FINAL SCIENTIFIC/TECHNICAL REPORT

Cooperative Agreement
DE-EE0005969
GM Light Duty Fuel Cell Electric Vehicle Validation Data

SUBMITTED BY

General Motors LLC (GM)
895 Joslyn Avenue
Pontiac, Michigan 48340

PRINCIPAL INVESTIGATOR

Pamela M. VeCasey
585-478-1148
pamela.vecasey@gm.com

SUBMITTED TO

U. S. Department of Energy
Fuel Cell Technologies Office
Jason Marcinkoski
jason.marcinkoski.ee.doe.gov

REPORTING PERIOD

03/01/2013 through 02/28/2018

SUBMITTED ON
May 24, 2018

Table of Contents

1. Executive Summary....................3
2. Comparison of Actual Accomplishments with Project Objectives....................3
3. Summary of Project Activities....................4
4. Products....................13
    a. Publications....................13
    b. Web site or other Internet Sites....................13
    c. Networks or Collaborations Fostered....................13
    d. Technologies/Techniques - n/a....................13
    e. Inventions/Patent Applications, Licensing Agreements....................13
    f. Other Products....................13

1. Executive Summary

General Motors LLC (GM) completed a multi-phase project with the Department of Energy to validate light-duty fuel cell electric vehicle (FCEV) performance and durability using dynamometer fuel cell system and real-world vehicle performance data. This project began with GM's Gen 0 Fuel Cell Fleet vehicles with Technology Insertion operating strategies and materials, and extended to GM's Gen 1 and early Gen 2 commercial-design intent Fuel Cell stacks and Fuel Cell Systems.

The intent of this project was to understand how fuel cell materials, system architectures, and operating strategies impact fuel cell stack durability under fully dynamic operating conditions such as those seen in a light duty vehicle application. More than 87,000 hours of system run time were accumulated under this project simulating several vehicle lifetimes under aggressive driver usage conditions.

Lessons learned from this demonstration project have helped expedite the development of a commercially viable, zero-petroleum, zero-emission, Fuel Cell propulsion system. Durability test results have enabled a substantial reduction in the precious metal content in the Fuel Cell Stack with each successive generation of stack design. Stack lifetimes between the first and current design iterations have increased nearly tenfold, while the overall precious metal content has been reduced by approximately 85%. The Gen 2 system power density (kW/gPt) is over five times that of the Gen 0 system. In addition, run time voltage degradation as a function of total platinum was reduced by more than an order of magnitude between the first and last phase of this project. GM is proceeding with a low volume production program aided by the results of the durability testing performed under this cooperative agreement.

2. Comparison of Actual Accomplishments with Project Objectives

A total of 15 stacks encompassing three generations of Fuel Cell stack and system design have been tested under this project while accumulating over 87,000 hours of actual and simulated vehicle operation. GM's first Fuel Cell Vehicle Fleet was originally intended to be a three-year demonstration project, however, the vehicles have lasted well beyond their expected lifetimes and have enabled fuel cell stacks to be tested on-road in real world applications for thousands of miles. Three of those vehicles attained 100,000 accumulated miles during the initial phase of this project. While the Gen 0 stack lifetimes were not as high as expected, the data was utilized to drive improvements in the material set, control strategies, test cycles, and balance of plant component design in the two subsequent generations.

Under this project, GM's Gen 1 stacks achieved well over 5000 hours of dynamic cycle testing while avoiding the cell primary failure mode encountered with the Gen 0 systems. The Gen 2 stacks all exceeded 5000 hour lifetimes, while demonstrating robustness to aggressive durability cycle testing and reduced system cost.

All data from the vehicle and module testing was supplied to the National Renewable Energy Laboratory (NREL) to be analyzed and compared to the performance of other OEM fuel cell systems over time. Over forty (40) GB of data was delivered to NREL for processing, along with a comprehensive system maintenance summary for each of the test platforms on a quarterly basis.

There were no Fuel Cell or hydrogen related safety incidents recorded during this five-year demonstration project and GM is proud of its' hydrogen safety record.

Table 1 summarizes the test results for the project showing total time to failure, time to 10% voltage loss at 288 A, precious metal utilization (kW/gPt), and voltage degradation rate (mV/gPt) relative to the Gen 0 system. The data referenced in the table is based on a 288A operating point to allow comparison across multiple generations of hardware.

Stack ID	Gen ID	Operating Modes	Test Protocol	Time to 10% loss @ 288A hours	288A Steady-State Voltage Degradation mV/hr	Actual End of Service hours	Failure Mode	Normalized Pt utilization kW/gPt [3]	Normalized voltage degradation rate mV / gPt [4]
S0753	Gen0	w/Standby w/ H2iP	Real world driving	100 [1]	0.080	1042	X-Over membrane failure	1.0	0.080
S1039	Gen0	286 hrs w/ Standby w/ H2iP	Real world driving	300 [2]	0.038	1115	X-Over membrane failure	1.0	0.038
S1049	Gen0	w/ Standby w/ H2iP	Real world driving	1000	0.066	1331	X-Over membrane failure	1.0	0.066
S1055	Gen0	w/ Standby w/ H2iP	Real world driving	800	0.080	985	X-Over membrane failure	1.0	0.080
S1072	Gen0	92 hrs w/ Standby w/ H2iP	Real world driving	700	0.051	1332	X-Over membrane failure	1.0	0.051
S1521	Gen0*	w/ Standby w/ H2iP	Real world driving	1500	0.040	2207	X-Over membrane failure	1.1	0.036
S1525	Gen0*	w/ Standby w/ H2iP	Real world driving	1700	0.037	1711	Sub-gasket tear related to manufacturing process	1.1	0.033
S1836	Gen1	No Standby no H2iP	PD6FC - 99% driver	6000	0.008	13395	X-Over membrane failure	2.5	0.003
S1837	Gen1	No Standby no H2iP	PD6FC - 99% driver	5500	0.008	8847	Stack did not reach End of Life	2.5	0.003
S1912	Gen1	No Standby no H2iP	PD6FC - 99% driver	5500	0.013	7509	Carbon corrosion due to anode starvation	2.6	0.005
S2341	Gen2	No Standby no H2iP	NEO5 - Accelerated	3000	0.023	8017	High cell resistance	5.6	0.003
S2342	Gen2	No Standby no H2iP	NEO5 - Accelerated	5500	0.013	9920	High cell x-over	5.6	0.002
S2343	Gen2	No Standby no H2iP	PD6FC - 99% driver	5000	0.014	10257	Stack did not reach End of Life	5.6	0.002
S2344	Gen2	No Standby no H2iP	PFC21 - hybrid 99%	8000	0.009	10068	Stack did not reach End of Life	5.6	0.001
S2345	Gen2	No Standby no H2iP	PFC21 - hybrid 99%	8000	0.009	9782	Stack did not reach End of Life	5.6	0.001

*Tech Insertion hardware Gen 0
[1] s/w change at 140 hrs
[2] cell voltage monitor replaced at 280 hrs
[3] Pt utilization normalized to Gen 0 loading
[4] Degradation rate normalized to Pt loading of Gen 0

Table 1 Performance Comparison

3. Summary of Project Activities

Phase 1

Phase 1 was intended to demonstrate the effectiveness of enhanced operating strategies and improved membrane materials on stack life as compared to prior DoE demonstration programs. These strategies included keeping hydrogen on the stack during extended off-time ("H2 in Park",) and enabling a standby mode during low speed and idle operation. The initial plan was for five stacks to be run to failure in real-world driving conditions in the greater Los Angeles area. Very early in the program, one of the primary refueling stations utilized by the GM vehicles had a system failure resulting in contaminated hydrogen being dispensed to the vehicles. The long-term effect of hydrogen contamination resulting in fuel cell stack anode starvation was unknown at the time and an in-vehicle recovery process was utilized to enable the stacks and vehicles to continue to operate. In addition to hydrogen contamination, two of the stacks developed failures that are normally repairable, but due to the transition of fuel cell organization from New York to Michigan, repair facilities were not available during the Phase 1 time-frame. Two alternate stacks were added to the project with agreement from the DoE to help quantify the contribution of fuel contamination to overall stack life.

Despite the addition of the two operating strategies mentioned above, the Gen 0 stacks did not last any longer on the road than similar on-road stacks run without the enhanced operating strategies. Those strategies were designed to reduce voltage degradation, rather than addressing the primary failure mode seen by Gen 0 stacks, which was membrane thinning. Five of the seven stacks run to failure during Phase 1 reached end-of-life due to cross-over, while two additional stacks were deemed end of service due to a manufacturing process defect leading to a low performing cell. Stack post-mortems suggest a key contributor to the membrane thinning was caused by dry-end anode starvation due to the flow-shifting architecture utilized in the Gen 0 systems. Neither of the subsequent generation systems utilizes the flow-shifting architecture. Fuel contamination was determined to not be a significant contributor to permanent stack failure if recognized early enough and remedial actions are taken. The membrane thinning did not have a measurable impact on fuel economy, but there were slightly higher hydrogen emissions detected in the exhaust. The two stacks, S1521 and S1525, utilizing a modified membrane material with slightly lower Pt loading, reduced the overall degradation rates by about half and exhibited longer time to cross-over failure, although the manufacturing defect prevented the stacks from reaching their full life potential.

Phase 1 also highlighted the challenges associated with running a public road durability test, although the on-road learnings provided valuable insight into system operating characteristics. Run time was limited by fuel availability and purity in the initial stages of the project, vehicle level hardware reliability, and traffic congestion in the Southern California areas where hydrogen fuel stations are concentrated. Figure 1 below shows the run time accumulation for the seven stacks that were run to failure in vehicles during Phase 1.

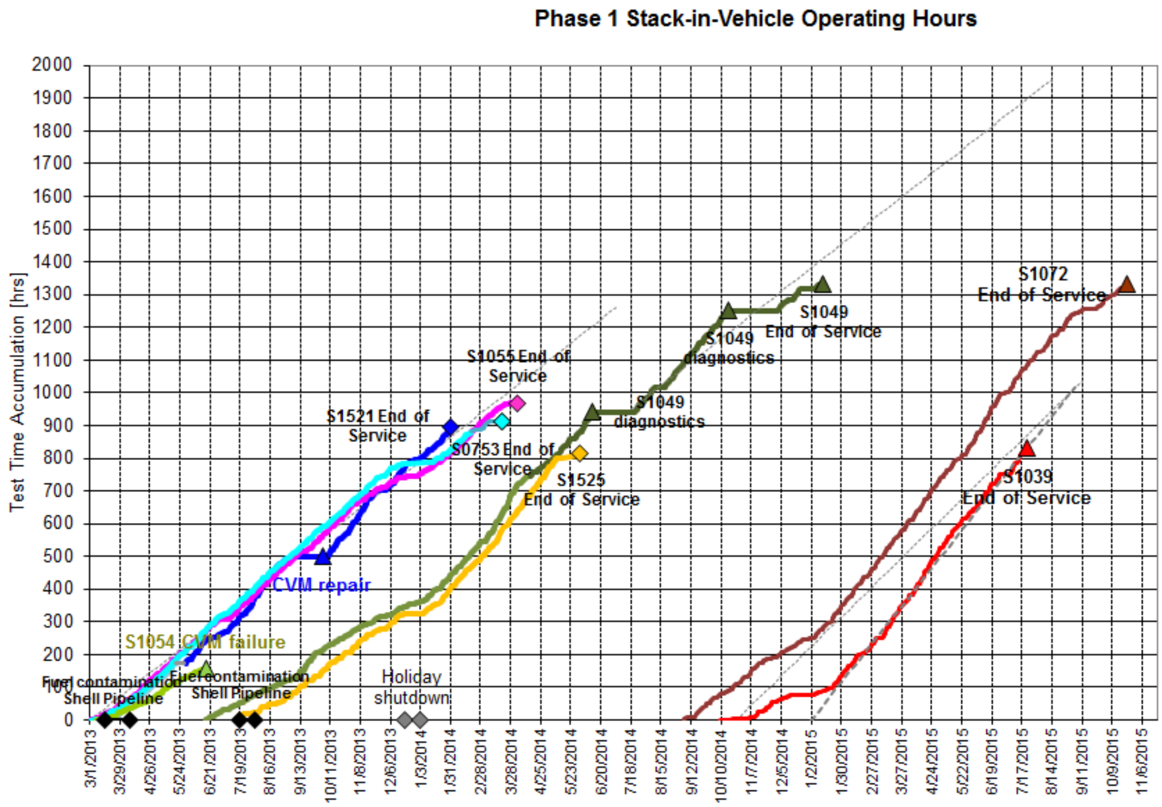

Figure 1
Phase 1 Run Time Accumulation on Gen 0 Stacks in Vehicles

Figure 2 shows the run time degradation at 288A for the Phase 1 stacks. The evaluation current, 288A, is based on a historical data reference point for comparison to prior DoE project platforms.

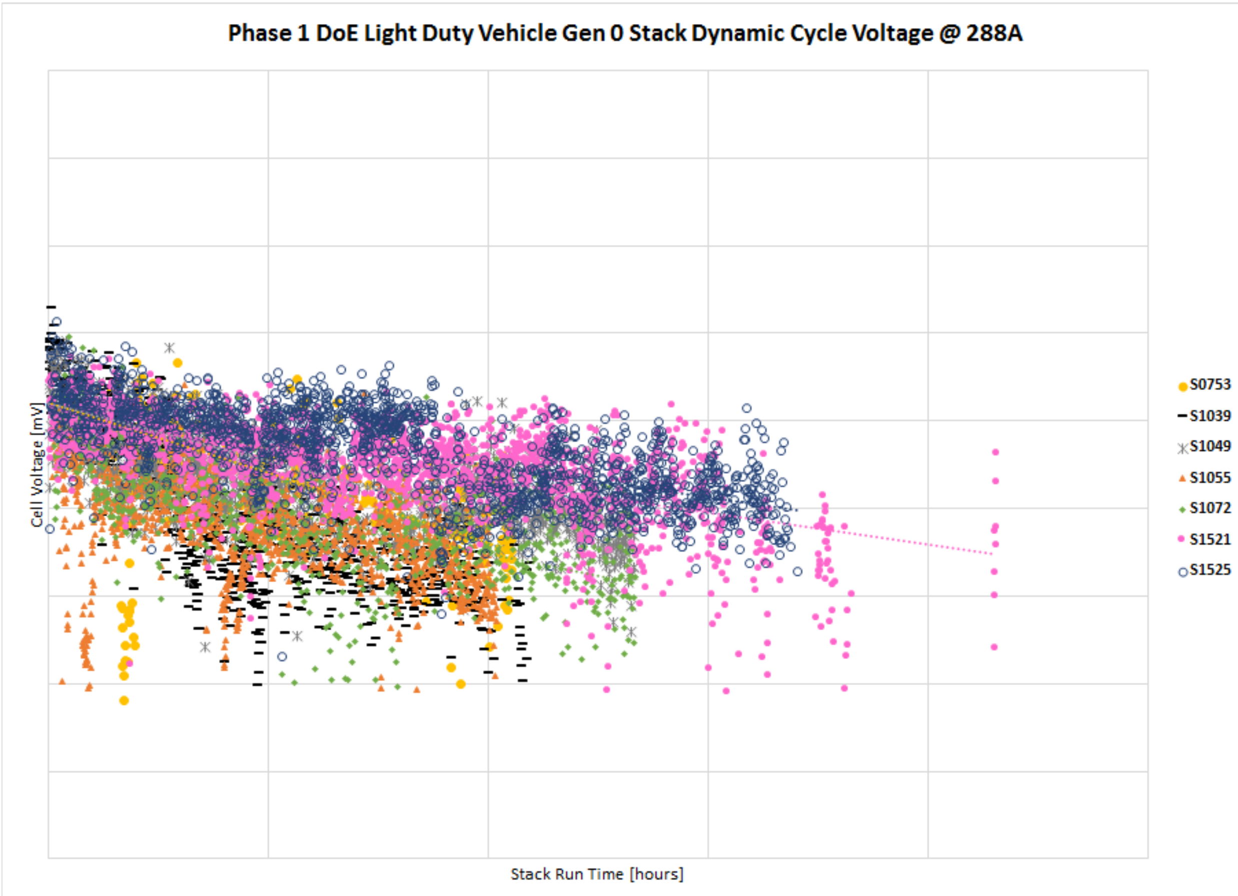

Figure 2
Phase 1 GM Gen 0 Stack Voltage Dynamic Cycle Degradation

Phase 2.1

GM's three Gen 1 stacks tested during Phase 2.1 of the project were operated with a significantly simplified system architecture. One stack, S1912, was a full-sized stack, while the other two stacks, S1836 and S1837, had 1/3 the cell count of a full-sized stack. Compared to the Gen 0 system which utilized two stacks, the Gen 1 system was comprised of a single stack with anode recirculation, a cell count reduction of over 25%, and less than 50% of the precious metal loading. In addition, the maximum current density target was increased by 20%, all while focusing on stack manufacturability and cost reduction. Despite the emphasis on cost reduction, the stacks achieved a nearly tenfold increase in stack life. Control system improvements included long off-time air start mitigation and peak voltage control to reduce overall voltage degradation. In addition, stack material developments helped delay by a factor of ten the cross-over failure mode that was the limiting factor in the Gen 0 fuel cell stacks. All three Gen 1 stacks were run on a severe test protocol based on a GM test track durability drive cycle

(PD6FC), and all over 2000 hours before experiencing 10% reduction in stack voltage at full power. The full-sized stack was deemed End-of-Life due to a low performing cell. Root cause analysis indicates the cell failure was cause by carbon corrosion due to anode starvation. Further investigation determined that the anode starvation was most likely caused by water accumulation due to an internal cell baffle design. The first membrane failure on the smaller stack occurred after 10,000 hours on test. Testing was concluded before failure on the second small stack to begin testing on the next generation hardware. Figure 3 shows the run time accumulation during Phase 2.1.

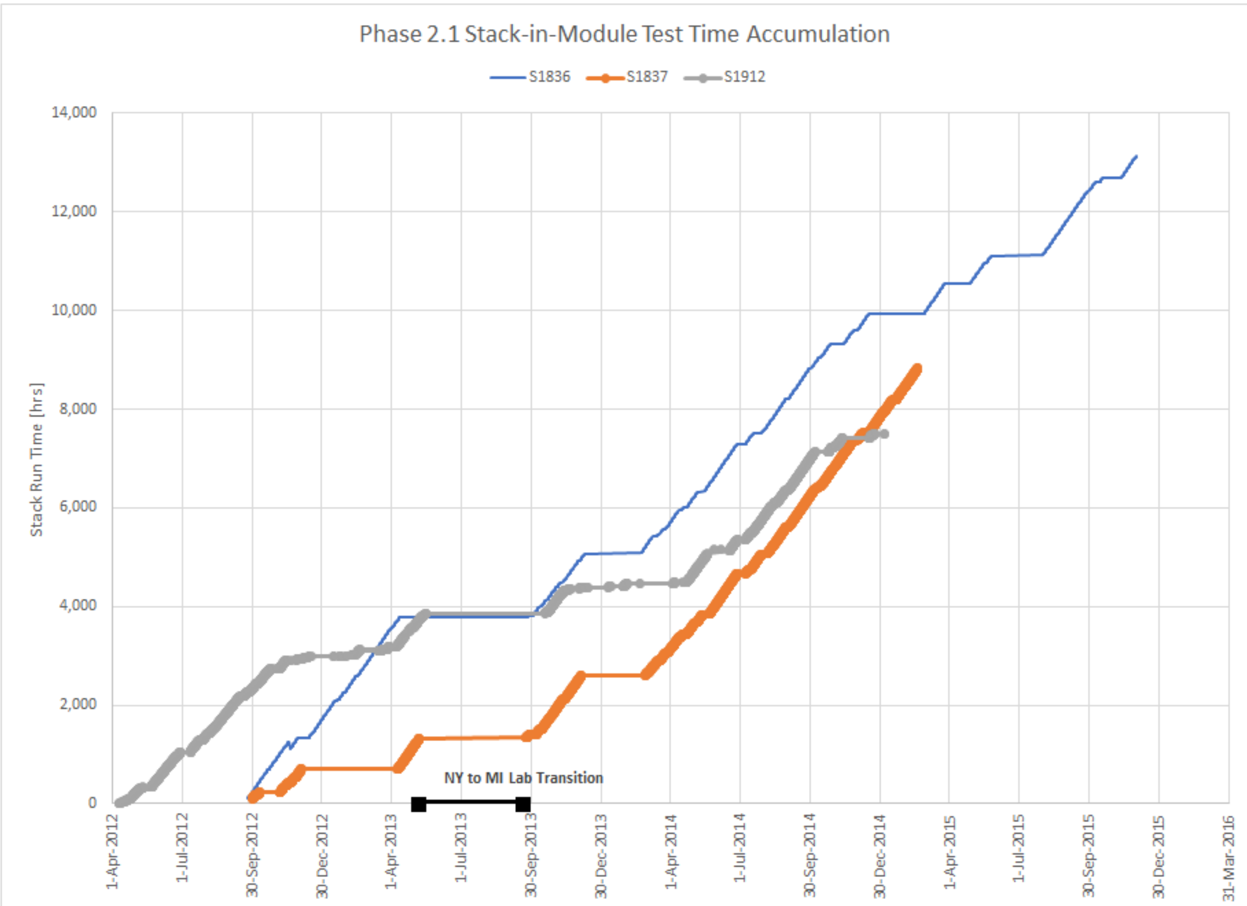

Figure 3
Phase 2.1 GM Gen 1 Stack Run Time Accumulation

Figure 4 shows the run time degradation at 288A for the Phase 2.1 stacks.

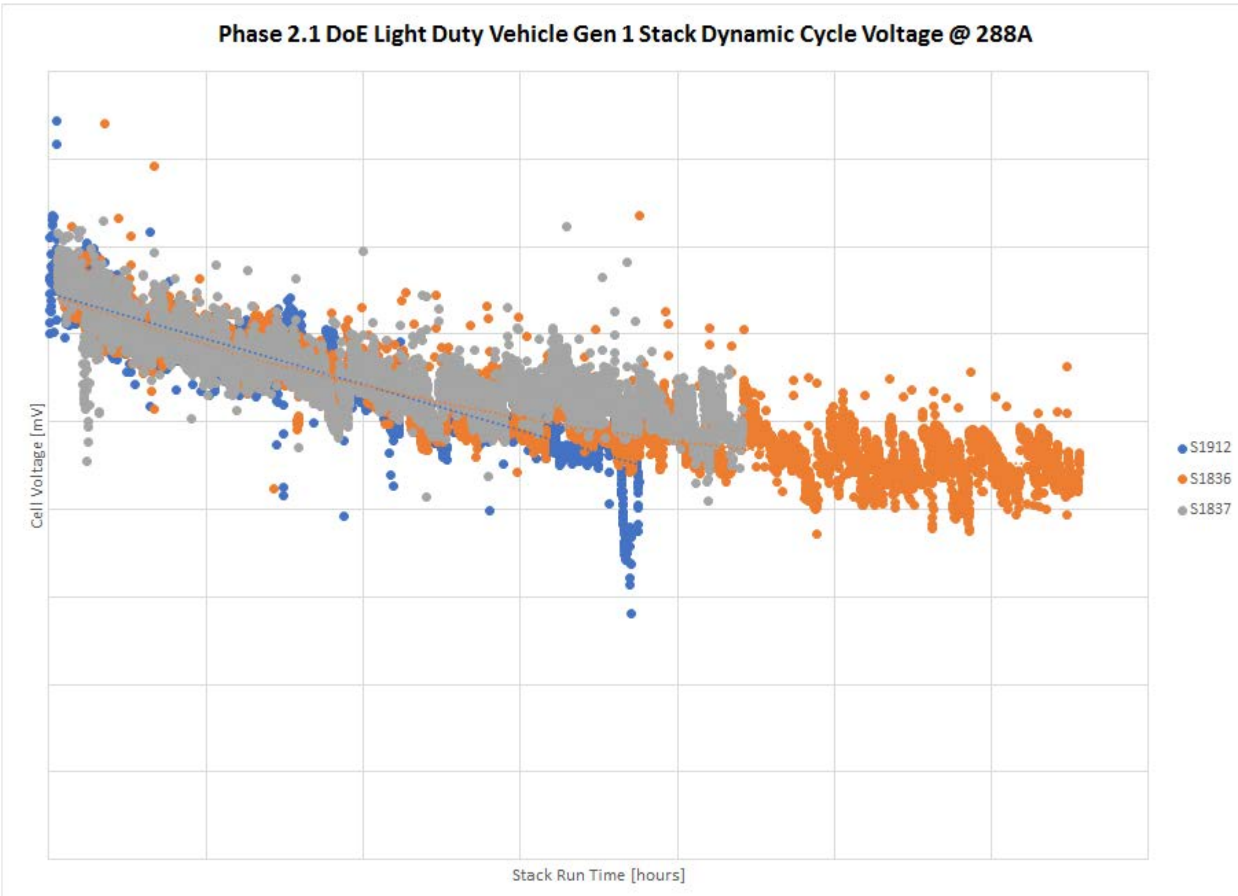

Figure 4
Phase 2.1 GM Gen 1 Stack Voltage Dynamic Cycle Degradation

Phase 2.2

Phase 2.2 for this project began in early 2016. Five Gen 2 stacks were tested, all with 1/3 the number of cells that encompass a full-sized fuel cell stack. GM's Gen 2 system architecture was also greatly simplified compared to the Gen 0 design and the cell footprint was reduced slightly while enabling higher current density operation. The stacks were run on three different test protocols with the emphasis on determining cell material robustness to harsh operating conditions.

One of the stacks, S2341, was run with the Gen 1 operating conditions under an extreme, approximately 2x durability protocol (NEO5) used to baseline the cell design against the previous generation hardware. The same NEO5 durability protocol was run on one other stack, S2342, to compare the effect of Gen 2 system operating conditions on voltage degradation and membrane life for the Gen 2 stacks. One 1/3 sized stack, S2343, was run on the PD6FC test protocol as a comparison to the previous generation (Gen 1) hardware and controls strategy. Two additional stacks, S2344 and S2345, were run on a protocol (PFC21) that simulates the effect of the vehicle hybridization strategy combined with the PD6FC drive cycle.

Late in the summer of 2016, several of the scroll-type compressors used to provide air to the stacks started to experience failure of the scroll-tip coating material. This resulted in dust particulates reaching the cathode inlet to the stack, particularly at the wet end cell. When this failure was discovered, all testing was halted while the issue was root caused and remedial action taken to remove the contaminants from each system. (This compressor type is not production intent hardware, but was utilized to match the scale of the 1/3-sized stacks.) Testing resumed once the system and stacks were cleaned and flushed, but the impact of the contamination resulted in eventual wet end cell failures. Adjacent comparison cells removed for analysis at the time of the wet end cell failures indicated that the contamination was concentrated at the end cell.

In late 2016 some of the stacks started indicating individual cells with high resistance. Several cells were removed for analysis and it was determined that the root cause was due to a supplier quality issue with the bipolar plate (cell) coating. Additional healthy cells were removed along with the failed cells for comparison analysis.

Three of the five Gen 2 stacks reached End-of-Life during the project timeframe. The stack run with the harshest protocol, (S2341 NEO5 cycle w/ Gen 1 conditions,) reached end of life due to high internal resistance, which increased by a factor of two over the course of the durability test. In addition to the overall high stack resistance, there was one cell that indicated high cross-over. Another stack, (S2343 PD6FC cycle) ended test due to a low performing cell that prohibited the stack from running the desired protocol. Both stacks showed evidence of the compressor dust in many cathode flow channels. One additional stack, (S2342 NEO5 cycle) reached end of life due to low performing cells with high parasitic current, but was still above the 90% beginning of life voltage at 5000 hours.

The two remaining stacks, (S2344 and S2345 PFC21 cycle,) did not reach end of test criteria during the project timeframe. Both stacks were several thousand hours beyond the 5000-hour demonstration target as of 28 February 2018. Near the end of this project, the team decided to take advantage of these well aged stacks to measure the impact of a simulated polluted air environment. One stack, S2344, was subjected to 10 ppb SO2 introduced into the cathode upstream of the stack, run with the same PFC21 simulated drive cycle for over 200 hours, and monitored for voltage decay. The other stack, S2345, was subjected to 1 ppb SO2 for over 400 hours on the PFC21 cycle. Stack voltage decayed as expected, and when the SO2 stream was removed voltage gradually recovered, indicating no permanent damage caused by the simulated pollution. In both cases, overall voltage decay was consistent with expected run time voltage decay. The SO2 test data for both stacks was delivered to NREL as a separate data package. Figure 5 shows the overall test time accumulation for the five stacks tested in Phase 2.2 of this project.

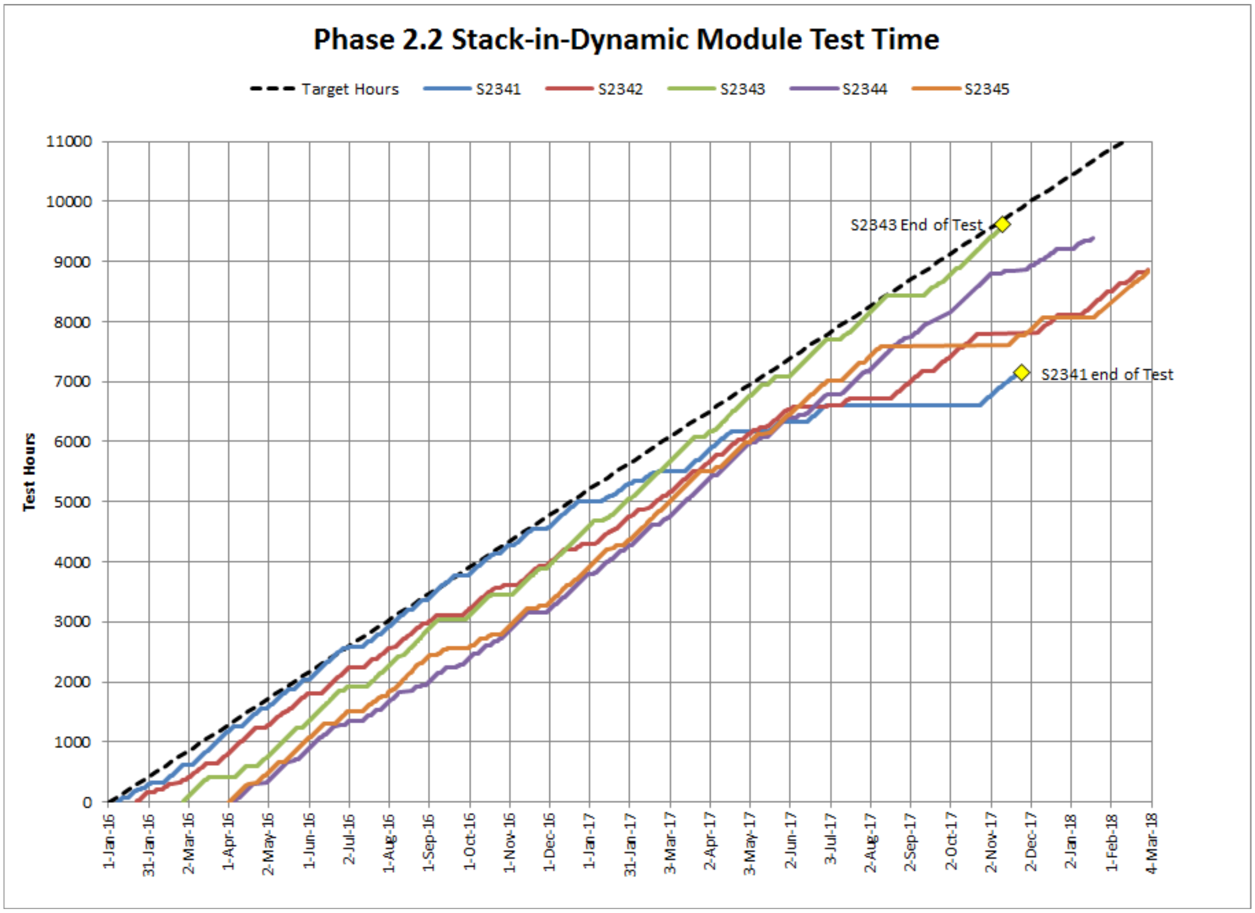

Figure 5
Phase 2.2 GM Gen 2 Stack Test Time Accumulation

Figure 6 shows the relative voltage decay for GM's Gen 2 stacks under various dynamic load cycle conditions. The SO2 data is not included on the overall voltage decay charts.

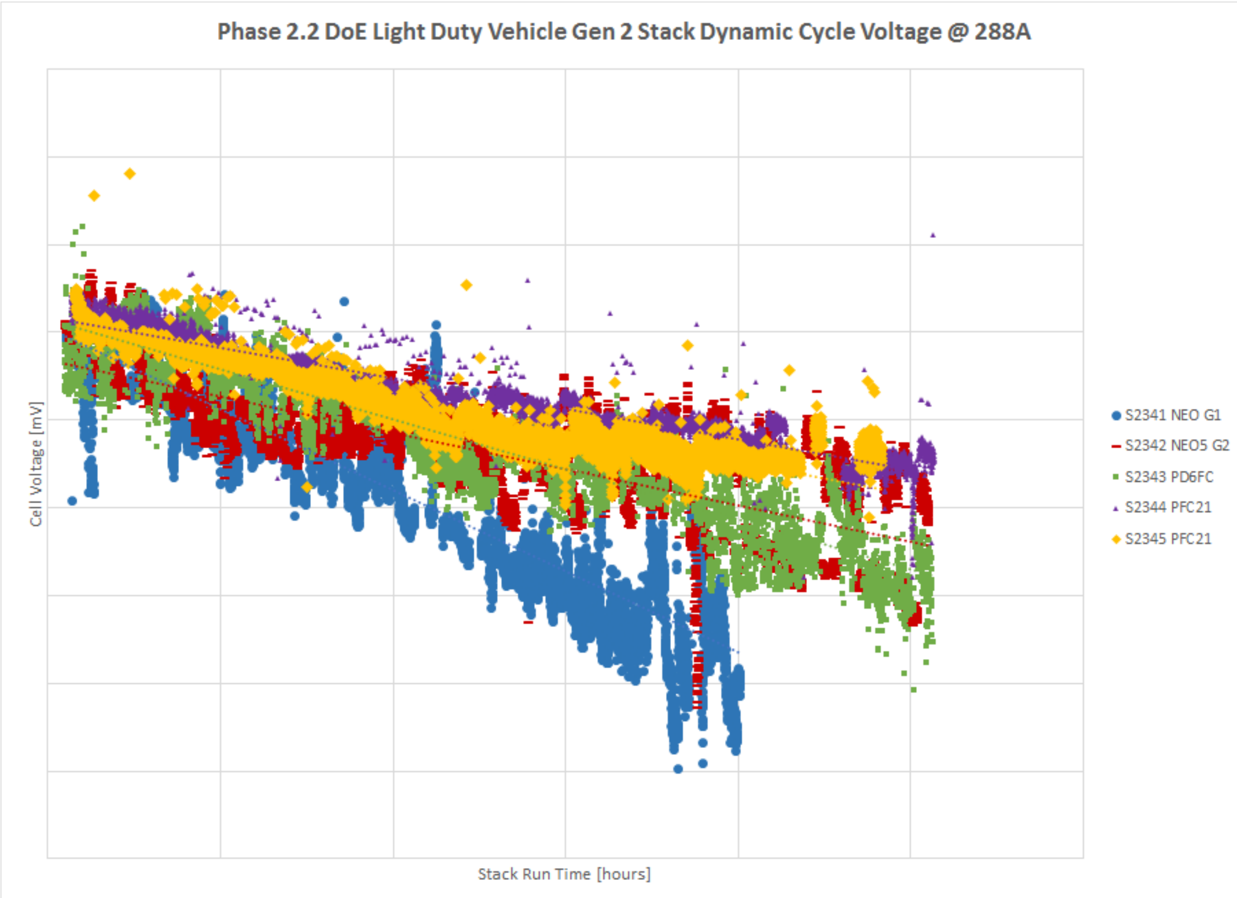

Figure 6
Phase 2.2 GM Gen 2 Stack Voltage Dynamic Cycle Degradation

Hardware replacements and software updates for each of the stacks tested were identified in the Maintenance Summaries delivered to NREL at the end of each quarter of testing. All data has been uploaded to the NREL secure website for further analysis and compilation.

4. **Products**

   a. **Publications – N/A**

   b. **Web site or other Internet Sites – N/A**

   c. **Networks or Collaborations Fostered – N/A**

   d. **Technologies/Techniques – N/A**

   e. **Inventions/Patent Applications, Licensing Agreements – N/A**

   f. **Other Products –** Data was provided to NREL for analysis.

Acknowledgment: This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Fuel Cell Technologies Office Award Number DE-EE0005969.