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HYDROGEN PRODUCTION THROUGH ELECTROLYSIS

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Abstract

This paper describes the progress of cost reduction activities on a proton exchange membrane (PEM) electrolytic hydrogen generator series at Proton Energy Systems, Inc. (Proton) under cooperative agreement DE-FC36-98GO10341 with the Golden Field Office of the Department of Energy (DOE).

Proton's goal is to drive the cost of PEM electrolysis to levels of \$600 per kilowatt for 10,000 standard cubic feet per day (scfpd) and \$1,000 per kilowatt for 1,000 scfpd of hydrogen gas output. Both of these costs assume a manufacturing volume of 10,000 units per year, and the cost per kilowatt is based on electrical power into the electrolyzer. In addition, this program will evolve the use of PEM electrolysis as an energy storage device to enable renewable technology as a sustainable energy source. Steps to achieve these goals was begun using the HOGEN® (registered trademark of Proton Energy Systems, Inc.) 40 hydrogen generator (1,000 scfpd) platform with aggressive efforts focused on reducing the cost of this unit over the past two years. The plan was to then build on the success of those efforts and apply that learning to the HOGEN 380 generator to leverage the efforts and accelerate the HOGEN 380 generator cost reduction as well.

For this past fiscal year, Proton has focused on several aspects associated with these cost reduction efforts. First, all of the previous cost reductions on the HOGEN 40 generator needed to be fully validated by testing to show they would meet the technical requirements of the product and support the customer and market requirements. Second, the control board on the HOGEN 40 was to be advanced into the HOGEN 380 generator product. Third, investigation work was to be conducted on power supply options for the HOGEN 380 generator based on some of the work on the HOGEN 40 generator, but advanced to incorporate the higher power levels required on the larger units. Fourth, cell stack cost reduction activities on compression hardware was to be advanced and cost traded with traditional spring washer approaches.

Finally, data was to be collected on renewable power input into a HOGEN 40 hydrogen generator using power conditioning equipment developed on the program.

The results achieved over the past two years of the cost reduction efforts for the HOGEN 40 hydrogen generator on this program are in line with the goals of the Department of Energy. Proton projects that the current design of the HOGEN 40 generator projected to 10,000 units per year would be in the range of $1,500 per kilowatt. Furthermore, continuing efforts on materials substitution and design enhancements expected over the next few years should bring the cost of the system to the $1,000 per kilowatt goal for a system of this size. Not only is Proton committed to this cost goal but also to increasing the pressure capability of the system to reduce or eliminate the need for downstream compression of gas. The ability to do this within the $1,000 per kilowatt goal is also within reach and is considered necessary to successfully reaching the $1,000 cost target.

Background

Since the inception of the program on April 15, 1998, Proton has successfully demonstrated a fully functioning integrated renewable hydrogen utility system in conjunction with STM Power at Arizona Public Service (APS) in Tempe, AZ. This system coupled a solar concentrating dish, an external combustion engine and a Proton HOGEN 300 hydrogen generator. The system was installed and operating from May of 1999 through the end of the Phase I program in December of 1999. A description of the technical performance of the system and a market assessment is detailed in the Final Technical Report [1].

The Phase I demonstration efforts and market evaluation showed that a hydrogen generator coupled with some form of renewable power and some form of energy conversion device has a distinct advantage over a battery system backing up the same renewable application. Proton should not attempt to determine which renewable technology will win out in the end, nor predict which energy conversion device will be the most cost effective. However, it is clear that the link to these alternatives lies in the ability to convert excess renewable power into hydrogen and have the hydrogen available for conversion back to power, on demand.

To that end, Proton proposed a Phase II that moved away from the solar concentrating dish effort and focused on cost reduction efforts aimed at the hydrogen generator family. The HOGEN 40 generator was chosen as the model for these cost reduction efforts even though the HOGEN 380 generator was used in the Phase I of the program. This was done for two reasons. First, the smaller size of the HOGEN 40 generator made cost reduction activities and hardware purchases less costly, and thus enable a larger scope of effort and impact on return. Second, advances are scalable. In other words, improvements and cost reductions made on the HOGEN 40 generator can be scaled to the larger HOGEN 380 generators with less financial and programmatic risk. The specifics of this proposal were outlined in the Technical Paper submitted for that year's annual review[2].

The cost reduction effort targeted the electrical controls and mechanical systems that were common across the range of hydrogen generators and would need to be used for future products involving renewable technologies. The control board design and development done on the program yielded significant reductions in both material and labor costs. In addition, mechanical system simplifications, plumbing and fitting reductions and part substitutions also played a large role in the cost reduction effort for both labor and material. These modifications coupled with new technology developments like a power interface for renewable input successfully moved the HOGEN 40 generator product towards renewable utility. By the end of

FY2001 many of these design improvements and cost reductions had been developed but not fully validated[3]. This led to some early indications about projected cost reductions that showed the progress ahead of originally projected efforts. These previous results are shown in Figure 1.

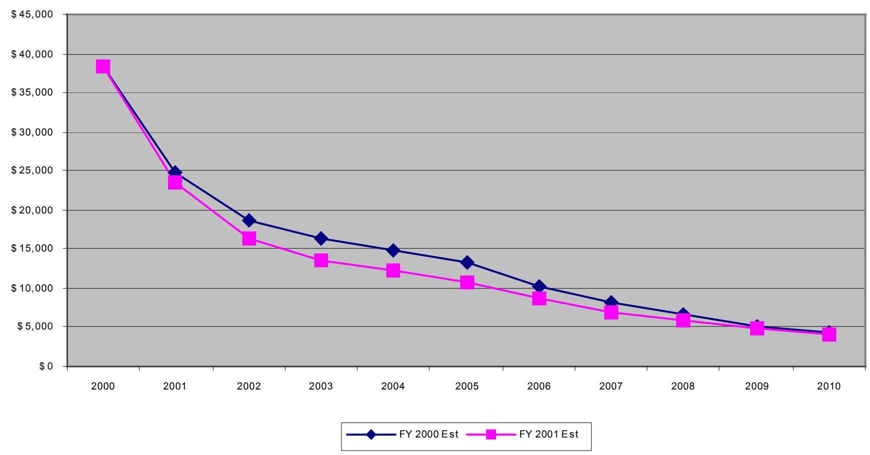

Figure 1 – HOGEN 40 (6kW) Generator Ten Year Cost Projection

Technology and Product Impact of Program

The breadth of this program and the impact it has on the commercial rollout potential of PEM electrolysis is worth spending a little time discussing. All of the products and technology that Proton develops is born from PEM electrolysis. Advances in the core of that technology cross from one product to the next and impact all areas of our business. All of Proton's cost reduction goals are focused on the long term markets associated with sustainable power. However, there are other markets where the hydrogen generator technology fits well and where products can move into commercial applications while the renewable technologies mature, come down in cost and become more commercially available.

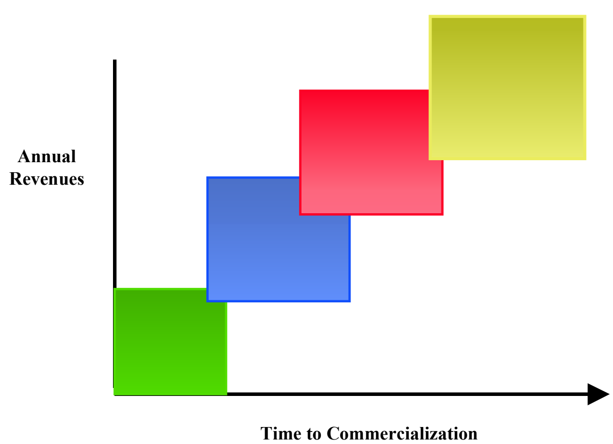

Figure 2 – Market Scope and Timing

These markets all have unique attributes that require different cost structures and pricing to compete effectively. Based on these markets and Proton's internal projections for numbers of units, market share and earnings, a detailed cost reduction plan was developed. The plan, as it pertains to hydrogen generators, focused on the HOGEN 40 generator and the HOGEN 380 generator with the near term emphasis on the HOGEN 40 generator. The cell stack sizes and system integration cost reduction tasks that are core to those products all transfer with minimal modifications to the other products.

When looking at the electrolysis cell stack, any changes to the cell materials of construction, the various catalyst loadings, or the stack embodiment, must be thoroughly tested to verify product integrity, safety and reliability. This type of testing can only be achieved through long duration testing of multiple configurations and designs. Regardless of the size of the cell itself, the improvements, or often more importantly the lessons learned, provide extremely valuable data and insight into possible cost reduction ideas. Cost reduction projections assume at least one year of full testing before any changes are made on customer deliverable hardware. This conservative approach is vital to maintaining quality hardware and satisfied customers.

Often overlooked in the PEM fuel cell and electrolyzer product area is the importance of focus on system cost and integration issues. These areas encompass, at a minimum, fluids management, gas pressure, gas purity, manufacturability and all of the safety requirements in the various countries. Add to this the complexities in packaging and shipping hardware through different environments and over varying road infrastructures, and the pathway to delivering a fully commercial product gets even more complex. Proton has made significant advances in commercializing industrial hydrogen generators. This has included significant efforts in obtaining domestic and international safety marks such as CE. This program has augmented these efforts by focusing on specific systems areas for cost reduction. These include the electronic control section, plumbing simplifications, component substitutions and exploration of various power conditioning options. As stated earlier, all of these cost reduction advances provide the building blocks for our other product areas and enable us to get real time commercial experience by applying these cost reductions to our industrial product lines.

Status of Progress

The following sections will discuss the specific areas targeted on this program, the milestones and objectives of each of those items and the status of progress to date.

Cell Stack Compression

This task was to study the cost and performance differences of changing the methodology of compressing the electrolysis cell stack from a large number of spring washers to a fewer number of larger spring washers. The study was to be completed by March of 2002. This change is depicted in the figures below.

<table>
<tr><th></th><th>Item</th><th>Component</th><th>Purpose</th></tr>
<tr><td>Current Hardware</td><td>1</td><td>Small Diameter Disk Springs</td><td rowspan="2">Compensate for reduction in compressive load due to the creep of cell sealing materials</td></tr>
<tr><td rowspan="4">Next Generation Hardware</td><td>2</td><td>Large Diameter Disk Springs</td></tr>
<tr><td>3</td><td>Alignment Bearing</td><td>Center alignment and hard contact surface</td></tr>
<tr><td>4</td><td>Compression Plate</td><td>Flexible plate to compress disk springs</td></tr>
<tr><td>5</td><td>Spherical Washer</td><td>Maintain bolt alignment</td></tr>
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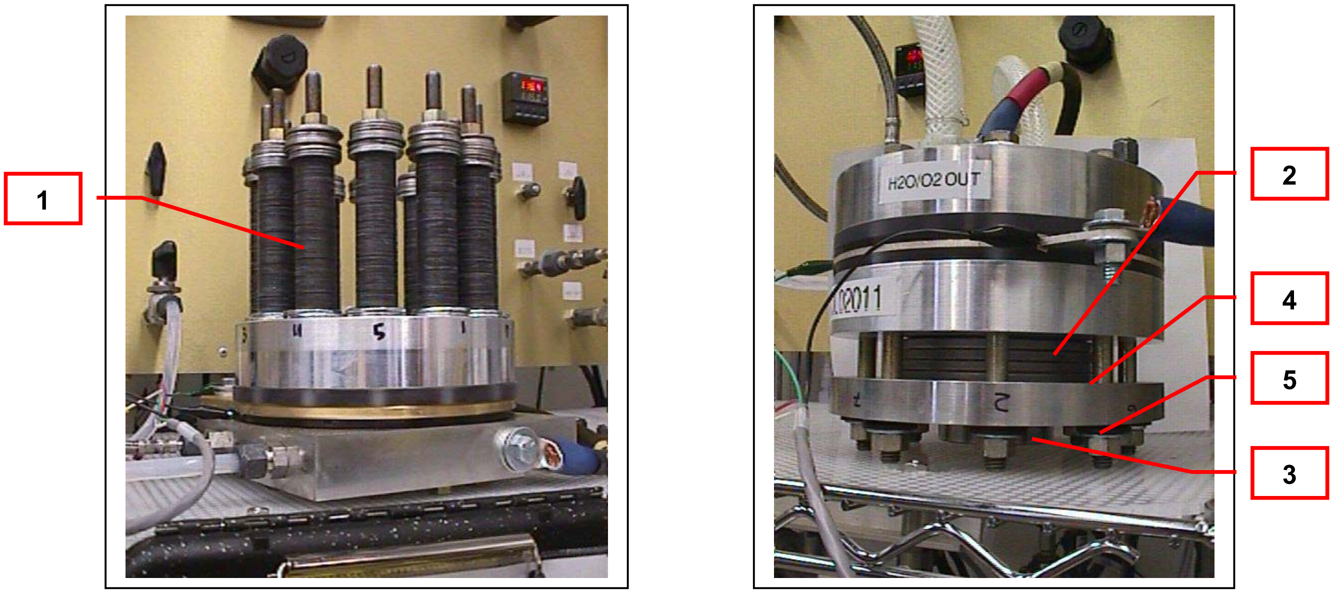


Figure 3 – Stack Compression Configurations

This effort was completed on schedule and has yielded some impressive results. Changing to the large diameter spring reduces the assembly time of the washers from 75 minutes to 5 minutes, and reduces the parts count from 1344 pieces to 15. From a manufacturing standpoint these are very impressive reductions that also have a tremendous impact on quality and consistency of assembly. Each of the smaller springs needs to be oriented in a certain way and with a certain ordering configuration on each rod. This complicated assembly is prone to mistakes which cause rework and could possibly jeopardize the sealing integrity of the cell stack.

Additional technical benefits are in the smaller overall envelope as well as a more uniform loading profile within the cell stack. The smaller envelope has potential benefits by allowing for possible packaging modifications to accommodate other assembly efficiencies or component changes. The loading uniformity improvement may improve overall cell stack and system efficiency by allowing for even distribution of electrical current as well as fluids flow passages.

Control System Cost Reduction

HOGEN 40 Generator Control Board

The HOGEN 40 generator control board design represents a significant cost reduction to the overall electrolyzer control system as presented in last year's final report. The cost reductions associated with this effort are impressive. The material cost for the control system has been reduced from approximately $1,600 to less than $300 with a 40 hours to one hour reduction in labor. This year's effort was focused on validating the design changes that were made to cost reduce the electrolyzer control system in order to insure that the integrity and reliability of the product was not compromised. The control board was developed beyond the prototype stage and underwent extensive design validation testing prior to production release. Validation of the control board included Highly Accelerated Life Testing (HALT), which exposed the board to environmental extremes in order to identify hardware limitations. The results of the HALT testing were fed back into the design process to further enhance the robustness of the control board design. Validation testing also included agency safety/EMC testing and equivalent certifications for UL, CSA, and CE. The control board also underwent operational testing to insure that the electrolyzer operated within design specifications through all modes of operation. Figure 4 below describes this validation testing.

TEST	STANDARD	NOTES
Highly Accelerated Life Testing		
Temperature	T0002436	Tested by Qualmark
Vibration	T0002436	Tested by Qualmark
Agency Certifications		
Safety		
NTRL-US (UL)	UL3111, UL3101	Tested by TUV Reinland
NTRL-CANADA (CSA)	C22.2 No. 1010	Tested by TUV Reinland
CE	EN60204	Tested by TUV Reinland
EMC		
CE	EN55011, EN61000	Tested by TUV Reinland
Operational Testing		
Hardware	VT-2002-0005	Proton Validation Testing
Firmware	VT-2002-0005	Proton Validation Testing

Figure 4 – Control Board Validation

HOGEN 380 generator control board

The cost reduction efforts on the HOGEN 380 generator control system have resulted in a greater than 90% control system cost reduction. The fact that the HOGEN 380 generator control board was developed off of the HOGEN 40 generator control board design and was able to maintain the same basic architecture and function has resulted in a much more dramatic hardware cost reduction. The current HOGEN 380 generator control system costs in excess of $10,000. The projected cost of the production control board in modest volumes is less than $500. As shown in Figure 5 the validated HOGEN 40 generator control board was used as the base platform for the HOGEN 380 generator control board.

This approach not only significantly reduced the amount of design time involved, but will also reduce the amount of product validation risk and effort in the later stages of development. A harness was also developed to eliminate the extensive point-to-point wiring, which resulted in a labor reduction of at least 60%. The HOGEN 380 generator control board specification was drafted and a prototype board was delivered for functional testing early this year. The prototype board was than incorporated into an electrolyzer system to verify the design and test the basic functionality of the cost reduced system. Basic design verification testing was completed and the board design was modified to incorporate the changes that resulted from the verification testing. The beta board will be delivered in early July and undergo extensive validation testing, as did the HOGEN 40 generator control board.

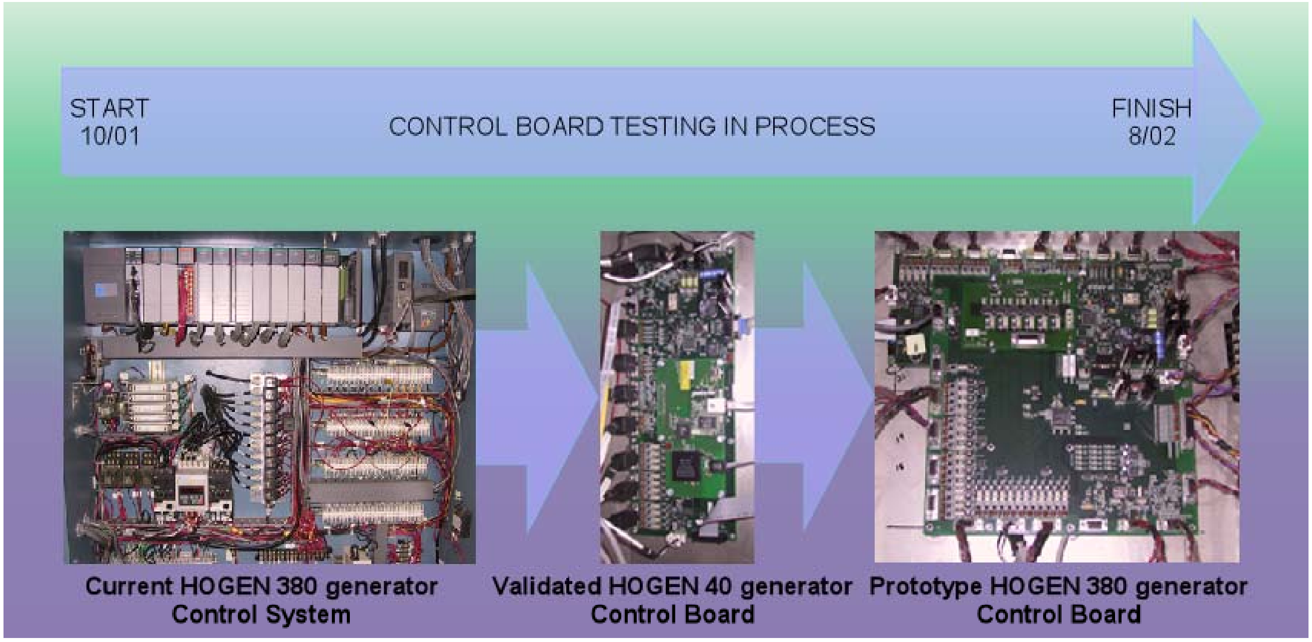


Figure 5 – Control Board Advancement

HOGEN 380 Generator Fluid Management Cost Reduction

This effort has shown very encouraging results. Following the same strategy as was used on the control board development a tremendous amount of cost reduction has been realized on the HOGEN 380 generator fluids system with a minimal amount of reengineering. As shown in Figure 6, the components that were developed for the HOGEN 40 generator were used as the platform for further cost reductions on the HOGEN 380 generator. The development efforts on gas drying for the HOGEN 380 generator have resulted in the development of a low cost pressure swing absorption dryer that can be manufactured in low quantities for under $4,000 compared to the previous design that was over $8,000. In higher volumes the cost of this dryer will be well under $2,000.

Power Conversion Cost Reduction

Cell Stack Characterization

It was decided that one of the first efforts that needed to occur for the power conversion cost reduction to be successful was a cell stack electrical characterization study. This task helped to understand the electrolysis cell stack as a power load. Figure 7 illustrates the cell stack voltage/current relationship as power is initially applied to the cell stack. As illustrated in the following data tables a series of cell stack voltage and current measurements were taken over a frequency range in order to determine the overall impedance of the stack. The data was taken from the rising edge of a current pulse to the stack at approx. 75ºF.

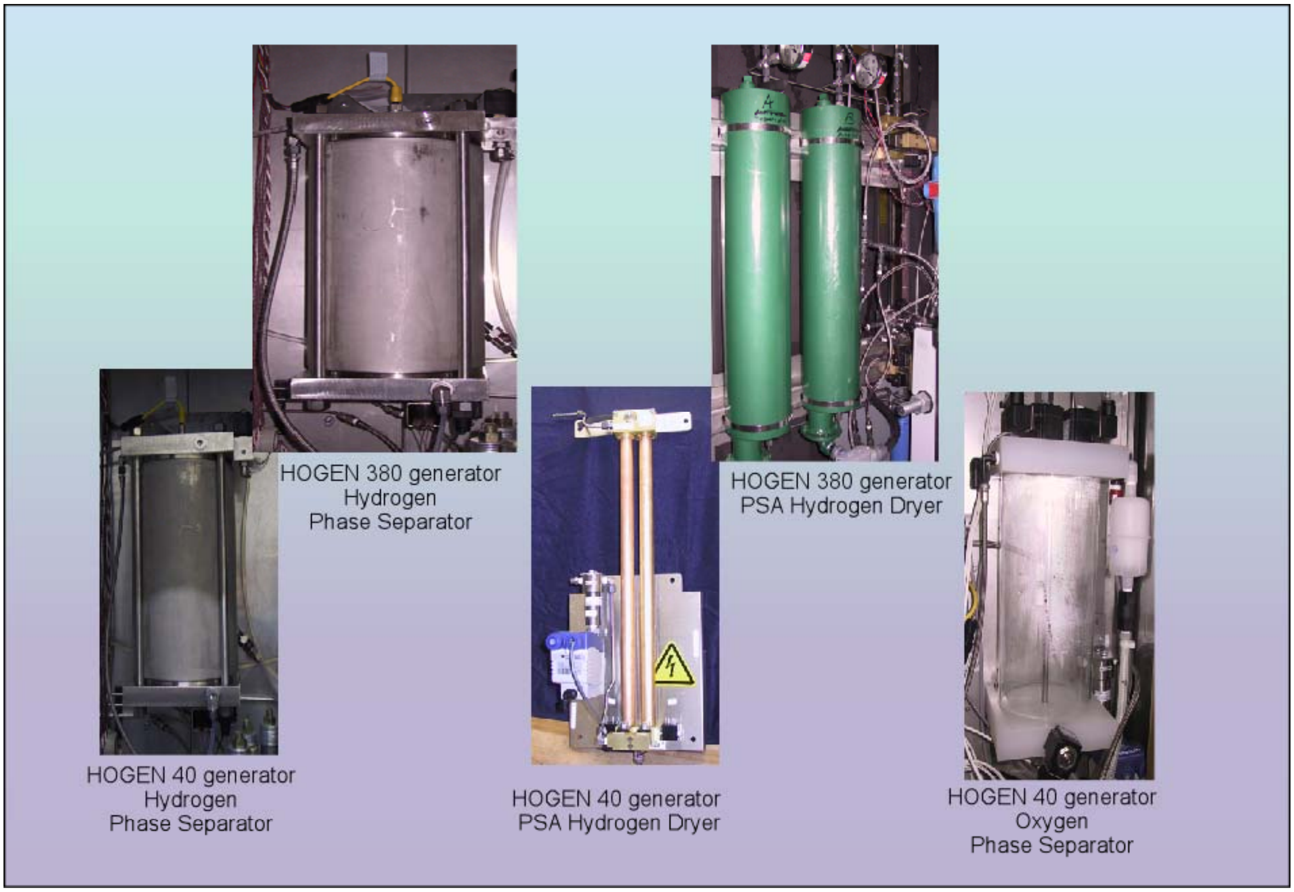


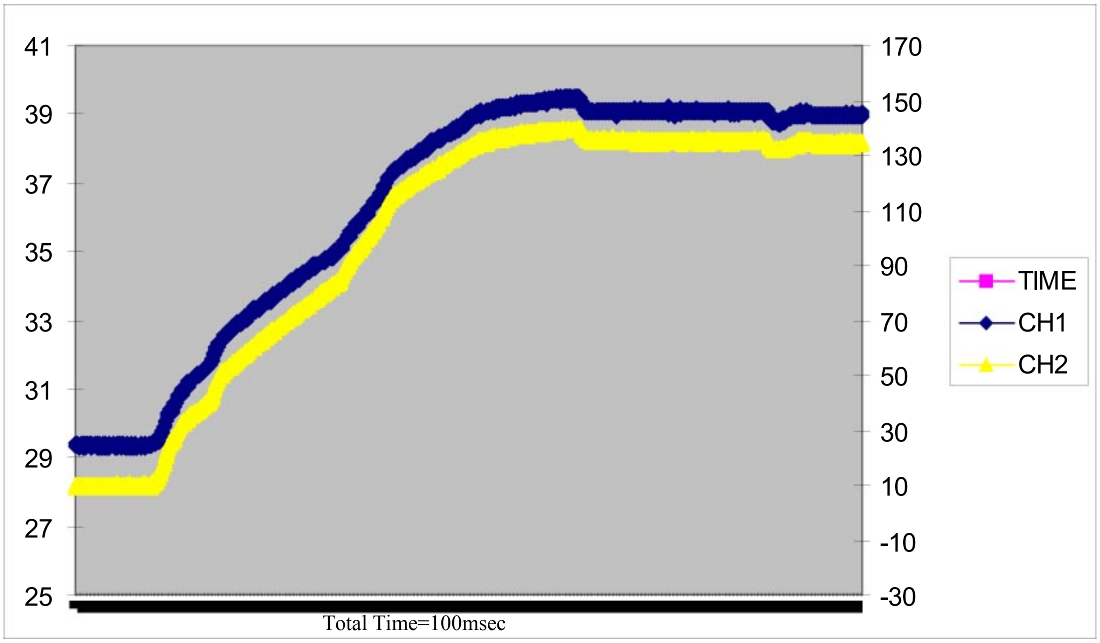
Figure 6 – Fluids Component Cost Reduction

Ripple Current in Cell Tradeoff Analysis

Another key element of the cell stack characterization is the affect ripple current has on the electrolysis cell stack during operation. The ability to withstand a degree of ripple current on the cell stack will allow the power electronics design to be dramatically less expensive due to the reduction in energy storage usually required for filtering.

An assumption can be made that the 70 Milliohms of measured impedance is the loss element of the cell stack. The basis for this calculation is that hydrogen production is dependant on average current (since the voltage is fixed) whereas power dissipation in the loss element depends on RMS current.

In the case of unity power factor, single phase would be an Average to RMS ratio of 0.707. (The power follows a sine wave current times a sine wave voltage equals sine squared.) That would also be the worst case. The average of sine squared is one half, the average of sine is 2/pi; the average of DC is 1. Baseline is 150A squared times 0.07 ohms equals 1575W.



Blue = stack volts Yellow = stack amps (note-current probe was overrange)

Figure 7 – Cell Stack Data

If we design for a >0.8 power factor and we try for something like constant current input over the sine wave voltage waveform, then it is the ratio of 2/pi to .707. Cranking through for 0.07 ohms and 150A, the extra power is 369W, which seems very acceptable. For the unity power factor case, the ratio of 0.707 is applied to the RMS current, THEN squared, so the resistive loss is doubled, or an extra 1575 W. There will be an added benefit in efficiency with the lower power factor design, which should be about 94% vs the current 85% average. For a 6kW converter output, the power gain will be 1.12kW.

In conclusion, the design approach should be to design for the minimal energy storage converter (i.e. least costly), but don't try for higher power factor than necessary. Extra resistive loss will be less than 1575W, which will largely be made up by efficiency gains. (Note that RMS line currents will be higher due to lower power factor.)
As illustrated below in the following tables (Figure 8), if the rise in impedance from 3k to 10k Hz is due to inductance, this calculates to about 400nH, which would be the inductance of a piece of wire about as long as the stack. Using the first table, if the difference of lowering impedance between 10 and 1 Hz was due to capacitance, it would equate to 0.5F. However, the Current and Voltage are in phase, so it can't be capacitive. The results of the testing that was performed at the varying frequencies indicate that the basic electrical model for the cell stack under operating conditions is very similar to a battery. A better defined electrical model would indicate that the stack is like a well behaved resistor of about 65 milliohms in series with a battery and a little series inductance.

Temp: 77F	PSI: 20-50	Idc: 25A	Vdc 30.5V	
Freq, Hz	Irms, amps	Vrms, volts	Phase, degrees	Z, milli-ohms
1	14 (p-p)	1 (p-p)	(in phase)	71
10	1.98	0.187	35	94
30	2.39	0.176	14	74
100	2.50	0.164	9	66
300	1.92	0.112	5	58
1k	1.51	0.082	-3	54
3k	0.85	0.052	-20	61
10k	0.15	0.013	(-60)	86

Note: positive phase = capacitive

Temp: 85F	PSI: 175	Idc: 80A	Vdc 34.7V	
Freq, Hz	Irms, amps	Vrms, volts	Phase, degrees	Z, milli-ohms
10	5.89	0.561	37	95
30	7.33	0.544	12	74
100	8.01	0.565	6	71
300	6.02	0.405	2	67
1k	3.24	0.204	-3	63
3k	0.85	0.061	-28	52
10k	0.11	0.011	(-60)	100

Note: positive phase = capacitive

Temp: 97F	PSI: 150	Idc: 25A	Vdc 30.2V	
Freq, Hz	Irms, amps	Vrms, volts	Phase, degrees	Z, milli-ohms
10	6.92	0.603	40	87
30	8.6	0.552	18	64
100	9.2	0.512	10	56
300	7.72	0.388	7	50
1k	4.81	0.220	-3	46
3k	1.33	0.072	-18	54
10k	0.192	0.014	(-48)	73

Note: positive phase = capacitive

Temp: 106F	PSI: 180	Idc: 80A	Vdc 33.4V	
Freq, Hz	Irms, amps	Vrms, volts	Phase, degrees	Z, milli-ohms
10	6.15	0.473	35	77
30	7.31	0.451	12	62
100	8.06	0.475	5	59
300	6.50	0.355	2	55
1k	3.70	0.192	-8	52
3k	0.966	0.059	-22	61
10k	0.112	0.0097	?	87

Note: positive phase = capacitive

Figure 8 – Cell Stack Tradeoff Data

Utility Grid Converter

With the cell stack characterization complete, a feasibility study and paper design based on a power electronics cost reduction effort for the HOGEN 40 hydrogen generator was conducted in the second quarter of FY02. It was concluded that the high cost of power conversion on these units is due mainly to two factors, buying an "off the shelf" design that is not optimized for the electrolysis application and providing galvanic isolation to the electrolysis cell. Another important discovery made during the study was the capability of the electrolysis cell to absorb significant line frequency ripple current. This allows for a significant reduction in the energy storage required in the converter, thus further reducing the overall cost of the converter.
The study concluded that a non-isolated power converter with minimal energy storage has the potential to achieve $.033/watt for the HOGEN 40 generator and $.05/watt for the HOGEN 380 generator.

Due to the initial results of the feasibility study, Proton is considering the design and development of a cost reduced power electronics package. It is evident that the path to the lowest cost for power electronics is in a design that is optimized for the electrolysis process and the only way to accomplish this is to develop the design "In House" or in cooperation/collaboration with a willing supplier.

Presently, the HOGEN 40 generator power electronics cost is $0.30/watt and delivers DC power at an average efficiency of 85%. The feasibility study identifies a design path with the ability to reduce the cost of power electronics to less than $0.10/watt and an average efficiency of 94%.

Renewable Energy Interface Converter

Sustainable Energy Technologies (SET) was contracted by Proton to develop an interface converter with the ability to accept a power input from a photovoltaic or wind source. SET delivered two 5kW photovoltaic interface converters that were tested by Northern Power Systems in Waitsfield, VT and found to meet the basic specifications of the design. SET also delivered an interface converter that was capable of accepting a wind turbine input, but due to the inability to interface directly to a wind turbine the converter was never tested beyond the basic power test. One of the PV converters has been delivered to the Illinois Institute of Technology (IIT) for integration into a renewable energy system utilizing one of Proton's HOGEN 40 hydrogen generators.

Plans for Future Work and Cooperative Efforts

The program continues to work with the Illinois Institute of Technology (IIT) who is actively working to integrate a converter prototype with their PV system currently on their campus. IIT previously purchased a Proton HOGEN 40 hydrogen generator to use as part of their system. Efforts have been slow to materialize, but good dialog continues and efforts to advance work at IIT will continue beyond the scope and timetable of this program. Separately, work has been advanced with Northern Power Systems on doing some actual testing on a PV system combined with a HOGEN 40 hydrogen generator. Results were indicated above and good progress and communication is ongoing.

For the balance of this year, the program will focus on further development of the HOGEN 380 control board and on advancing power supply alternatives and renewable interfaces. The program is currently expected to end by this fall.

Summary

A sustainable energy system utilizing renewable technology must have the fundamental capability of storing excess renewable energy when it is available so it can be utilized when the consumer needs it. Renewable technology is inherently intermittent based on the fundamental fact that the wind does not always blow and the sun does not always shine. Electrolyzer technology has great promise for helping to bridge the gap and make electricity available twenty-four hours a day, seven days a week. Proton's hydrogen generators also follow the load extremely well and can respond virtually instantaneously to fluctuations in power levels from the renewable device.

As the world of renewable technology continues to grow and become competitive, it is crucial to have a concrete pathway for a realistic and cost effective energy storage solution. Proton is committed to advancing the cost and efficiency of our electrolysis technology and products to meet these future energy needs. Our approach is to drive down the cost through deployment of the technology into early commercial markets like Industrial Gas and Backup Power. These markets offer opportunities to commercialize and learn at volumes that do justice to the technology and make business sense to investors. This pathway of tangible products and markets will allow Proton and our family of hydrogen generators to be ready when and as the renewable technology becomes readily available.

References

1. Friedland, R., Smith, W., Speranza, A., January 2000. *Integrated Renewable Hydrogen Utility System*, Phase I Final Technical Report and Market Assessment PES-T-99014.

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