Final Technical Report

August 11, 2003- October 31, 2007

Project Title: **"Back-up/Peak-Shaving Fuel Cell Systems"**

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Overview

This Final Report covers the work executed by Plug Power from 8/11/03 – 10/31/07 statement of work for Topic 2: advancing the state of the art of fuel cell technology with the development of a new generation of commercially viable, stationary, Back-up/Peak-Shaving fuel cell systems, the GenCore II.

The Program cost was $7.2 M with the Department of Energy share being $3.6M and Plug Power's share being $3.6 M. The Program started in August of 2003 and was scheduled to end in January of 2006. The actual program end date was October of 2007. A no-cost extension was granted.

The Department of Energy barriers addressed as part of this program are:

Technical Barriers for Distributed Generation Systems:

- Durability
- Power Electronics
- Start up time

Technical Barriers for Fuel Cell Components:

- Stack Material and Manufacturing Cost
- Durability
- Thermal and water management

Background

The next generation GenCore backup fuel cell system to be designed, developed and tested by Plug Power under the program is the first, mass-manufacturable design implementation of Plug Power's GenCore architected platform targeted for battery and small generator replacement applications in the telecommunications, broadband and UPS markets. The next generation GenCore will be a standalone, H2-in-DC-out system.

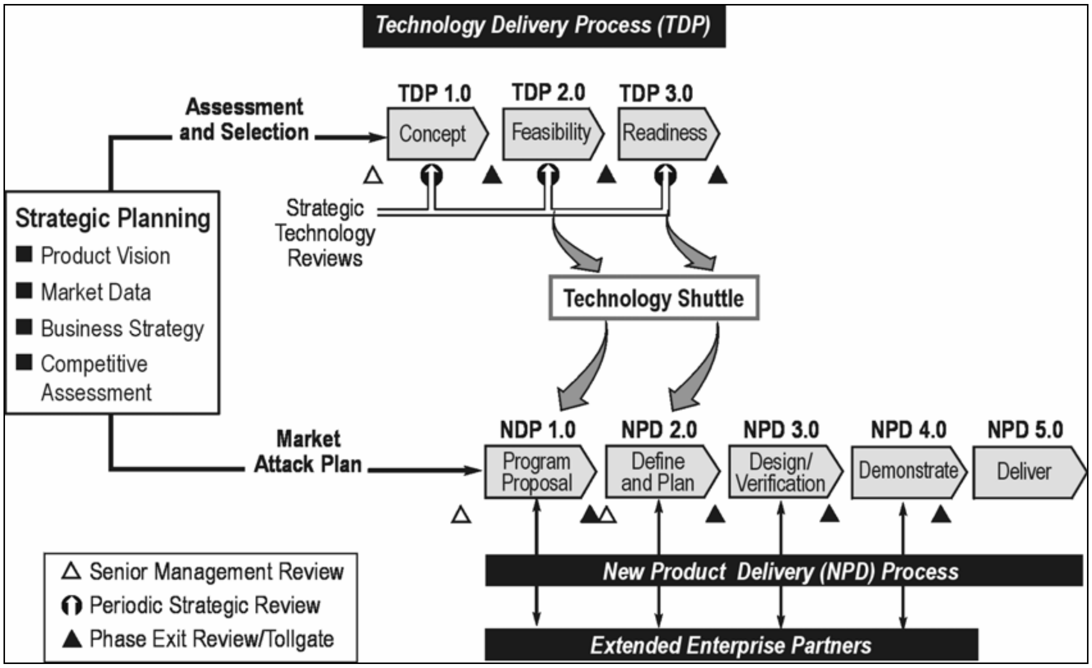
In designing the next generation GenCore specifically for the telecommunications market, Plug Power teamed with BellSouth Telecommunications, Inc., a leading industry end user. The final next generation GenCore system represents a market-entry, mass-manufacturable and economically viable design. The technology incorporates:

- A cost-reduced, polymer electrolyte membrane (PEM) fuel cell stack tailored to hydrogen fuel use
- An advanced electrical energy storage system
- A modular, scalable power conditioning system tailored to market requirements
- A scaled-down, cost-reduced balance of plant (BOP)
- Network Equipment Building Standards (NEBS), UL and CE certifications.

Glossary

- **TDP** – *Technology Delivery Process*. A proprietary process used by Plug Power as a risk management tool for technology development (shown in Figure 1).
- **NPD** – *New Product Delivery*. A proprietary process used by Plug Power as a risk management tool for product development (shown in Figure 1).
- **IOCs** – *Input/Output Constraints*. A method of defining the boundaries of a technology module and how it interacts with other systems.
- **CPs** – *Critical Parameters*. The important control points or 'knobs' through which module performance can be controlled.
- **FMEAs** – *Failure Modes and Effects Analyses*. A method of analysis where all failure modes of a module are grouped and analyzed in an attempt to identify and mitigate all possible failure mechanisms.
- **DVT** – *Design Verification Testing*. The first testing of the production intent design to detailed system requirements.
- **Df(M)** – *Design for Manufacturability.* Analysis used to determine the ability to execute the product build using standard manufacturing techniques.
- **Df(S)** – *Design for Serviceability.* Analysis used to determine the ability to service the product in a filed environment using standard tools and diagnostic techniques.
- **ITR** – *Integrated Test Rig.* A technology rig that combines several developmental subsystems to understand latitude and interactions.
- **EGR-** *Exhaust gas recirculation.* Involves the reuse of exhaust hydrogen to improve fuel utilization.
- **VRLA-** *Valve regulated lead acid***.** is the designation for maintenance-free lead-acid batteries
- **MEA-** *Membrane Electrode Assembly.* An assembly consisting of gas diffusion layers, anode and cathode electrodes and a proton exchange membrane.
- **EMI-** *Electro-magnetic Interference.* An usually undesirable) disturbance that affects an electrical circuit due to electromagnetic radiation emitted from an external source.
- **UL-** *Underwriters Laboratory.* Defines Standards for Safety to help ensure public safety and confidence, reduce costs, improve quality and market products and services.
- **NEBS-** *Network Equipment-Building System.* Refers to the family of documents that specify requirements for telecommunications equipment located in a Central Office

Figure 1: The TDP/NPD Process



The Gen Core Product family is envisioned to serve the telecom and utility back-up power market. The following statement of work was recommended for the development and demonstration of the GenCore Product.

Task 1.1 – Select Technology Concepts

Task 1.2 – Construct Models/ITR

Task 1.3 – Conduct System-Level Testing

Task 2.1 – Develop Dry Cathode Stack Operation

Task 2.2 – Integrate GenSys Stack

Task 2.3 – Develop Power-Scalable Stack

Task 2.4 – Develop H2 Regeneration Options

Task 2.5 – Develop Power Conditioning Platform

Task 2.6 – Introduce Advanced Electrical Energy Storage

Task 2.7 – Develop System Water Balance

Task 2.8 – Develop Advanced Hydrogen Storage

Task 3.1 – Perform UL Testing (GC5T)

Task 3.2 – Perform NEBS Testing (GC5T)

Task 3.3 – Perform Field Testing (GC5T)

Task 4.1 – Develop Master Strategy Proposal

Task 4.2 – Design and DVT Testing

Task 4.2 – Design and DVT Testing

Task 4.3 – Build Confirmation and Life Test Systems

Task 4.4 – Perform Integrated System Testing

Task 4.5 – Build Verification Test Units Task 4.6 – Conduct Field Demonstration

Task 4.7 – Certify Design to NEBS (GCII)

Task 4.8 – Certify Design to UL (GCII)

Task 4.9 – Demonstrate GCII at DOE

The original program plan is shown in Figure 2.

Figure 2: Program Plan

Task Number	Project Milestones	Task Completion Date				Progress Notes
		Original Planned	Revised Planned	Actual	Percent Complete	
1	Testing on GenCore 5T unit	3Q04		3Q04	100%	Complete.
2	Technology initiatives work launched	4Q04		4Q04	100%	Complete.
3	Build Integrated Test Rig	2Q04	4Q03	4Q03	100%	Complete.
4	Agree integrated program plan with BellSouth	2Q04		2Q04	100%	Complete.
5	Complete feasibility and robustness testing	2Q04		2Q04	100%	Complete.
6	Complete design and verification of system, start early customer acceptance testing	1Q05		1Q05	100%	Complete.
7	Ship one system for test at BellSouth site and two systems for UL and NEBS testing	1Q05	4Q05	1Q06	100%	Complete.
8	Ship two UL and NEBS test systems to DOE Argonne National Lab for third-party independent testing	3Q05	4Q05	Oct 2007	100%	Complete.

Statement of work summary
Following is a summary of each task as it was performed during the program.

Task 1.1 – Select Technology Concepts

The purpose of this task was to select technologies and contingency technologies for the next generation design. This was accomplished by exiting TDP 1.0 for each technology module. The program held technology go/no-go assessment in December of 2004 and the results are outlined in Table 1 below. These results describe which technology initiatives have yielded during the TDP process and will be included as part of the product development phase of the program.

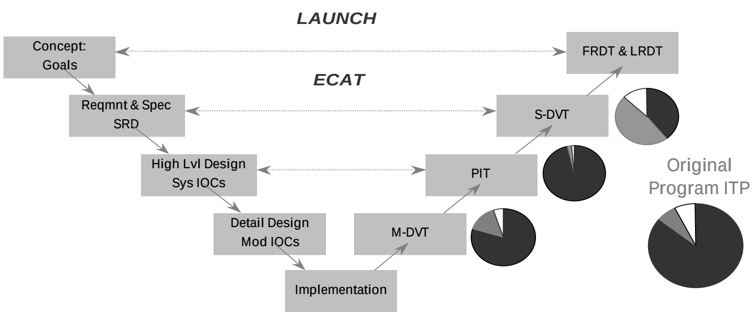
TABLE 1: Technology Go/No-Go Results

Technology Module	Go/No-Go	Comments
1. Dry cathode operation	No-Go	Will not in yield in program timeframe
2. GenSys™ stack integration	No-Go	Will not in yield in program timeframe
3. Power scalable stack	Go	
4. H_2 regeneration options	Go	Advanced end gas recirculation (EGR) option. System will not have an electrolyzer. Plug will continue a small amount of electrolyzer development work as part of this program. This is high payoff work with a very small percentage of program resources committed. Electrolyzer technology remains an important enabler for proliferation of hydrogen-based fuel cells.
5. Power conditioning platform	Go	
6. Advanced electrical energy storage	Go	Non-lead acid solution
7. System water balance	No-Go	Will not in yield in program timeframe
8. Advanced H_2 storage	No-Go	Will not in yield in program timeframe
9. Scale system	Go	
10. GenSys stack	Go	

Task 1.2 – Construct Models/ITR

The purpose of this task was to build analytical models and laboratory hardware to test and evaluate technology concepts. This is verified by exiting TDP 2.0 for each module.

The screening process for these modules passing TDP 2.0 consists of the rigorous evaluation of data from a battery of tests. Of over 150 tests which are part of the Plug Power integrated test plan, Module and System DVT Testing (that provides criteria for passing TDP 2.0) is approximately half of the integrated test plan. The chart below outlines the program testing philosophy and the number of tests performed to date on the platform. Subsets of these tests have to be repeated in the evaluation of each module.



	Active	Complete	Eval.	Failed	Passed	No Test Pln	Queue	Total
F&RDT			2	1				3
S-DVT	11		9			2	1	23
PIT	1	17	38	2	1	1		60
M-DVT	12	27	34		2	1	3	79
Total	24	44	83	3	3	4	4	165

Executed *Active* *Un-Executed*

Figure 3: Plug Power's Testing Philosophy

Test fixtures to support module testing were commissioned in the first quarter 2004. Examples of critical tests that were run and the associated data are contained in Table 2.

Table 2: Critical System and Module DVT Test Results

Parameter	Tests	Results	Issues
System Duty Cycle (> 50 start/stops per year)	• 200 start/stop cycles, continuous • 200 start/ stop cycles, with dormancy and conditioning cycles • Performance testing with stop/start cycling	Passed	• Are currently performing duty cycle tests > 225 start/stops in the laboratory and Environmental Chamber • Reliability testing will be continued as additional plans to remove risk
Operating Hours (1,500 hours life)	• 2,000 hour validation	Passed	• A system to date, running the predicted duty cycle, has run approximately 800 hours • Stacks have run > 2,000 hours and modeling and vendor data show components should last • Trends are positive, reliability fleet coming on line.
Time to Fuel Cell Governing (30 seconds)	• 0 to 5 kWe ramp test @25C • 0 to 5 kWe ramp test @ -40C/25C/+46C	Passed	• This is the time it takes for the fuel cell to be exporting 5 kWe with none required from the EESM • All tests performed in 15

			seconds or lower
Environmental Siting (-40C to +46 C +solar loading operation with 1.5% power de-rate/each 10C > 25C)	• 5 kWe output test @ +46C +solar loading • Dormancy to net zero output at –40C	Passed	• Cabinet temperatures oscillate to low temperatures (down to –9C) for short durations (15 seconds) at startup. Not considered a freeze issue.

Additionally, components for module test rigs (4 GC5T systems) were assembled and commissioned in the first half of 2004. The commissioning process consists of installing the rig, connecting it to a DC load bank and performing an established test procedure consisting of GO/NO-GO criteria. Typical criteria are a full load test and system ramp rate test. The system is considered commissioned if it passes all tests.

The module test rigs were converted later to use for field problem troubleshooting, EGR testing, next generation EGR opportunities, Test & Verification learning and manufacturing improvements.

Task 1.3 – Conduct System-Level Testing

The purpose of this task was to demonstrate technology readiness for the modules to be included in the GCII design. This is accomplished by each module being evaluated and passing TDP 3.0 exit screening. The ITRs were commissioned in February of 2004. The summary of all of the tests performed are in the following tasks.

Task 2.1 – Develop Dry Cathode Stack Operation

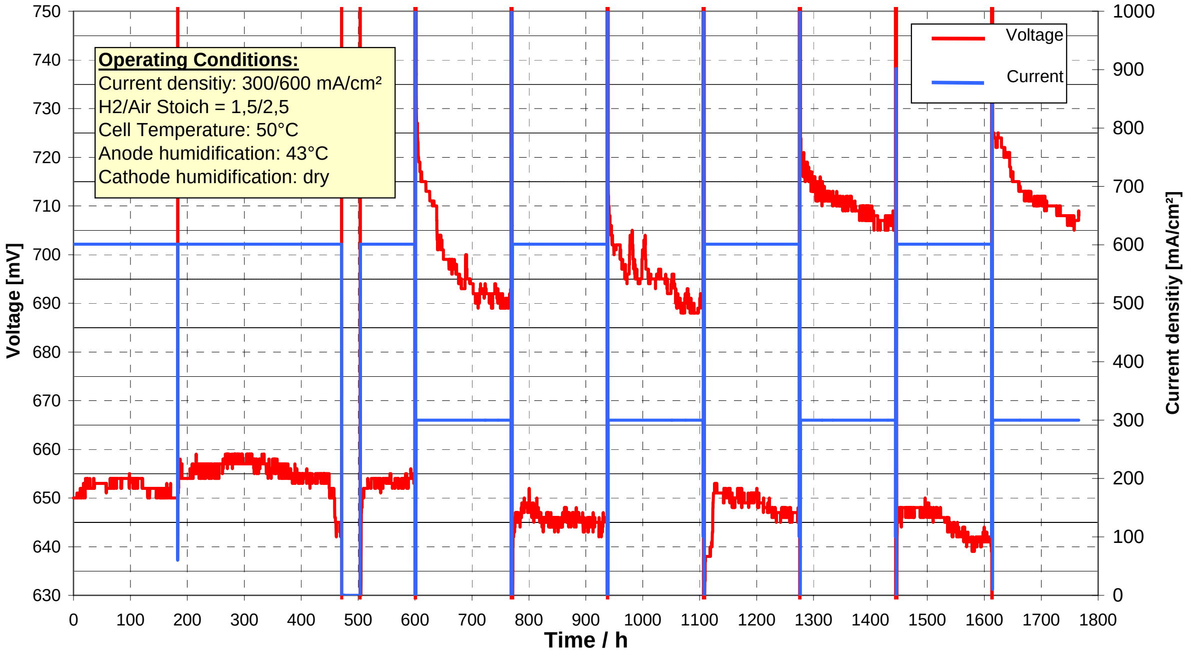
The purpose of this task was to develop MEA, stack and system capability to operate without cathode humidification. The program started this task early to plan by securing favorable initial test results from a supplier. The preliminary engineering work (IOCs, CPs and FMEAs) was completed and ready for the analysis of vendor data.

The vendor had 600 feasibility test hours run on a 50-cm^2 rig that matched Plug Power specifications. Plug Power was initially unable to duplicate vendor results on a 50-cm^2 sample and spent significant effort reconciling differences in test methods with the vendor. After resolving the differences, both were able to yield similar results. The vendor continued testing, accumulating 1800 feasibility test hours run on a 50-cm^2 rig that matched Plug Power specifications.

As shown in Figure 4, higher current produced higher water drag and therefore greater membrane humidification. At lower current, the membrane tends to dry out. Upon re-humidification, by operating at high current the voltage recovers but the dry-out process is reinitiated in low current operation.

A variety of commercial MEAs were tested under GenCore operating conditions with an un-humidified cathode. While there were distinct variations in the performance of the MEAs the general trends were similar; i.e. the membrane dried out but not to the point where the system would fail.

Figure 4: Endurance test of the Commercial MEA, 50 cm^2 GenCore Conditions



Two 8-cell modules underwent feasibility testing at Plug Power. Module 1 failed after 1,174 hours with below average performance. Module 2 achieved 2,835 hours. Performance had tailed off considerably and the module under went end-of-life analysis.

At the end of March 2005, it was determine that the dry cathode technology could not be incorporated into the system design because it could not be made ready in the program's timeframe and confidently demonstrate that the membrane would meet long-term performance and lifetime requirements in a fielded system.

Task 2.2 – Integrate GenSys Stack

The purpose of this task was to integrate the GenSys stack into the GenCore design. This task starts after the GenSys stack demonstrates technology readiness. Plug Power's goal is to establish a common stack platform across its products. Presently, the GenCore program uses a stack originally designed for its first stationary, reformate-based system and would like to move to incorporate the next-generation stack as soon as possible to enable volume pricing and reuse.

In March of 2005, it was determined that the GenSys stack is not on track to demonstrate technology readiness in this program's timeframe. The primary issue was due to cost. However, many of the learning from the GenSys stack could be adopted and implemented as identified in Task 2.3.

Task 2.3 – Develop Power-Scalable Stack

The purpose of this task was to design, test and integrate power scalable stack initiatives into the GCII design. Executing these initiatives will provide the product with a stack that has comparable performance to Plug Power's residential, reformate stack but reduces the number of required cells by 20%, the weight by almost 50% and the volume by 45%. The following stack initiatives were implemented in the GenCore stack:

- Reduced stack footprint and thin plates
- Advanced technology gaskets
- Reduced end-hardware size
- Functional integration into end hardware

- o Reduced cost, scalable scanner card interface
- o Next Generation MEA
- o Reduced number of cell stack, “scaled stack”, constructed, tested and cut-in to design

Many problems were encountered in implementing these major design changes.   Plug Power uses a structured problem solving process that is accomplished in eight steps. Following is an example of the problem set faced by the engineering team.

- o Anode plates have unacceptably high fallout due to cracks from the molding process. A short-term corrective action was the use of a mold release agent. Figure 5 shows an example of the finite element study.
- o The end hardware failed original hi-pot testing. The team worked optimizing the paint coating process with the supplier to improve the quality of insulating paint. Figure 5 shows the end hardware.
- o Scanner harnesses were determined to be susceptible to mis-wiring. The team worked to create a wiring harness design that was fool-proof for manufacturing or technicians in the field.
- o Scanner interface cards were determined to be reading incorrect voltages.   The team determined root cause was electrical noise on the cell zero (reference) line. A corrective action was put in place to shorten and reroute the line.
- o Experiencing voltage stability issues with next generation MEA.

Figure 5 : Molded Stack End Hardware, Molded Fittings, FEA of Plate Stress

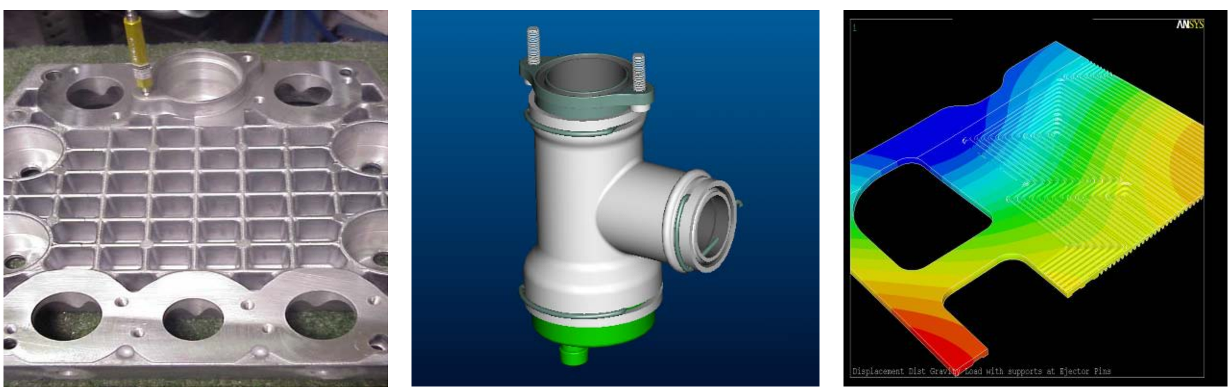
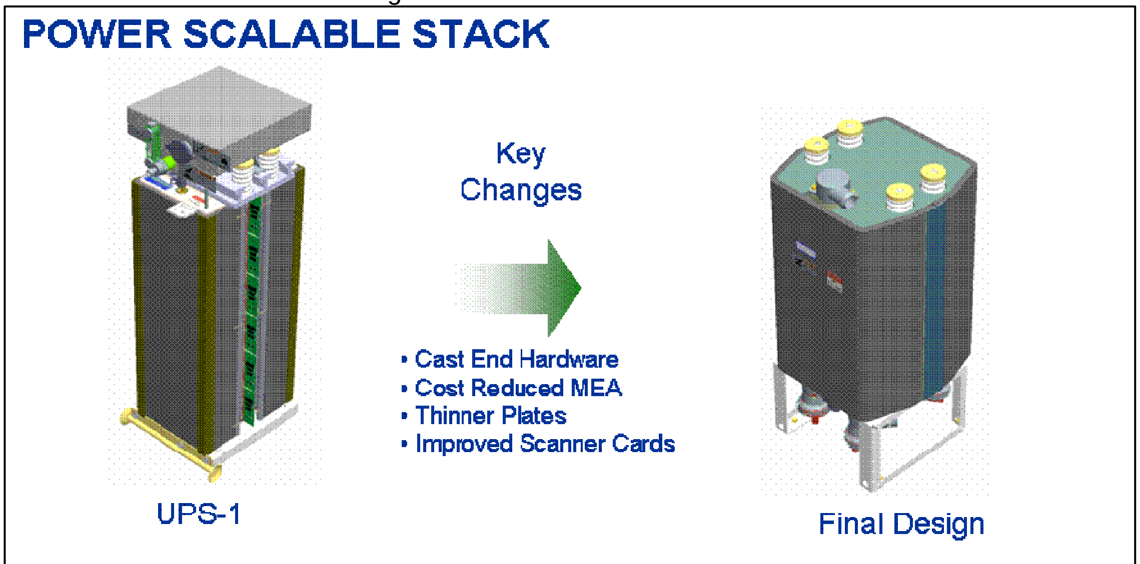


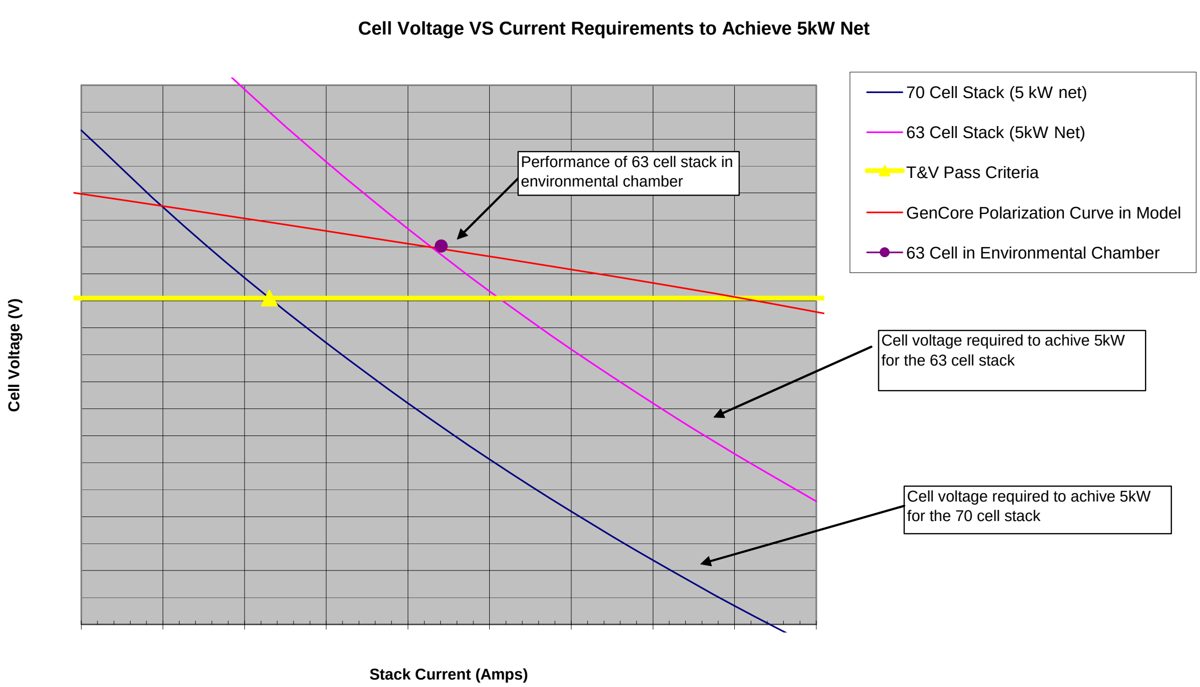
Figure 6 and 7 show data taken from a stack with the improvements identified. The number of cells was decreased and the operating current density increased, allowing for a substantial cost savings while maintaining the desired performance and lifetime.

Figure 6: Stack Performance Data



	UPS –1	Prototype	Final Design
Volume (L)	70	53	53
Weight (Lbs)	~100	~60	~60
Stack Cells (Relative)	100%	79%	71%

Figure 7: Power Scalable Stack

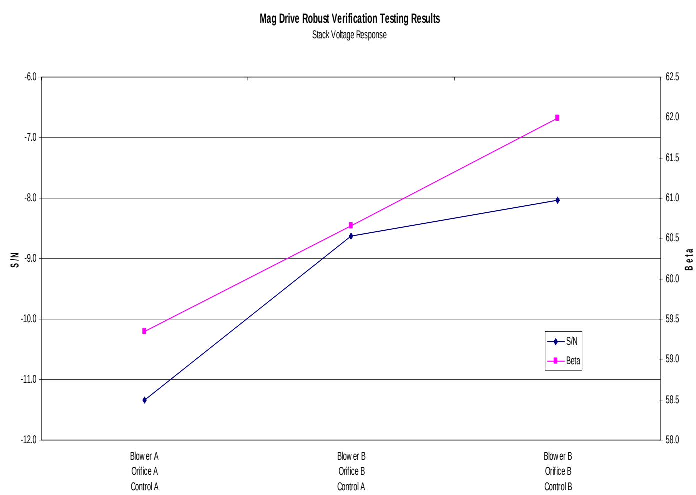


Task 2.4 – Develop H_2 Regeneration Options

The purpose of this task was the development of Advanced Exhaust Gas Recirculation (EGR) and Electrolysis options for the GCII design.

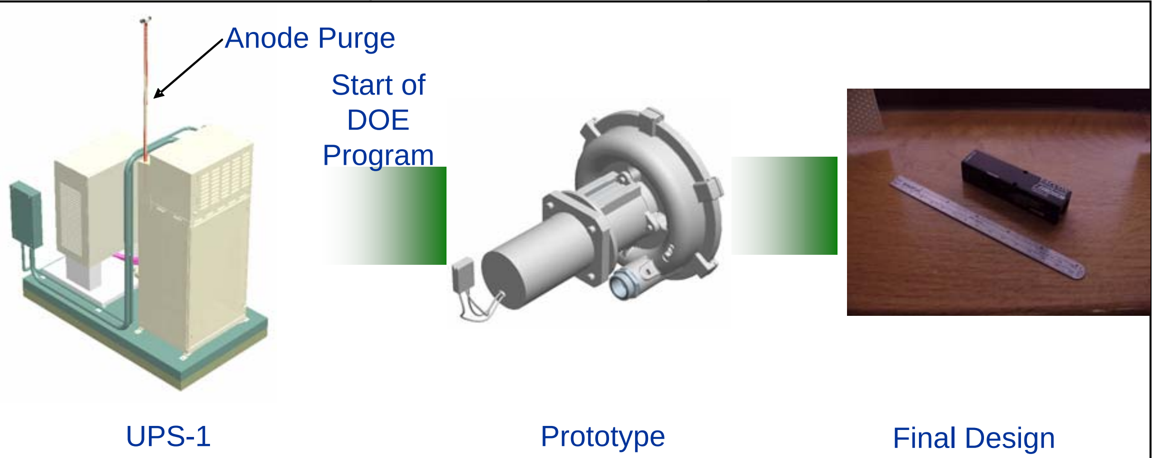
For Advanced EGR, robust design testing drove the selection of a new magnetic drive blower design. Robust design philosophy was used in EGR development. EGR design parameters were selected to optimize system performance reliably in the presence of noises as shown in Figure 8.

Figure 8: Signal to Noise Ratio Analysis of EGR Blower Options



The new design underwent testing and characterization which yielded a new bleed orifice configuration. Using EGR technology allows 100% H_2 utilization but also allows N_2 to build up in the anode circuit. This N_2 must be bled off to the cathode circuit. The original blower design had some natural leakage that allowed the N_2 to pass to ambient. The magnetic drive blower has no leakage and therefore required a larger bleed orifice. This design was adopted for the system and is shown in figure 9.

Figure 9 Advanced EGR configuration



	UPS-1	Prototype	Final Design
Technology	Purge	Blower EGR	Venturi EGR
Siting/H2 Exhaust	70 SLM, 30sec purge	< 1000ppm	< 1000ppm

The Advanced EGR option was very successful by maintaining the advantages of EGR:

- No purge
- Near 100% fuel utilization
- Steady performance at very low turndown (zero net power output)

The Advanced EGR configuration demonstrated a 15% more efficient loop while lowering DMC.

For the Electrolysis Module, twenty-two electrolyzer vendors were evaluated. The vendor selected uses KOH technology. Plug Power defined the scope of the prototype electrolysis system to be delivered. Plug Power and the vendor are completed a P&ID and specification for the module. The preliminary facility safety evaluation was completed and prepared for delivery of an electrolyzer module, however, all existing designs are more expensive than Plug Power specifications and had limited availability and long lead times. Negotiations with the vendor on cost and timing did not yield so the work under the program was discontinued.

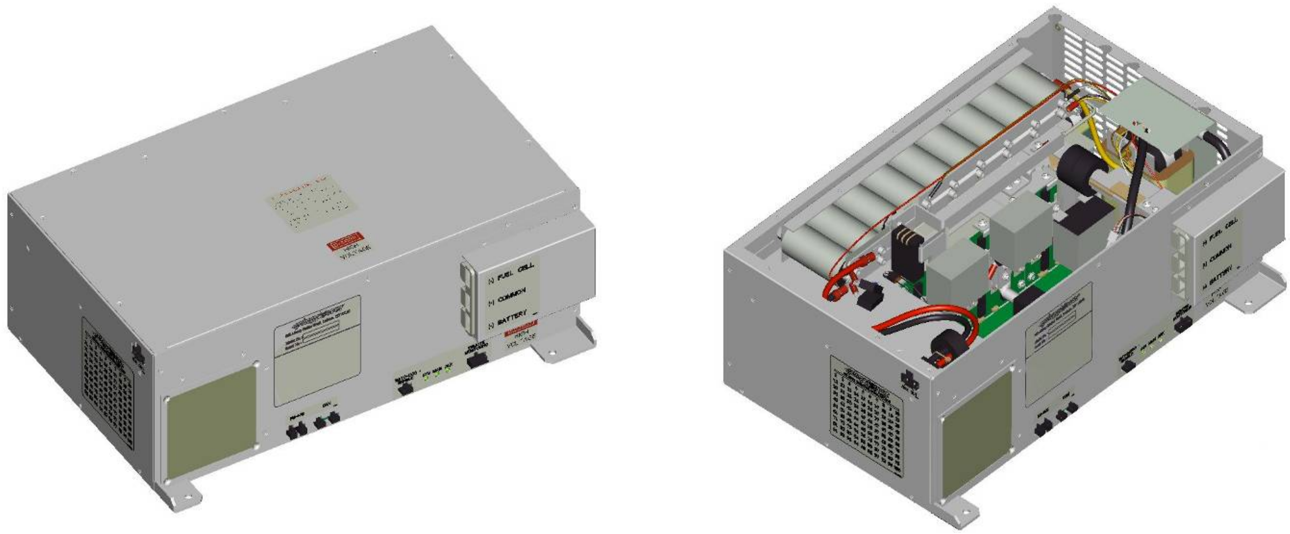
Task 2.5 – Develop Power Conditioning Platform

The purpose of this task was to develop a power-conditioning platform that can be tailored to customers' needs. This platform provides a significant volume and weight reduction over its predecessor with a 13% efficiency gain and a greater than 50% cost reduction.

EMI testing is complete and yielded a variety of design changes to make the platform compatible with FCC Class A. UL testing is complete and also yielded a variety of design changes in order to meet the design requirements.

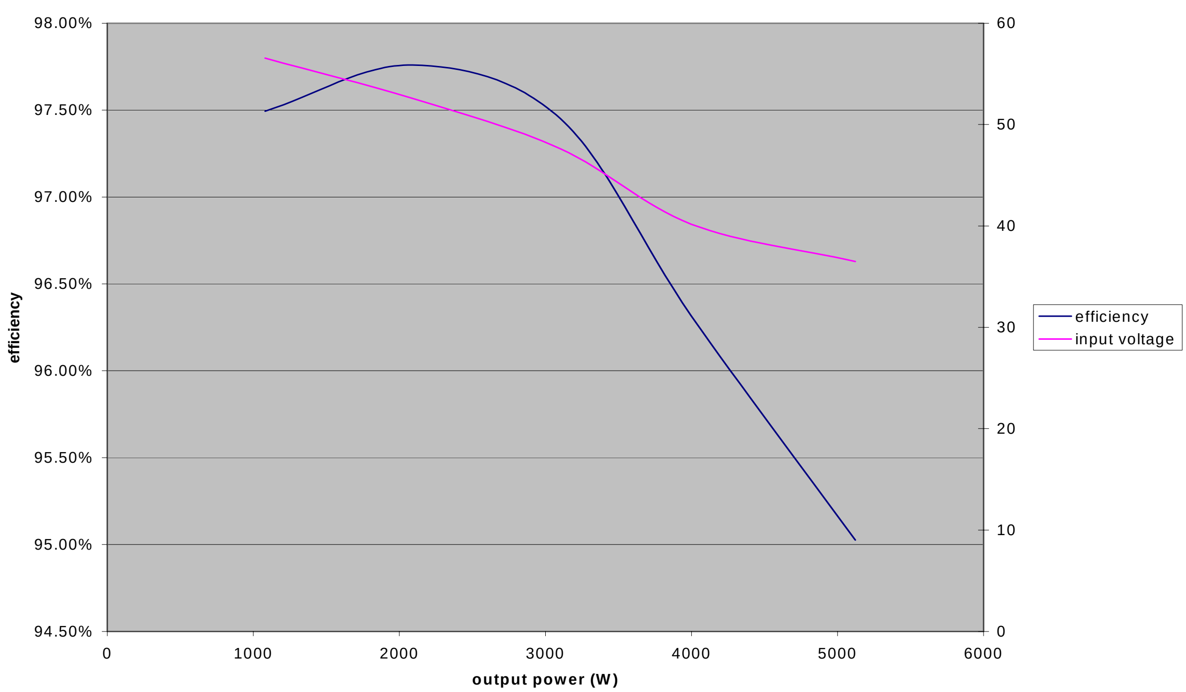
- Electromagnetic Interference issues. EMI testing required revised filtering and internal packaging design.
- UL Learning. The team was required to pot two circuit board components until a revision of the board could be made to reduce the voltage those components were exposed to.
- Additional insulation was required to pass hi-pot testing.

Figure10: Power Conditioning Platform, GC5T Version, with Cover and Without



In its final configuration, the power conditioning platform shown in Figure 10 is capable of delivering +48V DC, -48V DC, 24V DC and 120V DC. Figure 11 shows the results of the efficiency testing of the Power conditioning module.

Figure11: Power Conditioning Efficiency – 120V System



Task 2.6 – Introduce Advanced Electrical Energy Storage

The purpose of this task was to integrate advanced electrical energy storage into the design of the GCII. Supplier engagement of non-lead acid battery technology; i.e. super capacitors and alternate battery chemistries, started in Feb of 2004. Cost appears to continue to be the most significant barrier to incorporating non-lead acid technology.

Module testing for hybrid technology (super caps and VRLAs) started in June 2004. System integration efforts were underway until issues with the Advanced EGR prevented further development of the advance electrical storage module.

Task 2.7 – Develop System Water Balance

The purpose of this task was to enable the system design to recover as much water as it consumes. This task was linked to the electrolyzer technology module schedule and was not started since the electrolyzer work was cancelled. Water production characterization testing was completed.

Task 2.8 – Develop Advanced Hydrogen Storage

The purpose of this task is to develop commercially viable hydrogen storage systems using both standard steel bottles and composite cylinders.

For standard steel bottles initial engineering design for the H_2 storage system is complete. UL testing is complete. NEBs testing did not pass seismic and drop tests and the module had to be redesigned and retested. UL certification was completed as an on-site UL inspection of a supplier's facility was required.

As of December 2004, composite cylinders were determined to not meet the technology and program objectives of the GenCore next generation system at this time. The best vendor quotes were 3X above target and the composite solution presents significant short-term refueling problems with regard to both their transportation and the availability of high-pressure refill equipment among hydrogen merchants. The program stopped work on this initiative.

Task 2.9 – Scale System

The purpose of this task is to scale the system's BOP to meet reliability, size and cost targets. The first iteration of the design was successful with 66% reduction in volume, 53% in weight reduction, and 64% cost reduction.

Significant issues that influence manufacturability and serviceability needed to be addressed:

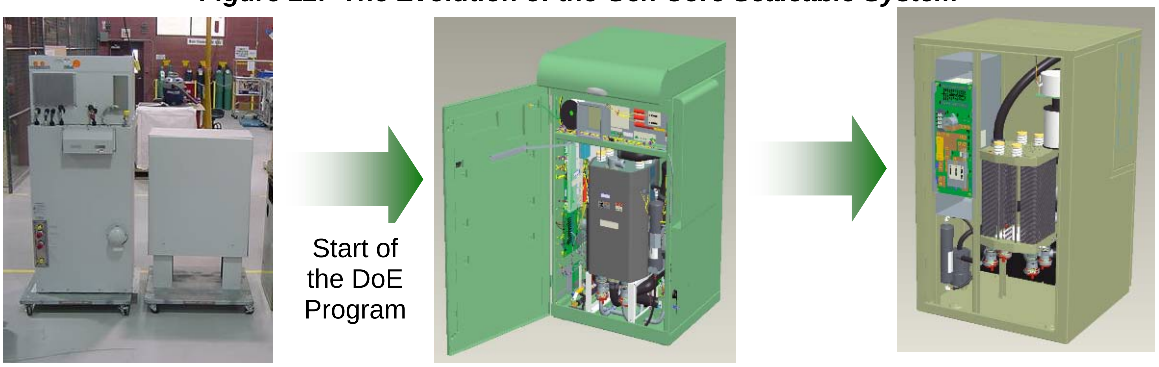
- Significant Df(M) and Df(S) issues
    - Difficult electrical energy storage installation
    - Difficult stack installation
    - Device connectors are susceptible to mis-wiring
    - Replace wire tie-downs with clips
    - Enclosure modifications required
    - Molex pin crimping issues
    - Access to customer connections is difficult
    - Accessibility to serviceable parts is limited
- There has been an emergent severe corrosion issue with glycol/DI water coolant and aluminum thermal management components.

Some key countermeasures were identified:

- System control card redesign for easier modem installation
- Scanner card redesign which eliminated a board and wire harnessing
- Shorter stack is easier to install and requires less time to build
- Enclosure changes have reduced component and harness installation time

The changes will be implemented as rolling cut-ins on the manufacturing floor. Figure 12 shows the evolution of the GenCore product design.

Figure 12: The Evolution of the Gen Core Scaleable System



Task 2.10 – GenSys Stack

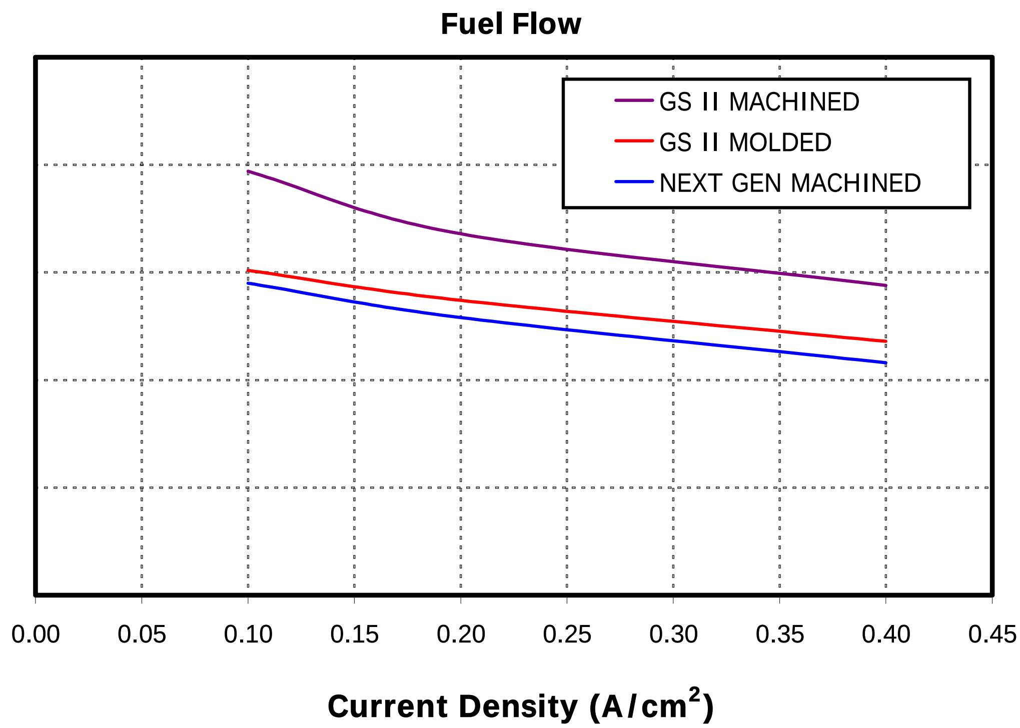
Efforts are focused on plate thickness reduction and gasket configuration as the major cost reduction activities. While water management as it affects peroxide formation and reactant distribution are the major thrusts for stack life improvement.

The detailed initiatives completed under the program were:

- Evaluate flow field design for a range of operating conditions
  –Machined plate testing complete
  –First molded plates on site, assembled and tested
  –Molded plates demonstrate clear superiority to machined
  –Prototypes have demonstrated 2X lower turndown ratios at equivalent stoichiometry
- Computationally study the impact of plate thickness on stack electrical and thermal management
- Investigate opportunities for automated or semi-automated assembly of stacks
- Computational study of plenum configurations
  –Intent: Improve Stack Power Density and Reduce Stack Weight by Right-Sizing the Distribution Plenum
  –Method: Advanced CFD Analysis using FLUENT
  –Have selected reactant plenum size that achieves cell-cell and channel-channel flow distribution criteria.
  –Have CFD Tool and understanding in place to quantify flow distribution impact of hardware changes
- Study impact of stack orientation on performance
  –Experimental work complete (performance testing of horizontal orientation)
- Investigate dry cathode operation
  –Hydration of membrane vs. anode flooding
  –Will be used to validate anode flowfield design
- Characterize how single low cell in stack will impact stack durability
- Determine impact of dormancy on performance
- Freeze/thaw tolerance evaluation
- Gasket technology development for cost reductions
  - Delivery of molded on gaskets

The greatest effort was spent improving the molded plate quality and molded on gasket quality. Figure 13 shows the difference in performance of molded and machine stacks. Once the EGR was selected for integration into the system, the desired convergence of the two stack designs seemed impossible and efforts on a convergent stack were discontinued.

Figure 13: GenSys stack performance



Task 3.1 – Perform UL Testing (GC5T)

The purpose of this task is to certify the GC5T design to UL. United Laboratories was selected as the certifying lab and UL testing was completed December 2003. UL certification received December 2003. Final UL report was completed February 2004 and is summarized in Table 3.

Table3: UL Tests and Results

UL Test (ANSI Z21.83)	Standard	Pass/Fail	Resolutions Required
720 Test	System must run for at least 720 hours and demonstrate its fuel system still passes the Maximum Allowable Leakage test.	Pass	Provided additional information that drove the change to a magnetic drive EGR blower.
Ultimate Strength Flammable Gas	Fuel system must withstand three times its maximum working pressure for one minute and sustain no rupture, fracture or deformation. The system must then pass the Maximum Allowable Leakage test.	Pass	None.
Locked Rotor	Surface temperatures on the windings of motors must not exceed 302 F with the rotor locked.	Pass	Upgraded control card design for the radiator fan.
Noise	System must maintain a noise	Pass	Upgraded radiator fan

	output of < 76 db at maximum output.		to reduce noise.
Ultimate Strength Liquids	Fuel system must withstand one and one-half times its maximum working pressure for thirty minutes and sustain no rupture, fracture or deformation. The system must then pass the Maximum Allowable Leakage test.	Pass	None.
Protection Parameters	The system shall demonstrate automatic shutdown for the following anomalies: high coolant temp, low ventilation flow in the fuel compartment, low coolant flow, smoke/fire, safety circuit sensors out-of-limits.	Pass	None.
Exhaust Gas Temp.	The average temperature of the exhaust gasses of the system shall not exceed the rating of the material of the venting system.	Pass	None.
Surface and Component Temperatures	The maximum temperature of any surfaces that may be contacted by personnel performing routine service may not exceed 152 F.	Pass	None.
Wind Test	The system shall start and operate normally, without damage or malfunctioning, and without creating a hazard or unsafe condition, when exposed to 40 mph winds. The system will then have to pass Hi-pot testing.	Pass	Required redesign of enclosure ventilation outlet.
Leakage Current	The leakage current of the system shall not exceed 0.5 milliamperes.	Pass	None.
HIPOT	Each high-voltage circuit in the system shall be tested at 1000 v plus twice the rated voltage of the circuit for one minute without measurable dielectric material breakdown.	Pass	Required additional insulation in the PCM.
Rain	The system shall start and operate normally, without damage or malfunctioning of any part and without creating a risk of electric shock, when subjected to a simulated rainstorm. The system will then have to pass Hi-pot testing.	Pass	Required redesign of enclosure ventilation outlet.
Ground Continuity	The system's enclosure, frame and similar non-current carrying metal parts are electrically continuous with an electrical resistance of not more than 1 ohm to the point of connection of the ground.	Pass	None.
PCM - evaluate to UL 1012	Evaluate the PCM to "Power Units Other Than Class 2."	Pass	Required circuitry changes in the PCM.
H2 Storage System -	Fuel system must withstand one	Pass	None.

Leakage	and one-half times its maximum working pressure for thirty minutes and sustain no rupture, fracture or deformation. The system must then pass the Maximum Allowable Leakage test.		
H2 Storage System - Ultimate Strength Flammable Gases	Fuel system must withstand three times its maximum working pressure for one minute and sustain no rupture, fracture or deformation. The system must then pass the Maximum Allowable Leakage test.	Pass	None.
H2 Storage System - Ground Continuity	The system's enclosure, frame and similar noncurrent carrying metal parts are electrically continuous with an electrical resistance of not more than 1 ohm to the point of connection of the ground.	Pass	None.
H2 Storage System - 720 Test	System must run for at least 720 hours and demonstrate its fuel system still passes the Maximum Allowable Leakage test.	Pass	None.

Figure 14: Successful Pass of UL Smoke Testing Demonstrating Ventilation and Air Changes

Task 3.2 – Perform NEBS Testing (GC5T)

The purpose of this task is to certify the GC5T to NEBs. NEBS stands for "Network Equipment-Building System." It is a term commonly used to refer to a family of documents that apply to telecommunications equipment located in a Central Office. Two of the most common documents used for testing are GR-63-CORE, Network Equipment-Building System Requirements: Physical Protection, and GR-1089-CORE, Electromagnetic Compatibility and Electrical Safety -- Generic Criteria for Network Telecommunications Equipment.

Reliability of the telephone system is considered a national security issue, is demanded by consumers and makes good business sense. Therefore, NEBS testing is taken very seriously by both Regional Bell Operating Companies (RBOCs) and other service providers as well as manufacturers developing equipment used for the telecommunications network.

Telcordia Labs was selected as the certifying lab, test plans were developed and testing executed. Below are the major subcategories to which the GC5T was tested.

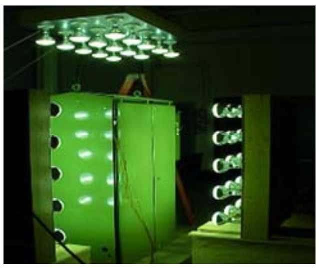
- Electrostatic discharge
- EMI
- Lighting/AC power fault
- Electrical safety
- Corrosion resistance
- Bonding and grounding
- Temperature, humidity and altitude
- Fire Resistance
- Equipment handling
- Earthquake, office vibration and transportation vibration
- Airborne contaminants
- Acoustic noise
- Reflectance, glare and illuminance
- Structure and construction

Figure 15 shows pictures of the actual testing of the GenCore unit to the NEBS certification standards GR 1089, GR- 63 and GR-487.

Figure15 : NEBS Testing of the GenCore

GR 1089 - Electromagnetic Compatibility (EMC) and Electrical Safety

- System-level Electrostatic Discharge (ESD)
- Electromagnetic Interference (EMI)
- Lightning and AC Power Faults
- Steady-state Power Induction
- Electrical Safety
- Bonding and Grounding



GR-63: Network Equipment Building Systems (NEBS) Requirements for Physical Protection

- Temperature and humidity
- Altitude
- Flammability
- Earthquake
- Vibrations
- Airborne contaminants
- Acoustic noise
- Illumination.

GR-487: Generic Requirements for Electronic Equipment Cabinets

- Water and Dust Intrusion
- Wind Driven Rain
- Rain Intrusion
- Lawn Sprinklers
- Weathertightnesss
- Acoustical Noise Suppression
- Wind Resistance
- Impact Resistance
- Firearms Resistance
- Fire Resistance
- Corrosion Resistance
- Shock and Vibration
- Transportation Shock
- Transportation Rail
- Transportation Vibration
- Installation Shock
- Environmentally Induced Vibration
- Earthquake Resistance (Zone 4)

The following list of problems was the result of the NEBS testing and was addressed in the next design iteration.

- EMI testing required revised filtering and internal packaging design.
- The initial design had significant issues with passing the seismic Zone 4 tests, the drop test and the rail test that are requiring enclosure and packaging changes.
- Significant product design learning has been received since beginning NEBs testing. The following bullets are a selection of the over fifty design comments received from the testing agency. This is invaluable information in understanding the requirements of a telecommunication design.
  - Threaded, corrosion resistant (stainless) steel pad or pole mounting hardware, as well as exposed stainless steel cabinet components, shall be passivated to remove surface impurities.
  - All cabinet components made from polymeric compounds shall be resistant to fungus growth. They shall have a fungus growth rating of zero when tested according to ASTM G 21.
  - The manufacturer shall utilize Master Color Standards to identify available cabinet colors. The color of each standard shall be characterized using the CIELAB system of color notation as described in ASTM D 2244. If the customer requires a cabinet color differing from that normally available, an appropriate Master Color Standard shall be utilized.
  - It is desirable that the cabinet be capable of withstanding, without mechanical damage or loss of function, the dynamic impact loads resulting from a wind

speed of 22 m/sec (50 mph) swinging the door open prior to activation of the door restraints.

- Some customers require that all exterior doors and removable access panels have provision for a padlock. In such cases, the padlock hasp shall accept a 0.64 cm (1/4 in) diameter padlock shackle. The normal use of the padlock shall not result in damage to any painted surface.
- Condensation - The manufacturer shall provide instructions and procedures to minimize the formation of condensation on installed electric telecommunications equipment prior to turn-up, in various environments. These procedures shall be documented in the cabinet installation and maintenance manuals.
- Some customers require that the pad extend 61 cm (2 ft) beyond the opened doors of the cabinet to allow for additional working space in and around the cabinet.
- Some customers require that the cabinet manufacturer provide information regarding the rate of temperature rise -- under the solar conditions, loads, and conditions as specified in R3-187 -- in the event that the cabinet active cooling system becomes disabled.
- 150 MPH wind, Perpendicular to largest vertical surface. Cabinet should only have equipment that is present at initial installation (excluding, batteries, circuit packs). Force should be applied 6 inches from the top of the cabinet.
- Cabinet will be subjected to an impact of 100 ft-lbs to each vertical and top surfaces. A 7.3 kg diameter ball will be used. The ball will be dropped 1.9 meters from the top of cabinet. Ball will be 2.4 meters above tied as a pendulum and positioned so that at rest ball is resting against vertical wall. The ball shall then be pivoted until it is raised 1.9 meters and then released. Metallic surfaces of cabinet shall be tested at room temperature. Non-metallic shall be conditioned for minimum 8 hours at -29C prior to testing and should be tested within 10 minutes of being taken from E-chamber
- Cabinet shall resist shotgun blast without any penetration from any BBs. This is done by a 12-gauge shotgun from a 2-3/4 inch, maximum load, from a 28-inch modified choke barrel. A 1-ounce or 1-1/8 ounce load. No.6 steel shot load shall be fired at a distance of 15m perpendicular to the cabinet's vertical surface or test panel.
- System shall be placed in E-chamber for 30 days and exposed to a salt fog spray consistent with GR-2836-CORE and accordance with ASTM B 117. Fans used to circulate air. If fans fail before 14 days it shall be noted. When finished, remove and wash thoroughly in warm, clear water and examined for internal or external for corrosion or damage. A steel cabinet shall have a rust grade of 9 or better per ASTM D 610. If non-metallic there shall be no signs of degradation. FANS- should be exposed to salt fog while non-functioning for 30 days. Can be mounted in cabinet or oriented as it would be in the cabinet. After 30 day period, the fan shall be energized and operate at rated speed for a minimum of one hour after this exposure.

The next design iteration was tested and completed in March of 2004.

Task 3.3 – Perform Field Testing (GC5T)

The purpose of this task is to field test the GC5T. In 2004 thirteen systems were installed and data gathered. These installations are in lab facilities and at telecommunications huts connected to DC buses. The systems have logged over 3,000 operational hours and 2,500 start/ stops. Detailed information on customer training, shipping, installation, commissioning, data collection and operation has been received and is driving design and process improvements that will be addressed in the next round design and cut-in to manufacturing.

Each site host has had technicians certified in Plug Power's Fuel Cell Technician Training Program. The technicians validated the training material and contributed significantly to the program's understanding of customer requirements.

- Shipping: one of the systems was slightly damaged during shipment. The top of the enclosure experienced paint rubs and the EGR fuel line was slightly compressed by the batteries that were allowed to vibrate because their hold down brackets were not tightened sufficiently. This drove packaging and hold down bracket design changes.

- Configuration control: three of the systems shipped with an outdated set of firmware installed on the PCM. New PCMs were shipped to the customers and they were successfully able to swap the PCMs in the field. All remaining PCMs were inspected to ensure configuration and the process for qualifying PCMs was transferred from the lab to manufacturing to prevent reoccurrence.

- Data collection: The GC5T modem is incompatible with European standards. The customer required an adapter to a wireless modem that he could communicate with.

- Operation: One system had to be pulled from the field because of low DC output and unusual cathode exhaust. The customer was sent a new system and the poor performer was evaluated by an 8D Problem Solving team that identified a root cause.

Figure 16: GC5T Installed and Operational at a Site Host's Telecommunications Facility

Task 4.1 – Develop Master Strategy Proposal

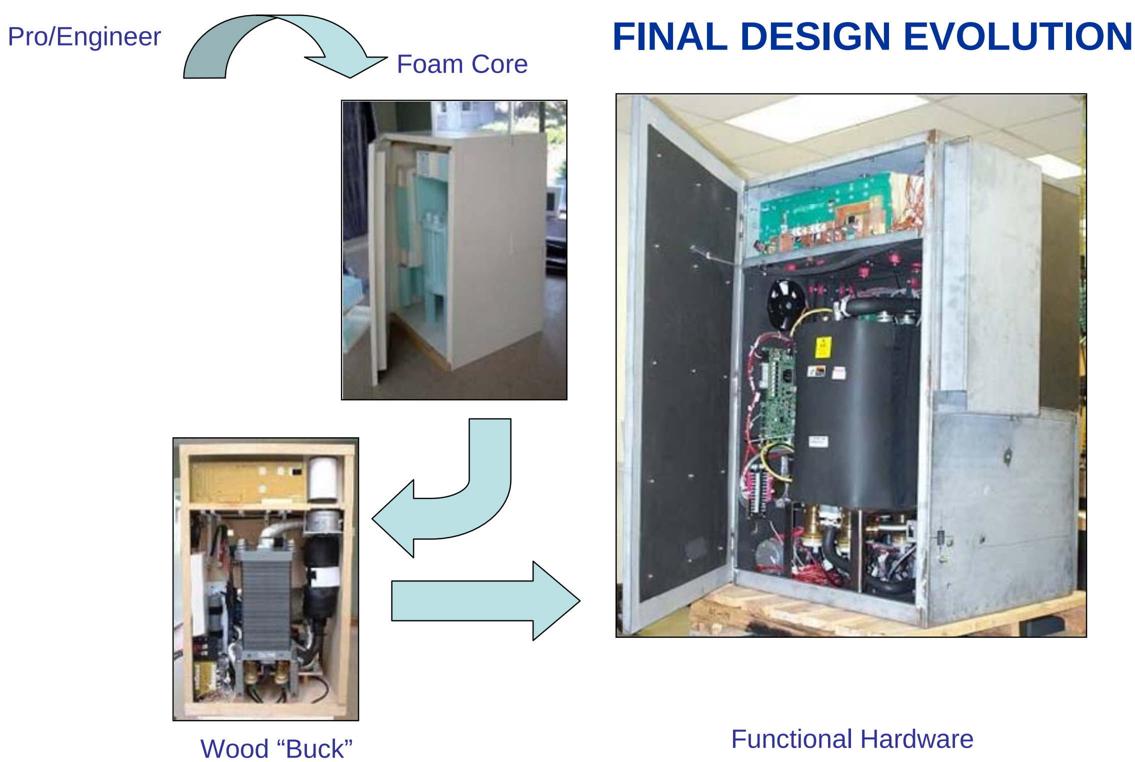
The purpose of this task is to develop the full program proposal for the GCII program. Drafts of the major elements of the proposal (preliminary schedule, preliminary program plan, supply chain management plan, customer support plan) are developed. The program had conference calls with BellSouth for integration purposes. Marketing goals were further refined based on realities of 2004 and 2005 customer tests.

Task 4.2 – Design and DVT Testing

DVT testing was completed in 2005. Task has begun in light of experience with the first generation GenCore, the technology, initiative accomplishments and having received marketing goals for the next generation system.

Several system layout and packaging conceptual designs were evaluated and down selected. Module layout concepts were completed and Figure 17 shows the outcome of the design iteration. Final system requirements document, input/output constraints, critical parameters, and failure modes analysis complete. Final engineering drawings complete. High level system testing completed. Final DVT report was completed.

Figure 17 : Next Generation GenCore Design



Task 4.3 – Build Confirmation and Life Test Systems

Ten confirmation and life test systems were built and commissioned. These systems are the test beds for the high-level system testing described above and the program’s reliability testing. Significant problems were encountered with the advanced EGR. System latitude under certain operating conditions decreased stack life to an unacceptable level. The team spent several months tuning control algorithms to make the EGR acceptable across the broad operating conditions.

Task 4.4 Perform Integrated System Testing

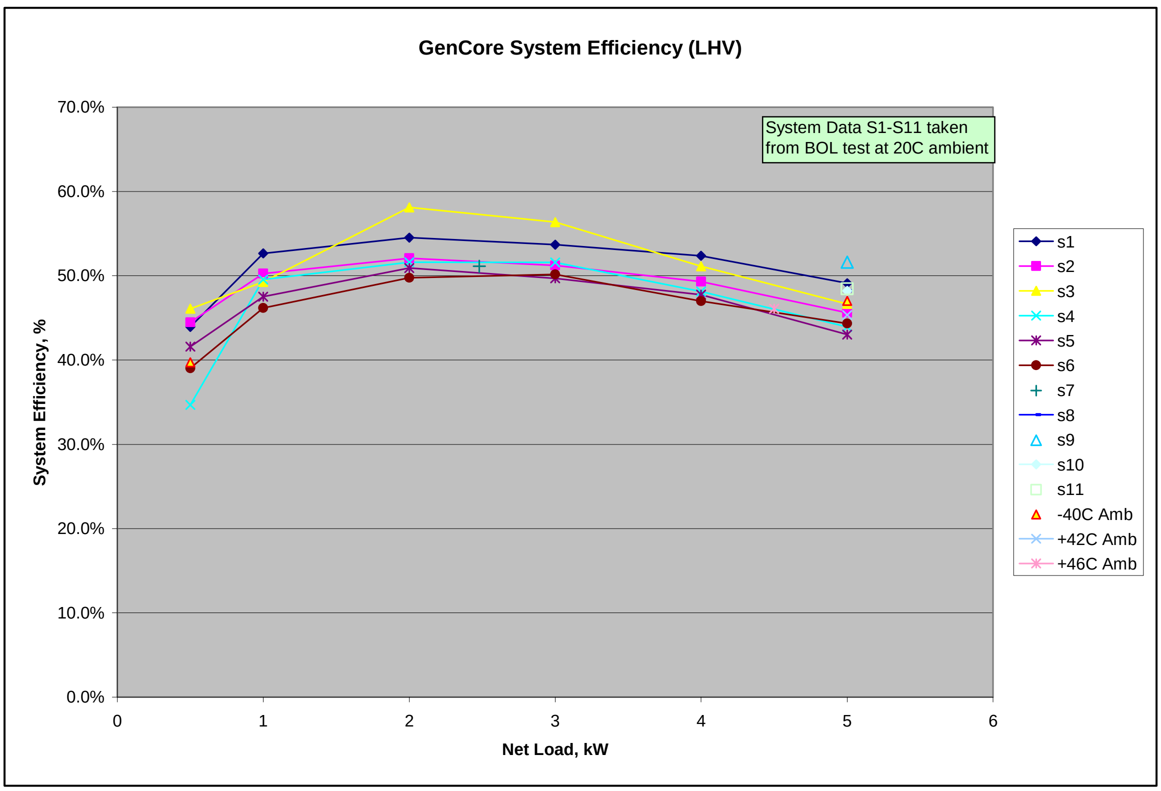
The purpose of this task is to test the full system against high-level system requirements. This is a repetitive process throughout the program as new initiatives and problem fixes are cut into the design.

Units were shipped to BellSouth and Argonne National Labs with advanced energy storage. The system at Bell South was commissioned on June 6, 2006 and continues to operate. Argonne National Labs in Illinois commissioned and ran the GenCore unit. This unit had all of the DOE program improvements and advances except for the actual enclosure and a reduced cost pumping mechanism. The system at Argonne National Labs was installed and tested to the agreed upon test plan. A final test report was submitted by Argonne National Labs in December 2006 and their test report is contained in Appendix A.

Task 4.5 – Build Verification Test Units

Verification test unit build is complete. Systems were built and tested against high-level system specifications generated during this program. See Figure 18. All systems constructed meet high-level system specifications. These systems will now replace some of the older systems in the reliability fleet or will be used as test beds for reliability and cost improvements. Additionally, these systems were used for a full-up system efficiency test to measure the design's progress against DOE targets.

Figure 18: GenCore System Efficiency



Task 4.6 – Conduct Field Demonstration

BellSouth has received one unit and it was commissioned in June 2006. This unit had all of the DOE program improvements and advances except for the actual enclosure and advanced EGR. System is fully operational and running to reliability standards as of this report.

Task 4.7 – Certify Design to NEBS (GCII)

A 24 Volt unit with advanced EGR and energy storage was tested in April 2007. The following was achieved:

- FCC, CE and NEBS Class A Radiated Emissions (RE)
- System RF signature met Class B limits with the doors open after quasi-peaking.
- CE and NEBS Radiated Immunity requirements met in running mode
- FCC, CE and NEBS Class B Conducted Emissions

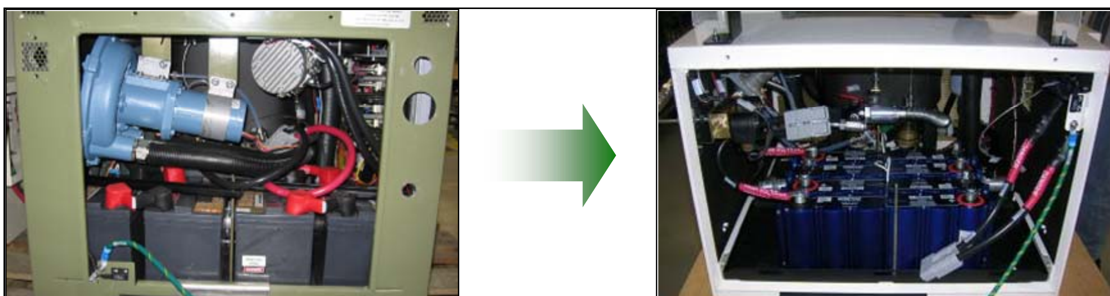
Task 4.8 – Certify Design to UL (GCII)

Advanced EGR certification for the Next Generation System was complete in March 2007. Further witness testing was performed in June of 2007.

Task 4.9 – Demonstrate GCII at DOE

Plug Power requested a no cost program extension thru October 31, 2007 to complete the installation of the unit at the FAA site is Bismarck, North Dakota. The one of a kind system has the enclosure, reduced cost EGR and advanced energy storage. The Advanced energy storage design utilizes ultra capacitors and is shown in Figure 19.

Figure 19: Advanced Energy Storage Design



UPS-1

Final Design

	UPS-1	FINAL DESIGN
Technology	Batteries	UltraCaps
Energy Storage	3 MJ (5kW for 10 minutes)	150 kJ (5kW for 30 Seconds)
Weight	108 lbs	44 lbs

It is the third and final deliverable. The unit was very late to plan mainly because the advance energy storage module needed a reliable EGR solution. Given that the solution was not deemed reliable by Plug Power standards until the introduction of the product in July of 2007, the energy storage development was delayed. Standard models are sold with batteries, and the advanced energy storage is an option. A site visit to the FAA was conducted in September of 2007 and the unit was installed on October 19, 2007. Pictures of the commissioning of this final unit are in Figure 20 below.

Figure 20: Commissioning of the FAA unit

The following information was obtained from the customer regarding the performance of the unit at the FAA site:

> **From:** Stanley.Lee@faa.gov [mailto:Stanley.Lee@faa.gov]
> **Sent:** Tuesday, May 13, 2008 10:21 PM
> **To:** Cassala, Vincent
> **Cc:** Angel.Cuadrado@faa.gov; Lyndin.L.Foss@faa.gov; Pravin.Patel@faa.gov
> **Subject:** Re: Stanley Lee/AGL/FAA is out of the office.
>
> Greetings Vinny,
>
> No, I am not aware of that. Below is a response on your request:
>
> 1. No commercial power outages that I know of. Only self induced commercial power loss for testing purposes. These generally lasted from 15 to 30 minutes.
>
> 2. Plug Power has a good understanding of the FAA operations. During the initial site visit, Plug Power representatives sincerely listen to our needs and understand the urgency of the backup power requirements for FAA communications equipment. Plug Power had installed a 5 KW system for FAA immediate need and Ultra-caps were installed when it becomes available.
>
> 3. If the FAA budget has allocated funds for fuel cell installations and local System Support Centers (SSC) requested, we will implement fuel system in locations that require backup power.
>
> 4. The fuel cell has demonstrated the ability to handle the site load quite nicely. Although a true outage of some duration will be the real test.

5. My exposure to the fuel cell since the ultra-cap mod. has been very limited. I can't say I have noticed any real change in performance.

6. In order for FAA to fund the new equipment system, the fuel cell program must have a budget line item. Presently, there isn't any budget line item for the fuel cell program.

Best regards,

Stanley Lee, P.E.
AJW-C15C
Central Service Area
Engineering Services
Infrastructure Support Center, Chicago
847-294-8457 (O)
847-294-8469 (F)

Summary

- In 2003 and 2004, the Program executed a broad-based initiative to determine requirements for the platform's commercial design, collecting data by:
  - Extensive laboratory testing at Plug Power
  - Field testing of the GenCore® prototype system (13 systems)
  - Certifying the prototype to UL and NEBS requirements
  - Developing a Backup Power Fuel Cell System Requirements Document (SRD) with BellSouth
- Additionally, the Program evaluated ten enabling technologies and selected six for inclusion in the commercial design.
- Finally, the Program completed a new product development of the commercial product design, combining the technical, certification and customer requirements with the feasible technology initiatives in the design of the next-generation platform and field tested the units at real customer sites in 2005, 2006 and 2007.

Figure 21 shows the evolution of the design and the milestones achieved.

Figure 21: Evolution of the GenCore Design

	UPS–1	Prototype	Final Design
Life	800 Hours	1500 Hours	1500 Hours
Coolant	Paralux	Propylene Glycol	Propylene Glycol
H2 management	Purge	Blower EGR	Venturi EGR
Energy Storage	Batteries	Batteries	Ultra Caps
Stack Cells (Relative)	100%	79%	71%
Humidifier	Enthalpy Wheel	Membrane	Membrane

Acknowledgements

Plug Power would like to thank the Department of Energy for funding this program as well as our partners and subcontractors including: Bell South, Argonne National Labs, the FAA, Air Gas and TeleCordia.

Publications and Presentations

1. W.D. Ernst, Small Scale Distributed Stationary Systems – A Status Report. 9th Grove Conference. Westminster, England, October 2005.

2.   Bin Du, Qunhui Guo, Richard Pollard, Daniel Rodriguez, Christopher Smith, and John Elter, "Proton Exchange Membrane Fuel Cells (PEMFCs): Technology Status and Challenges for Commercial Stationary Power Applications". JOM is Journal of The Minerals, Metals & Materials Society, Volume 58, Issue 7, July, 2006

Appendix A

Argonne National Laboratory

Test Report

Summary Report

PERFORMANCE AND LIFE OF THE GENCORE 5-KW FUEL CELL SYSTEM FROM PLUG POWER, INCORPORATED

Prepared for the
U.S. Department of Energy
Hydrogen, Fuel Cells and Infrastructure Technologies Program

Prepared by
I. Bloom and J. Basco
Electrochemical Technology Program
Argonne National Laboratory

December 2006

FOREWORD

The U.S. Department of Energy, Hydrogen, Fuel Cells and Infrastructure Technologies (HFCIT) Program, supported this work. The HFCIT program managers are Nancy Garland and Kathi Epping. The tests were conducted in the Electrochemical Analysis and Diagnostics Laboratory (EADL) at Argonne National Laboratory, which is operated under the auspices of the U.S. Department of Energy under Contract No. DE-AC02-06CH11357.

EXECUTIVE SUMMARY

A GenCore, 5-kW fuel cell system (5T48) was obtained from Plug Power, Inc. The GenCore represents an intermediate stage of development of fuel cell technology. It was designed to a satisfy requirements developed for its intended application as a telecommunications back-up power system using bottled hydrogen as fuel. In this application the system remains in a ready condition to supply power reliably and with the shortest possible start-up time when grid power is lost. Operation is not continuous and not more than a few hundred hours of operation is expected in any one year consisting of multiple runs of minutes to tens of hours. The stack in the system consists of 63 polymer electrolyte membrane based fuel cells which are electrically connected in series. Cell 1 is the most negative cell; and cell 63, the most positive. The performance and life of the system was evaluated according to a test protocol developed for an application for which the system was not originally designed. Under this test protocol the life of unit was rated at 1000 h.

The performance of the module was evaluated in terms of polarization curves and constant power tests at 25% of rated power. The evaluation demonstrated that 5 kW could be produced at 48% energy efficiency. The life of the system was gauged by using a combination of cycling protocols, two from Plug Power and one from DOE. The results are compared summarized in Table E-1. Since no technical targets were available for stationary systems using direct hydrogen, no comparisons can be made.

Table E-1. Summary of Performance Data from the GenCore 5-kW System

Characteristic	Units	Performance
Stack power density	W/L	104^{+}
Stack specific power	W/kg	201^{+}
Stack efficiency at 25% of rated power	%	50*
Stack efficiency at rated power	%	47.8*
Durability with cycling	hours	1148**

$^{+}$Stack only; using the system weight and volumes decreases these values by a factor of 8.3 to 8.4.
*Based on the service data from the GenCore unit.
**Composite total, consisting of all cycling regimes. Individual cycling times are as follows. 12-h-on/12-h-off: 224 h; 1-h-on/23-h-off: 242 h; DST: 682 h.

The end of test was reached when the stack voltage decreased by more 10% during the dynamic stress test duty cycle. At that time, the average cell voltage had dropped to 0.54 V from 0.66 V at 500 mA/cm^2.

TABLE OF CONTENTS

Page

LIST OF FIGURES AND TABLES

Page

LIST OF FIGURES AND TABLES (continued)

Page

1 INTRODUCTION

As part of the Department of Energy's (DOE) Hydrogen, Fuel Cells and Infrastructure Technologies Program, the Electrochemical Analysis and Diagnostics Laboratory at Argonne National Laboratory evaluated a 5-kW GenCore system (5T48) from Plug Power, Inc. The GenCore unit is a complete system, which includes its own air, water and fuel management subsystems. It was designed to a satisfy requirements developed for its intended application as a telecommunications back-up power system using bottled hydrogen as fuel. In this application the system remains in a ready condition to supply power reliably and with the shortest possible start-up time when grid power is lost. Operation is not continuous and not more than a few hundred hours of operation is expected in any one year consisting of multiple runs of minutes to tens of hours. When attached to the telecommunications system (the customer bus), the GenCore unit was designed to output a maximum of 5 kW. The performance and life of the system was evaluated according to a test protocol developed for an application for which the system was not originally designed. Under this test protocol the life of unit was rated at 1000 h.

The delivered system was packaged in the enclosure, as shown in Figure 1.1. This system contained ultracapacitors instead of the usual lead-acid batteries for system startup.

The system contained a polymer electrolyte fuel cell stack which consisted of 63 cells which were electrically connected in series. Cell 1 was the most negative; cell number 63 was the most positive. The active area was 262 cm^2 per cell. Bottled hydrogen was the fuel.

Figure 1.1. GenCore 5-kW System

The system was interfaced to the test facility control computer and alarm system by using analog signals. As suggested by Plug Power, a safety switch was installed between the load and the GenCore system.

The test plan, which outlines the planned experiments, is given in Appendix I. All experiments followed DOE's test plan for gauging the durability of fuel cell hardware for transportation applications.

2 RESULTS

Graphs of performance and other figures are given in Appendix II as Figs. 1 to 21.

2.1 Characterization

2.1.1 Sequential Polarization Curve (Figs. 1 to 3) The sequential polarization curves consisted of a 6 minute hold at desired current densities, a 15-s current interrupt and a final 1-minute hold at the set current density before going to the next point.

In practice, the polarization curve was obtained demanding that a certain system power level be delivered to the customer power bus. However, the data of interest were obtained at the stack level from the service interface of the GenCore system. It also should be noted that, even at zero power being delivered to the customer bus, the stack is still under load. This is seen in the service data. The stack still powers internal devices, such as fans and pumps. Thus, the polarization curves do not start at zero current.

Fig. 1 shows the polarization curve at characterization. There is some difference in the polarization behavior which depends on the direction of current increase/decrease. This difference, about 1 V for the stack, is most evident in the mid- to low-current density ranges, 100 to 200 mA/cm^2. A maximum power of 5.6 kW was measured.

Examining the cell-by-cell voltages during this polarization experiment (Fig. 2) shows that the cell voltage ranges from 0.65 to 0.68 V at 500 mA/cm^2. The average cell voltage is 0.67 V at characterization. Also from Fig. 2, cells 1 and 63 appear to be the weakest.

Fig. 3 shows how the thermodynamic efficiency of the stack changes with current density. At about 25% of measured maximum power, the efficiency is about 50%. At higher power levels the efficiency decreases to about 48%. It should be noted here that these data are from a model that is internal to the GenCore service data interface. Since no direct measurements of fuel consumption were made, these values are approximate.

2.1.2 Random Polarization Curve (Figs. 4 to 7). The objective of this experiment is to measure the polarization behavior free of the humidification artifacts. In the sequential polarization, the high humidification level at the high current densities may enhance the conductivity of the membrane on the decreasing current portion of the experiment. The randomness of this experiment removes this possible artifact from the data.

Fig. 4 shows the response curve from random polarization experiment. During this experiment, the response at each current density was measured twice. Based on Fig. 4, there was very little difference (beyond experimental error) between the two measurements. A maximum power of 5.5 kW was measured.

Fig. 5 shows how the cell potential at 500 mA/cm^2 varies with cell number. Cells 1, 32 and 63 appear to be weaker than the others. The maximum cell voltage was 0.68 V and the minimum, 0.64 V. The average cell voltage in the stack was 0.66 V.

Fig. 6 shows the energy efficiency of the stack vs. current density. At about 25% of measured maximum power, the efficiency is about 51%. At higher power levels the efficiency decreases to about 48%.

Comparing the results from the two types of polarization curves (Fig. 7) shows that there are differences between them. At the intermediate current densities (100 to 400 mA/cm^2), the difference between the curves ranges from 0.4 to 2.4 V when comparing the random curve to that from increasing current curve and from 0.5 to 1.4 V when comparing the random curve to that from the decreasing current curve.

2.1.3 Constant Power for 50 h (Figs. 8 to 9). Fig. 8 shows the voltage, current and power response of the stack during the constant power test. The power level was 1.5 kW. It should be noted that there was an initial settling period of about 6 h. Thus, the stack was truly at constant power for about 44 h. During the 44 h of the test, the potential of the stack of the stack decreased. The average rate of the stack voltage decrease was 19.6 mV/h or about 0.3 mV/h/cell.

Analysis of the cell data showed that some cells were weaker than others. A histogram showing the frequency that a given cell was the weakest in the stack is given in Fig. 9. If two cells displayed the same voltage and that voltage was lower than that from the other cells, it is possible that two (or more) cells would be labeled as the weak cells. From the figure, cells 1 and 63 were the weak cells during this experiment.

2.2 Aging/Durability

Three aging protocols were used during this portion of the test. The first two were suggested by Plug Power as being typical of what they use and third was from DoE's durability test plan. The protocols were 12-h-on/12-h-off, 1-h-on/23-h-off and dynamic stress test (DST) cycling. As used here, the "on" periods were when the GenCore unit was delivering power to the customer bus, and "off", when it was idle and not delivering power to the customer bus (that is, the unit was still powering its internal components). The protocols were used for 224, 242 and 682 h, respectively. The cumulative time for the durability test was 1148 h.

Before starting the durability tests, the stack was characterized in terms of its polarization behavior. The same characterization test was used at the end of the aging period. These intermediate characterization tests are called reference performance tests or RPTs. The RPTs are numbered sequentially, starting at the beginning of the aging experiments.

2.2.1 12-h on/12-h off (RPTs 0 to 2; Figs. 10 to 12). Figure 10 shows how the polarization response of the stack changed during this aging period. During this aging period, the stack potential at 500 mA/cm^2 decreased from 41.2 to 40.6 V for an average rate of decline of 2.6 mV/h or about 0.04 mV/h/cell.

The uniformity of the cell voltages at RPT2 is given as a histogram in Fig. 11. From this figure, cell 63 appears to be the weakest cell in the stack. The average cell voltage was 0.68 V. The maximum cell voltage was 0.69 V and the minimum, 0.66 V.

Fig. 12 shows the thermodynamic efficiency of the stack after the aging period. At full power, the stack was 45.2% efficiency and at 25% of rated power, the efficiency was 51.5%.

2.2.2 1-h on/23-h off (RPTs 2 to 4; Figs. 13 to 15). Figure 13 shows the polarization response of the stack with aging. During this aging period, the relative amount of time at high potential, though not at true open circuit, was about twice as long as that in the previous aging period. As expected, the polarization curves indicate that there was a decline in stack voltage with time on test. During this aging period, the stack potential at 500 mA/cm^2 decreased from 40.6 V to 39.7 V at an average rate of 3.8 mV/h. This rate corresponds to a cell-level rate of 0.06 mV/h/cell.

The uniformity of the cell voltages at RPT4 is given as a histogram in Fig. 14. From the figure, cell 63 is the weakest cell in the stack. At RPT4, the average cell voltage at 500 mA/cm^2 was 0.63 V with the maximum and minimum voltages of 0.65 and 0.61 V, respectively.

Fig. 15 shows the thermodynamic efficiency of the stack at RPT4. At full power, the stack was 44.3% efficiency and, at 25% of rated power, it was 46.9% efficient.

2.2.3 DST cycling (RPTs 4 to 8; Figs. 16 to 19). Fig. 16 shows the response of the GenCore unit during DST cycling. From the figure, the unit did not keep pace with the changing current demands. The voltage response did not mirror the square transients well; instead, they were truncated.

Fig. 17 shows how the polarization curves change with aging during the DST cycling portion of the aging experiment. It should be noted that the GenCore unit generated more current as the stack voltage declined to keep the power output of the unit constant. The unit reached the end-of-test during this aging period. During this aging period, the stack voltage declined from 39.7 V to 33.8 V, a decrease of more than 10%. The average rate of decrease for the stack was 9.0 mV/h or about 0.14 mV/h/cell.

Fig. 18 shows the uniformity of the cell voltages at RPT8. As expected, the weakest cell was cell 63. It should be noted that, in general, the cell voltages declined markedly at 500 mA/cm^2. The average cell voltage had dropped to 0.54 V from the initial value of 0.66 V at 500 mA/cm^2.

Fig. 19 shows the thermodynamic efficiency of the stack at RPT8. At full power, the efficiency of the stack is 33%; while at 25% of rated power, it is 42.4%.

2.2.4 Summary of aging data (Fig. 20). Fig. 20 shows the stack potential at 500 mA/cm^2 behavior from all the RPTs. The figure shows that the stack potential decreases during the aging experiments. In the beginning, the apparent rate is low and appears linear. Additionally, the rate appears to depend on the amount of time the stack was idle. When the stack went into the DST portion of the aging experiments, the apparent, initial rate was lower than those of the previous periods. However, as the DST aging experiment continued, the stack potential decreased sharply.

2.2.5 End-of-Test Examination (Fig. 21). The GenCore test lasted longer than its rated life. The door to the GenCore unit was opened to determine if there were any changes in the balance-of-plant. Fig. 21 shows that there was a colorless liquid present on the bottom of the GenCore unit and on the bottom grey plate of the stack. After conferring with Plug Power, this liquid is most likely ethylene glycol from the cooling system.

3 Comparison to DOE's Technical Targets

Since no technical targets were available for stationary systems using direct hydrogen, no comparisons can be made. Instead, the performance and life data are summarized in Table 3.1.

Table 3.1. Summary Performance Data from the GenCore 5-kW System

Characteristic	Units	Performance
Stack power density	W/L	104^{+}
Stack specific power	W/kg	201^{+}
Stack efficiency at 25% of rated power	%	50*
Stack efficiency at rated power	%	47.8*
Durability with cycling	hours	1148**

$^{+}$Stack only; using the system weight and volume decreases these values by a factor of 8.3 to 8.4.
*Based on the service data from the GenCore unit.
**Composite total, consisting of all cycling regimes. Individual cycling times are as follows. 12-h-on/12-h-off: 224 h; 1-h-on/23-h-off: 242 h; DST: 682 h.

3.1 Stack Power Density

The volume of the stack is 53 L. The measured power was 5.5 kW, resulting in a power density of 104 W/L. This unit was not designed for transportation applications.

3.2 Stack Specific Power

The specified dry weight of the stack is 27.3 kg. Using this value and the measured power yields a specific power of 201 W/L.

3.3 Energy Efficiency @ 25% of rated power

The calculated system thermodynamic energy efficiency at 25% of rated power (1.25 kW) was 50% at steady state. This efficiency was calculated from an internal model that Plug Power incorporated in the system.

3.4 Energy Efficiency @ rated power.

The calculated system energy efficiency at rated power (5 kW) was 47.8%. This efficiency was calculated from an internal model that Plug Power incorporated in the system.

3.5 Durability

The durability of the device was 1148 h. This is longer than the rated lifetime of the device. Since no data are available, no comparison can be made to DOE's target for stationary power systems using direct hydrogen.

Appendix I.

DOE / ANL TEST PLAN FOR

Plug Power GenCore PEM FUEL CELL SYSTEM

[Created: 25-May-06]
[Revised: 29-Aug-2006]

Approved: ....
Kathi Epping, DOE **Date**

Acknowledged:.. ....
Dan Rodriguez, Plug Power **Date**

Acknowledged:.. ....
Ira Bloom, EADL *Date*

DOE / ANL TEST PLAN FOR

Plug Power GenCore PEM FUEL CELL SYSTEM

1.0 <u>Purpose and Applicability</u>

This document outlines a series of tests to assess the performance of a 5-kW fuel cell system by Plug Power. The system is designed for telecommunications backup power applications and will undergo performance evaluations using the procedures developed by ANL and Plug Power.

The stack will be tested at Argonne National Laboratory (ANL).

2.0 References

1. Test Procedures for the Argonne National Lab Fuel Cell Test Facility, Revision 0, March 2001
2. Fuel Cell Power Systems Performance Test Codes, ASME PTC 50-2002, November 2002

3.0 Equipment

Existing ANL-EADL equipment will be used to conduct these tests.
Measurements will include:

- Stack Voltage
- Stack Current
- Output Voltage
- Output Current
- Coolant Inlet and Outlet Temperature
- Coolant Inlet Pressure
- Coolant Flow
- Coolant Conductivity
- Fuel Inlet and Outlet Temperature
- Fuel Flow
- Fuel Inlet Pressure
- Fuel Relative Humidity
- Fuel Outlet Pressures
- Oxidant Inlet and Outlet Temperature
- Oxidant Flow
- Oxidant Inlet Pressure
- Oxidant Relative Humidity
- Oxidant Outlet Pressures

4.0 Prerequisites and Pre-Test Preparations – Incoming Inspections

4.1 The stack will be visually inspected for signs of shipping or other damage. The actual weight of the stack as received will be recorded. Digital photographs will be taken before and after setup.

4.2 Prior to the start of testing, a pre-test readiness review will be conducted using the released version of this test plan and the associated test procedures. The readiness review should be attended by the project engineer (or designee), the test laboratory manager, and the test engineer assigned to the test. An external readiness review involving DOE Manager may be required at his/her discretion, and it may be in addition to or in lieu of an internal review.

4.3 Prior to testing, the GenCore unit will be checked out by a technician from Plug Power. The technician will install the ultracapacitors.

5.0 Stack Specifications

5.1 Stack Construction	63 PEM fuel cells
5.2 Stack Nominal Voltage	60 V OCV; TBD V at full power
5.3 Stack Operating Temperature	50^{o}C (inlet coolant temperature)
5.4 Stack Weight	41 kg (dry, maximum)
5.5 Stack Internal Resistance	TBD Ω
5.6 Limiting Conditions	
Lowest Cell Voltage	< TBD V

5.7 Operational Procedure and Limits
Maximum constant current 109 A
Minimum voltage TBD V OCV; TBD V at full power – these are programmable

5.8 End-of-Testing Criterion: Stack testing will last approximately 3000-4000 h. Testing will stop here or until directed by the Test Lab or the DOE Program Manager.

6.0 Safety Concerns and Precautions

- The unit develops >50 V_{DC} when reactants are introduced. To avoid electric shock, the terminals should not be touched. The unit must be kept out of water.
- The unit should be stored and used in an area that is shielded from accidental exposure to personnel. Storage of the unit should include covering of port fittings to avoid accidental contamination from foreign matter.
- Since hydrogen is in use, a sign stating "Hydrogen in Use" will be

posted on the laboratory door. There will be proof of adequate ventilation before testing begins.

- Continual monitoring of the hydrogen sensor on the unit to ensure hydrogen external leaks have not occurred.

7.0 Tests to be Performed under this Test Plan

The stack will be subjected to the performance test sequence given below:

Sequence Number	**Test**	**Approximate Test Time [hours]**	**# of Iterations**
7.0	**Checkout / Verification Tests** The stack will be manually cycled between current levels sequentially from 0A to 100A to verify proper integration of the unit and test equipment.	8	1
7.1	**Sequential Polarization Curve** Current levels of 0, 10, 20, 40, 60, 80, and 109 A will be attempted. The pulsed-polarization curve technique will be used. Each current level will be held for 6 min; the current	1.5	1

	interrupted for 15 s (OCV) and the current turned back on for 1 min. Curve will be completed ascending (from 0 to 109 A) and descending (109 to 0 A). This test may be repeated, if necessary. The stack will be held at OCV for no more than 2 minutes. Changes in current level will occur over a period of 15-30 seconds.		
7.2	**Random Polarization Curve** Current levels of 0, 10, 20, 40, 60, 80, and 109 A will be attempted. The pulsed-polarization curve technique will be used. Each current level will be held for 6 min; the current interrupted for 15 s (OCV) and the current turned back on for 1 min. The current levels will be chosen at random. Each current	1.5	1

	level will occur twice in the sequence and the same current level will not occur sequentially. This test may be repeated, if necessary. The stack will be held at OCV for no more than 2 minutes. Changes in current level will occur over a period of 15-30 seconds.		
7.3	**Constant Power** The unit will be held at 25% of rated power for a period of 50 h.	50	1
7.4	**Start/Stop/Durability** After completing the above tests, the unit will undergo a reference performance test and then be subjected to start/stop/durability testing. The	500	1

	testing is divided into two types, depending on duration. (a) Long duration runs: The unit will perform a duty cycle of 12 hours on and 12 hours off for a period of 250 h. For each on-cycle, the power level will be chosen at random and will be in the range of 1 to 5 kW. Response time of the unit will be measured. (b) Short duration runs: The unit will perform a duty cycle of 1 hour on and 23 hours off for a period of 250 h. For each on-cycle, the power level will be chosen at random and will be in the range of 1 to 5 kW. Response time of the unit will be measured.		

	Reference performance tests, as described in Section 7.6, will be performed to gauge system performance with time on test.		
7.5	**Driving Duty Cycle** After completing the test described in Section 7.4, the unit will be undergo a reference performance test and then be subjected to a driving duty cycle. The profile is given as Fig. 1 and Table in Appendix A. The 6-minute profile will be repeated continuously. Reference performance tests, as described in Section 7.6, will be performed to gauge system performance with time on test.	500+	1
7.6	**Reference Performance Tests** Reference performance tests will be conducted on a periodic basis	4-5	12-14

	during the tests in Sections 7.4 and 7.5 to gauge the change in performance of the unit. The reference performance test will consist of the same sequential polarization curve that was used in Section 7.1. The polarization curve will be measured after the system has been running at 1 kW for 30 minutes. The interval for the reference performance test is approximately 100-125 h.		

8.0 Anticipated Results

8.1 Performance and Durability Testing

The goal of these tests is to provide an unbiased basis for the comparison of the GenCore with other polymer electrolyte fuel cell technologies. The results will also help model the performance of the unit under steady state and transient conditions and under long-term operation. For this purpose, using laboratory control of the experimental conditions is mandatory.

8.2 Deliverables

Monthly summary reports will be sent to DOE. A final report will be sent to DOE.

9.0 Contacts

Company	**Name**	**Phone**	**Email**
Plug Power	Dan Rodriguez	518-782-7700 x1350	dan_rodriguez@Plug Power.com
EADL /	Ira Bloom	630-252-4516	Ira.Bloom@anl.gov

ANL			
US DOE	Kathi Epping	202-586-7425	Kathi.epping@ee.doe.gov

Appendix A.

Figure 1 Dynamic Stress Test

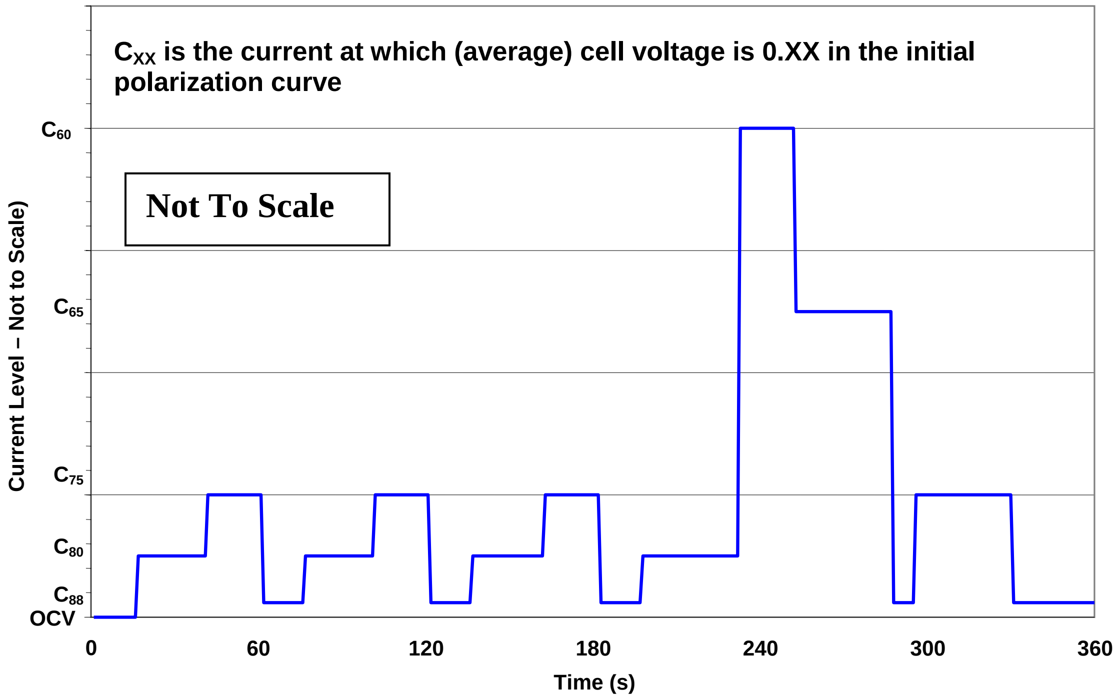


Table 1 – Current Density vs Time for the Cycle Profile

Step	Duration sec	C_{XX}		Step	Duration sec	C_{XX}
1	**15**	**OCV**		9	20	C_{75}
2	25	C_{80}		10	15	C_{88}
3	20	C_{75}		11	35	C_{80}
4	15	C_{88}		12	20	C_{60}
5	24	C_{80}		13	35	C_{65}
6	20	C_{75}		14	8	C_{88}
7	15	C_{88}		15	35	C_{75}
8	25	C_{80}		16	40	C_{88}

Appendix II.

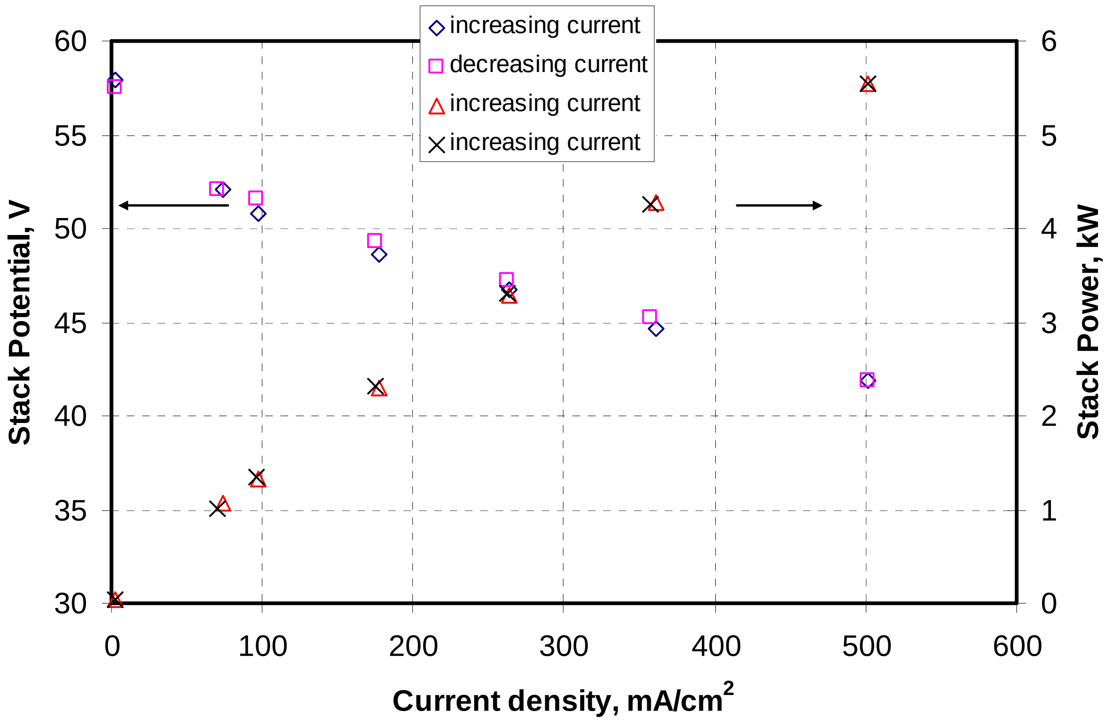


Fig. 1. Stack potential and power vs. current density at characterization.

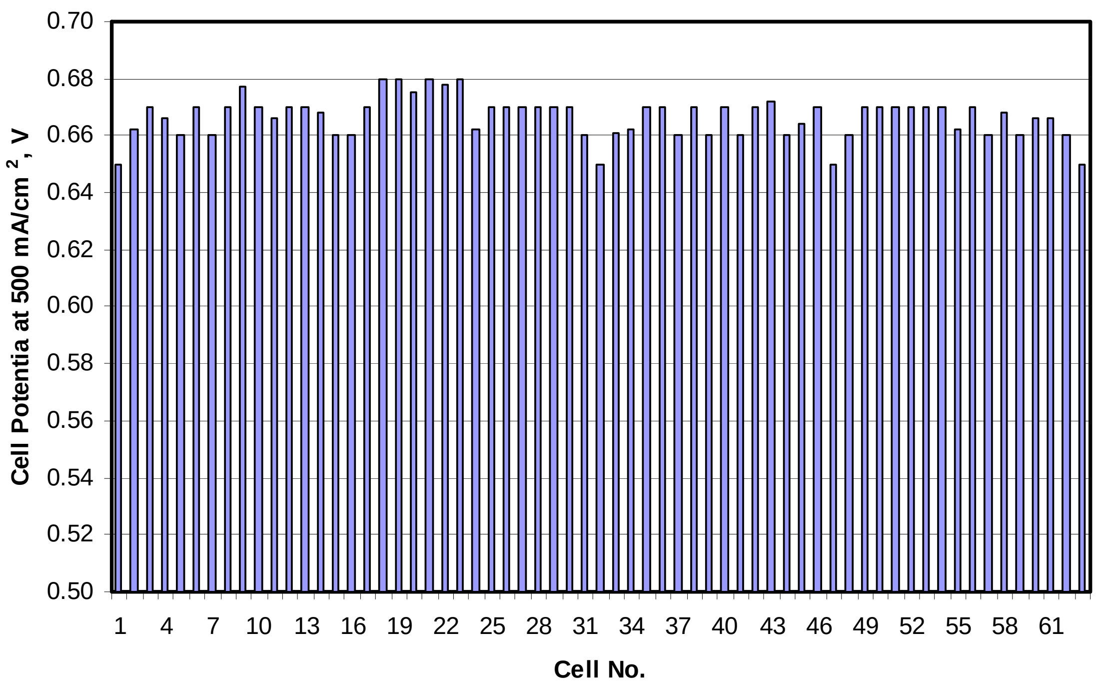


Fig. 2. Cell potential at 500 mA/cm^2 vs. cell number at characterization.

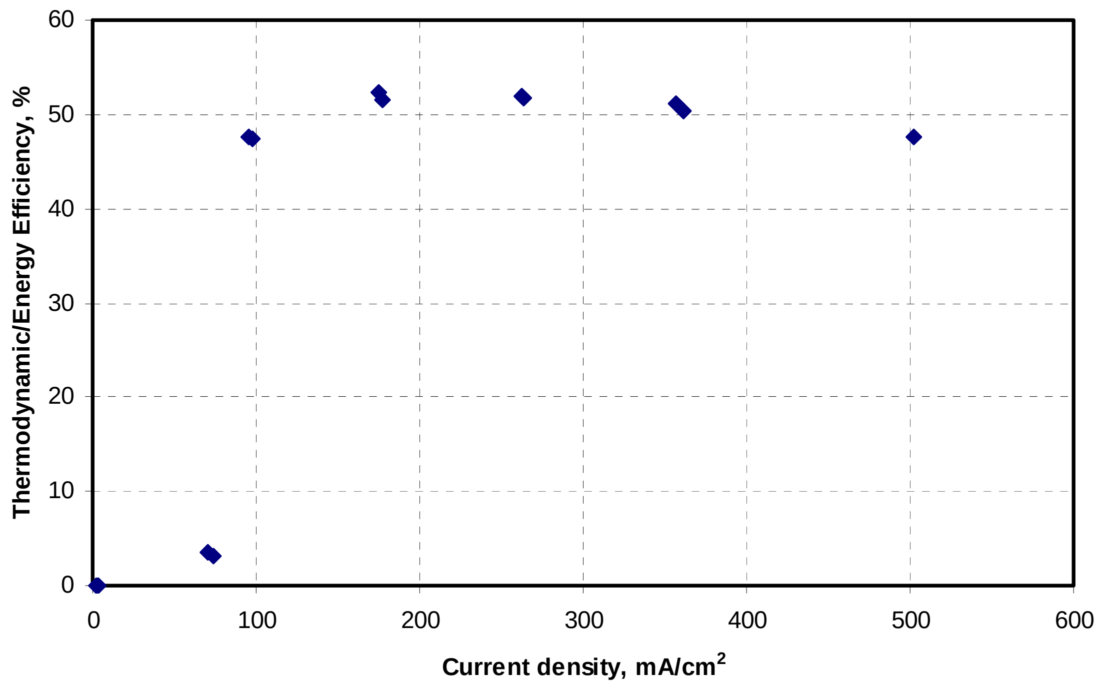


Fig. 3. Thermodynamic/energy efficiency vs. current density at characterization.

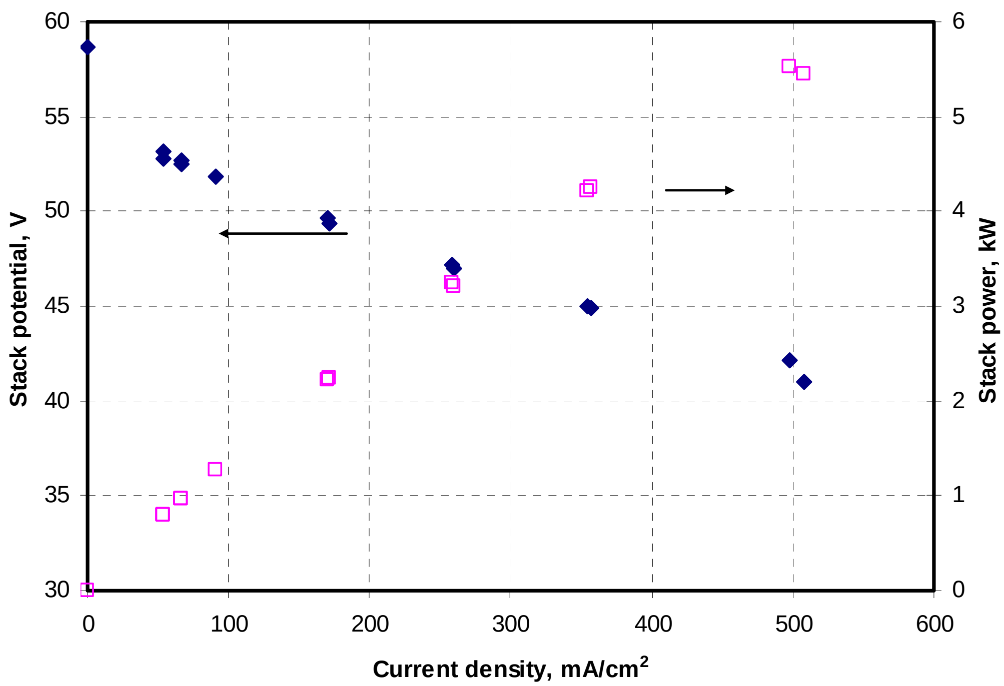


Fig. 4. Stack potential and power vs. current density from the random polarization curve.

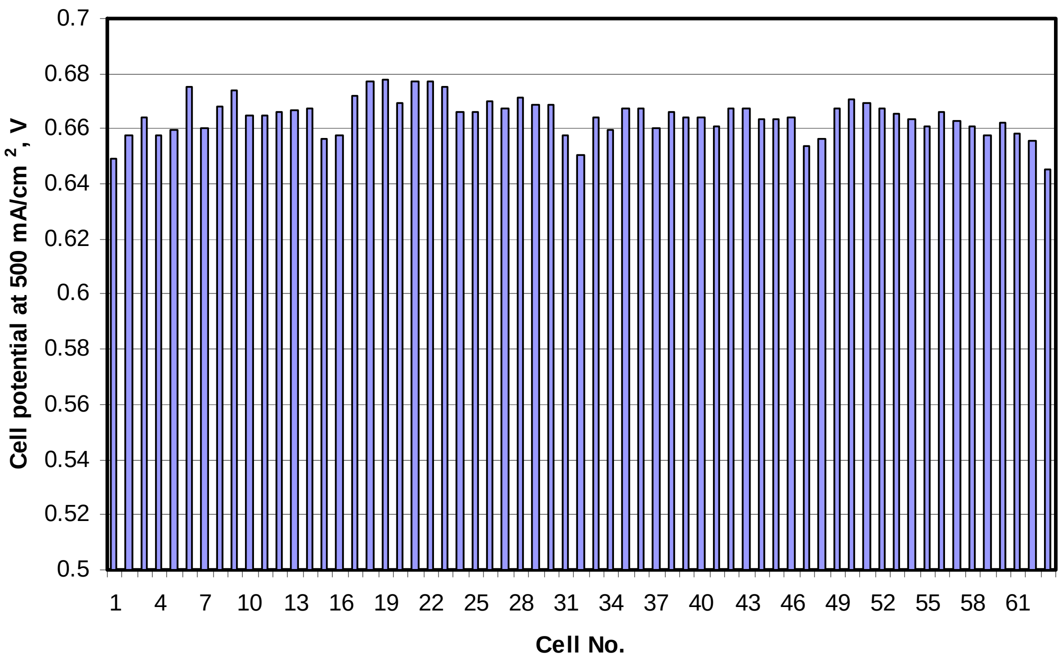


Fig. 5. Cell uniformity histogram from the random polarization curve.

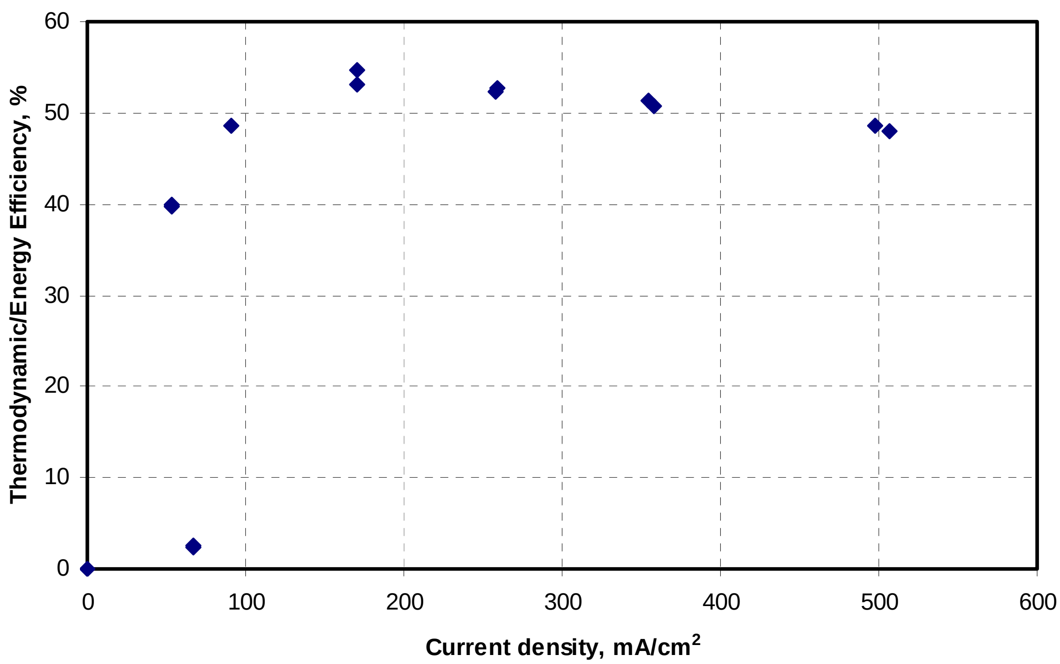


Fig. 6. Thermodynamic/energy efficiency vs. current density from the random polarization curve.

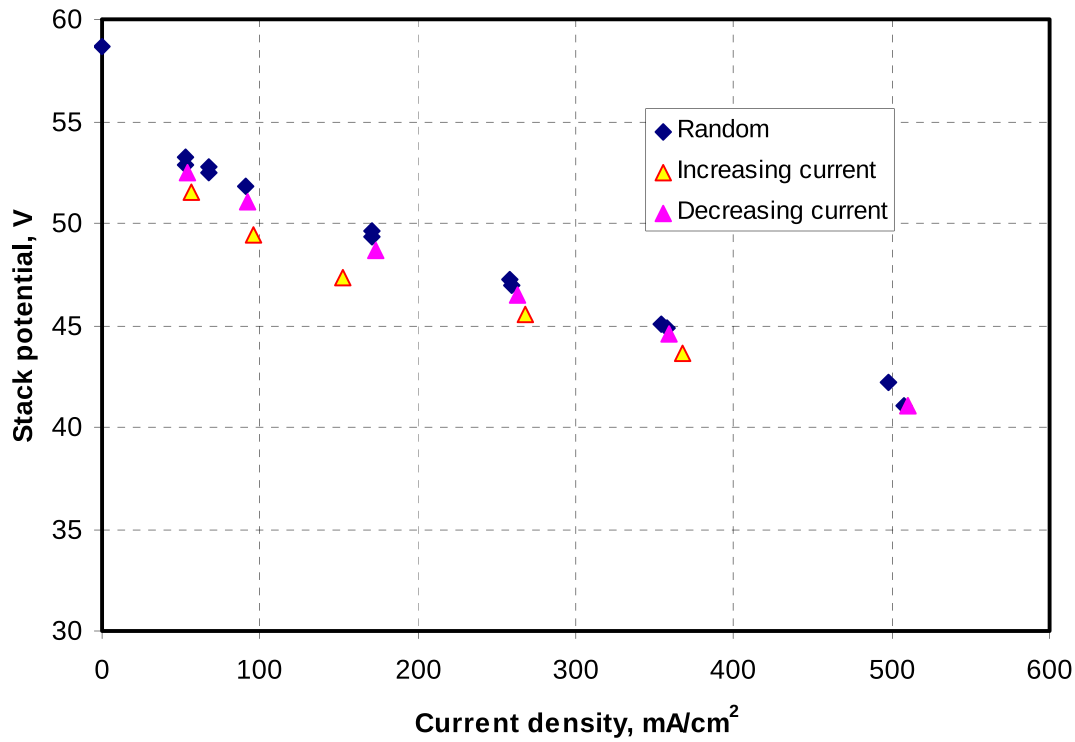


Fig. 7. Comparison of the results from the sequential and random polarization curves.

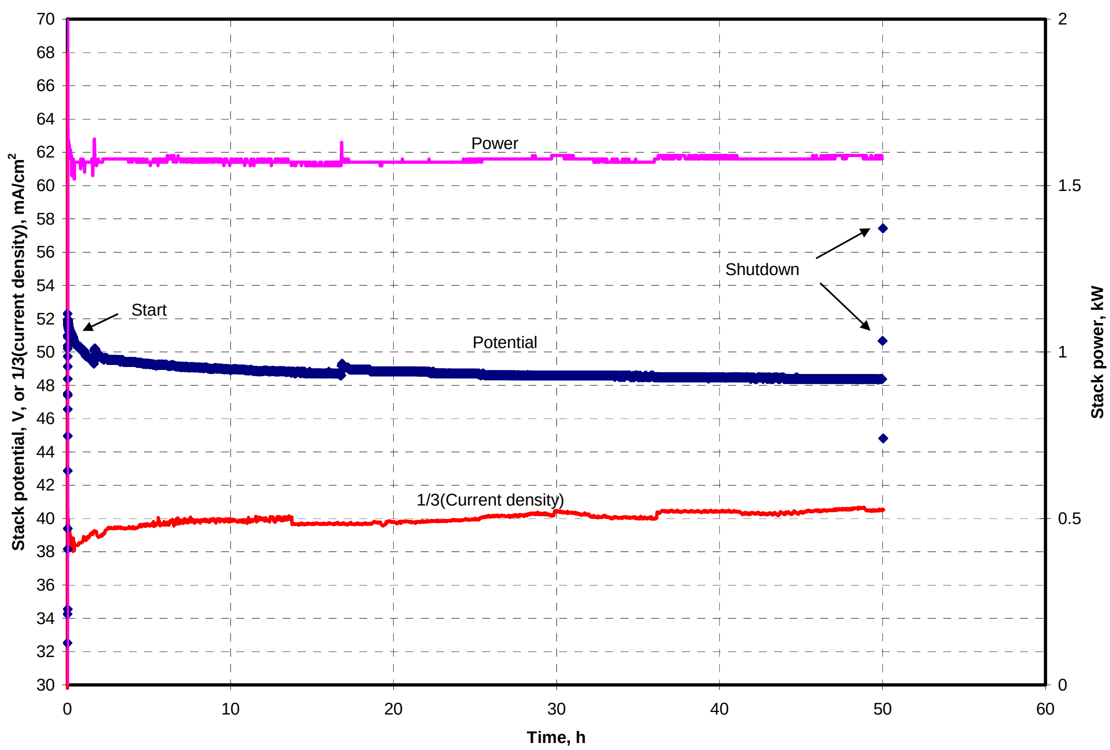


Fig. 8. Stack voltage, current and power vs. time during the constant power test.

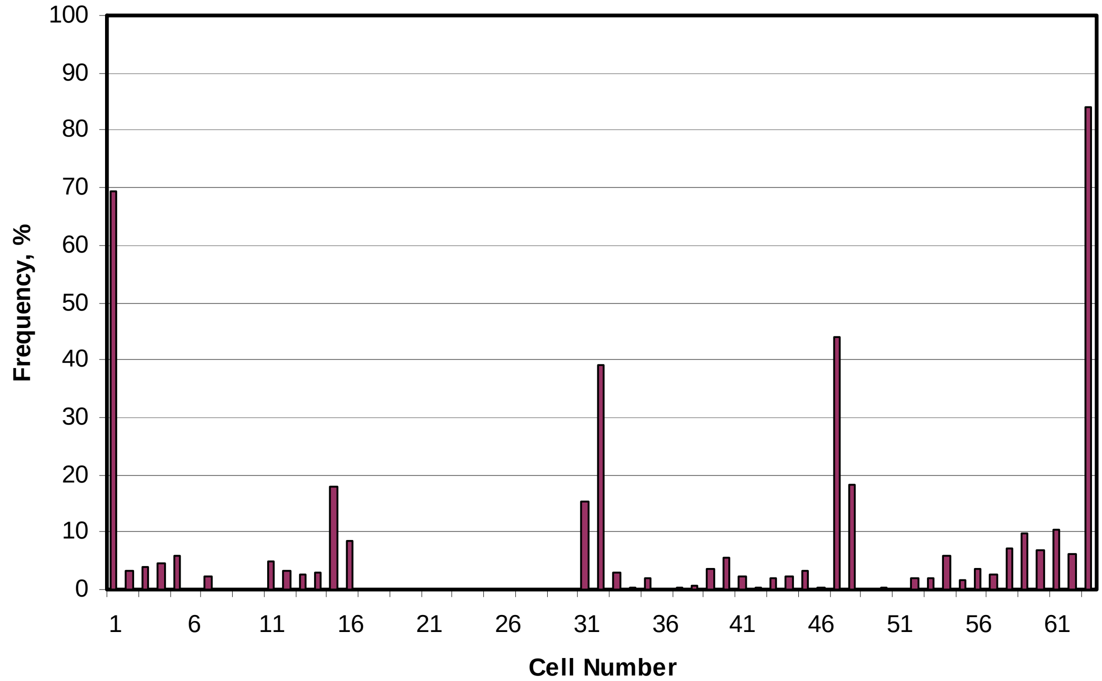


Fig. 9. Histogram showing frequency vs. cell number that a given cell is the weakest in the stack during the constant power test.

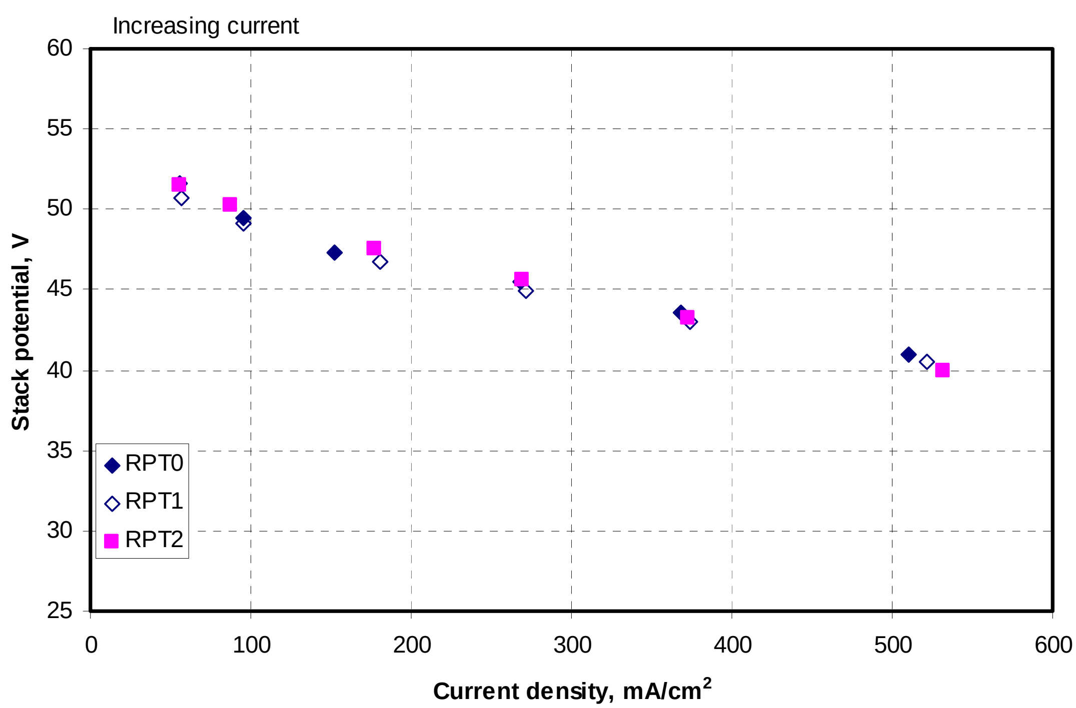


Fig. 10. Stack potential vs. current density during the 12h/12 off aging experiment. RPT0=start of the aging period; RPT2=end of the aging period.

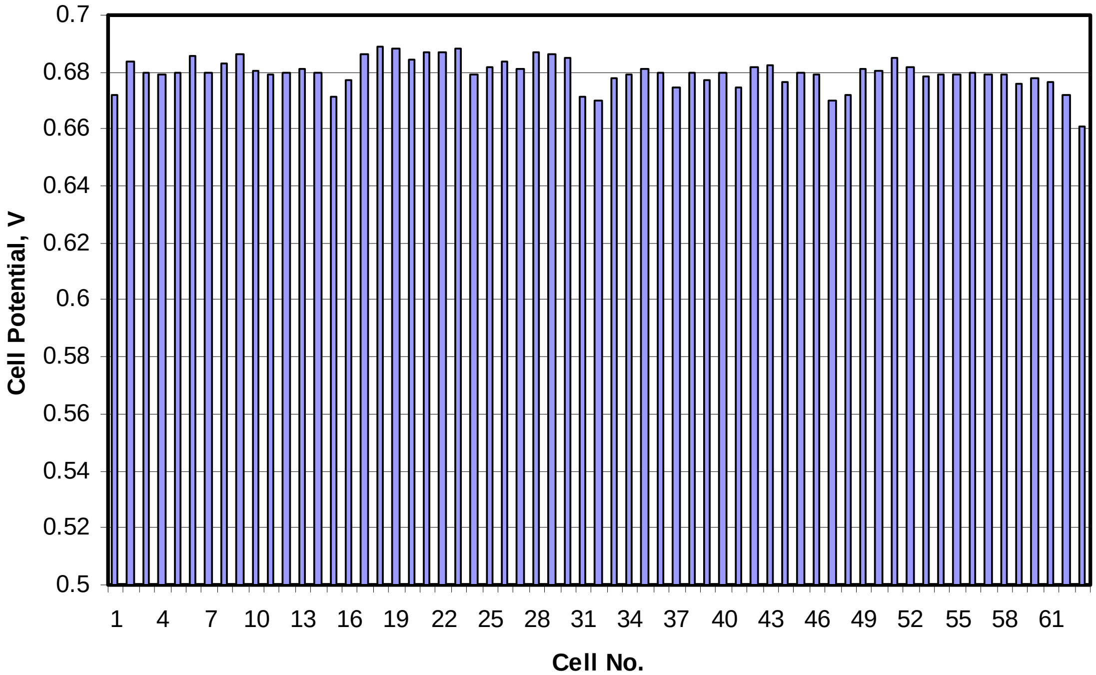


Fig. 11. Cell potential at 500 mA/cm^2 vs. cell number showing the uniformity of the cells at RPT2.

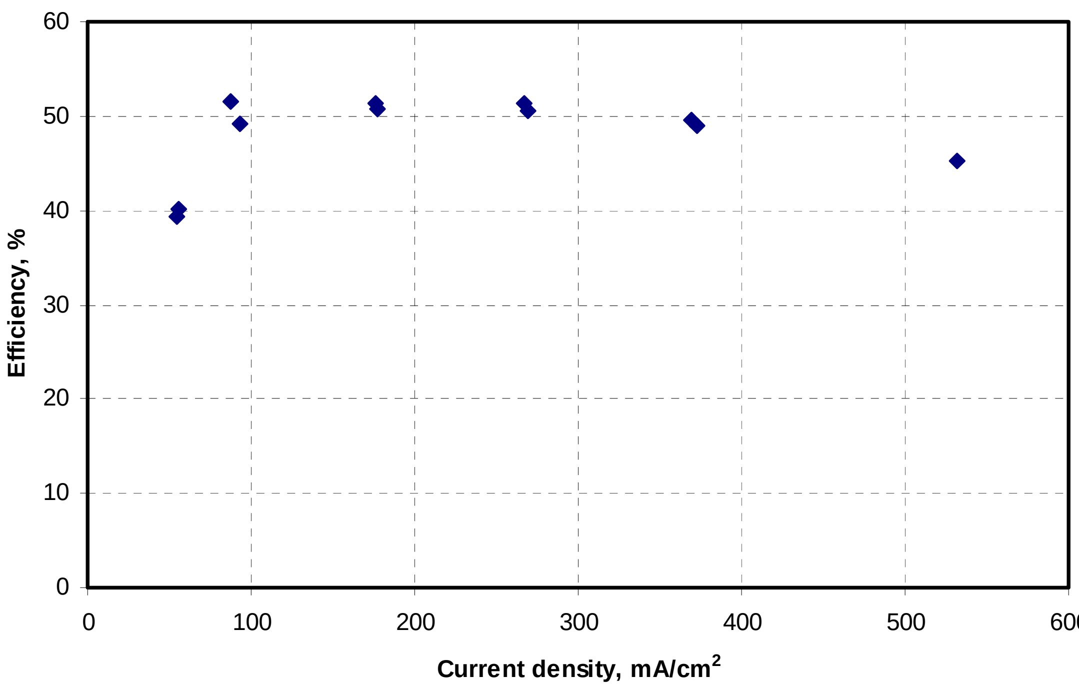


Fig. 12. Thermodynamic/energy efficiency of the stack at RPT2.

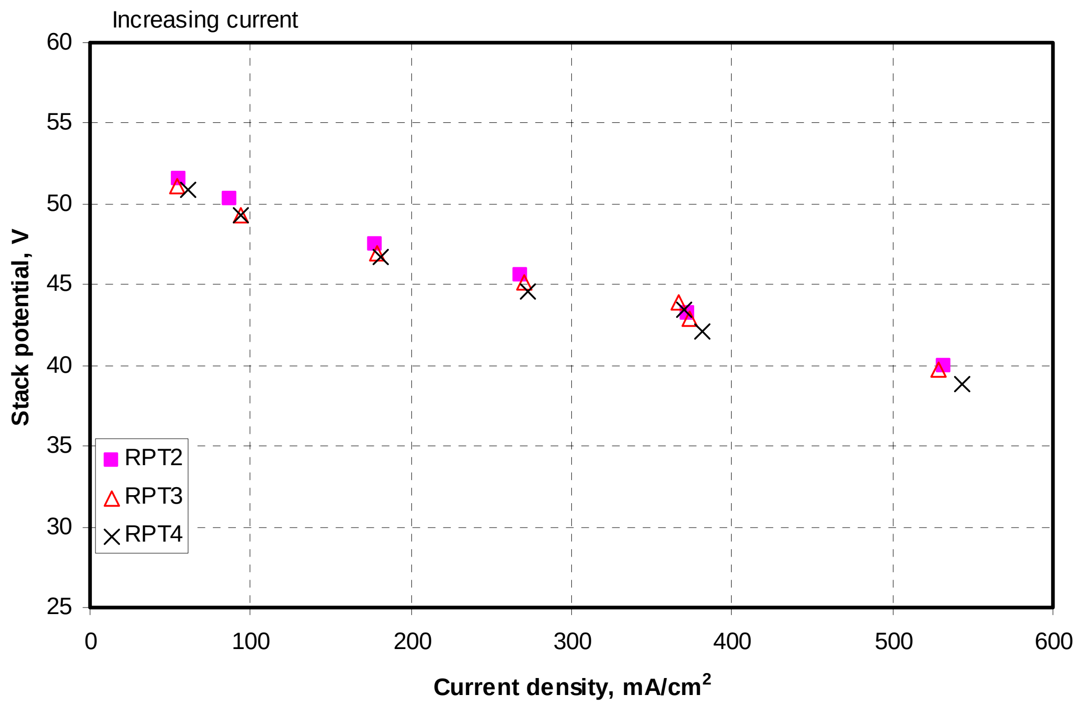


Fig. 13. Polarization behavior during the 1 h on/23 h off aging period. The reference performance tests are designated RPT2, RPT3 and RPT4.

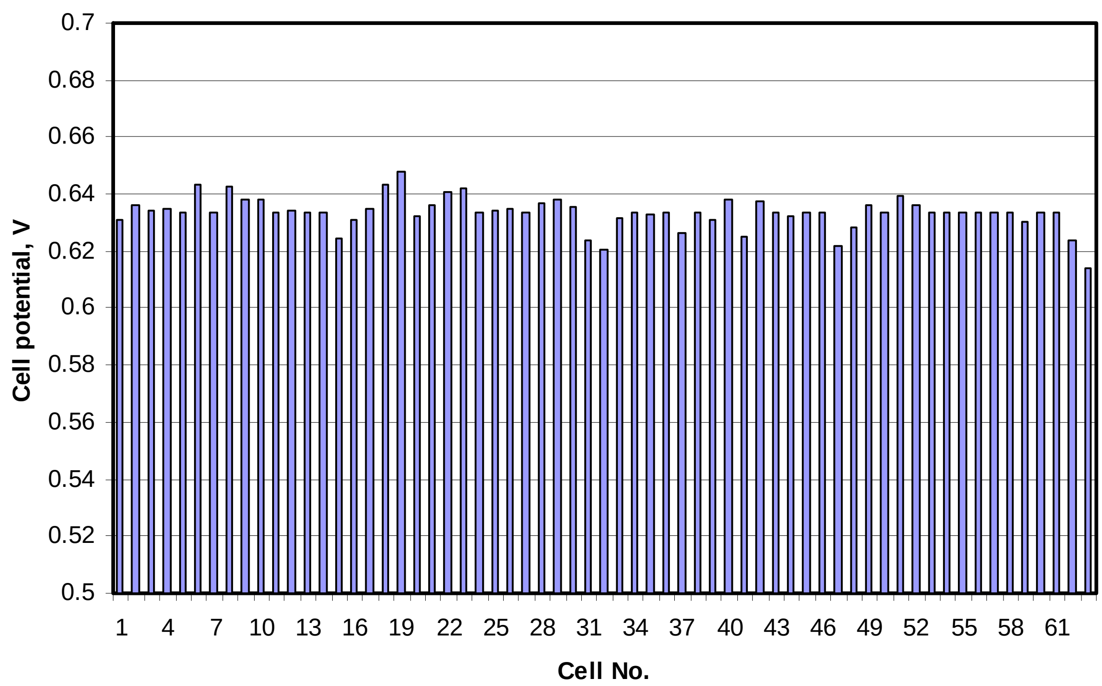


Fig. 14. Histogram of cell potentials at RPT4 (end of 1-h on/23-h off aging period).

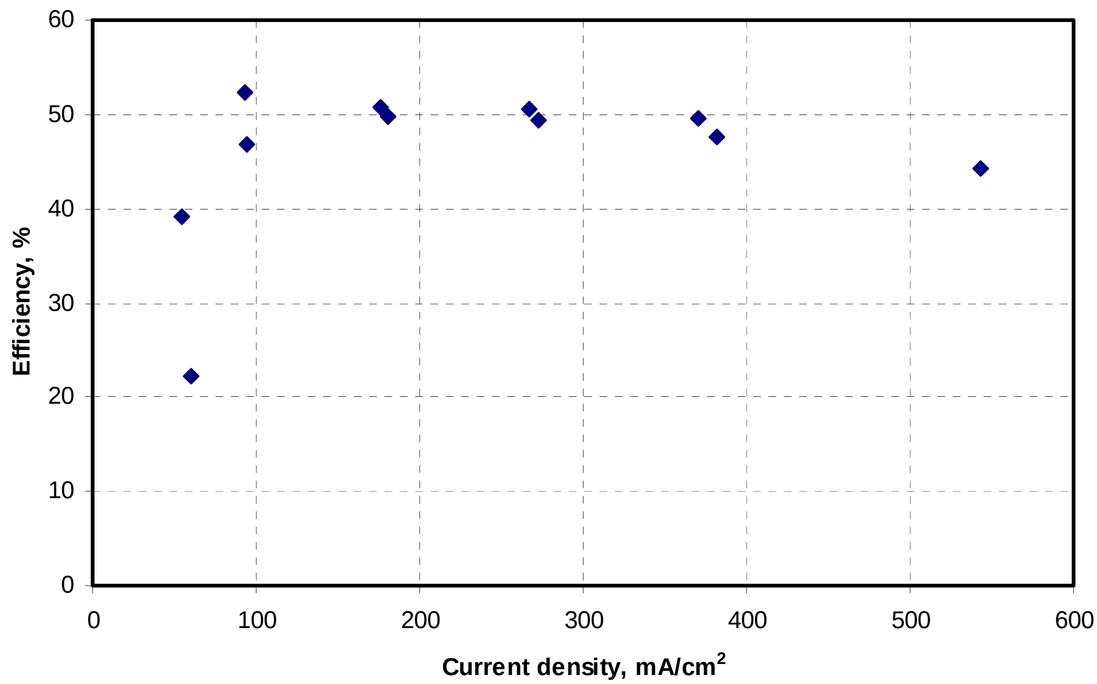


Fig. 15. Thermodynamic/energy efficiency of the stack at RPT4 (end of 1-h on/23-h off aging period).

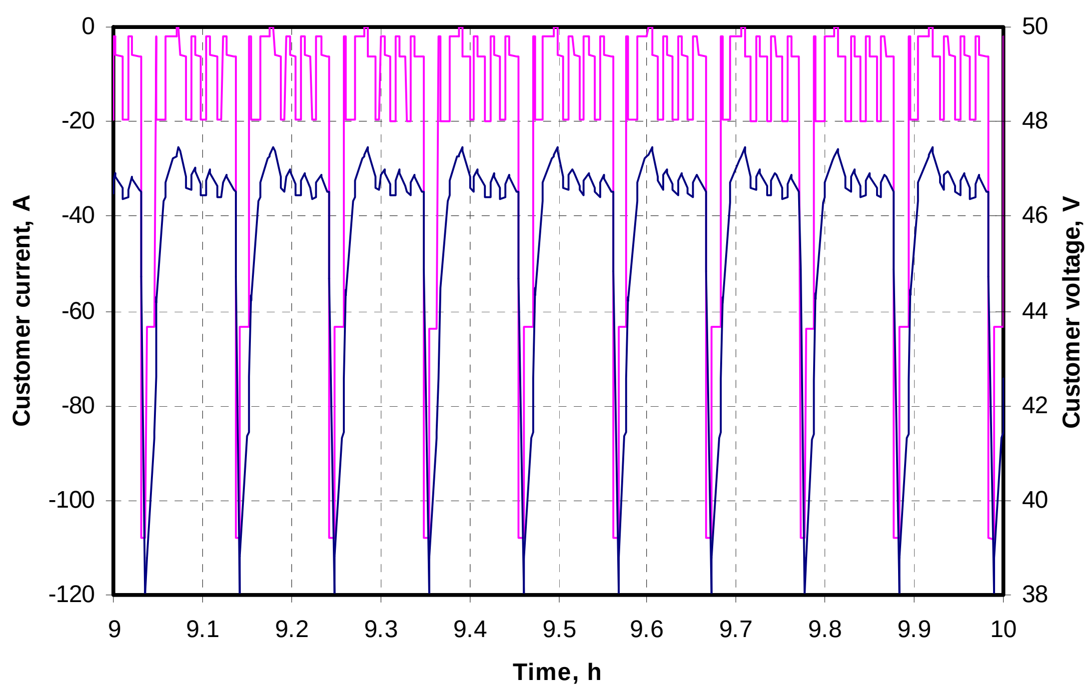


Fig. 16. Customer current (magenta) and voltage (blue) vs. time during DST cycling. The label "customer" refers to the current and voltage that would be on the customer bus while the GenCore unit was operating.

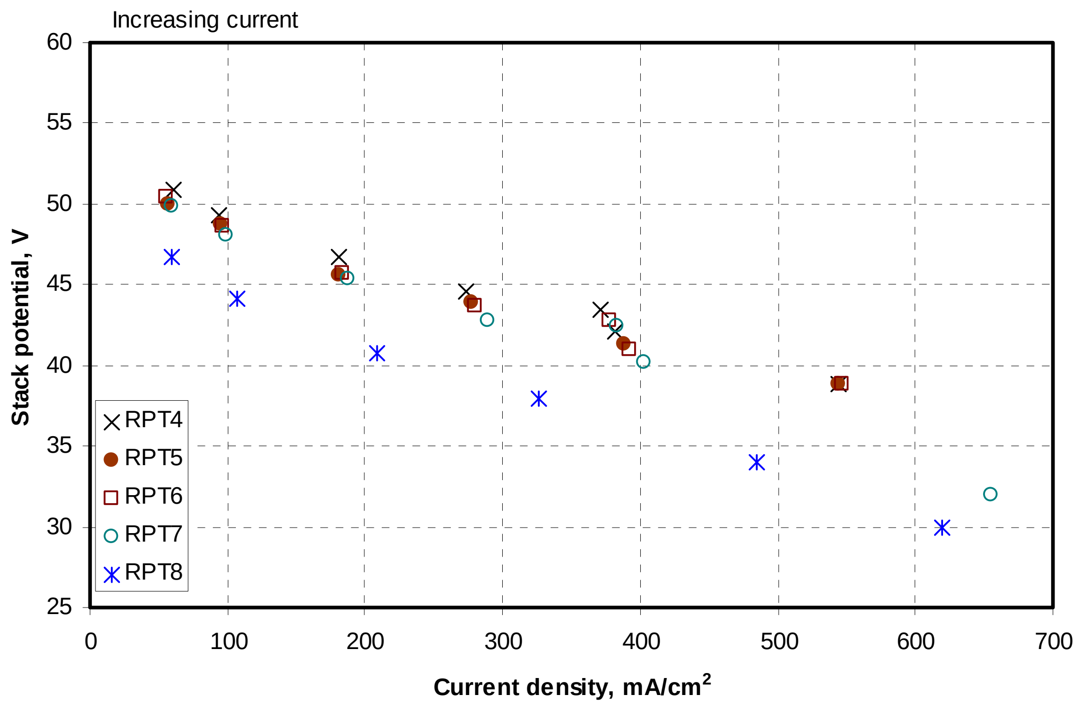


Fig. 17. Polarization behavior of the GenCore stack during the DST cycling portion of the aging experiment (RPTs 4 to 8). As the stack aged, more current was generated to keep the power output constant.

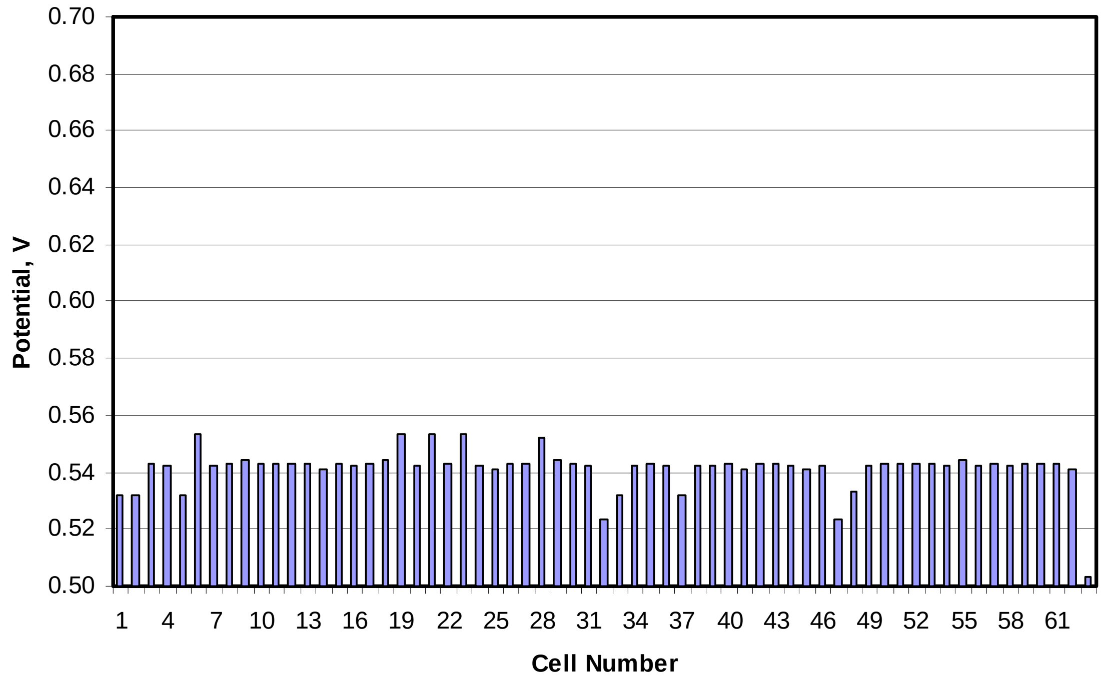


Fig. 18. Cell potential at 500 mA/cm^2 vs. cell number showing the uniformity of the cell voltages at RPT8.

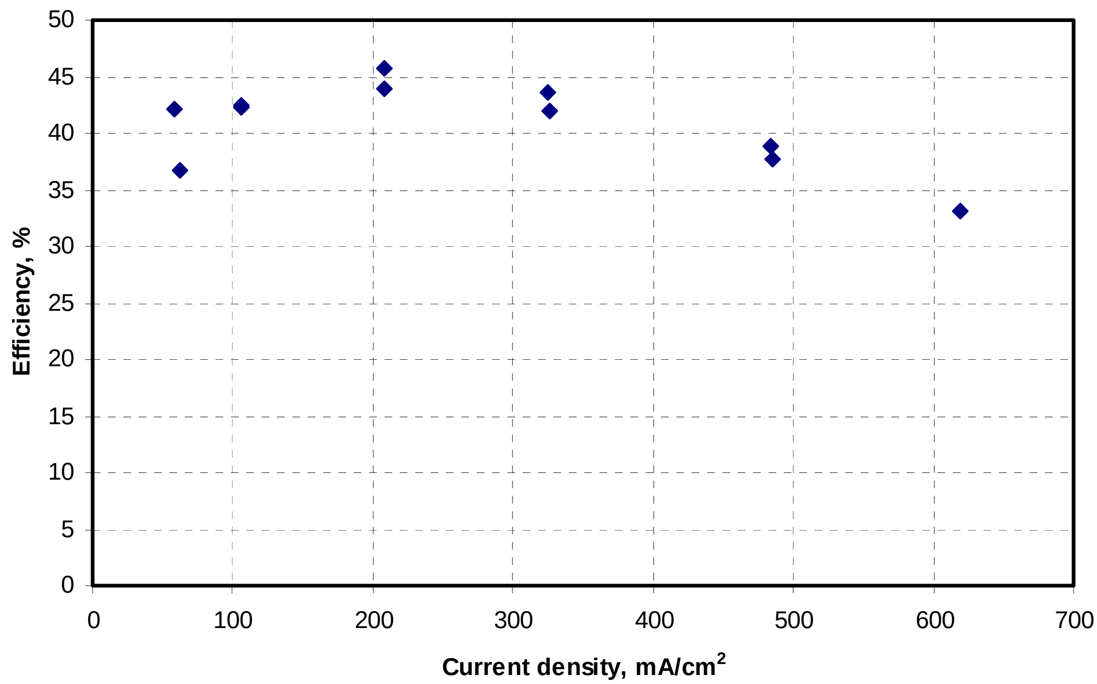


Fig. 19. Thermodynamic/energy efficiency vs. current density for the stack at RPT8.

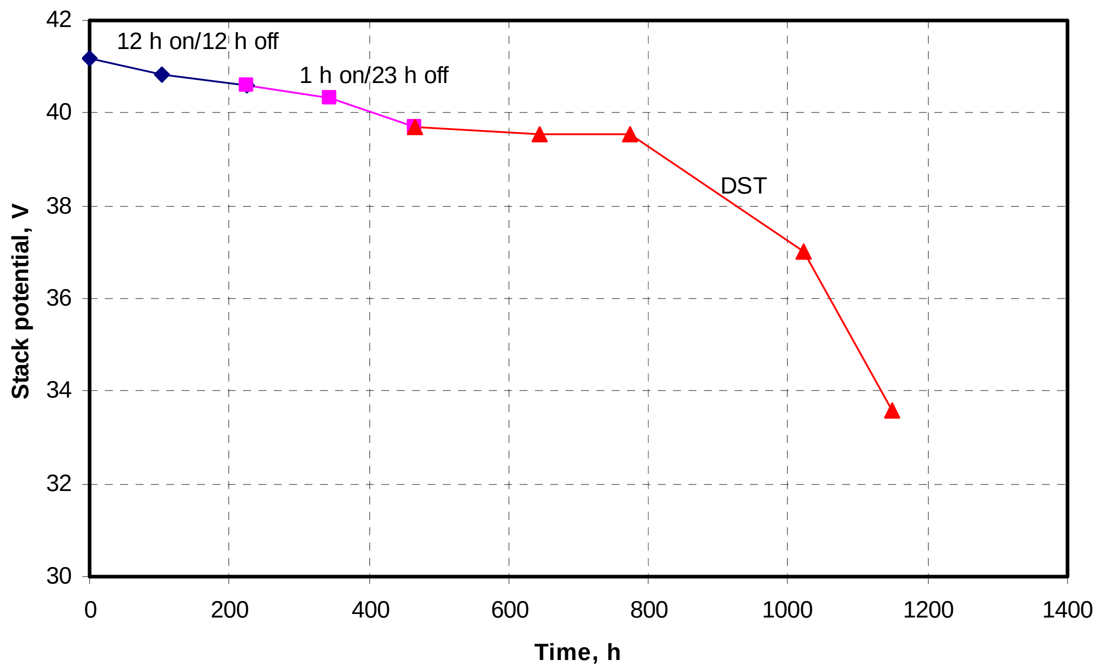


Fig. 20. Stack potential at 500 mA/cm^2 vs. time for all aging experiments.

Fig. 21. Photograph of the inside, left-hand (as you look at it) corner of the GenCore unit. There is a colorless liquid present on the bottom of the unit; most likely this is ethylene glycol-based coolant.