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Abstract

This report summarizes the progress made during this contractual period in achieving the goal of developing the solid oxide fuel cell (SOFC) cell and stack technology to be suitable for use in highly-efficient, economically-competitive, commercially deployed electrical power systems. Progress was made in further understanding cell and stack degradation mechanisms in order to increase stack reliability toward achieving a 4+ year lifetime, in cost reduction developments to meet the SECA stack cost target of $175/kW (in 2007 dollars), and in operating the SOFC technology in a multi-stack system in a real-world environment to understand the requirements for reliably designing and operating a large, stationary power system.

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Executive Summary

The overall goal of this U.S. DOE-sponsored project was the development of solid oxide fuel cell (SOFC) cell and stack technology suitable for use in highly-efficient, economically-competitive, commercially deployed electrical power systems. The development of this technology will advance the nation's energy security and independence interests while simultaneously addressing environmental concerns. This project incorporated the following supporting objectives:

- Increase SOFC stack reliability to achieve a design life of > 4 years.
- Demonstrate progress toward a degradation rate stability goal of < 0.2% per 1,000 hours at an NOC operation point by 2020
- Meet the SECA stack cost target of $175/kW (in 2007 dollars)

The goal of this project was to demonstrate, via analyses and testing, progress towards a stack life of ≥ 4 years and stability (≤ 0.2% per 1000 hours degradation) in a low-cost SOFC stack design. The scope of this project included laboratory R&D and testing of SOFC cells and stacks in order to advance and validate the reliability, robustness and endurance of Delphi's SOFC technology. The work focused on cell and stack materials & design, those aspects of the balance-of-plant that are found to negatively impact the stack with respect to life and degradation, and performance evaluation, including evaluation under operating conditions and using fuel compositions anticipated for commercially-deployed systems.

At the cell level, emphasis was placed on the use of electrochemical impedance spectroscopy (EIS) to identify sources of performance degradation. Once identified, the highest priority degradation mechanism(s) contributing the most to cell and stack degradation were addressed with focused projects and increased resources.

At the stack level, focused projects were completed to further the electrochemical performance stability, durability, and reliability. Cost reduction activities, through manufacturing enhancements and cell and stack design and materials development were also evaluated. Stack design development focused on the repeating unit to manifold seal. Materials development focused on high temperature coatings for sealing areas and current carrying areas, as well as the seal materials themselves (cell to retainer and repeating unit to repeating unit). Improvements in stack electrochemical performance stability, durability, and reliability were confirmed on discrete component tests and in stack testing, utilizing both the Gen 3 and Gen 4 stack platforms.

At the system level, the design and build of a thermally self-sustaining SOFC system to test and evaluate the technology at an 8 kW - 12 kW scale was completed and tested for 600 hours. The 8 kW - 12 kW system incorporated nine (9) SOFC stacks in an electrical architecture that used a series-parallel connection strategy consistent with the projected requirements of a larger stationary system. The input fuel for system testing purposes was desulfurized, reformed natural gas. The system test demonstrated that multiple stacks could be connected together and controlled as a single system in a self-sustaining mode. In addition, the system was operated in an outdoor environment that simulated a commercial deployment, including realistic fuel composition, which was much more challenging than a laboratory environment. Key operating metrics from the test were as follows:

- 29.2 kW of heat transferred from the system to the geology
- 3.2 kW/m of heat flux supplied by the system
- 55% combined heat-and-power efficiency
- 25.8% fuel utilization

Results and Discussions

Objectives:

The overall goal of this U.S. DOE-sponsored project was the development of solid oxide fuel cell (SOFC) cell and stack technology suitable for use in highly-efficient, economically-competitive, commercially deployed electrical power systems. The development of this technology will advance the nation's energy security and independence interests while simultaneously addressing environmental concerns. This project incorporated the following supporting objectives:

- Increase SOFC stack reliability to achieve a design life of > 4 years.
- Demonstrate progress toward a degradation rate stability goal of < 0.2% per 1,000 hours at an NOC operation point by 2020
- Meet the SECA stack cost target of $175/kW (in 2007 dollars)

TASK 2 - Cell and Stack Technology, Engineering, and Delivery

2.1 Cell Development

The objectives of this subtask were to 1) continue the discrete cell and cell component accelerated testing to characterize and confirm electrochemical performance stability 2) develop more stable, high performance, lower-cost cathodes, anodes and electrolytes and 3) fabricate and test a significant number of cells of various sizes to assess the performance impacts of cell material, design, and process changes on electrochemical performance and stability

2.1.0 Cell Testing

Electrochemical impedance spectroscopy (EIS) has been a useful tool in diagnosing fuel cell properties to complement voltage performance data. Impedance measurements on small button cells were routinely conducted and helpful for development. Button cells don't, however, exactly mimic the environment and interface characteristics experienced by full size cells and by multi-cell stacks, nor do they seem to exhibit the full range of degradation mechanisms seen in full size stacks. During the contract period, efforts were focused to develop the ability to conduct EIS measurements on full size stacks to better understand realistic cell and stack degradation mechanisms which might be indicated by the cell impedance. The combination of voltage and impedance data is also useful in stack development to understand the impact of design variables on cell performance. The work included the evaluation of several test parameters, including the EIS frequency range, number of data points, and measurement dwell time. This included evaluations on both Gen 3 stacks and Gen 4 stacks. Due to equipment (load bank) limitations, stacks of 24 repeating units or less were able to be measured.

An example of the Nyquist plot from a Gen 3 stack is shown below, Figure 1, where 3 different cells of different designs were compared. Clearly the signature output of the cells is different and helps to explain the contribution of the design alternatives. Clear differences in the ohmic resistance are present but also in the polarization resistance where Design B shows a different signature. As expected, a strong relationship between the total resistance and the voltage output exists.

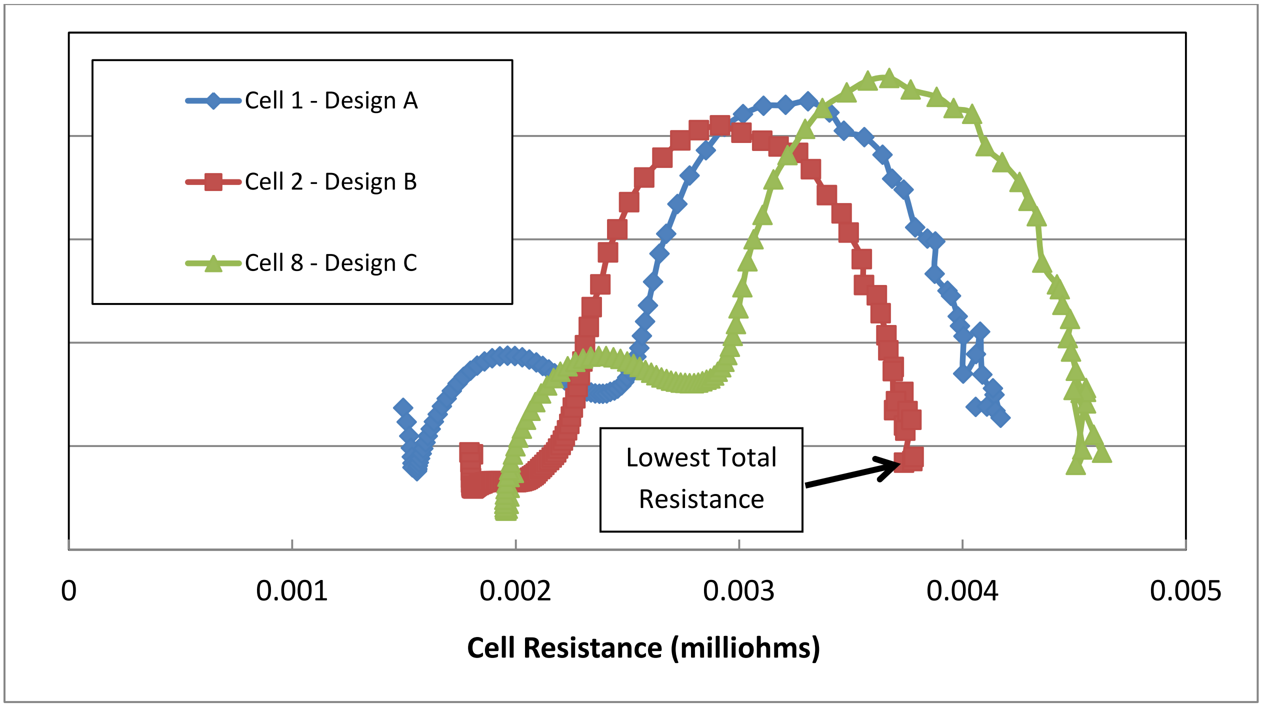

Figure 1. Nyquist plots from a Gen 3 stack with various repeating unit configurations.

Another example shown in Figure 2 contrasts two other cells from a different stack focused on interconnect design alternatives. In this case a clear difference is again seen by the Nyquist plot and supports the design development.

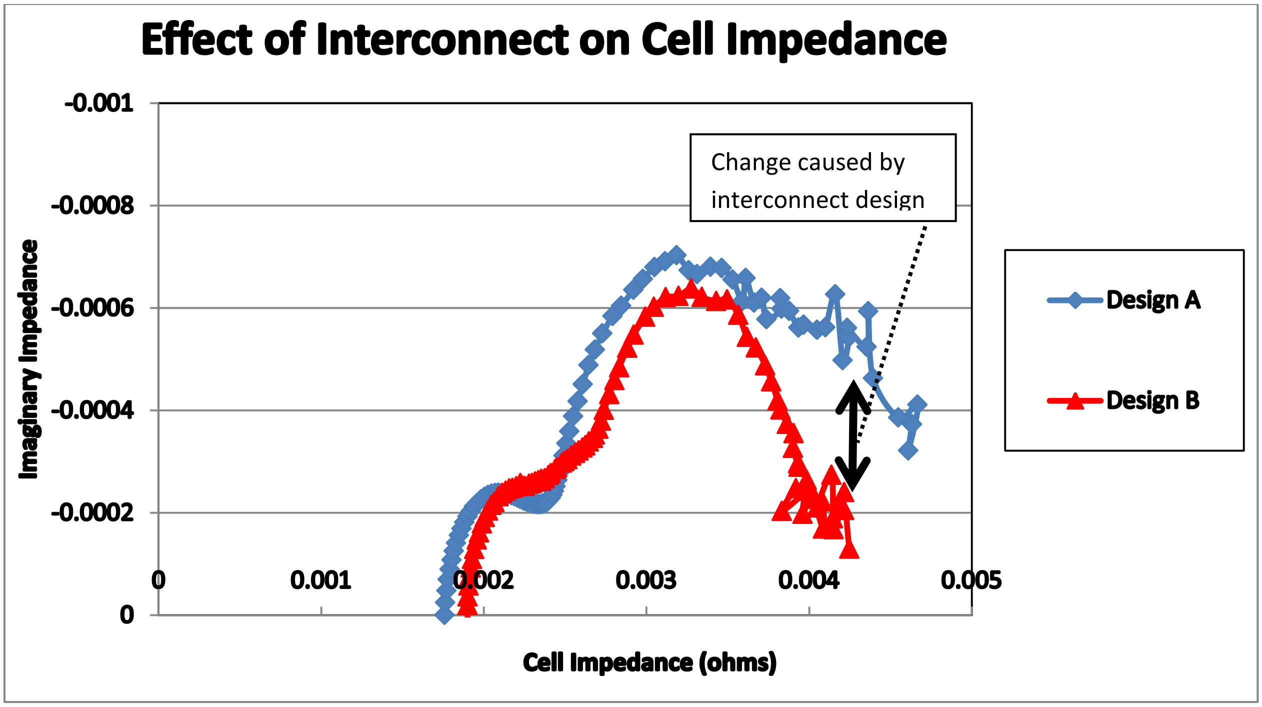

Figure 2. Nyquist plots for cells with various interconnects

2.1.1 High Performance Cathode Development

- Improved cathode stability to meet the long-term SECA durability and degradation targets
- Increased overall electrochemical performance of the cathode.
- Continued cost reduction activities by developing a low cost, qualified, production capable material supply to meet the SECA stack cost target

High Performance Cathode

An active focus during the reporting period was to develop and confirm a high performance cathode (HPC) solution with support from production capable suppliers. This was accomplished with a variety of button cells, process development, and full size stack testing Statistical analysis of the performance data comparing the "standard" cathode to the HPC cathode shows similar but more stable performance of the new cathode. Common practice to include cells of both types in a single stack helps to make the comparisons. An example from one stack is shown in Figures 3 and 4, which shows comparison in both voltage and overall degradation in a 23-cell Gen 4 Stack, G047 after 3700 hours of constant current durability.

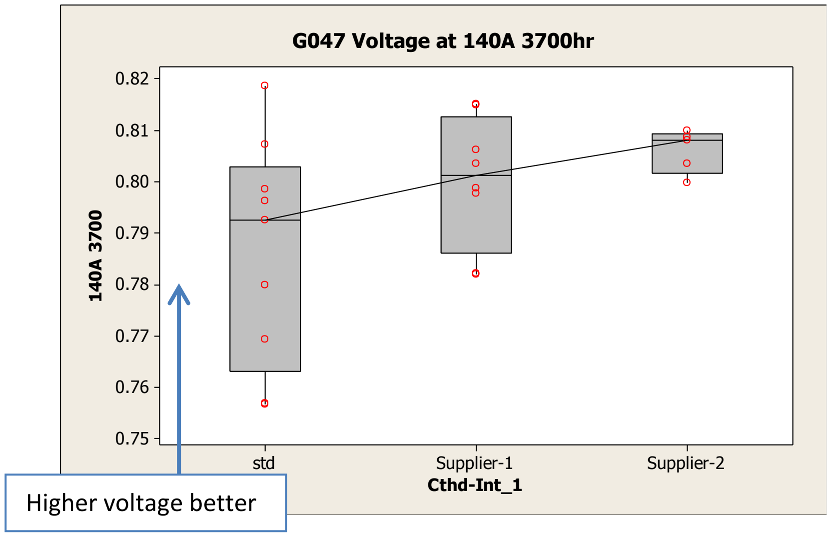

Figure 3: G047 boxplot of cell voltage for different cathodes at 3,700 hours operation at 140 amp constant current

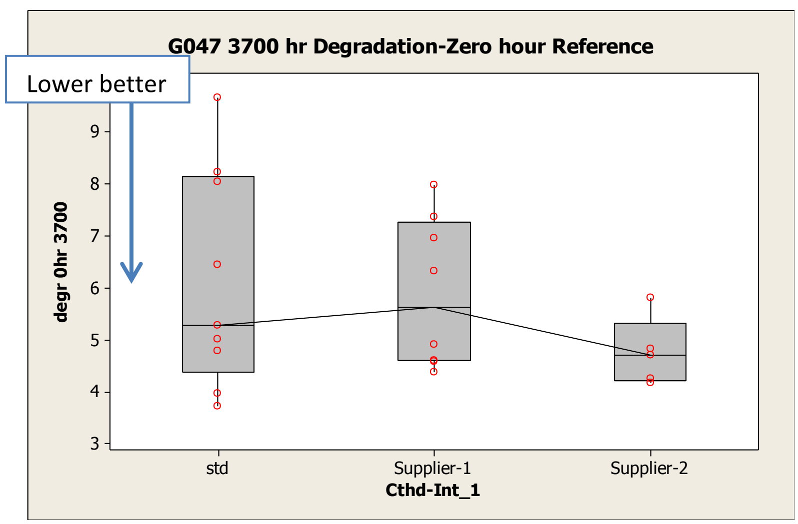

Figure 4: G047 boxplot of degradation for different cathodes at 3,700 hours operation at 140 amp constant current

Cathode Infiltration

Based on the previous results of improved performance by cathode infiltration in the literature, collaboration with NETL resulted in multiple cathode infiltration trials. Initial samples were infiltrated using the standard cathode, and further attempts were conducted using the high performance cathode, with both the Gen 3 and Gen 4 format cell. Two different infiltrant materials were processed and tested. Several stacks have been built and tested and did show improved performance over the non-infiltrated standard cells after a period of several thousand hours.

Analysis by electrochemical impedance spectroscopy (EIS) showed no significant differences in the ohmic resistances between infiltrated and non-infiltrated cells. The increase in performance for the infiltrated cells was attributed to a decrease in the polarization resistance as shown in Figure 5. This is output from a 9-cell stack assembled with five standard cells and four infiltrated cells. Figure 6 also shows that the majority in increase in resistance over time is due to ohmic increases, rather than polarization, although the increase in polarization resistance was reduced for the infiltrated cells as compared to the standard cells.

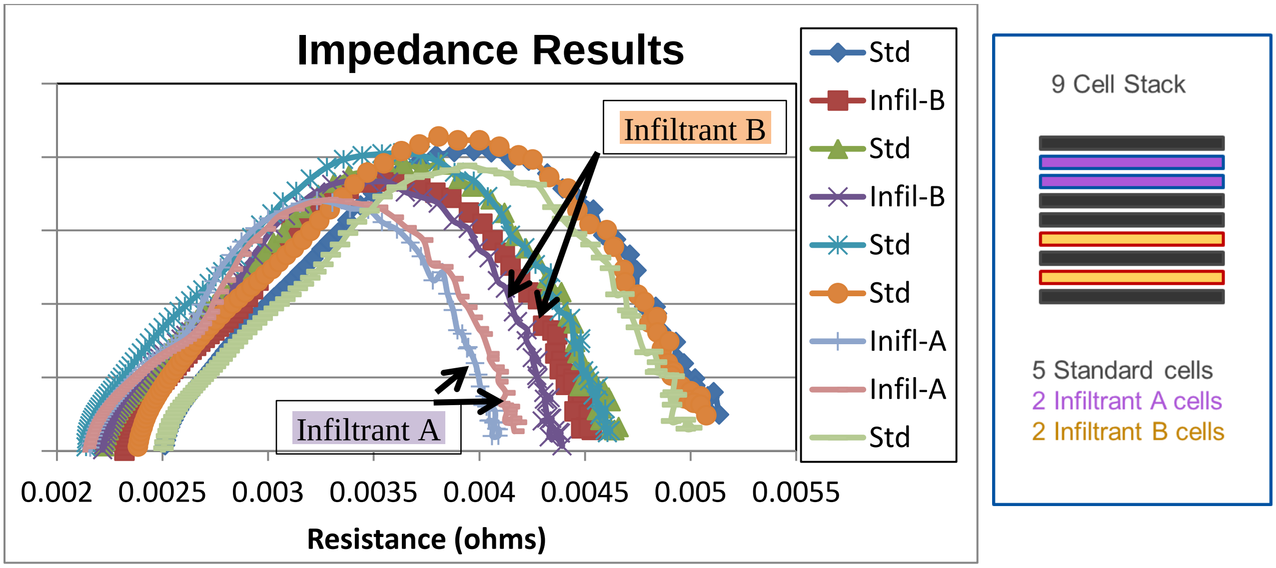

Figure 5: Infiltrated vs. standard non-infiltrated cells

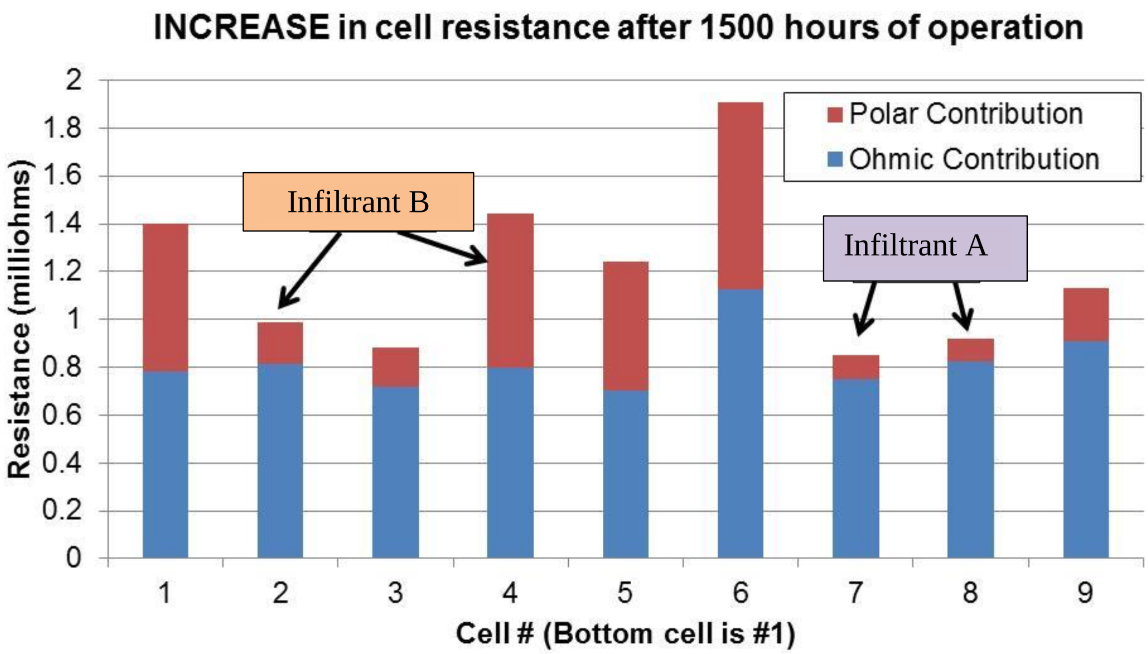

Figure 6: Increase in cell resistance after 1500 hours testing. Ohmic increases were the largest contributor to all cells but infiltrated cells show a lesser increase in polarization resistance.

NETL conducted process development on the infiltration process as well to speed up the process and confirmed that the infiltration attempt was successful in achieving a perovskite phase. Their data indicate that a formulation was identified that applies sufficient infiltrate mass in a single step process, with (or without) a capping layer.

Based on these encouraging results for the standard cathode additional Gen 3 and Gen 4 cells with the high performance cathode were infiltrated in Q1 2015 and are being included in recent and upcoming stack builds for long term testing with voltage and impedance monitoring.

2.1.2 High-Performance Anode and Electrolyte Development

- Improved long-term durability and performance stability to advance to the target of 4 years of continuous operation. Various anode interconnect materials will be tested to determine the contribution to power degradation.
- Continued cost reduction activities to meet the SECA stack cost deliverable
- Improved overall electrochemical performance of the cell.

Limited efforts were focused on anode or electrolyte development during the contract period with exception of identifying low cost, production capable suppliers for both the materials and the processing of the cell materials. As a result of those efforts, some subtle differences in performance were noted. A test stack, that included five cells made with the current standard bilayer materials, and five cells with bilayer materials made with a new (reduced cost) process, showed a performance difference with the new material showing reduced performance. In this test stack, repeating units 1 through 5 were standard cells, and repeating units 6 through 10 were non-standard cells. Figure 7 shows the cell voltage output differences.

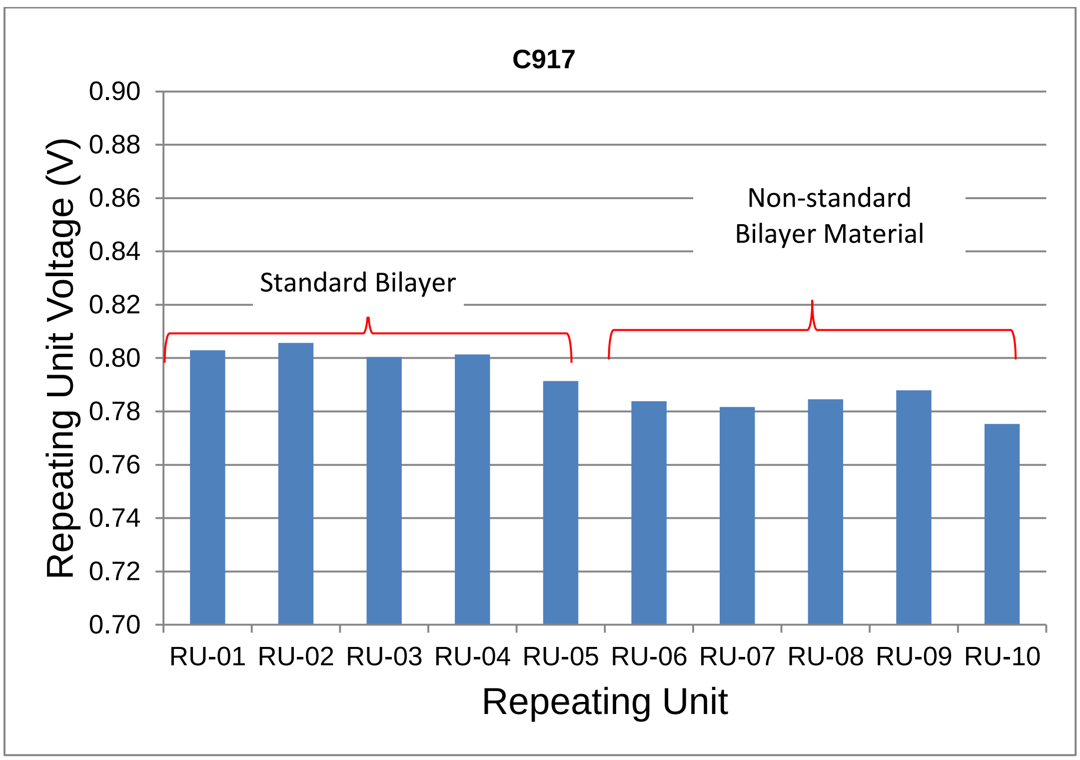

Figure 7: Cell performance difference between standard bilayer material and non-standard bilayer material

2.2 Stack Development

2.2.0 Degradation Rate Improvement

- Electrochemical impedance spectroscopy of cells and stacks to understand the respective contributions to stack degradation in various operating conditions
- Microstructural investigation of long term durability tested cells and stacks to identify microstructural changes which lead to stack degradation

Understanding and quantifying stack degradation is of significant interest. Voltage performance as well as impedance output of multiple stacks were monitored during long term durability. The overall degradation rate is assessed per 1,000 hours of operation. The degradation appears to be higher initially and usually levels with additional exposure as seen in Figure 8.

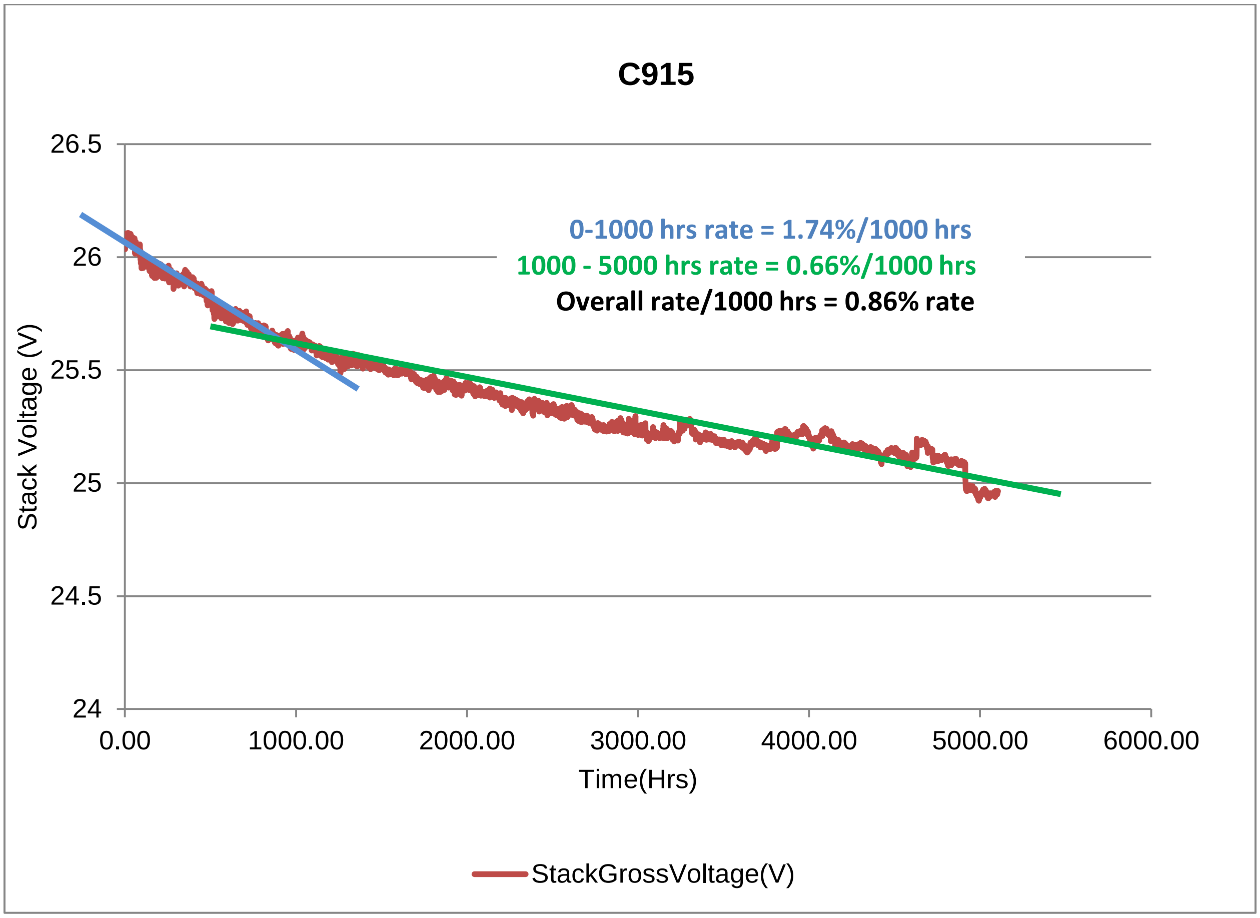

Figure 8. Stack voltage degradation rate of change during durability testing. Degradation rate is higher in first 1000 hours compared to its long-term rate.

Stacks running long term durability include two types: those of a consistent repeating unit design and those in which not all the repeating unit designs are common, which we term development stacks. The development stacks are for evaluating possible cost reduction alternatives or performance improvement alternatives, making overall estimate of stack degradation difficult as design combinations may perform differently. Typically performance interpretation of development stacks is supported with statistical analysis to understand if the design alternatives have a significant effect on performance or degradation, which guides development.

Over the contract period, 34 stacks were built ranging from 4 cells to 30 cells, which includes the stacks supporting the SECA test systems, as well as a host of development stacks. Given the application focus on the multi-stack test system, about 80% of the builds were of the Gen 3 format. Long term degradation rates for non-development stacks ranged from 0.18% per 1,000 hours to 2.3% per 1,000 hours.

EIS data was collected for stacks with 24 repeated units, or less. Analysis of this data indicates that ohmic increases over time are more significant to total resistance than polarization resistance increases. This understanding over time will help in targeting improvements associated with mechanisms that impact the change in ohmic resistance over time.

1.2.1 Interconnect Technology Development

- Improved interconnect/interfacial stability to meet the long-term durability targets (> 4 years)
- Improved interfacial ASR performance of the interconnect (thereby improving cell and stack performance stability)
- Continued cost reduction activities by developing low cost, production manufacturable interconnect coating processes to meet the SECA stack cost target
- Development of accelerated bench testing for performance evaluation of interconnects and interconnect surface modifications

Several activities related to interconnect performance improvement were evaluated over the contract period. The focus includes both the actual interconnects and their respective coatings, the interconnect contact pastes, and the interconnect design. Multiple development stacks were built to support the evaluations. Again the focus is primarily driven by the desire for cost reduction and high volume viability. In some cases process development and supplier development were required to support the effort. One particular interconnect material showed significantly reduced performance as compared to the standard design, as shown in Figure 9, even after short term exposure. Statistical analysis confirms this difference is of statistical significance ($p=0.000$) and of practical significance as well showing a dramatic decrease in performance.

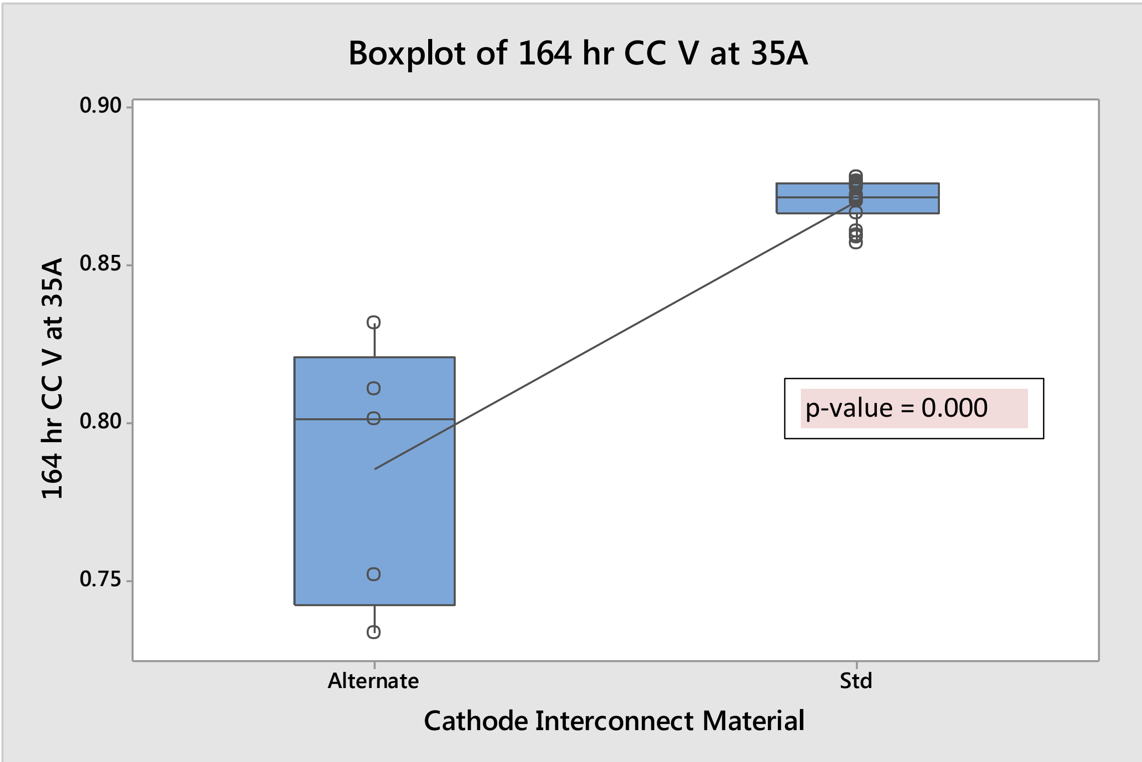

Figure 9. Voltage performance of cells within stack of two different cathode interconnect materials.

A final area of development relates to the general interconnect design for both the anode and cathode interconnects. The focus here relates to the mechanical integrity of the interconnects and their adaptability to coating and flow characteristics.

2.2.2 Seal Development

2.2.2.1 Cell to Retainer Seal

- Develop a brazing process which is compatible with the SOFC cell and retainer and does not result in significantly reduced electrochemical performance of the cell
- Conduct accelerated bench testing of cell to retainer seals
- Engineer new cell to retainer joints which are not subject to the same degradation mechanisms currently active

Delphi continued to look for alternative materials or processing methods to improve the current braze material used for the cell to retainer joint. Several strategies were pursued, which included the material formulation and braze protection.

Also, driven by the cost reduction efforts, alternative cell retainer coating technologies were evaluated which, in some cases, had resulted in a difference in the response of the braze material, suggesting an interaction of the coating with the braze material. Responses such as braze porosity, mechanical strength and chemical interaction , were considered. Blending the current braze alloy with a new alloy material resulted in a wide range of wetting response which may prove useful in tailoring the process (Figure 10).

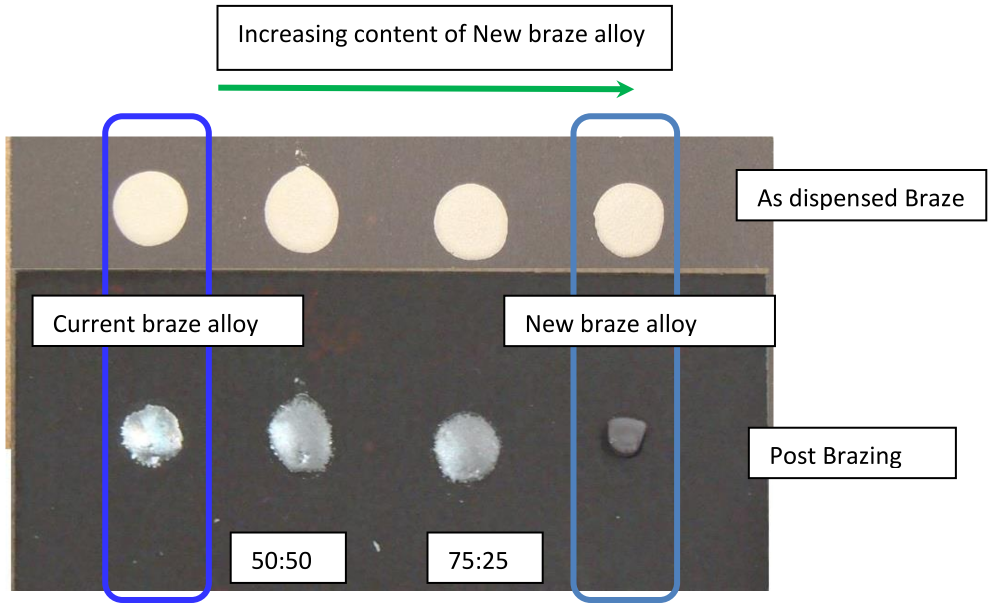

Figure 10. As dispensed braze and braze wetting behavior on coated stainless steel substrate, comparing range in mixture of two braze alloys

Several development stacks over the contract period included various braze joint materials for long term testing. Testing was also complemented by coupon level testing in a dual atmosphere environment under thermal cycling conditions.

2.2.2.2 Repeating Unit Seal Development

- Using the accelerated dual atmosphere test stand developed during the previous contractual period, conduct accelerated bench testing of repeating unit to repeating unit seals
- Engineer new seals, including the seal material itself, the mating surfaces to be sealed, and the design of the seal joints for decreased stress, using the accelerated test platform to help validate their performance
- Provide analytical support for the characterization of new seal materials

Thermal cycle testing was conducted on special Gen 3, two-cassette, stack samples made by sintering a single repeating unit seal between two cassettes. The two-cassette stack sample configuration was advantageous over coupon samples because it had the same dimensional footprint as an actual Gen 3 repeating unit, and was processed in the same way as a regular Gen 3 stack of a higher repeating unit construction. The two-cassette stack could be leak tested, and was of a construction thin enough to provide useful observations via real-time x-ray.

Two-cassette stack samples were made with repeating unit seals from different fabrication processes and compositional additive variations. These were evaluated by first leak testing, after the initial sintering process, then by leak testing again at periodic intervals after thermal cycling exposure in a regular air atmosphere, with no externally applied load, in an infrared furnace. The infrared thermal cycling profile was developed to substantially accelerate the rate of thermal cycling when compared to that of a stack in a typical operating environment. The thermal cycle profile, infrared furnace, and a two-cassette stack specimen are exhibited in Figure 11.

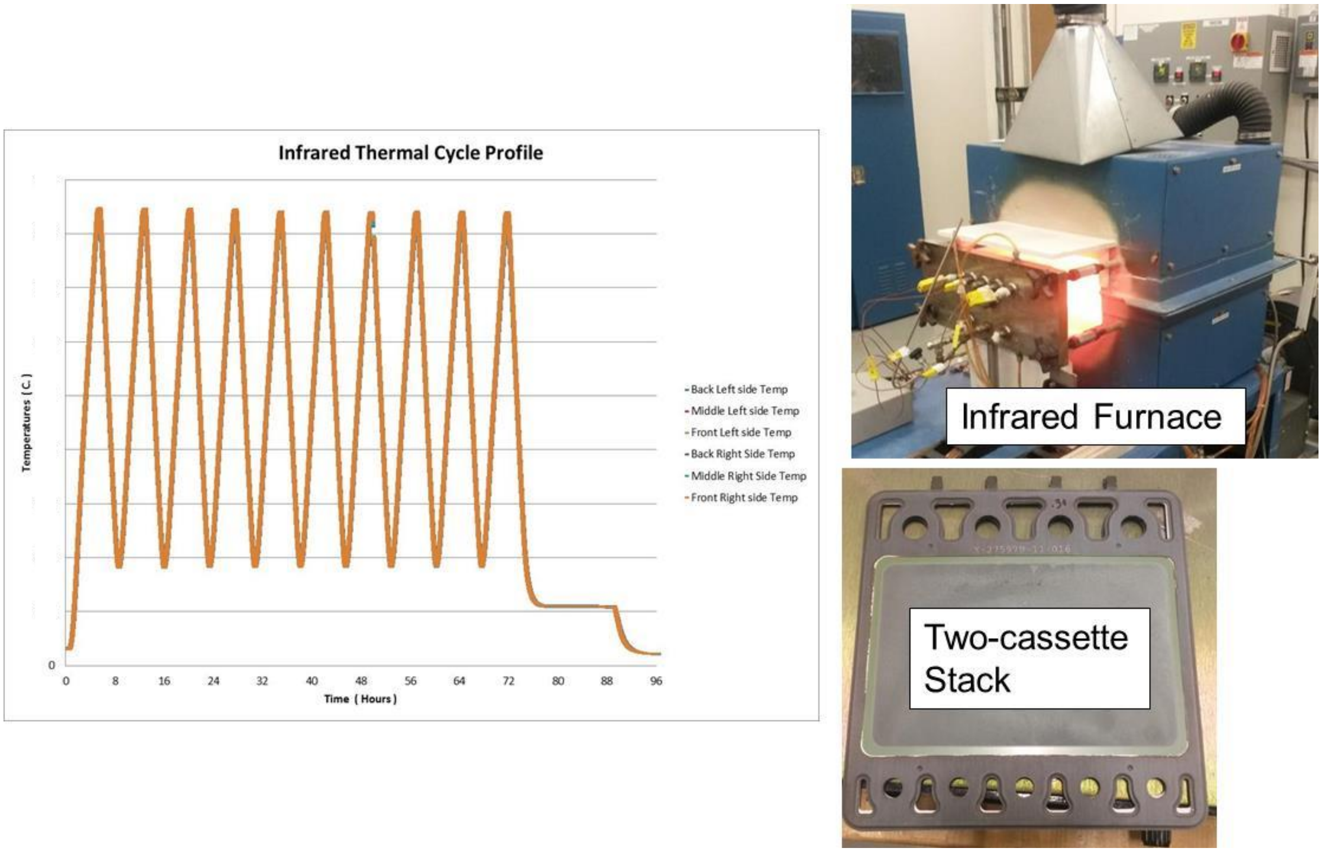

Figure 11: IR thermal cycle profile, furnace, and two-cassette stack sample.

A summary of the results of the infrared thermal cycle test are shown in Table 1.

Description	Cycles completed before leak spec exceeded
Base composition, Fabrication process 2	40
Base composition, Base fabrication process, Supplier B	80
Composition 2, Fabrication process 2	80
Base composition, Fabrication process 2, Supplier A	170
Base composition, Fabrication process 3	110
Base composition, Fabrication process 2, Supplier B	240*
Base composition, Fabrication process 4	160

* Did not exceed leak specification

Table 1: Two-cassette stack infrared thermal cycle test results summary

Much effort was focused on improving repeating unit sealing of Gen4 stacks. Teardown investigations have led to developing theories that stack leaks may be caused by the following factors:

1.) Inadequate compression load on seals
2.) CTE mismatch and thermal stress at the manifold to stack attachment
3.) Inadequate repeating unit seal joint strength

In order to determine the root cause of repeating unit seal leakage, thermal cycling tests were conducted on three separate stacks. Stack G080 was a 30-cell Gen 4 stack which was deep thermal cycled between operating temperature and near room temperature as a baseline. G080 was considered a standard build for the timeframe of the testing. A typical thermal cycle for G080 is shown in Figure 12. During the thermal cycle, the stack reached operating temperature in about four hours, was held at operating temperature and under load (for a performance test) for about one hour, and then cooled to near room temperature in about a nine hour total cycling window.

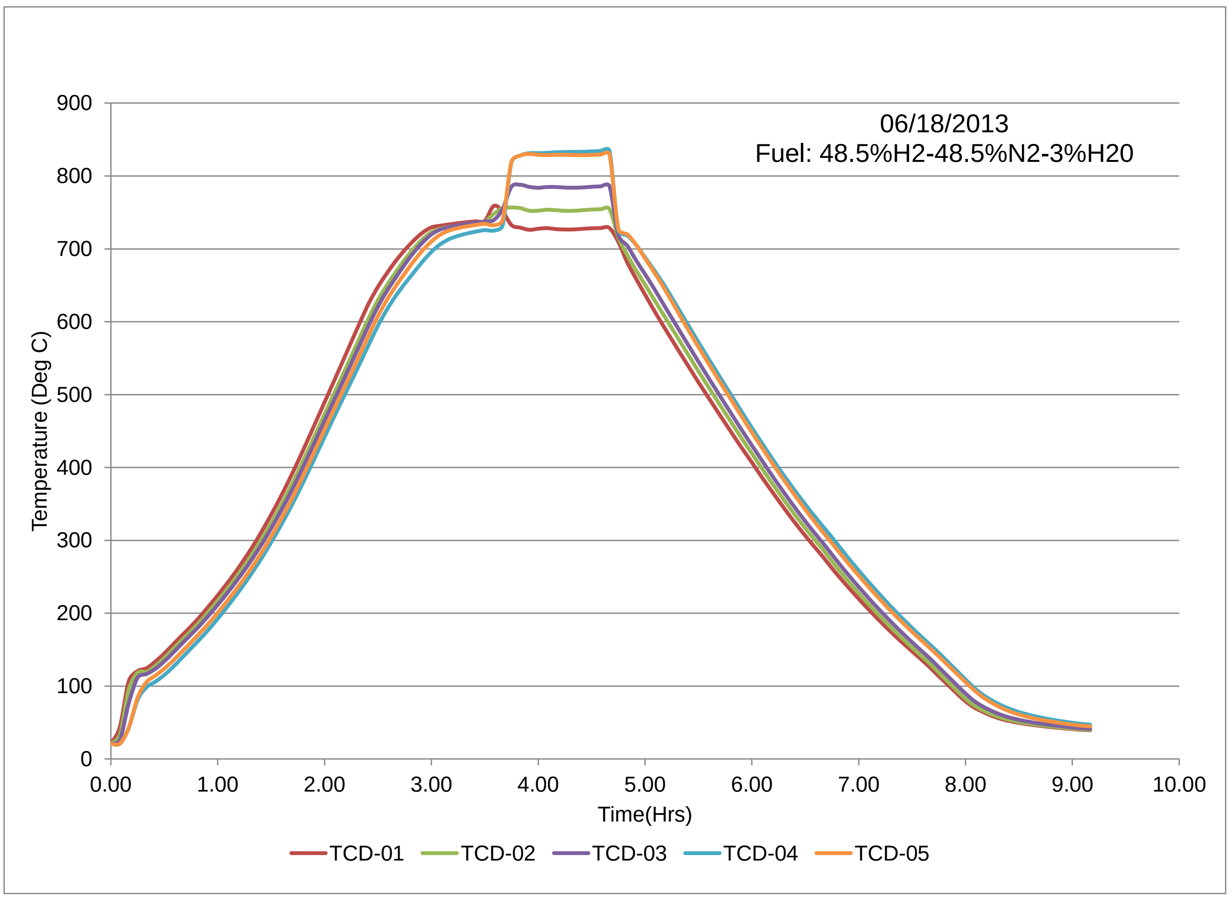

Figure 12 – Temperature profile within a stack during thermal cycling.

Repeating unit voltage performance was recorded for each thermal cycle. Figure 13 shows a typical plot of the repeating unit voltages during the heat up and stack performance measurement portions of each thermal cycle.

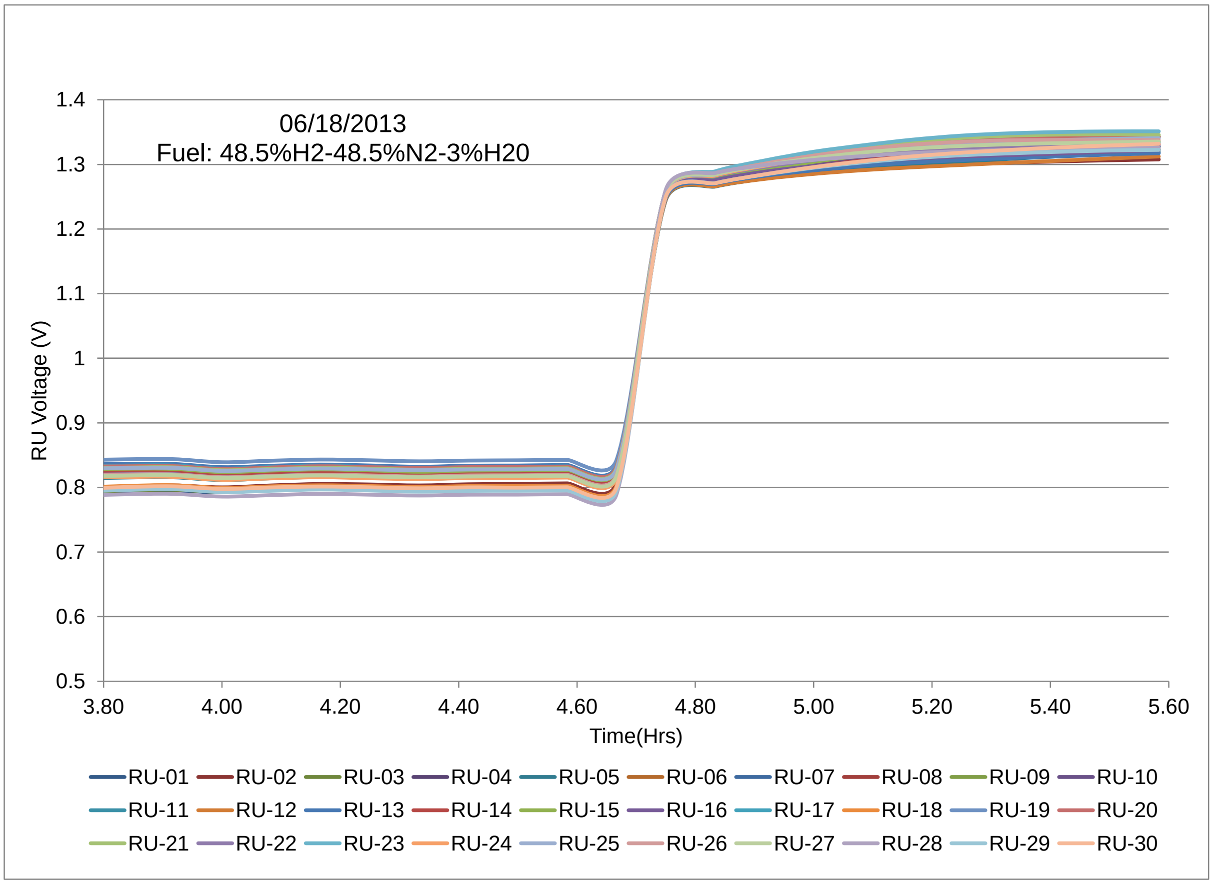

Figure 13 – Repeating unit voltage profile during stack thermal cycling

Baseline 30-cell Gen 4 stack G080 was thermal cycled for 111 deep thermal cycles from operating temperature to near room temperature. A performance measurement was conducted at operating temperature during each thermal cycle. The results are shown in Figure 14. The mean repeating unit voltage remained very stable throughout the thermal cycling test, but the top cell voltage deteriorated after about 40 thermal cycles.

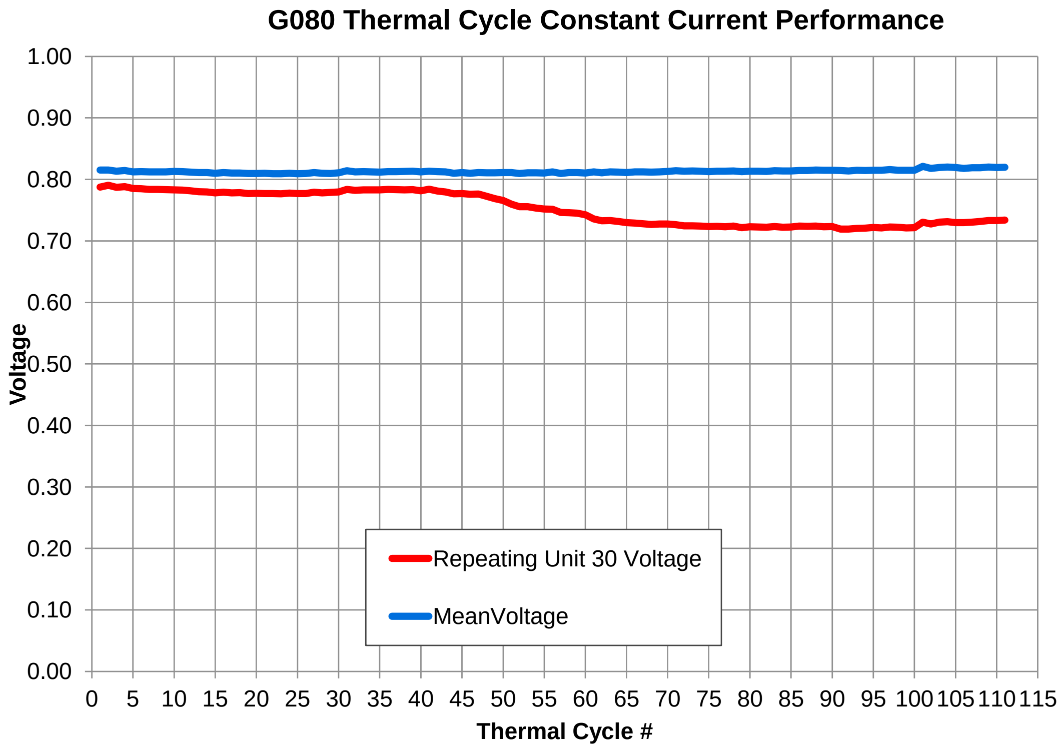

Figure 14 – Voltage performance of stack G080 during deep thermal cycling

The second Gen 4 stack was built to confirm the positive impact of loading on the stack. This was accomplished on 30-cell Gen 4 stack G040, during the entire thermal cycling test, by loading the stack externally through the test stand load frame, applying a load similar to that used during stack sintering. This stack was thermal cycled 78 times prior to terminating the testing. Again, no repeating unit seal leakage occurred, but thermal fatigue failure of a metal seal plate did occur which resulted in leakage beginning at approximately 60 cycles. The thermal cycling results of stack G040 are shown in Figure 15. Note that both the mean repeating unit voltage and the top cell voltage remained very stable throughout the 78 cycles of the thermal cycling test. Also, the current was adjusted at about 46 thermal cycles.

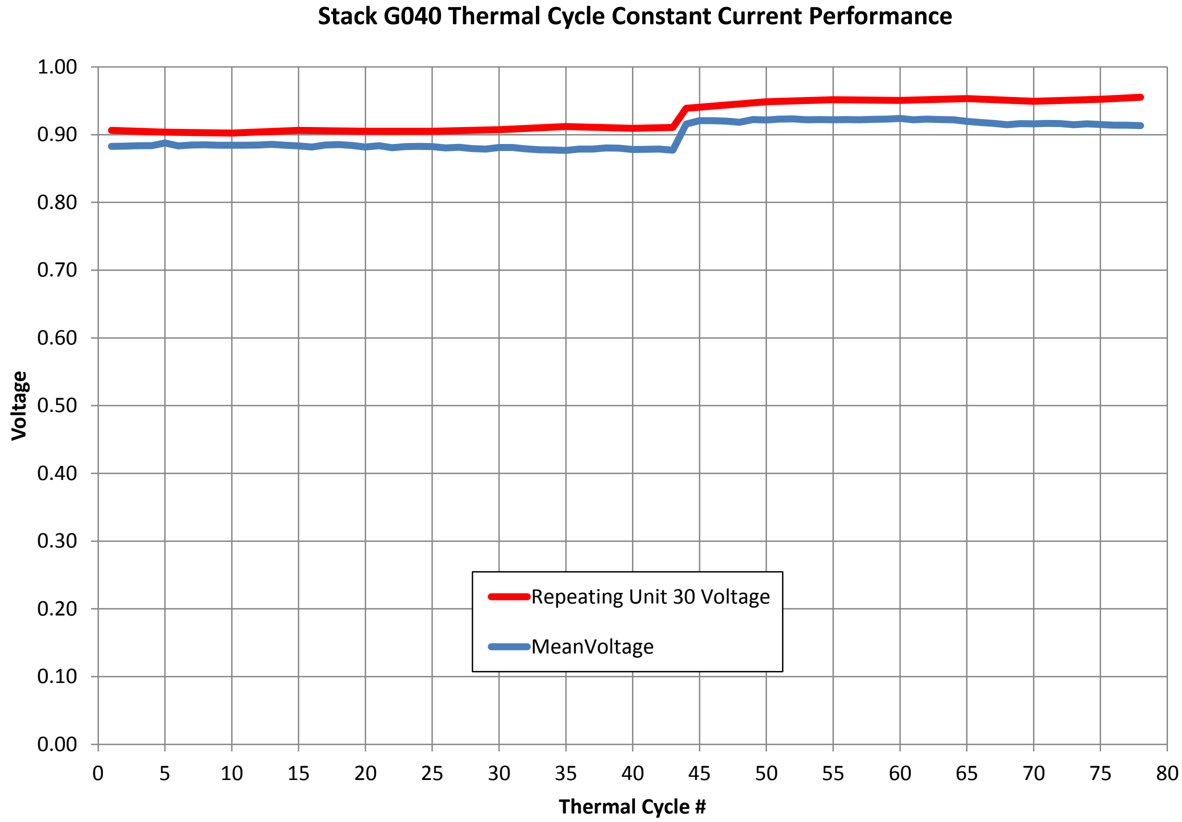

Figure 15 – Voltage performance of stack G040 during deep thermal cycling

Based on the positive results of maintaining a constant load on the stack during thermal cycling, the load mechanism on the third stack (40-cell Gen 4 stack G079) was modified to improve/maintain the applied load to the stack through its self-contained load mechanism. The thermal cycling results of stack G079 are shown in Figure 16. Stack G079 completed 170 thermal cycles with no failure of the repeating unit seal at the lower end of the stack. The stack did, however, develop some leakage after approximately 63 cycles due to thermal fatigue cracking of the metal seal plate. Seal plate cracking and leakage extended to multiple locations increasing the leak over time. At 170 thermal cycles, it was decided to terminate the testing. Teardown results show the cracking occurred at similar locations as on stack G040. Consideration of an alternate seal plate material or design is possible for the future. It was encouraging, however, that the repeating unit seal interface remained intact, suggesting an improvement over past performance as a result of the change.

Repeating unit seal development was again focused on finding more cost effective forming methods, materials, and production capable suppliers. Evaluation of alternatives was supported with accelerated bench testing under a wet dual atmosphere using the rapid thermal cycle (RTC) test stand, the temperature profile shown in Figure 16.

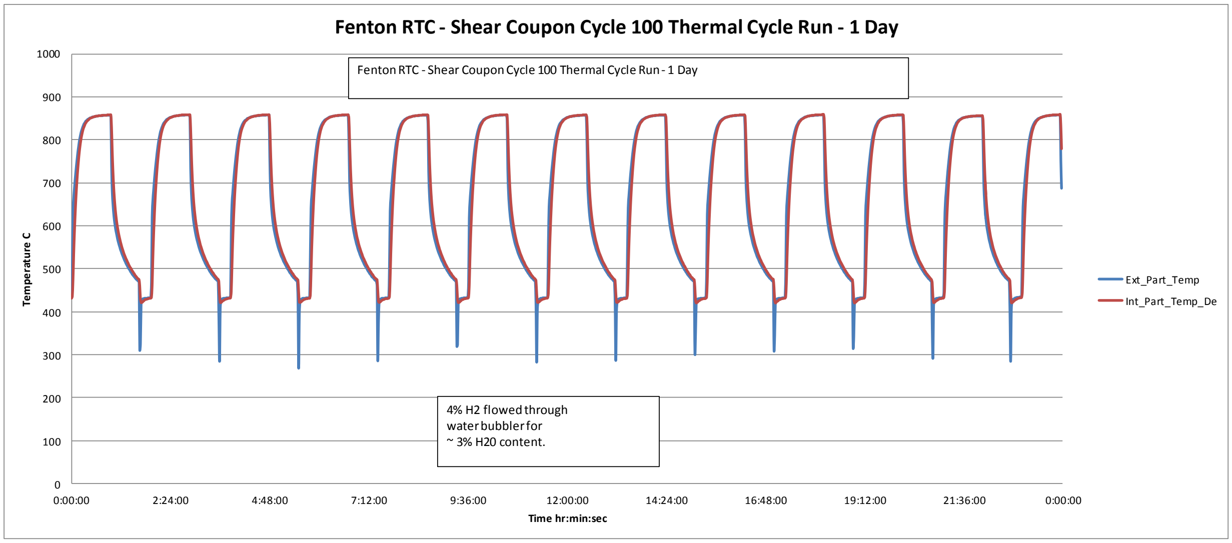

Figure 16: Thermal profile in Rapid Thermal Cycle test stand showing 24 hours of cycle data.

2.2.3 Performance and Durability Evaluations of Stacks

The objective of this task was to perform developmental testing of stacks (of a variety of sizes and/or configurations) for evaluation and verification of new concepts and designs, in order to improve stack electrochemical performance stability and durability. Some key areas of testing included:

- Electrochemical performance evaluations in continuous current extended durability
- Electrochemical performance in thermal and load cycling operating modes
- Electrochemical testing in accelerated aging conditions, such as elevated current density

During the contract period many stacks completed testing on various test stands at the Metro Park facility in Rochester, NY, the Fenton, MI facility, and at the Colorado School of Mines, Golden, CO, in support of the SECA multi-stack test system. Stacks were tested with both blended gases as well as reformate and had ranges of exposure. The longest running stack during the period continues to run after more than 15,000 hours, while many other stacks experienced many thousands of hours of exposure.

Quantifying our stack technology performance has been continuously underway with multiple stacks, both the Gen 3 and Gen 4 designs, running long term durability during the entire contractual period. Testing of full sized stacks has typically been performed in both thermal cycling and constant current durability modes. As stack design, material, and process improvements were developed, they were incorporated into test stacks as rolling changes for durability testing and confirmation. Most of the stacks which were durability tested contained a variety of improvements, and as such, that the overall degradation rate for the stack is typically an average of the degradation rates of numerous changes being investigated at the time.

Stack C865 is a 6-cell Gen 3 stack which had been run on a constant current durability test out to 15,000 hours, and is continuing to run. The test fuel is 48.5H2-48.5N2-3H2O. The voltage performance and power density of stack C865 are shown in Figure 17. During the first 1,000 hours, the durability conditions were varied significantly until fixed at about 1,000 hours. The voltage plot shows the stack voltage performance from the 1,000 hour mark forward. Note also that the current density was lowered at about 3,300 hours, and then raised back to the original current density at about 6,800 hours, where it continues to operate. The stack showed little voltage degradation between 1,000 hours and 15,000 hours. Low degradation is partially attributed to the stack operating conditions. This stack demonstrates very stable voltage over time, but lower power output when compared to running the stack under typical operating conditions. The low degradation rate represents a positive step to increased stack durability lifetime and major incentive for application to future durability stacks.

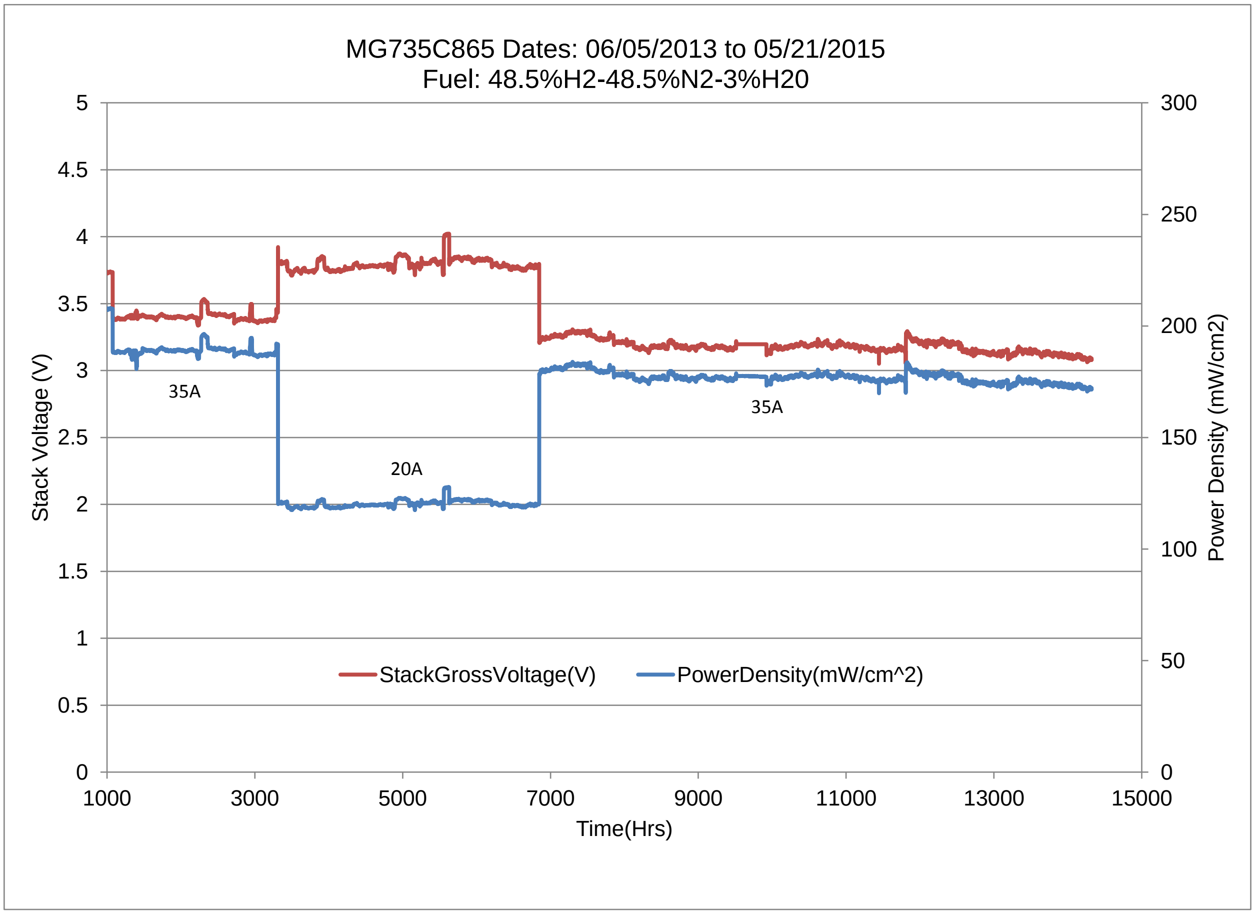

Figure 17: Stack C865 voltage performance during constant current durability testing

Stack G097 is a 40-cell Gen 4 stack which was run on a constant current durability test out to about 5,900 hours. The voltage performance and power density of stack G097 are shown in Figure 18. Note that the current density was lowered at about 3,300 hours, and the test was completed at the lowered current density. The average degradation rate for this 40-cell Gen 4 over the 5,900 hour test period was calculated to be 1.05% per thousand hours, on average, across all repeating units.

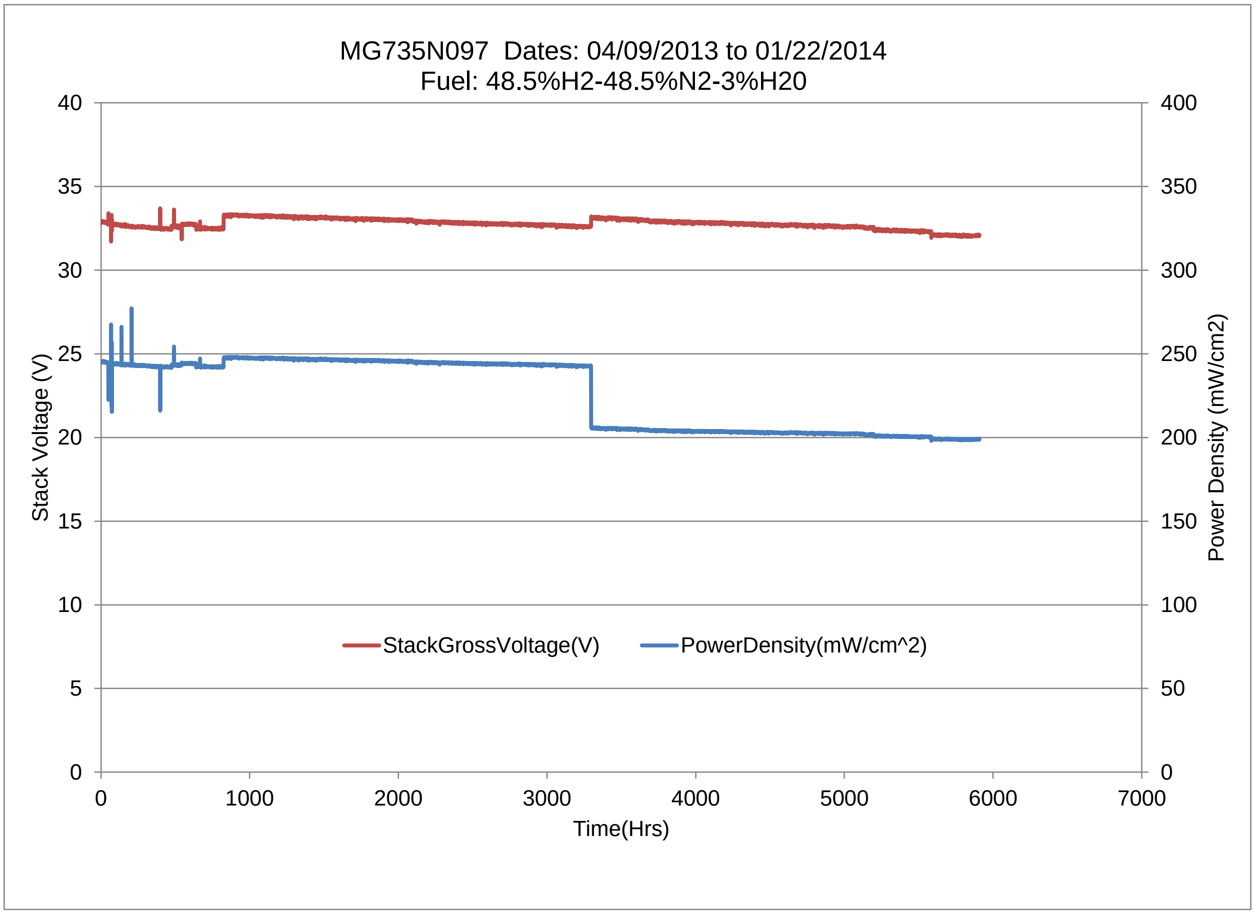

Figure 18: Stack C097 voltage performance during constant current durability testing

2.2.4 Increasing Stack Robustness to Electrical Shorting

- Development of a high dielectric strength seal between the lower current collector and the stack manifold to increase the breakdown voltage of the stack
- Confirm the increased dielectric breakdown voltage with a stack and manifold test

Increasing the dielectric strength to electrical shorting is a key priority for stacks connected in series, as is the plan for larger stationary power systems. The main approach was to develop a dielectric barrier using a material of high dielectric strength at operating temperature, which is compatible to the repeating unit seal. High temperature voltage dielectric resistance performance testing was conducted for a number of material candidates, several of which showed good promise (Figure 19). Practical considerations have narrowed the choices to a preferred candidate. Material and process development was conducted in-house and then later discussed with possible production capable suppliers.

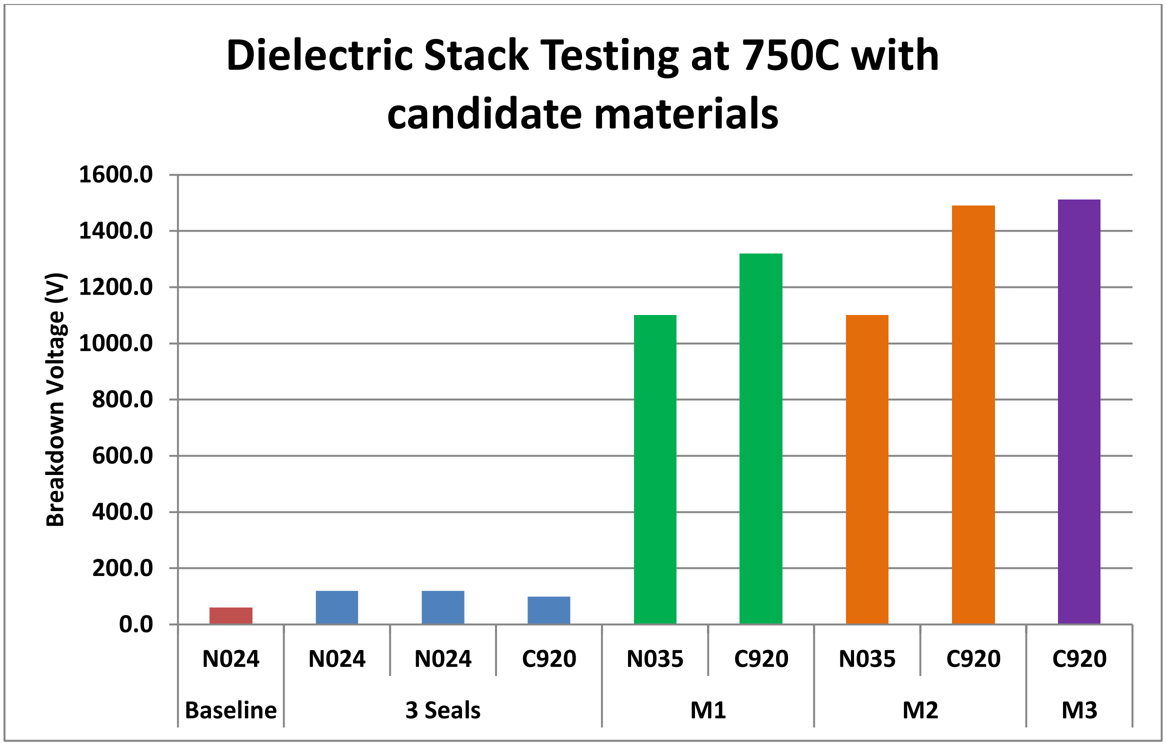

Figure 19: Stack manifold dielectric breakdown voltage at 750C

Multiple stacks, with an in-house made dielectric barrier, were assembled and sintered to gain operational experience. Stacks of both the Gen 3 and Gen 4 configuration were built over the period with dielectric barriers.

Two external suppliers of the dielectric material were identified and both have provided us with ready-to-assemble dielectric sheets for stack tests. Supplier A used their own material and process set, but showed an incompatibility issue between the seal and the barrier. Supplier B used the Delphi-developed dielectric material and fabricated the sheets using an alternate manufacturing process, showing good mechanical strength (Figure 20).

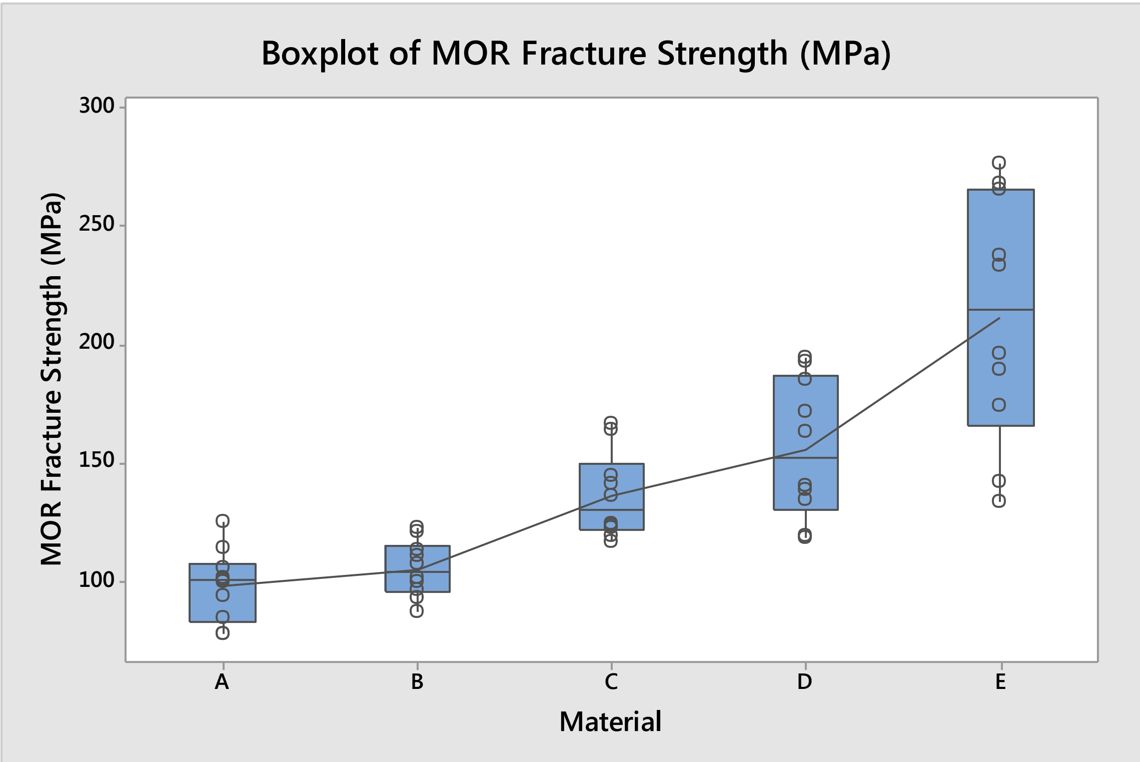

Figure 20: MOR Fracture strength of dielectric material options processed by Delphi and external suppliers.

2.3.0 Cost Reduction

- Metal coatings from lower cost, production capable processes and suppliers
- Lower cost process for formation of repeat unit seals
- Lower cost supply of thin cell tapes (active anode, electrolyte, backing layer, etc.)

2.3.1 – Metal Coatings

Metal coatings for oxidation resistance and, more importantly, chromium retention, are of great importance in SOFC. The cost of coatings for our stainless steel parts consumes a considerable portion of the total cost of the stack, both at the prototype level and at estimated production volumes. As a result, considerable incentives exist to find more cost effective alternatives with similar or superior functional performance. A priority for a lower cost alternative for the repeating unit sheet metal parts (cell retainer and separator plate) exists due to the cost multiplication in a stack with numerous repeating units. The coating requirements are relatively demanding for both parts. The cell retainer requires a suitable sealing surface to interface to the repeating unit seal and to the cell braze, while protecting the open area from Cr migration and maintaining compatibility for repeating unit welding. The separator plate requires an active area with good conductivity and oxidation resistance as well as a perimeter sealing surface.

Two production capable commercial suppliers were identified as potential cost effective replacements to the current method for both the Gen-3 and Gen-4 retainers and separators. During the contract period multiple tests were conducted in support of coating alternatives for all seal interfaces in the stack. Stacks with alternative coatings applied to the retainer have experienced in excess of 5,000 hours, showing good promise for implementation.

The active area of the separator plate is another opportunity to find lower cost alternative solutions. High temperature resistance testing was conducted on the various candidates to understand their relative conductivity, as measured by their Area Specific Resistance (ASR). Repeatability testing of multiple samples of the same design, suggested some measurement variation. Long term testing of the best candidates, in an oxidizing environment, was conducted as well as stack testing to understand if these differences translate to increased stack performance (Figure 21).

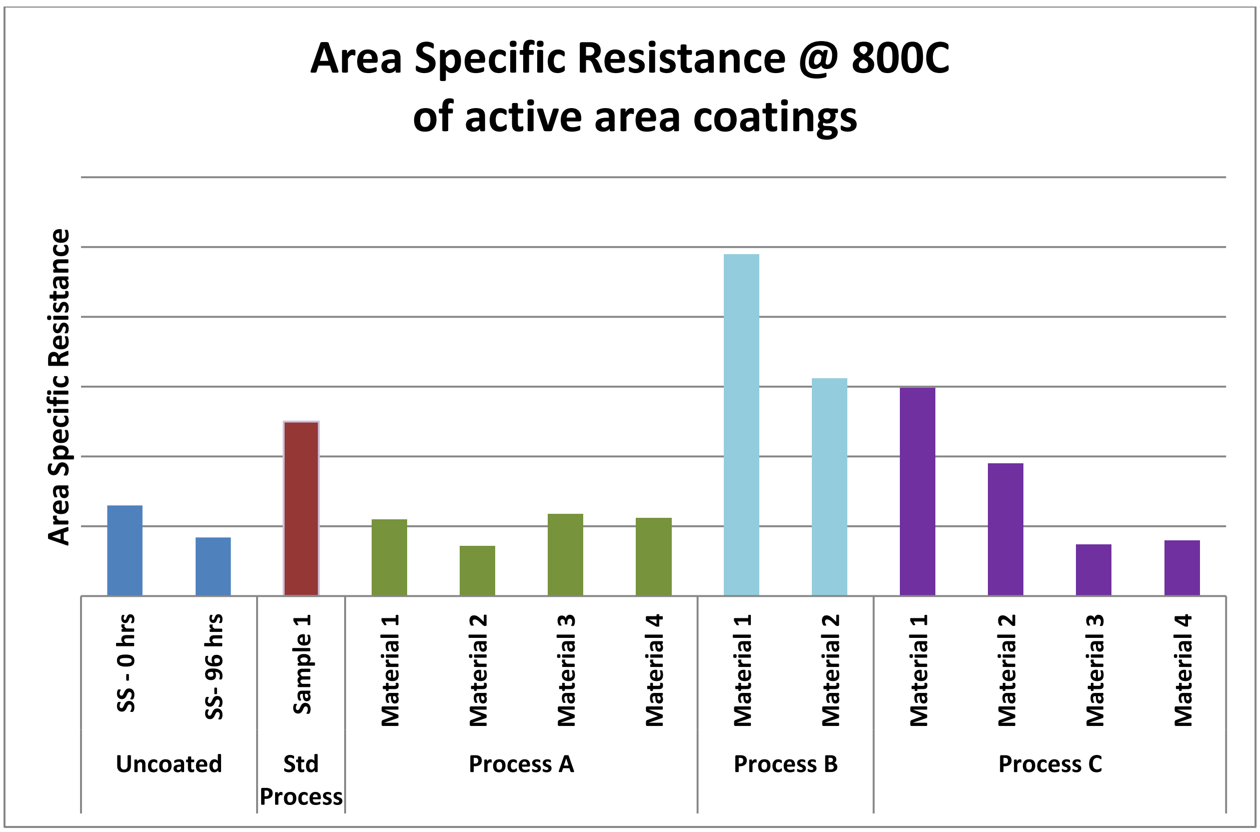

Figure 21: ASR comparisons of various interconnect coating alternatives

Stack testing of alternative coatings suggested that the performance of the low cost alternative was statistically indistinguishable (p-value > 0.05) from the baseline performance, and offered a significant cost reduction even at prototype volumes.

Figures 22 and 23 show voltage and/or voltage degradation analysis for cells containing alternate coatings, within two different stacks. Voltage performance showed encouraging output to date with no discernable difference to repeating units with the more expensive baseline. More extensive run time and end-of-test analysis will support an implementation decision.

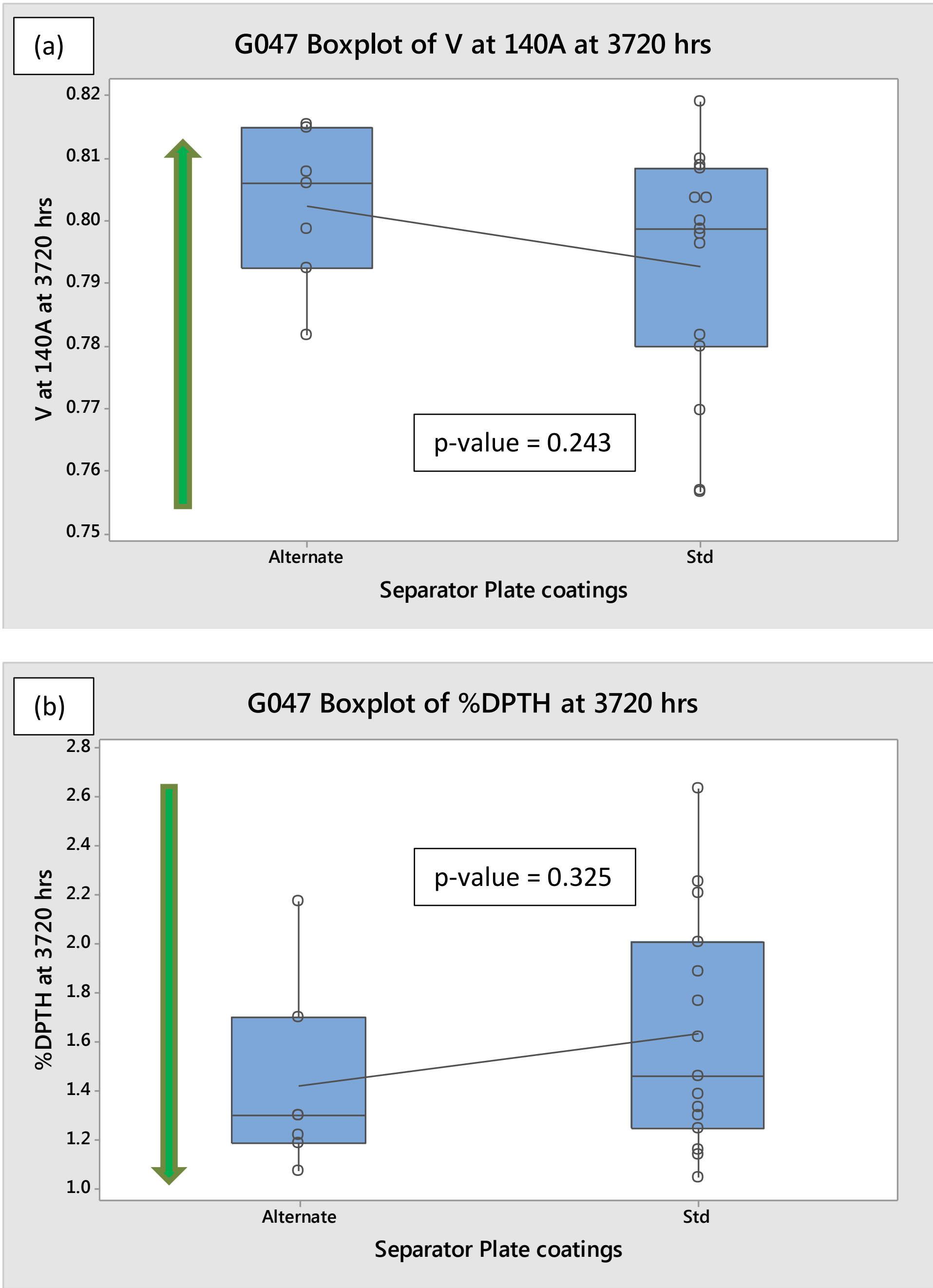

Figure 22. G047 23-cell Gen 4 stack with alternate separator plate coatings show good performance in voltage (a) and degradation rate per 1000 hours (b) after 3720 hours. Preferred direction of output noted with arrow.

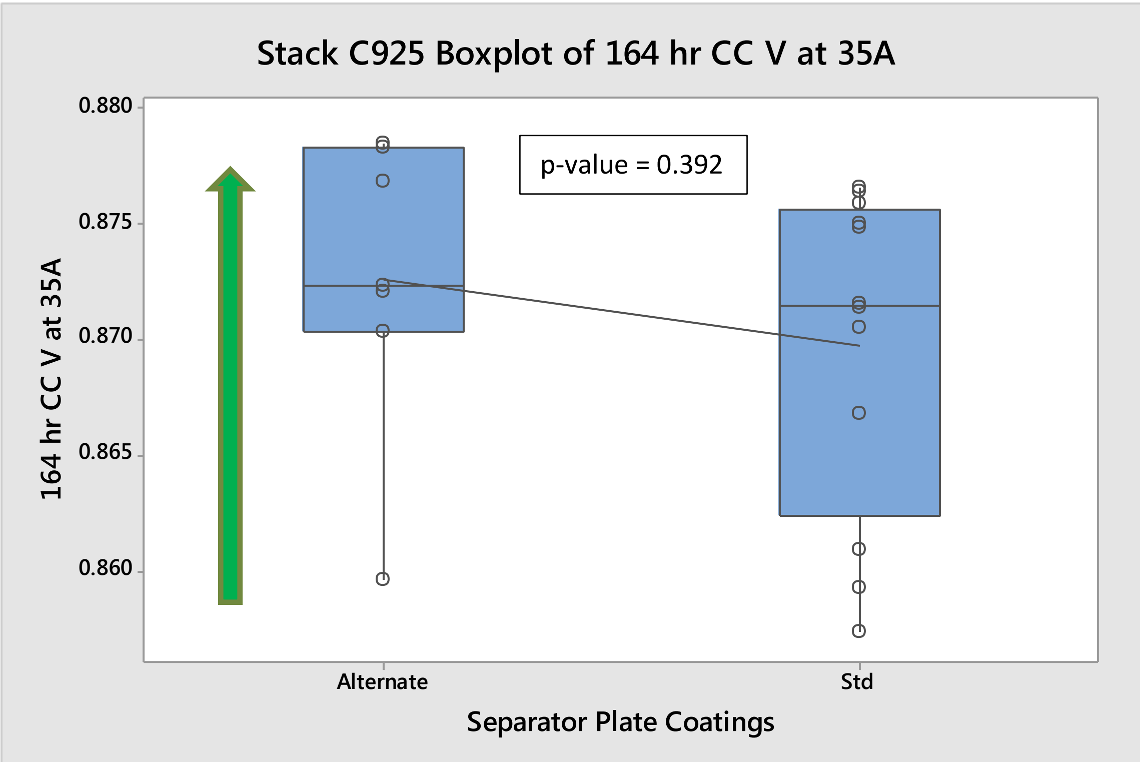

Figure 23: Voltage output from cells in 24-cell Gen 3 C925 stack built with alternate separator plate coatings. With 95% confidence, no statistical difference between the mean of the two groups is confirmed.

2.3.2 – Repeating Unit Seals

Two aspects of repeating unit seal cost were investigated. First, the efficiency of the forming process used to create the finished part dominates cost at lower volumes. Second, the inorganic ingredient costs become especially important at high volumes. Reduction of ingredient costs will require evaluation of alternative ingredients and suppliers. Alternate production feasible forming processes are under consideration. Prototype hardware, cost estimates, and coupon and stack level testing, have been conducted to evaluate the options to drive more favorable prototype and volume production pricing alternatives. Lower cost alternative base materials have also been evaluated. As a repeating unit seal is provided between each repeating unit, the incremental cost improvements are quickly multiplied. Several stacks are under test with alternate experimental seal materials to understand their long term performance. Initial end-of-test and metallographic results are encouraging.

2.3.3 – Thin Tapes

Two alternate suppliers of bilayer tapes have been identified and continue to be developed. A pilot scale run was conducted at Supplier A in late October 2014, which yielded electrolyte and active anode tapes (Figure 24). To date, in-house made slurries have been provided for all Supplier A coating work. Recently, slurries made at a third party have been shipped to Supplier A for the next rounds of work. A later goal will be supplier-site slurry fabrication.

Figure 24: Gen 3 fired bi-layer made with Supplier A process.

While significant work was focused on identifying and developing a lower cost supplier solution, comparing the performance of the resultant product was also key. Several attempts to date have resulted in somewhat reduced output performance over our current standard solution, as seen on button cell samples as well as full size cells within a stack assembly (Figure 25). Work remains to understand these differences and overcome them.

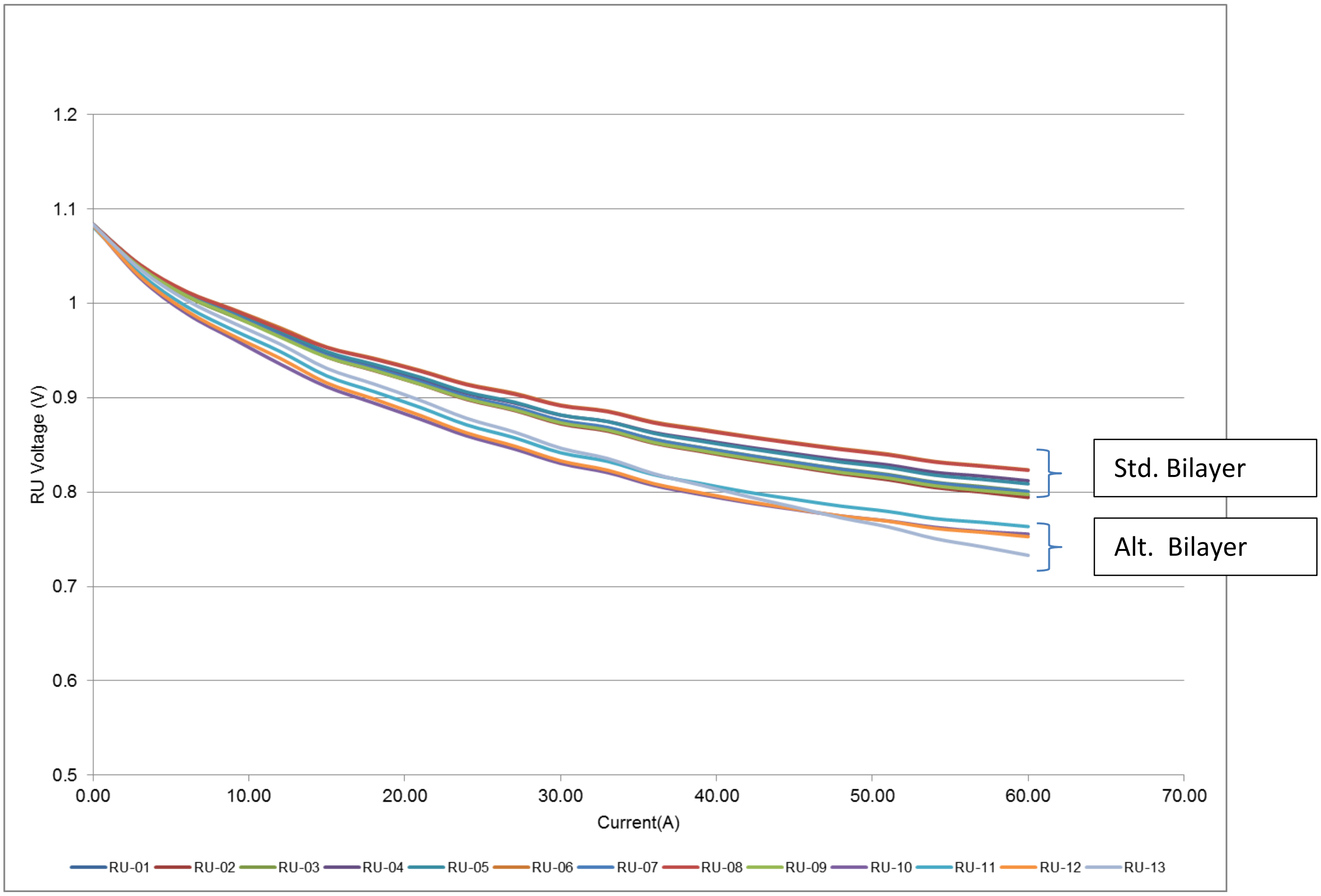

Figure 25: Gen 3 stack C957 polarization curve. Stack includes cells with standard bi-layer and alternate bilayer construction. The alternate bilayer shows reduced performance to date.

Summary of Stack Cost

The SECA cost target for the stack assembly is \$225/kW with a 2011 dollar basis. This converts to \$238.10/kW per a 2014 dollar basis.

Delphi provided a cost analysis on a 40-cell Gen 4 stack which was tested with syngas ($50H_2$-$50N_2$ fuel) and which produced a maximum power of 7.5 kW at Delphi's test facility in Rochester, NY. This stack was also used to provide data on durability.

The 40-cell Gen 4 stack produced a peak power of 7.5 kW at 0.78 volts average per repeating unit with $48.5\%H_2$-$48.5\%N_2$-$3\%H_2O$ (50/50 fuel) at 50% utilization. Analysis shows that the specified fuel blend, representing a natural gas reformate, is close to Delphi's test gas blend of $40\%H_2$-$10\%CO$-$25\%CO_2$-$25\%H_2O$. This has shown to provide a lower power output when compared to the 50/50 fuel on a separate 30-cell Gen 4 stack. This analysis provided the factor used to calculate the peak and NOC powers provided in the cost per kW, and in the cost and test sections of the stack cost report which was submitted 11/14/2014, as shown in figure 26.

Delphi Stack Cost Summary			
(Assumes one 50 cell Gen 4 stack at 9.4 kW peak and 5.9 kW NOC)			
Item	**Cost/Stack**	**Cost / kW Peak \$USD**	**Cost / kW NOC \$USD**
Stack Assembly Factory Cost 2011 Dollar Basis	\$2,314.18	\$246.09	\$395.91
Stack Assembly Factory Cost 2014 Dollar Basis	\$2,414.55	\$256.76	\$413.08

Figure 26. Stack Cost Summary

Cost numbers cited in this report are for a 50 cell stack at an annual volume of 71,000 units. Delphi's November 14, 2014 total factory cost is \$2,314.18 per stack assembly. Using a rated power output of 9.4 kW, the cost of the stack is \$246.09/kW and \$395.91/kW at 5.9 kW NOC. The factory cost includes equipment and plant depreciation, tooling amortization, equipment maintenance, utilities, indirect labor, cost of capital, manufactured materials, purchased materials, fabrication labor, assembly labor, and indirect materials costs.

Summary of System Test

The design and build of a thermally self-sustaining SOFC system to test and evaluate the technology at an 8-12 kW scale was completed. The multi-stack section of the SECA test system was comprised of three Geothermic Fuel Cell (GFC) modules, each containing three Gen 3 SOFC stacks. The total system was tested (under continuously applied load) for 192 hours, fueled by reformed natural gas.

System and Stack Integration

The design and build of a thermally self-sustaining SOFC system to test and evaluate the technology at an 8-12 kW scale was completed and is shown in Figure 27 below. Three GFC modules were coupled to a reactant-gas preheat device and inserted into the earth on the grounds of the Colorado School of Mines, in Golden Colorado. Each GFC module contained three 1.5kWe SOFC stacks. The GFC system was operated for a total, non-continuous operating time of 600 hours, fueled by reformed natural gas and hydrogen fuels. Figure 28 shows the test site layout and the installation of the GFC into the bore hole.

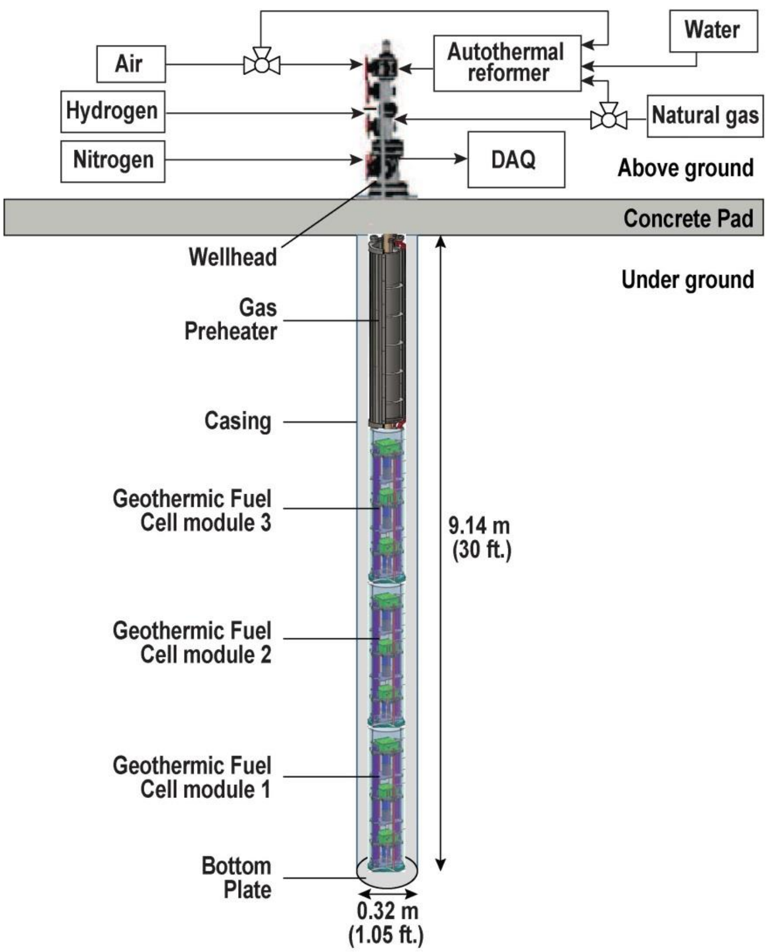

Figure 27. GFC system schematic

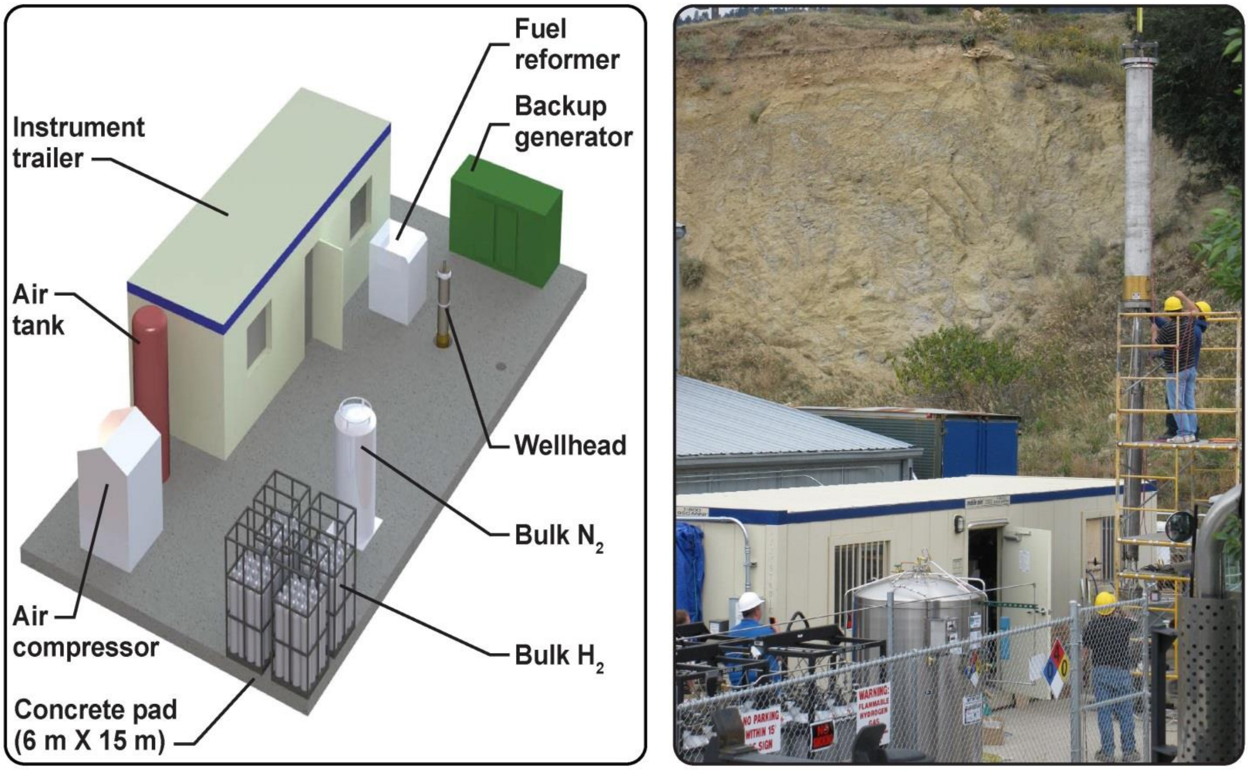

Figure 28. GFC Test Site at the Colorado School of Mines, Golden CO

The GFC was continuously operated, using reformed natural gas, for approximately 192 hours, with the current draw set at 65A for the last 100 hours of operation. This operating point was selected to favor heat generation (29.1 kW_{th}) over electricity production (4.4 kW_e). A quasi-steady operating point was observed over a 24 hour period, and thermodynamic analysis revealed a combined-heat-and-power efficiency of 55% at this condition. Heat flux to the geology averaged 3.2 kW/m across the 9-m length of the GFC assembly.

The ground temperatures, as a function of depth and radial distance from the well casing, are shown in Figure 29. It can be seen from the plot that the ground temperatures are increasing at a rate of over 3^{O}C in the 24-hour period of consecutive measurements.

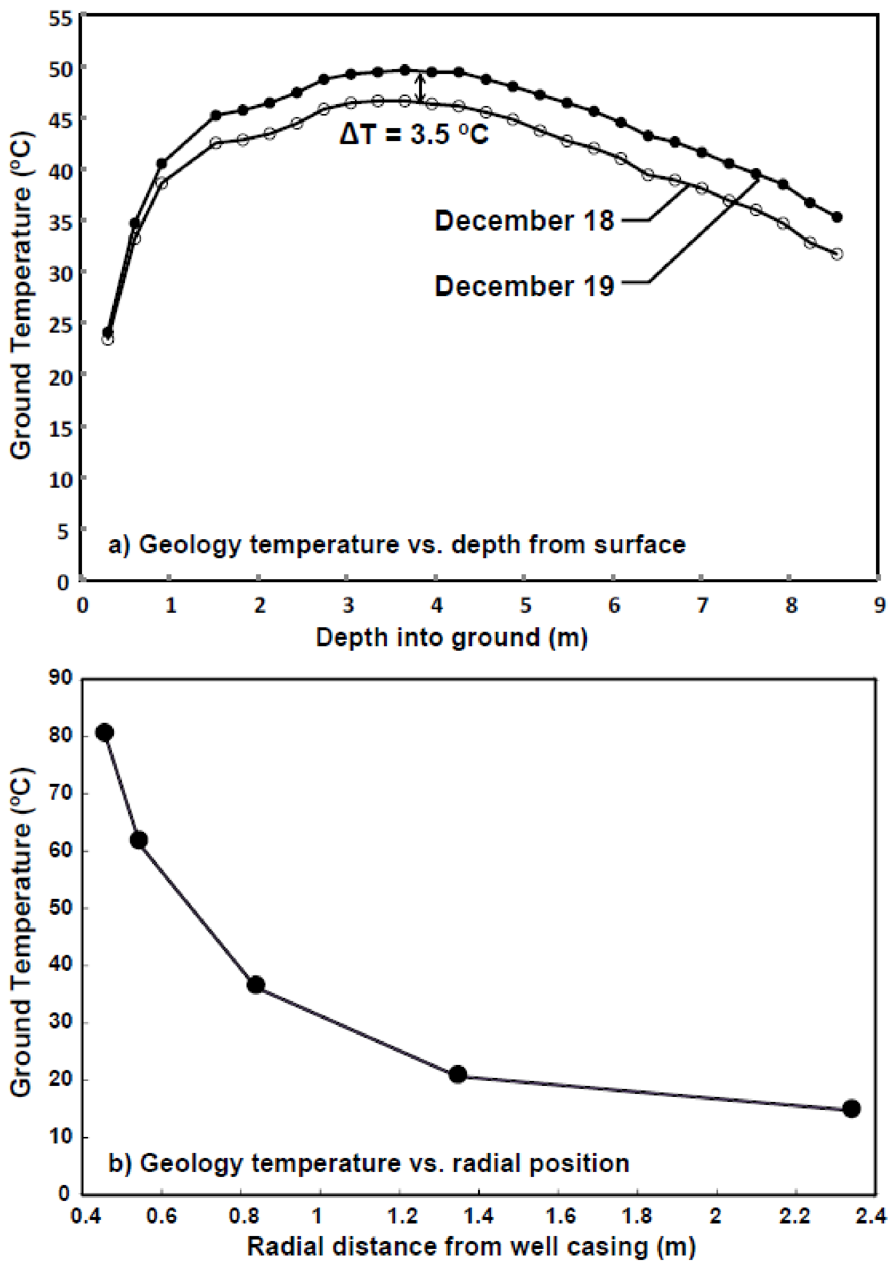

Figure 29. Ground temperatures near the GFC: a) as a function of depth below the surface; b) as a function of radial distance from the well casing measured at depth of 4m below the surface

The distribution of energy across the GFC at the 65A operating condition is shown in Figure 30. 4.4 kW of continuous electric power was generated by the SOFC stacks. This power is less than one third of the rated capacity of the combined stacks, resulting in a 7.2% electrical efficiency. This low electrical efficiency was primarily attributed to the low fuel utilization value of 26% used during the testing to generate more heat than electricity. It is expected that as the geology increased in temperature, more energy could be diverted towards electricity generation, rather than heat liberation.

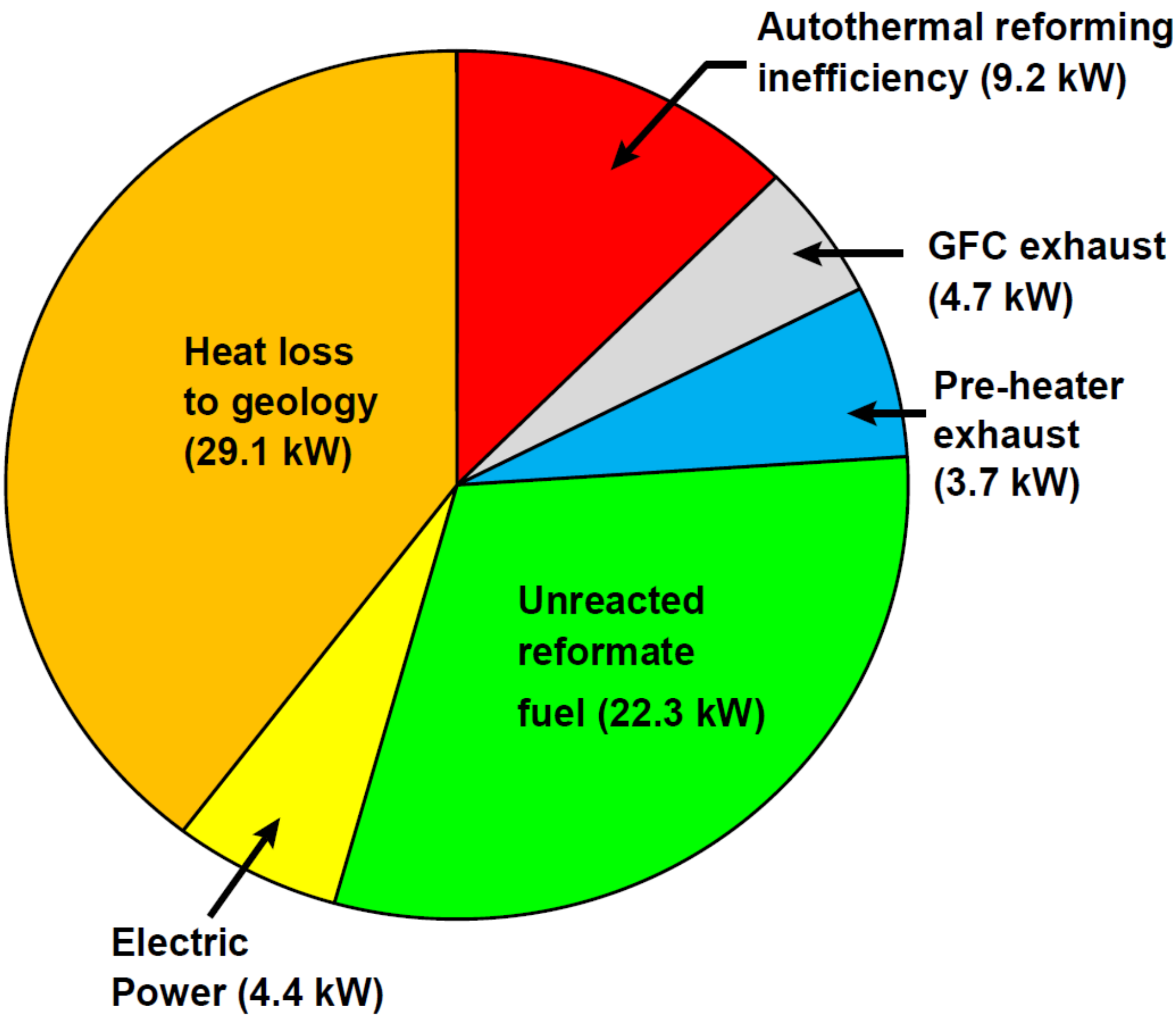

Figure 30. Distribution of energy across the GFC system at 65A

Figure 31 below is a plot of the SOFC stack voltages over the final 190 hours of testing. All stacks performed similarly, as indicated by the narrow voltage distribution. The reduction in voltage that occurs at the 125 hour point was due to carbon formation in the reformer blocking the fuel flow to the stack anode inlet. The cause of the carbon formation was found to be a leak in the reformer air supply fitting, causing an increase in the fuel/air ratio.

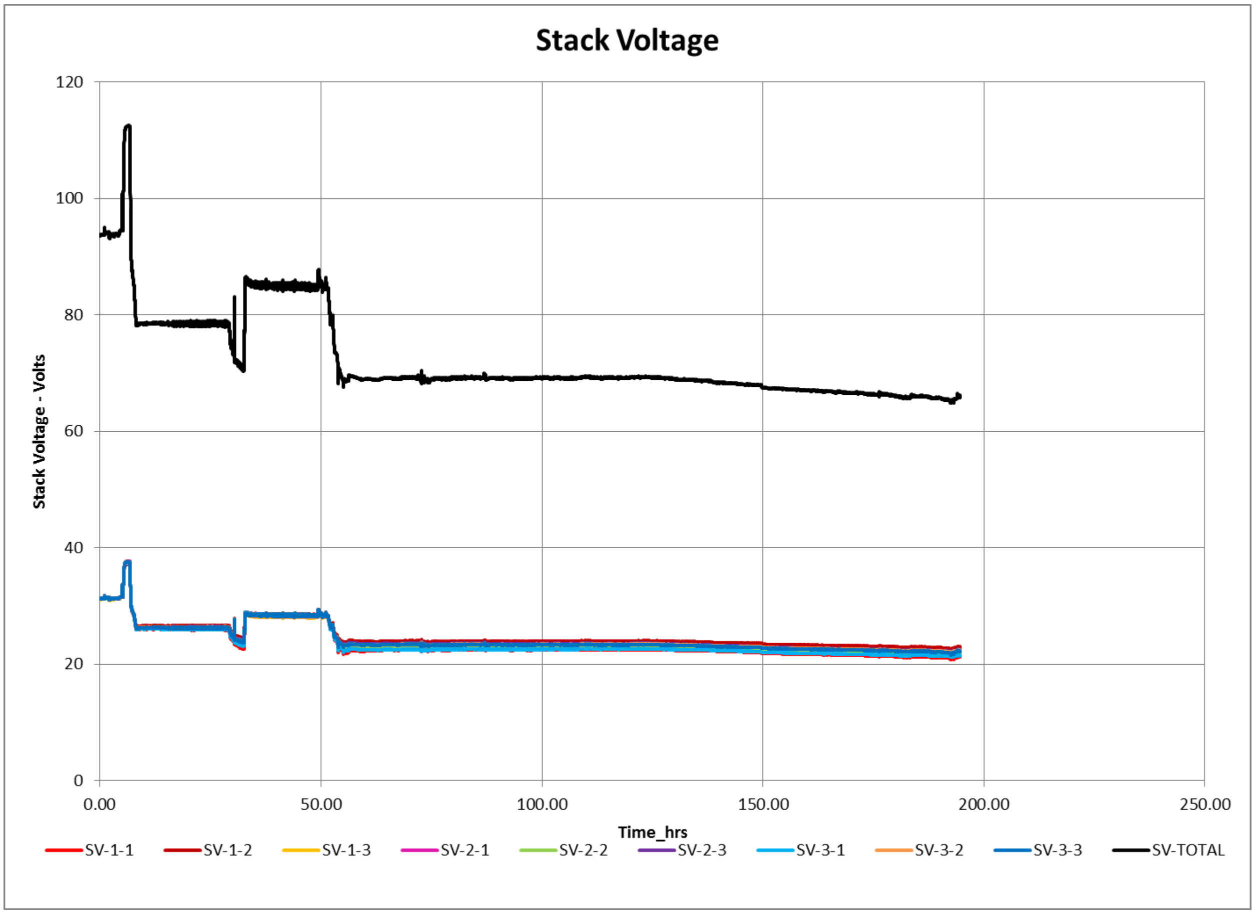

Figure 31. SOFC stack voltage and total GFC voltage during the GFC system test.

Conclusions

Stack Reliability

Delphi has demonstrated stable Gen 3 stack performance at NOC out to approximately 15,000 hours, thus far. Gen 4 stack performance at NOC has been demonstrated out to about 6,000 hours. The operational conditions are important contributors to stack performance, and Delphi has gained further understanding of the impacts of many of these parameters on the long term performance of SOFC stacks. Stack reliability has routinely increased during Delphi's participation in the DOE's SECA program.

Stack Degradation

Delphi has tested a number of cells and stacks during this period, both of Gen 3 and Gen 4 configurations. Tests have included routine constant current durability, thermal cycling, accelerated thermal cycling, and have employed numerous changes to stack operational conditions. Combining the testing with electrochemical impedance spectroscopy has enabled

Delphi to identify performance degradation mechanisms which can contribute to the stack degradation rate. Targeting those mechanisms will allow us go from a current degradation rate of about 1%/1000 hours to a lower stack degradation rate, closer to the SECA NOC target of 0.2%/1000 hours by 2020. Stable long term performance is considered a requirement for the stacks to be incorporated into large stationary power systems.

Cost

Delphi calculated a high volume, stack factory cost of $256.76/kW (in 2014 dollars), compared with the SECA targeted factory cost of $238.10/kW (in 2014 dollars). The cost reduction activities which Delphi pursued during this contractual period, specifically metal coatings, repeating unit seals, and tape sources, will be instrumental in achieving the targeted cost set forth in the SECA program.

System Test

The system test demonstrated that multiple stacks could be connected together and controlled as a single system in a self-sustaining mode. In addition, the system was operated in an outdoor environment that simulated a commercial deployment, including realistic fuel composition, which was much more challenging than a laboratory environment. Key operating metrics from the test were as follows:

- 29.2 kW of heat transferred from the GFC to the geology
- 3.2 kW/m of heat flux supplied by the GFC
- 55% combined heat-and-power efficiency
- 25.8% fuel utilization

The balance-of-plant issues were the most problematic, with failures of the air delivery and natural gas reforming subsystems causing significant down-time. As a result of these balance-of-plant failures, the system could not be operated for the targeted length of time (1,000 hours) to determine the stack degradation rate.