers from section 3.1.4.2.4 of the Hydrogen, Fuel Cells, and Infrastructure Technologies Program Multi-Year Development and Demonstration Plan:

Q. Capital Cost of Electrolysis Systems
T. Renewable Integration

Technical Targets

Table 1 lists the relevant technical targets which flow down from the overall DOE goal of $2.85 / kg for distributed hydrogen. Costs per kilogram H2 were evaluated based on the H2A Forecourt Generation model assumptions.

			2010 DOE Target	2005 Status	2010 Projected Capability	Notes
Cell Stack	Efficiency	% (voltage)	76% (1.6V)	76% (1.6V)	76% (1.6V)	Electrodes demonstrated acceptable current density to meet stack cost targets.
Cell Stack	Cost	\$ / kg H_2	$0.39	$0.60	$0.35	2005 cost based on full production scaleup of bench scale stack. 2010 capability based on material entitlement.
Electricity (System)	Cost	\$ / kg H_2	$1.89	$2.63 (52.6 kWh/kg)	$2.20 (44 kWh/kg)	Industrial rate of 5 cents/ kWh assumed. Lower cost electricity is required to meet this target with alkaline electrolysis.
O&M	Cost	\$ / kg H_2	$0.38	$0.81	see notes	Maintenance cost projection is part of the scope of the continuation project.

Table 1: Performance to Technical Targets

Summary of Products

Multiple products were generated in the course of this work including:

Technologies & Techniques

- Plastic monolithic stack design
- Large high-surface electrode manufacturing method
- High-performance electrode composition
- Electrochemical CFD modeling of large electrolysis cells in 3D

Publications

- Zhou, Z. and Carpenter, M.A. :"Annealing Advanced Hydrogen Absorption in Nanocrystalline Pd/Au Sensing Films"; Journal of Applied Physics 97, 124301 (2005)
- Zhou, Z *et. al*: "All Optical Hydrogen Sensor Based On a High Alloy Content Palladium Thin Film"; Sensors and Actuators B, March 2005

Patent Applications

- Patent Pending: Monolithic Multicell Electrolysis Stack

Other Products

- Capital and energy cost estimates for novel electrolyzer stacks
- Conceptual Design Report for a power park installation
- Conceptual Design drawings
- 3D Virtual Tour of vehicle service area concept

Approach

Project tasks were set to meet this overall goal:

1) Research early adopter and long-term markets to determine customer requirements for an electrolyzer product.
2) Develop a technical strategy and create a preliminary design capable of meeting the customer needs and the DOE cost goals.
3) Engineer and analyze electrochemical cell materials and configurations capable of meeting the performance and cost goals
4) Build a bench-scale electrolysis system of at least 3 cells in order to demonstrate proof of the low cost electrolyzer technical concept
5) Test the bench scale system and predict product performance and cost of hydrogen based on the results.

Additional tasks were set in anticipation of demonstrating the new electrolyzer technology at a vehicle fueling station incorporating local power generation:

6) Prepare an education and outreach capacity for the demonstration site.
7) Develop a novel hydrogen safety sensor for the automotive fueling application.
8) Prepare conceptual designs for turnkey hydrogen vehicle fueling or hydrogen-fueled electrical power generation facilities.

Project Results by Task

Task 1: QUANTIFY MARKET REQUIREMENTS

Goal: Identify target size and product specifications that satisfy customer requirements.

Accomplishment Summary: Market requirements for early adopters of hydrogen electrolyzers were determined in Q42004.

Accomplishment Details:

The primary commercial interest in electrolyzers at the start of the project was from power utilities seeking to fully utilize power generation, transmission, and distribution assets during periods of low consumer demand. Since excess wholesale electricity is inexpensive, the primary requirement for the utility customer is low capital cost.

Low maintenance costs are also important in keeping the cost of hydrogen down. The product specification for a utility customer will therefore include requirements for unattended operation with dispatch from a central location and limited planned maintenance.

Recently, GE has entered discussions with industrial hydrogen producers. There is potential for electrolysis hydrogen to displace SMR (Steam Methane Reforming) hydrogen in central generation applications as electrolysis costs come down and natural gas prices continue to rise.

The end use of the electrolyzed hydrogen determines the target product sizes. Potentials for end uses are:

Generator cooling hydrogen makeup skid:	1 kg H2/hr
Power parks, small renewable firming, fleet refueling:	5 kg H2/hr
H2A Forecourt, Grid substation energy storage:	20-800 kg H2/hr
Central-Scale Hydrogen Production	1000 - 6000 kg H2/hr and larger

As we gather further information about the market for large commercial electrolyzers we will seek demonstration opportunities aligned with developing the right technology for that market. Based on the needs of the early adopter industrial customers, we are developing a product prototype at the 1-5 kg/hr scale that embodies the technologies needed to manufacture modular building block stacks for larger systems. The product prototype will be designed in accordance with the priorities of low capital cost and minimal maintenance costs.

TASK 2: PRELIMINARY SYSTEM DESIGN AND LABORATORY DEVELOPMENT

Goals:

- Determine cost structure for electrolysis equipment
- Identify opportunities for cost reduction
- Devise cost reduction strategy
- Develop cell tests capable of testing range of concept materials, operating conditions, and geometry
- Carry out jugular experiments to validate concepts to reach performance and cost goals.

Accomplishment Summary:

Current and target costs for the electrolyzer stack and balance of plant have been specified. Our research indicates that the best strategy consistent with our intended market is to reduce stack cost with a technology and design solution while taking advantage of economies of scale and volume to reduce system costs. Cell tests have confirmed the entitlement of our cell materials to reach the performance targets that will achieve the stack cost goals.

Accomplishment Details:

The cost of produced hydrogen is comprised of capital, energy, and maintenance costs. If electricity is available at low cost, the sensitivity of total hydrogen cost to improvements in efficiency is not great. In addition, there is a limit to the reduction in energy costs because the conversion efficiency cannot be greater than 100%. Therefore, we chose to concentrate our efforts on a dramatic reduction in capital cost. In the current market, the cost of either the electrolyzer stack or the balance of system equipment alone is too high to reach the target of $2.85/kg. GE is addressing these two costs in different ways. Our research indicates that, based on the relative entitlements of the stack and system capital costs, the best strategy consistent with our intended market is to reduce stack cost with a technology and design solution while taking advantage of economies of scale and volume to reduce system costs. The resulting numerical targets determined at the beginning of the project are shown in Table 2:

	$/ kg H2	Assumptions
energy	$0.72	1.5 cents / kWh off–peak electricity
amortized capital (stack and system)	$1.74	0.5 capacity factor, 1500 kg/day plant
maintenance	$0.20	unattended operation
TOTAL	$2.66	

Table 2: Initial (April 2004) Cost of Hydrogen Targets, Off-Peak Scenario

Capital costs here include installed costs of the electrolyzer system, compression, and storage hardware. Using a simple financial model, we determined that the capital cost target could be met if the stack cost were reduced to approximately $10,000 per kilogram H2/hr production capacity. This target stack cost proved to be consistent with DOE targets when we analyzed them using the H2A model for forecourt production later in the project.

A major component of electrolyzer stack cost is the stack structural materials and assembly labor. Taking advantage of GE’s advanced materials capability we have invented a low cost electrolyzer stack which eliminates the cost and complexity of the traditional assembly of the cells with bolts and insulating gaskets. The GE stack module is constructed by assembling multiple cells into a single non-conductive plastic frame, which also provides for internal liquid and gas passages. The frame may be constructed from individual plastic components by various joining methods or in one piece by a molding or casting process. A patent application on this concept was filed on April 12, 2005 with the US Patent & Trademark Office.

An additional stack cost reduction comes from the development of a low-cost technique for manufacturing electrodes. We leveraged established GE metal coating technology to produce structured, high surface area, low-cost electrodes through wire-arc spraying of nickel and catalyst material on a base metal substrate (Figure 1). Single cell testing determined an optimal material composition that would meet the performance and cost requirements of the product electrolyzer stack.

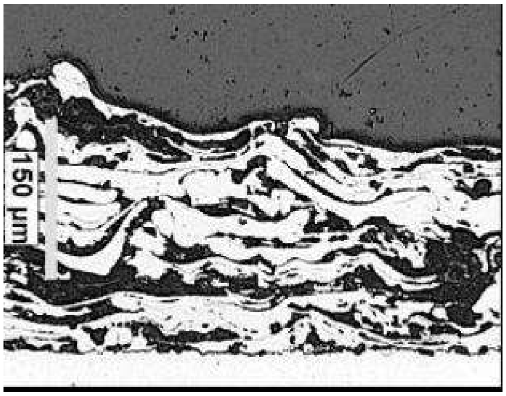


Figure 1: Cross-section micrograph, high surface area electrode

Current density in an electrolysis cell increases as voltage increases. Cell efficiency is a function of the cell voltage and hydrogen production rate is directly proportional to current density. The cost of hydrogen due to capital cost is inversely proportional to current density: the smaller the stack, the less expensive it is. Cost of hydrogen due to energy consumption is of course proportional to efficiency. Therefore, for any cost of electricity and given a function relating stack cost to current density, one can find an optimal cell voltage that minimizes the total cost of hydrogen due to energy and capital costs. We developed such a model and used it to find the optimal operating point as shown in Figure 2. In our early analysis the target stack efficiency was set to 68%, comparatively low because of the assumption of low cost wholesale power.

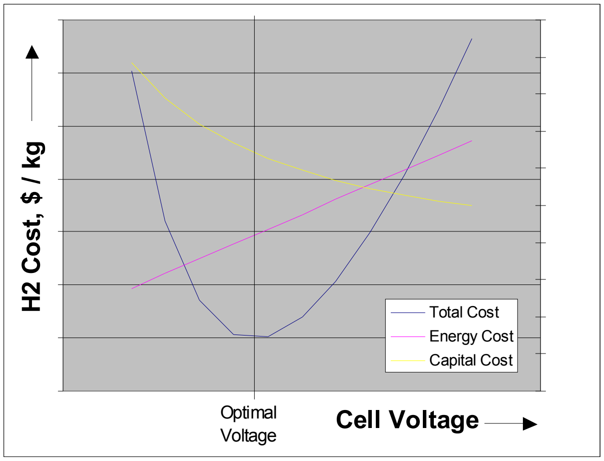


Figure 2: Selection of Lowest Cost Operating Voltage

Later in the project we re-evaluated the top-level targets for energy, capital and maintenance costs to be consistent with the H2A model assumptions released in May, 2005. We found that our initial stack cost target of \$10,000 per kgh^{-1} capacity would meet the DOE stack cost goal of \$0.39 / kg H2. The H2A Forecourt Model assumption of a \$0.05/kWh industrial electricity rate, however, changes the optimal stack efficiency for lowest cost hydrogen to approximately 76%.

With respect to the balance of system costs, we have studied the projected costs of equipment such as compressors, water treatment systems and storage tanks. By taking advantage of economies of scale for systems in the 20-800 kg/hr scale the costs of the balance of system can be reduced to a level consistent with the overall cost of hydrogen target. System optimization for low cost, as well as O&M cost estimation, is a feature of the proposed continuation project.

TASK 3: ELECTROCHEMICAL CELL ENGINEERING ANALYSIS

Goals: Explore the potential for advancing the performance of electrochemical cells through attention to the following topics:

- electrode materials
- electrolyte development
- diaphragm development
- cell geometry configuration
- stack materials

Accomplishment Summary:

An electrode composition and production method with entitlement for target cost and performance has been validated. Advanced electrolyte solutions incorporating dissolved electrocatalysts were tested in the laboratory flow cells. An electrochemical CFD tool was developed to study the effects of electrolyte flow rate and optimize cell geometry for efficient bubble removal. Potential stack materials were evaluated for durability under operating conditions.

Accomplishment Details:

Electrode Materials

The relationship between current and voltage in an electrochemical cell is a good indicator of its performance. The thermodynamic minimum voltage required to split water into hydrogen and oxygen at 25^{o}C and 1atm is 1.23V, and the value under other conditions is described by the Nernst equation. The rate of hydrogen production is directly proportional to the current, and to produce hydrogen at rates of industrial interest a higher voltage must be applied to the cell. The excess voltage is determined by the overpotentials of the anode and the cathode, the electrical resistance of the solution and the electrical resistance across the membrane. The electrode overpotentials can be estimated from Tafel plots, which describe the current / potential relationship for specific electrode materials.

The excess voltage increases the power consumption of the stack and reduces its efficiency. The efficiency can be determined by the ratio of the thermodynamic voltage to the voltage necessary to achieve the required production rate. Typical alkaline electrolyzers operate at 1.8 to 2.6V, which translate to cell efficiencies of 68% and 45% respectively.

To reduce the overall cost of hydrogen we developed electrode materials that can be manufactured at low cost and maintain high efficiency in high current density operation.

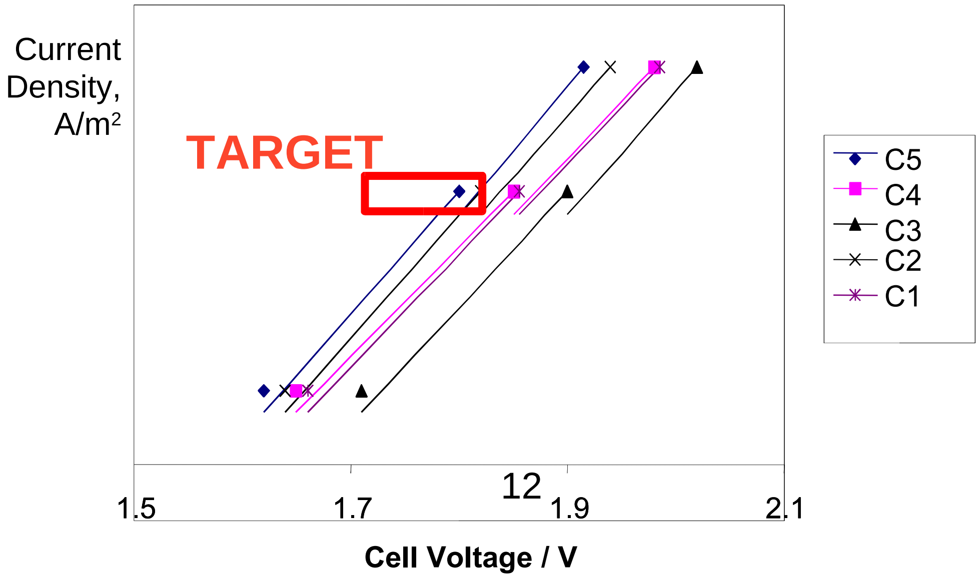


Figure 3 Figure 3: Electrode Composition Testing shows a comparison between several electrodes of differing composition made by depositing an active layer on a base metal substrate. The active layer requires no precious metal catalysts and in full-scale production its cost will approach that of the base materials bulk costs. The performance benefit comes from the deposition method and resulting microstructure, which results in an extremely high effective surface area. The target current density plotted in Figure 3 is set by the cost requirements as outlined under Task 2 and Task 6. The actual number is business confidential and may be obtained by contacting the Principal Investigator directly. The C5 composition achieves the required current density at a voltage consistent with the energy cost targets.

Accelerated life testing methods will be used to confirm the suitability of the improved electrodes for long-term, low maintenance operation. Factors affecting the final composition and structure of the electrode will include corrosion potential and material stability under constant current loading and on-off cycles.

Electrolyte Development

Performance effects of cobalt and molybdenum activators in the electrolyte were studied. The cathode overpotential was reduced by up to 12% on nickel electrodes at low current densities, showing a potential for similar reductions in energy costs. However, the additives are consumed as the cell operates and when they are gone the overpotential returns to its original value. Due to the transient nature of the effect and the low sensitivity of hydrogen cost to energy cost in our model, we have elected not to pursue the development of advanced electrolytes at this time.

Diaphragm Development

A literature study identified several non-asbestos diaphragm materials for study. Ceramic materials such as those based on nickel oxides or metal titanates have low specific resistance but tend to be unstable as they reduce in the presence of hydrogen. Challenges for polymer membranes include poor wettability, the risk of puncture if contacted by a metal electrode, and the possibility for gas bubble crossover through pores. We tested various polymer diaphragms in operating cells to determine impedance and in pressure hold tests to determine the maximum differential pressure before gas crossover. From these studies we downselected a commercially available diaphragm material and specified a thickness and pore size. This diaphragm was used successfully in the bench scale electrolyzer system test, meeting cell performance requirements and demonstrating low gas crossover as measured by hydrogen purity measurements.

Cell Geometry Configuration

For the electrolyzer to operate well, water and electrolyte must be distributed evenly along the electrode surfaces while oxygen and hydrogen gas is carried out of the cell.

Bubbles on the electrode reduce active reaction area, and the presence of bubbles also decreases the effective electric conductivity of the electrolyte by reducing the cross-sectional area of pure electrolyte available for current transport. This is a complicated and non-linear physical situation, which the model has successfully predicted. [Figure 4]

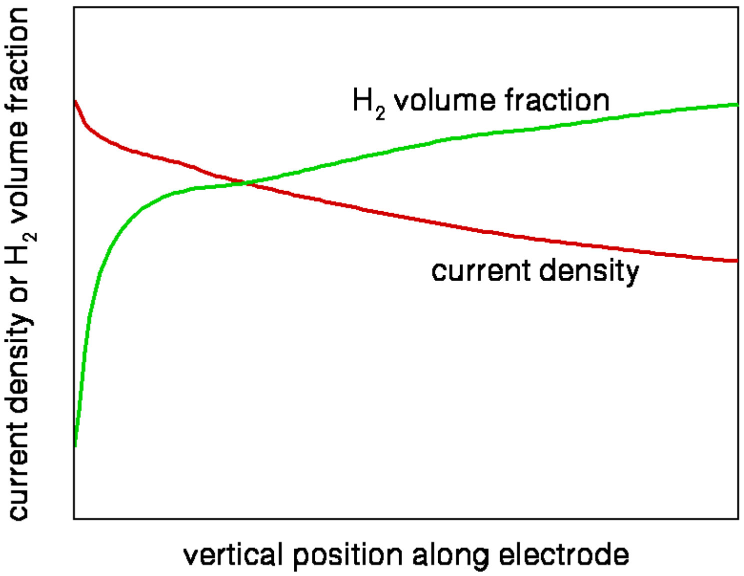


Figure 4: Effect of evolved H2 on local current density

In order to optimize the cell design for fluid flow we are developing analytical models that predict both gas and liquid distributions as gas is formed at the electrode surface and liquid flows through the cell. The basis of the model is the commercial computational fluid dynamics (CFD) code Fluent 6.1, to which we have added user-defined functions based on a first principle understanding of the two-phase flow and the electrochemical reactions.

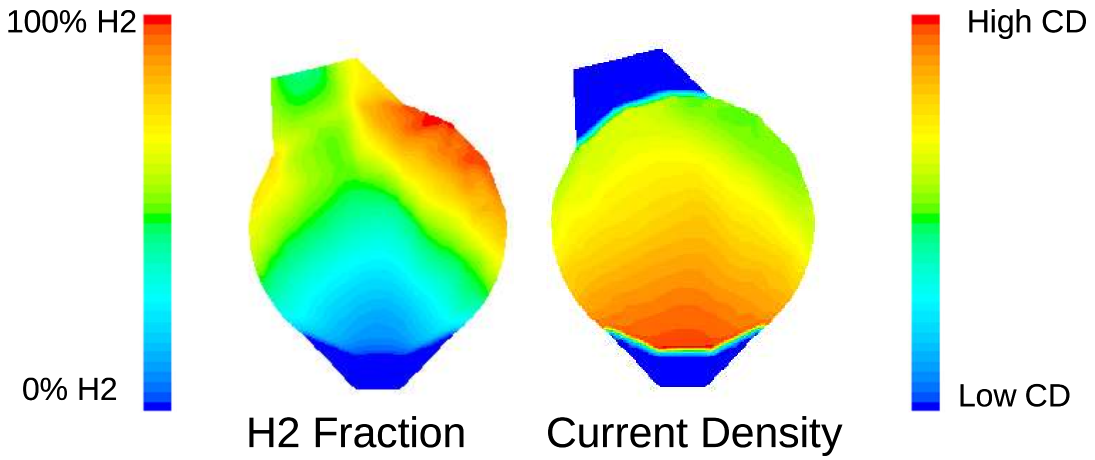
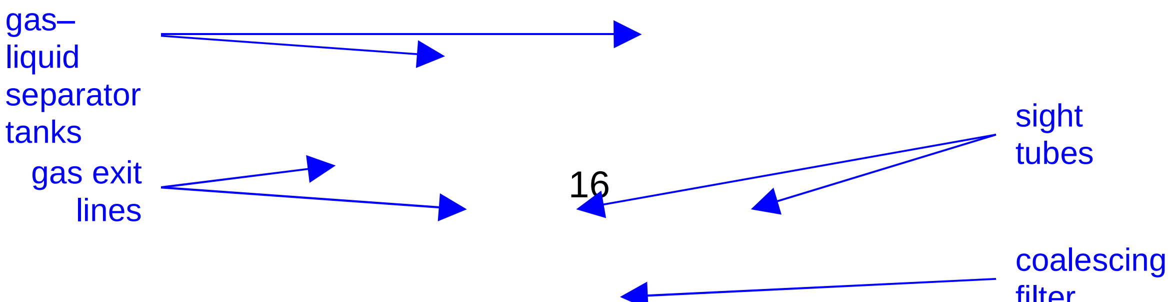


Figure 5: Cell CFD Results

In the 4Q2004 the model was expanded from 2D to 3D. This model will be used to optimize the shape and geometry of large cells necessary to make cost effective electrolyzer stacks in the megawatt size range needed for utility applications. Figure 5 shows the effect of bubble generation on current density in the baseline case of a large (.5 m^2) round cell. The maximum current density is near the entrance at the bottom of the cell, where the hydrogen concentration is lowest. The minimum current density is near the top of the cell on the side opposite the exit, where hydrogen bubbles have accumulated.

Structural Materials

The plastic housing for the stack will be required to resist the exposure to hot alkaline solution over the lifetime of the stack. The primary mechanical stress on the housing will be due to the internal stack pressure, which depending on the end use application may be as high as 30 bar. We tested several polymers supplied by GE Advanced Materials. The polymer Noryl™ retained its mechanical properties after 4 weeks of accelerated testing at high temperatures in alkaline solution. This material is also highly formable and is suitable for the assembly methods that are the key element of our low cost stack strategy.



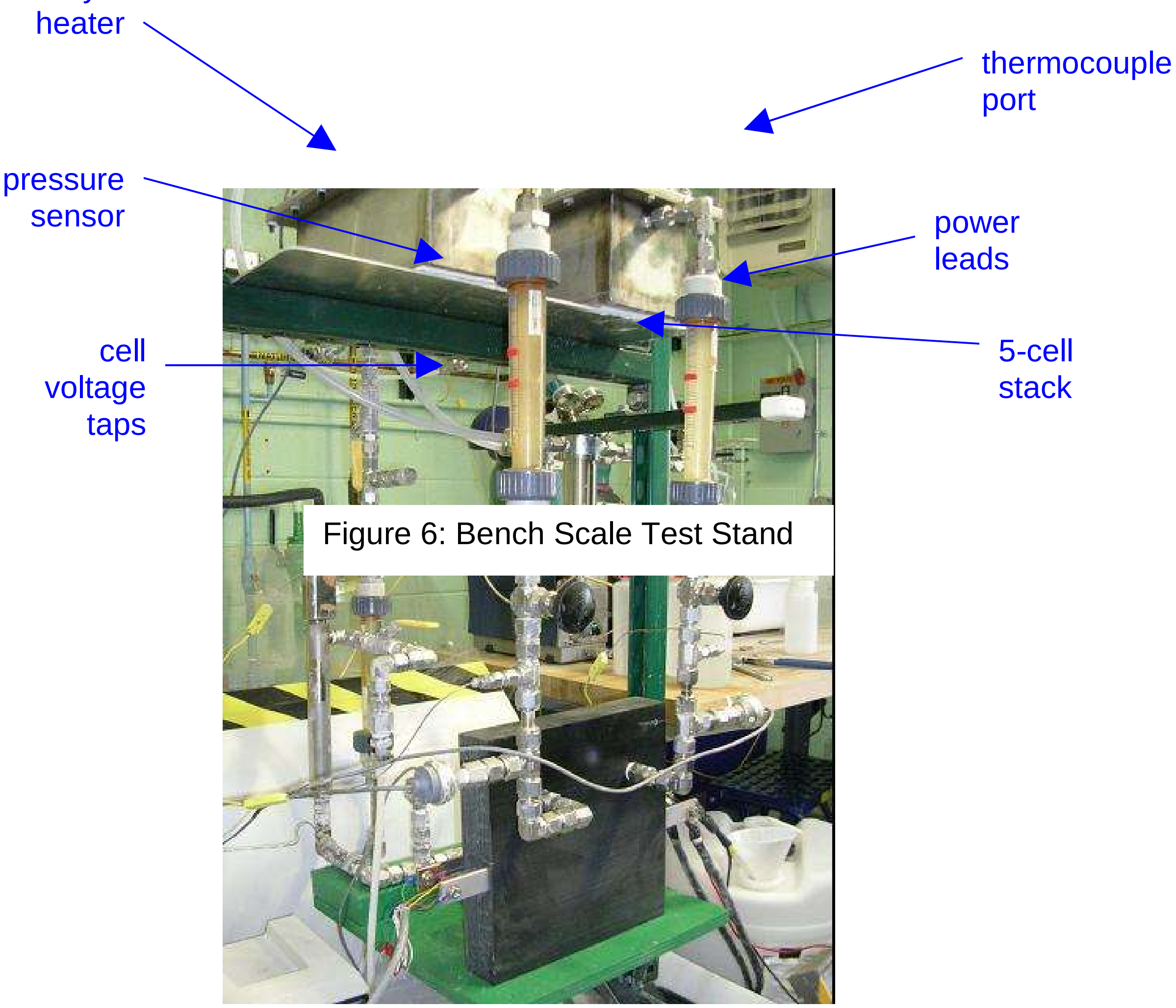


Figure 6: Bench Scale Test Stand

TASK 4: BENCH SCALE SYSTEM ENGINEERING

Goals: Design and construct a bench scale electrolysis stack to validate the low cost concept. The system is to consist of:

- Stack with minimum 3 cells
- Power conversion equipment
- Water handling and treatment equipment
- Necessary balance of plant and control systems

Accomplishment Summary:

Three five cell stacks embodying the novel GE monolithic plastic stack invention have been built and tested. The test system includes a 50A DC power supply, an electrolyte heater, gas separators and dryers, pressure and temperature sensors, control and monitoring software, and an off-line gas chromatograph. The bench scale system does not include on-line water handling or active cooling, as the scale of the system is too small to demonstrate these subsystems effectively.

Accomplishment Details:

Our design concept for low cost manufacturing has been proven by tests on a stack of five cells embodying the monolithic plastic design described earlier. Construction costs for this first unit stack show entitlement to reach the aggressive targets we have set for full scale production. The test stand pictured in Figure 6 is capable of measuring hydrogen flow rate, temperatures and pressures at various points, and evolved gas compositions by means of an online micro GC (gas chromatograph). The stack operates at ambient pressure and the gases are released to atmosphere.

TASK 5: BENCH SCALE SYSTEM TESTING

Goals: Demonstrate bench scale electrolyzer stack. Confirm entitlement to reach DOE targets for cost of hydrogen, capital cost, and system efficiency.

Accomplishment Summary:

Performance targets set based on the goals for cost of electrolyzed hydrogen were reached in the bench scale test stack. The bench scale testing also confirms the operability of the low cost monolithic stack concept, which at appropriate scale and production volume will meet the capital cost targets. The bench scale system has proven operable over a wide range of input voltages, and can be operated in a high efficiency mode.

Accomplishment Details:

The energy cost is primarily a function of system efficiency, which can be demonstrated in the bench scale system. Since they rely on economies of scale, achievement of the capital cost targets cannot be demonstrated directly by the bench scale system. The model we have developed applies the fully realized manufacturing costs including materials, specialized tooling and labor to find the amortized cost per kilogram of hydrogen produced over the life of the electrolysis system. The detailed assumptions include business confidential information, and may be requested by contacting the Principal Investigator directly.

The marketing study performed under Task 1 determined that the off-peak generation scenario of Table 2 was appropriate for early adopter customers. In other applications power at 1.5 cents / kWh may not be available. For example, the DOE Forecourt model assumes retail industrial electricity at a rate of 5 cents / kWh.

Based on the targets and the specific cost ($\$/m^2$) of the electrolyzer, our cost model further specifies a target current density that must be reached at a voltage consistent with the energy cost budget. The target varies with the cost of electricity: as explained in the results of Task 2, the optimal current density and voltage for lowest cost hydrogen tend to decrease as the cost of electricity increases.

Tests have concluded on 5-cell stacks with electrodes comparable to “Electrode C4” and “Electrode C5” of Figure 4. Gas purity as measured by the micro GC is acceptable for safe compression, storage and use. Stack performance is stable and linear over a wide range of cell operating voltages as shown in Figure 7. The “target zone” on the graph represents the approximate range of optimal current density / voltage performance consistent with meeting low cost of hydrogen targets over a range of possible electricity costs. For reference, the target cell efficiency for the wholesale off-peak electricity price assumption is 68%. The target cell efficiency to meet DOE cost requirements with the H2A Forecourt assumptions is 76%. In Figure 7, the actual current densities are business confidential and are therefore plotted without scale.

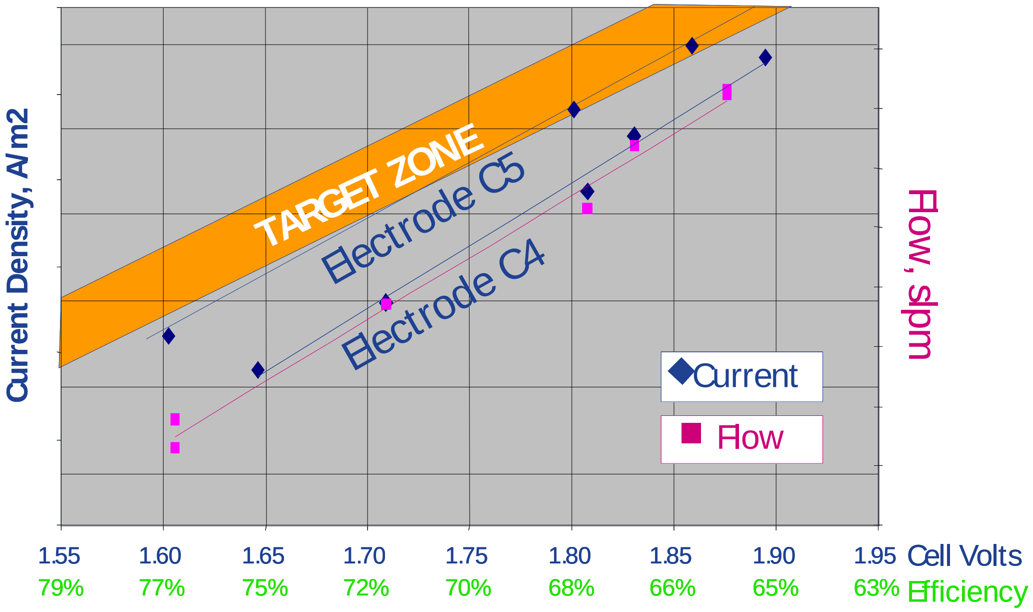


Figure 7: 5-Cell Stack Performance

The 5-cell stack with the “C5” electrode performed almost as well as the single cell test, and achieved current densities within the target zone for most of the operating range. It is to be expected that a stack of electrodes underperforms a single electrode, since the series electrical connection between electrodes forces all electrodes to operate at the current density of the least active cell. Further work on manufacturing variation between electrodes can improve stacked electrode performance. Additional catalysts and improvements to the deposition technique may also improve current density / voltage performance.

Hydrogen output rate should be directly proportional to the input current. On the graph of Figure 7, the blue line represents input current as a function of average cell voltage and the red line represents measured hydrogen output flow as a function of the voltage. The two axes are scaled such that if the input current is fully utilized in the stack to make hydrogen, the current and flow points would be coincident. Nearly 100% of the current is making hydrogen through the entire operable range of 1.6 to 2.0 volts per cell. This indicates that shunt current losses and current collection and distribution losses are minimal. The remaining inefficiency is accounted for by the small amount of hydrogen crossing the diaphragm to the oxygen side, which is within the specification limits.

The actual cost of constructing the bench scale test stack is estimated at $3200, or approximately $6400/kW. It should be expected that this is much higher than the target for fully realized manufacturing as this stack was hand-built and is several orders of magnitude smaller than the stack envisioned to meet the $2.85/kg target.

Based on the successful operation of the bench scale stacks and the achievement of the performance goals specified by our cost modeling, we are confident that our stack and system concept will meet the $2.85/kg goal at an appropriate scale and production volume.

TASK 6: EDUCATION AND OUTREACH

This task was originally planned to develop an education and outreach capability at a New York State hydrogen demonstration site. When the demonstration was not funded, the task was redirected to encompass technical analysis, planning, and business acceleration in New York State. In May 2006 we determined that the revised task was not required to meet the overall technical goals of the program and this task was cancelled. After discussion with the DOE Project Manager, additional work on bench scale testing was performed in lieu of this activity as described in Task 5.

TASK 7: SENSOR DEVELOPMENT

Goals for 2004 were to complete the reliability measurements of the low temperature hydrogen sensor and an analysis of sensitivity measurements in the presence of air, CO, and background humidity. This work by SUNY Nanotech is complete and a manuscript detailing the results was accepted for publication by *Sensors and Actuators B* in March 2005. SUNY Nanotech also completed initial measurements and analysis of data for the high temperature hydrogen sensor based on YSZ-Pd/PdO. A manuscript reporting on this work was accepted for publication by the Journal of Applied Physics in April 2005.

The complete articles are appended to this report.

TASK 8: CONCEPTUAL DEVELOPMENT

Goals: Prepare a Conceptual Design Report including drawings, overviews of relevant codes and standards, and a video “virtual tour” of a proposed hydrogen power park demonstration site.

Accomplishment Summary: The Conceptual Design Report was assembled, including its appendices, the drawing package, and the 3-D Virtual Tour video. The Report was reviewed within GE Global Research, using an overview Power Point presentation that is included as an appendix in the full report.

Accomplishment Details:

The Conceptual Design document prepared under this contract focuses on key planning considerations required to develop turnkey hydrogen vehicle refueling or hydrogen fueled electrical generation facilities. It provides a hydrogen vehicle refueling and hydrogen fueled electrical generation reference conceptual design. The Conceptual Design document is intended to provide a starting point for future development of these types of facilities as well as a basis of design for engineering and planning purposes. Furthermore, it is an excellent tool for education and detailed information dissemination in support of furthering the objectives of hydrogen technology and application advancement. In support of these objectives, a 3-D virtual tour illustrating how these conceptual designs could be applied to a highway service facility will be provided.

The Conceptual Design Report was assembled, including its’ appendices, the drawing package, and the 3-D Virtual Tour video. The report was reviewed within GE Global Research, using an overview Power Point presentation that is included as an appendix in the full report.

The Table of Contents for the Report includes the following sections for both a refueling system installation, and a stationary energy storage and power generation installation:

- a. System Overview
- b. Major Components
  - i. Hydrogen Generation
  - ii. Hydrogen Compression
  - iii. Hydrogen Storage
  - iv. Hydrogen Dispenser (or H2-ICE as appropriate)
  - v. System Instrumentation and Controls
- c. Standard Design Configuration and Application Envelope
- d. Capital Cost Estimates
- e. Project Development and Implementation Model and Schedule

Appendix (A) PowerPoint Overview of Conceptual Design Report
Appendix (B) Codes and Standards and their application
Appendix (C) DRAFT Version of NFPA 52
Appendix (D) Failure Mode and Effects Analysis
Appendix (E) Conceptual Design Drawings
Appendix (F) 3-D Virtual Tour of Conceptual Design applied to a service area (.avi file to be submitted as a CD-ROM)

Scaleup for Project Continuation

In 2005, GE constructed an electrolyzer test facility at the Global Research Center in Niskayuna, NY. This facility is capable of testing alkaline electrolyzer with production rates of about 1 kilogramH2/hr. As of this writing, an 18 cell ambient pressure stack with full product scale electrodes has been constructed and is in the process of being installed and qualified in the system. [Figure 8]

Figure 8: 1 kg/hr ambient pressure stack in GE test facility

GE has proposed a continuation to the successfully completed Phase I project. In Phase II, GE will design and construct a pressure-capable stack at the 1 kg/hr scale. Research in the next phase will focus on stack and system reliability measurements and system reliability growth. Operation and maintenance costs will also be estimated as part of the continuing project.

Appendix 1: Conceptual Design Report

Conceptual_Design_ Presentation...

H2 External DOE Feb 2 2004 EFA...

New_Baltimore_Functional_Model...

Appendix 2: Sensor Development Publications

JAP article _ Annealing Advanc...

Sensors and Actuators Article_...