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14. ABSTRACT

This report covers efforts by the Hawaii Natural Energy Institute (HNEI) of the University of Hawaii under the ONR-funded Ion Tiger UAV award that included testing of Ion Tiger fuel cell stacks in HNEI's Hawaii Fuel Cell Test Facility located in Honolulu, Hawaii. Work was focused on steady-state stack characteristics of Protonex fuel cell stacks under various operating conditions. In addition, Hardware-in-the-Loop testing was performed to characterize dynamic limitations due to balance-of-plant components, effect of hybridization on performance and stability, and operational strategies to maximize fuel usage.

15. SUBJECT TERMS

Fuel Cells, Fuel Cell Stacks, Fuel Cell Testing, Hardware-in-the-Loop Testing

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Final Technical Report: Fuel Cell Stack Testing and Durability in Support of Ion Tiger UAV

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1.0 EXECUTIVE SUMMARY

This report provides an overview of work conducted under Grant Award Number N00173-08-2-C008, award title 'Ion Tiger UAV', funded through the Office of Naval Research to the Hawaii Natural Energy Institute (HNEI) of the University of Hawaii.

The work reported here summarizes research and testing services provided by HNEI in support of the Naval Research Laboratory's Ion Tiger UAV development. Numerous detailed monthly reports and specific research reports were provided to the Ion Tiger UAV team throughout the contract, while this report only highlights the main accomplishments of HNEI. Work performed at HNEI focused on steady state stack characterization of Protonex fuel cell stacks under various operating conditions to identify limitations of the stack, as well as third party validation of the manufacturer's claims. In addition, hardware-in-loop (HiL) testing was also performed to characterize dynamic limitations due to balance of plant components, effect of hybridization on performance and durability, and operational strategies to maximize fuel usage.

In order to initiate stack testing early in the program as part of Task 1 of the original statement of work, HNEI altered an existing UTC Power single cell test station to support parametric studies and evaluation of loss mechanisms during stop, start, and storage conditions of the Protonex stack systems. These alterations along with the existing components in the system were sufficient for steady-state or pseudo-steady state stack performance and efficiency evaluations per plans. HNEI and Protonex worked to develop a protocol for automating test sequences allowing the running of multiple polarization curves at various conditions. These tests assisted in identifying regions of operation where low current operation might lead to flooding and voltage instabilities, or high current operation where limited oxidant supply or humidification would decrease the maximum current density achievable. In addition this matrix testing helped characterize and validate improvements made by Protonex throughout the stack development process.

Under Task 2 of the original statement of work, HNEI also provided research services in the area of system characterization and HIL testing. To accomplish this task HNEI developed an Ion Tiger (IT) System simulation allowing characterization of the performance of the stack and balance of plan (BoP) under simulated flight conditions, operational strategies and mission load profiles initially using fuel cell data measured in Task 1. Following successful implementation of the system simulation, the actual stack, air blower, purge system, and humidifier were installed in HNEI's HIL test station. This allowed HNEI to complete several real-time, dynamic hybridization studies utilizing key system hardware components with the actual UAV mission profiles while simulating alternative operational strategies proposed by the Ion Tiger UAV development team throughout the contract. Analysis of the results provided insights into the benefits and/or limitations of these proposed strategies, which were intended to increase mission duration and/or the stack and component durability.

2.0 STEADY STATE TESTING OVERVIEW

2.1 Test Station Upgrades

In order to initiate stack testing early in the program, HNEI altered an existing UTC Power single cell test station to support parametric studies and evaluation of loss mechanisms during stop, start, and storage conditions of the Protonex stack systems. These alterations included:

- Automated back-pressure control of gases for pressurized testing.
- Enhancement of the existing test stand humidifier's heating/cooling characteristics to allow higher gas flow rates.
- Additional flow controller channels were added to enhance system flexibility and allow testing of larger stacks.
- Data acquisition channels (hardware and software) were added to allow individual cell voltage monitoring of stack systems up to 40 cells, with the flexibility to expand to higher channel counts if required.
- Multiplexed cell resistance monitoring.

These alterations along with the existing components in the system were sufficient for steady-state or pseudo-steady-state stack performance and efficiency evaluations per plans ('steady state' with respect to fuel cells implies studying changes on the order of 30 sec to 15 min, as opposed to < 1sec, which is considered 'dynamic'). The resultant specifications of the existing steady-state station allowed for testing of small area, nominal 500 W stacks with a maximum of 48 cells.

Work was completed on modifications to the UTC Power test station by May 2008 to allow for testing of Protonex stack systems. The 48 channel differential cell voltage measurement system was installed and tested, along with additional valves to allow running dead-ended on the anode with a timed purge valve on the anode outlet. Validation of these systems and associated automation scripts was performed using a 50 cm^2, 2-cell stack.

2.2 Protonex 1st Generation Fuel Cell Stack (M250 Series) Performance Testing

2.2.1 Testing Overview

Test Engineers from HNEI and Protonex participated in a conference call on May 23, 2008 to discuss the initial round of stack testing to be performed at HNEI. The discussion covered the following:

- General system questions such as coolant temperature control, purging valve operation, dead-ended operation, etc.

- Protonex would send a B grade stack for initial testing. HNEI and Protonex agreed the initial testing should consist of reproduction of Protonex results at HNEI using conditions to be provided by Protonex.
- Protonex would provide purge valves for operation of the stack. Protonex informed HNEI the typical valve operation is to purge for 250 to 500 msec every 2.5 minutes, with the purge duration optimized to establish 92-95% hydrogen utilization. A two-valve purge system may be used in future stack generations.
- Testing procedures in evaluating various temperature and relative humidity conditions, start/stop and storage durability issues, impurity issues, and protocol development specific to ONR's Ion Tiger were discussed.

The first Protonex fuel cell stack arrived on Friday, May 30, 2008. The stack type was identified as M250 generation, stack ID# 242503. This generation stack consists of 36 individual cells with an active area of 18.8 cm^2 per cell. During June 2008, HNEI completed an initial test run on M250 Stack 242503 provided by Protonex. Figure 2-1 shows results of the HNEI test superimposed on the data provided by Protonex for Stack 242503 run with cathode conditions of 2.8 stoich, 50 °C, and 75% RH. Excellent correlation between test facilities was achieved.

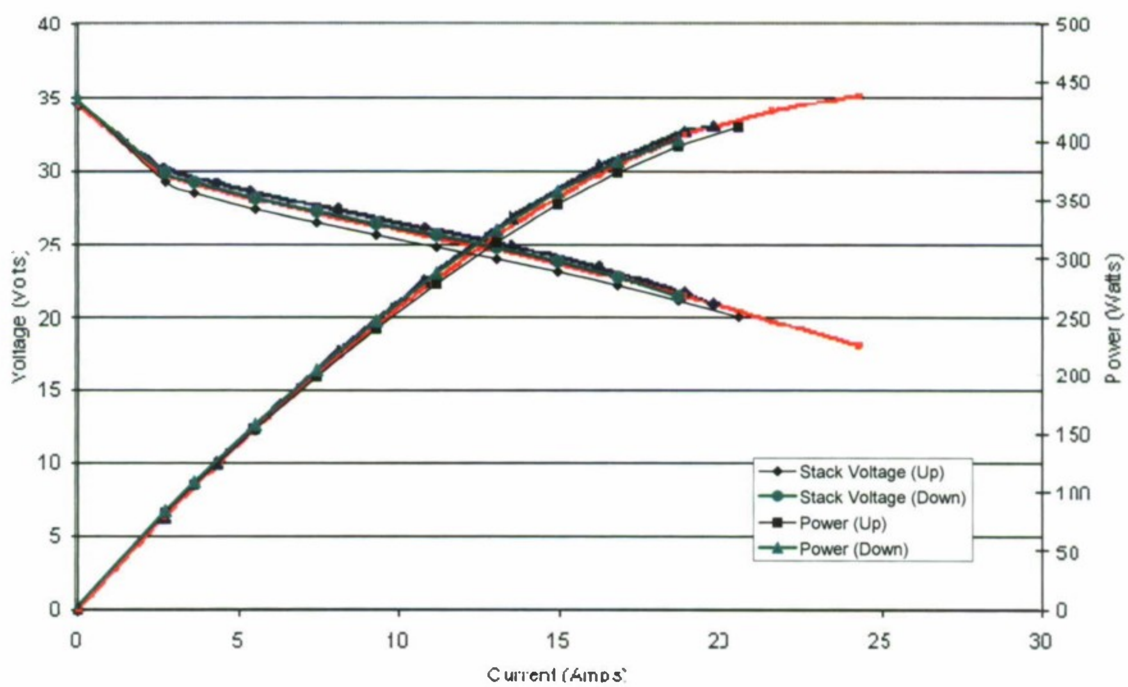


Figure 2-1 HNEI and Protonex interlaboratory polarization curve comparison of Protonex M250 Stack 242503

Results of this test were also used to evaluate/validate the test station in order to meet future experimental requirements, as this was the first runs performed with a full stack. HNEI implemented additional minor changes to the test stations and continued discussion with Protonex to establish the path forward.

During July 2008, HNEI and Protonex worked to develop a protocol for automating test sequences allowing the running of multiple polarization curves at various conditions. Figure 2-2 shows the time series data from three consecutive polarization curves under varying relative humidity conditions obtained using this protocol. The testing sequence incorporated Protonex's proprietary air starvation procedure and a 30 min. equalization period at the new condition prior to each new test. Polarization curves were measured in a descending manner.

HNEI and Protonex agreed upon a baseline condition for monitoring changes in the cell performance. The baseline conditions were 50 °C, 2.8 stoich, 75% RH, and 1 L/m coolant flow rate. The baseline polarization curve was performed periodically during the matrix study.

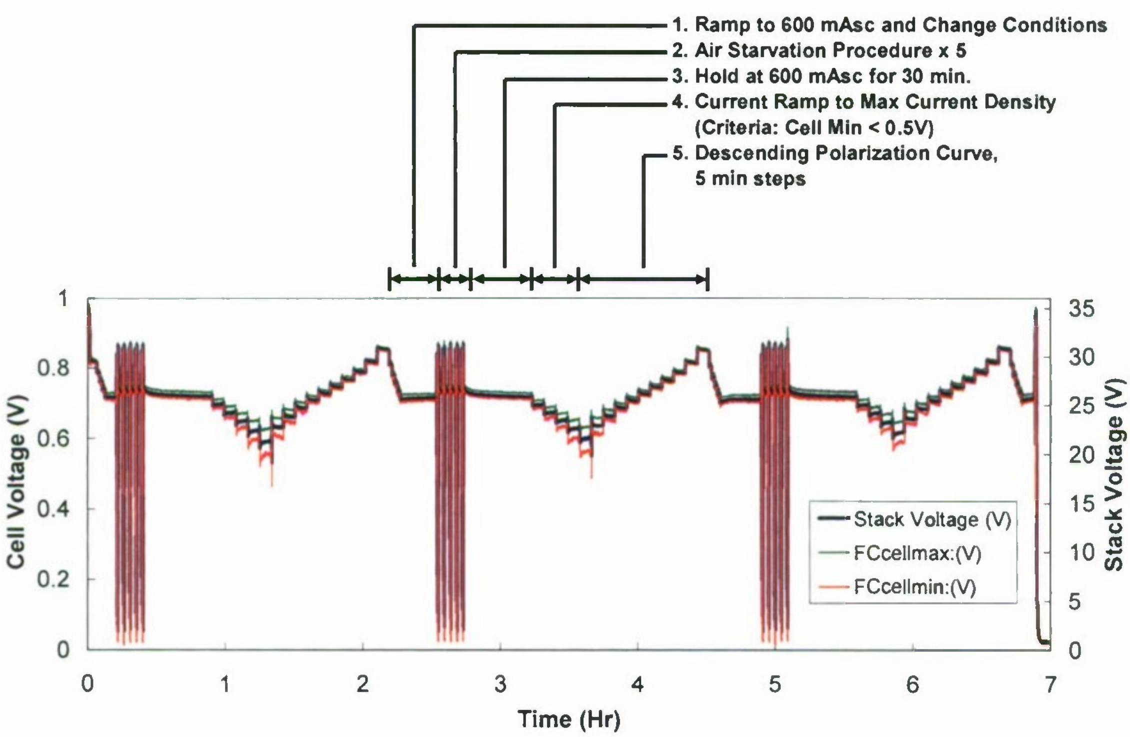


Figure 2-2 Polarization matrix, protocol evaluation example: Data taken from 50 °C, 2.8 stoich testing while varying cathode relative humidity from 75% to 100% to 50% RH for each polarization curve

During August, HNEI completed a 4 x 3 x 3 (cell temperature, relative humidity, and stoichiometry) polarization matrix on Protonex M250 stack 242503. At the request of NRL, an additional temperature (80 °C) was added to the 3 x 3 x 3 matrix. As the amount of data produced was quite substantial, only an overview of the results is provided here. A second M250 stack, Stack #242690, was also tested with the focus on durability throughout the testing sequence.

2.2.2 Performance Matrix Results and General Trends Observed on M250 Stack 242503/242609

Figure 2-3 presents bar plots of the maximum power achieved while maintaining the minimum cell voltage greater than 0.5 V for all conditions tested on M250 Stack 242503. At 50 °C and 60 °C, the performance decreased with increasing relative humidity, while at 70 °C and 80 °C the performance increased with increasing relative humidity. At the higher temperatures and low relative humidity (RH), the cell performance appears to be relatively independent of stoichiometry and the performance increases significantly with increasing RH. This can most likely be attributed to an offset in the stack water balance leading to dry-out, where the membrane resistance dominates the cell performance losses.

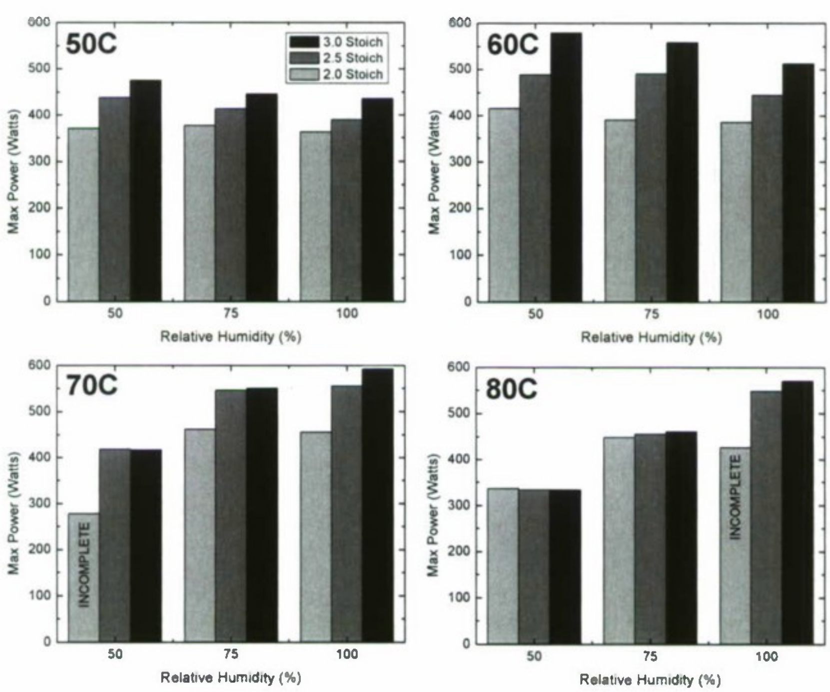
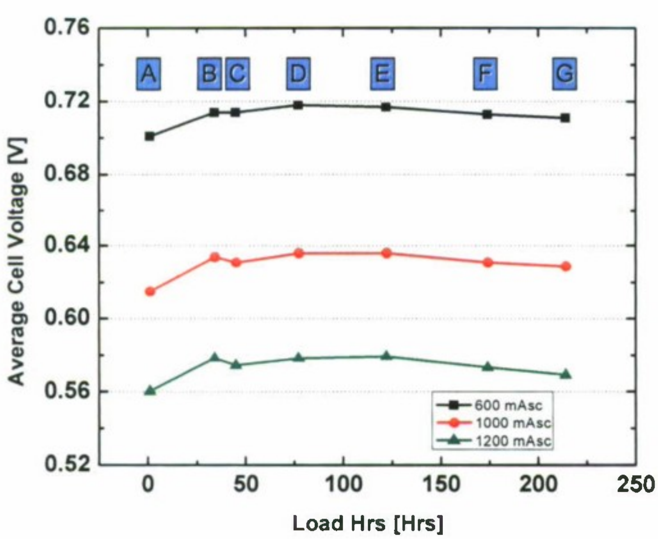


Figure 2-3 M250 Stack 242503 Polarization Matrix Results: Max Power vs. RH and Stoich at 50, 60, 70, and 80 °C

2.2.3 Baseline Performance/Durability Trends Observed on M250 Stacks 242503/242609

Figure 2-4 presents the average cell voltage vs. load hrs at 3 different current densities of the baseline curves performed periodically throughout the matrix testing performed on M250 Stack 242609. Following the 50 °C and 60 °C testing, the baseline performance was very repeatable, but decreased following the 65 °C and 70 °C test sequences. The 80 °C data set was eliminated in the M250 Stack 242609 ('A' grade stack) sequence, as increased degradation was observed following the test when performed earlier on the M250 242503 stack ('B' grade stack).



A. Cell received – Initial test w/ static coolant flow (comparison w/ Protonex data made w/ this data)
B. After 50C test sequence w/ static coolant flow
C. After adding coolant flow control from 500 – 1800 cc/m, and removing cathode outlet fittings to decrease pressure drop from fittings and manifold
D. After repeat 50C test sequence
E. After 60C test sequence
F. After 65C test sequence
G. After 70C test sequence

Figure 2-4 Variation in average cell voltage of M250 Stack as a function of load hours and testing conditions at different current densities

2.3 Protonex 2nd Generation Fuel Cell Stack (IT Series) Performance Testing

During November 2008, HNEI began testing the Ion Tiger (IT) Stack 242748 delivered to the test facility in October 2008. The IT Stack 242748 utilizes the 'low humidity' MEA. Testing on IT Stack 242748 stack was initially halted after the first two polarization curves due to a crack in the external manifold, which caused H_2 to leak into the coolant flow. Protonex has since supplied HNEI with replacement manifolds and the IT stack is under test again as of December 3rd, 2008.

Figure 2-5 and Figure 2-6 present the power output at 1200 and 1500 mAsc, respectively. At 1200 mAsc no individual cell dropped below 0.5 V at any condition so data under all test conditions is presented. At 1500 mAsc the 0.5 V cell voltage limit was breached at several test conditions. In addition, no experiments were performed at 50% RH, 1.6 Stoich at either 65 °C or 70 °C as the cell voltages were unstable. These conditions do not show any results.

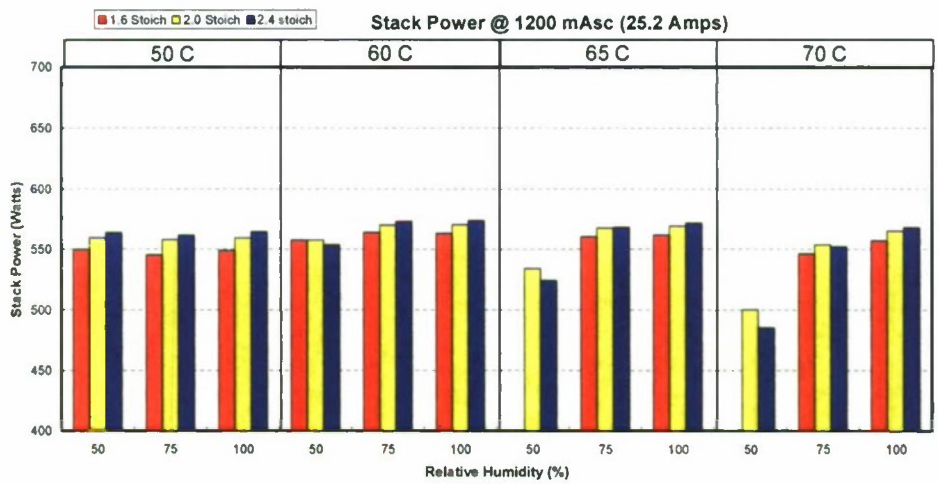


Figure 2-5 IT Stack 242748 Power Output @ 25.2 Amps (1200 mAsc)

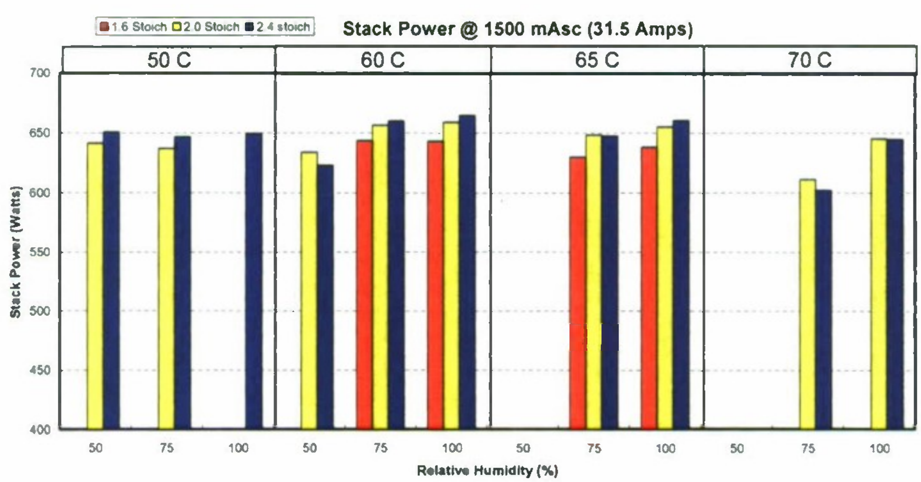


Figure 2-6 IT Stack 242748 Power Output @ 31.5 Amps (1500 mAsc)

The goal of the IT matrix testing was to identify regions of operation where either low current operation might lead to flooding and voltage instabilities, or high current regions where limited oxidant supply or humidification would decrease the maximum current density achievable. In order to present these results a voltage limit/maximum current density map was created and is shown in Table 2-1. Table 2-1 allows the user to easily correlate operating conditions (temperature, stoichiometry, relative humidity, and current density) for which the minimum cell voltage remained within the operating limits set forth in the test plan and also identify the cells for which a voltage limit breach occurred under a specific condition.

Table 2-1 Ion Tiger PTX242748 Voltage Limit/Maximum Current Density Map

	R.H. [%]	50									75									100								
Temp. [C]	Stoich \ J[mAsc]	150	300	400	500	600 to 1100	1200	1300	1400	1500	150	300	400	500	600 to 1100	1200	1300	1400	1500	150	300	400	500	600 to 1100	1200	1300	1400	1500
50	2.4																											
	2.0	13									34									32							31	
	1.6	31	5	5				13			4						13			34		31			13			
60	2.4	16																										
	2.0	4		5							35																	
	1.6	16	5	5					15		32	5								36	36							
65	2.4							35			24																	
	2.0	16	16	16	16				35		16									36								
	1.6	X	X	X	X	X X X	X	X	X	X	35	34								36								
70	2.4						35				5																	
	2.0						35				16																	
	1.6	X	X	X	X	X X X	X	X	X	X	14	5	5			15				35							15	

Legend:

- = All Cell Voltages Remained > 0.5V
- 5 = Minimum Cell Voltage Dropped to < 0.5V, w/ Cell #; Current step ended early.
- X = Condition Not Tested
- 5 = Minimum Cell Voltage Dropped to < 0.5V, w/ Cell #; Test halted at this current level.
- = Current level not tested due to voltage limit breach at lower current level.

2.3.1 Comparison of Protonex M250 vs. IT Stack Performance

Figure 2-7 presents the initial stack voltage and power curves for the IT Stack 242748 (labeled IT001 in Figure 2-7) and M250 Stack 242690 at 50 °C, 75% RH, and for air stoichiometries of 2.0 and 2.4. These conditions were considered to be within the middle of the operating condition ranges with respect to the relative humidity and temperature. Significant improvements are observed in the 2nd generation Protonex Ion Tiger Stack, with the maximum power approaching 650 W at 1500 mA/cm^2, while maintaining the stack voltage above 20 V or ~0.55 V/cell.

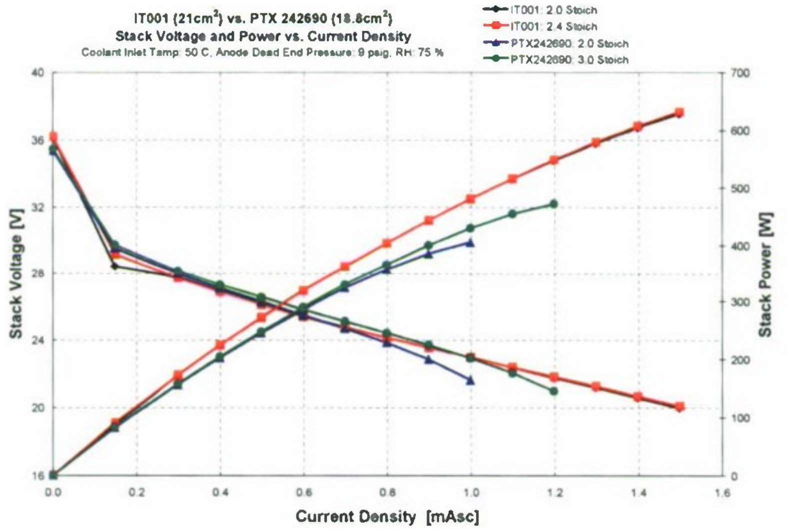


Figure 2-7 Stack Voltage and Power comparison of M250 and IT stack designs at nominal operating conditions

The main goal of the parametric matrix testing was to not only provide comparisons of improvements under nominal, mid range operating conditions, but also evaluate limitations in terms of combinations of conditions known to be detrimental to PEM fuel cells. Figure 2-8 presents a series of comparisons of power density and specific power density under cool and dry, cool and wet, hot and dry, and hot and wet conditions. Power density comparisons provide data normalized to the cell unit area, while specific power density incorporates both the cell unit area and stack mass. The data presented in Figure 2-8 is taken at 1000 mA/cm^2 as this represented the maximum current density achieved under all these conditions for the M250 stack. While the IT stack only moderately outperforms the IT stack with respect to power density, the specific power density was improved significantly. It should be noted not only is the overall mass of the IT stack lower, but the overall volume was also reduced. Figure 2-9 displays the specific power density at 1200 mA/cm^2 demonstrating improvements in maximum specific power density on the order of 1.5 to 2 for the IT stack vs. the maximum achieved for the M250 stack under adverse conditions.

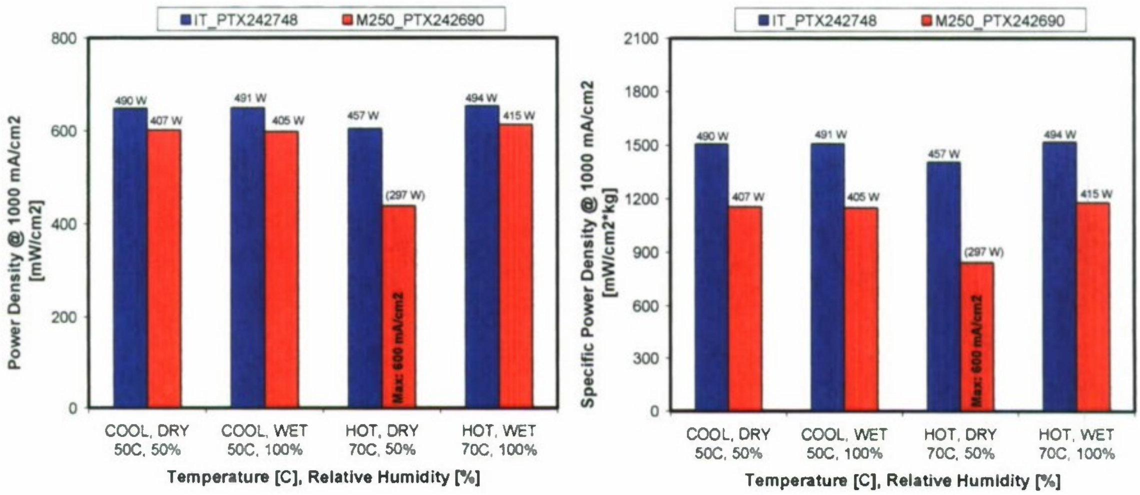


Figure 2-8 Power density and specific power density comparisons at 1000 mA/cm^2 between the M250 and IT stack generations under adverse conditions

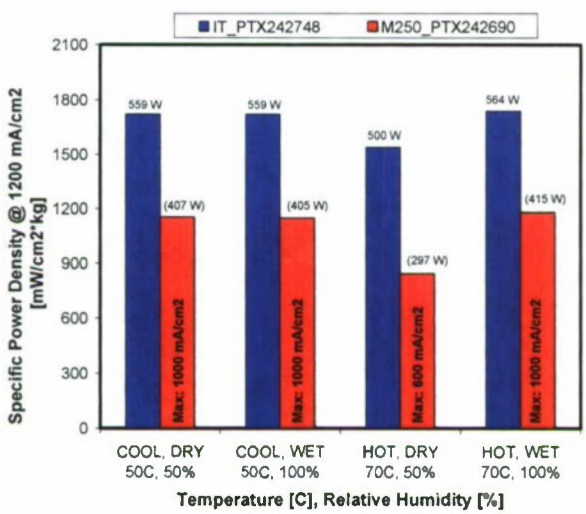


Figure 2-9 Specific power density comparison of the IT stack at 1200 mA/cm^2 vs. the maximums achieved with the M250 stack under adverse conditions

2.4 Steady State Shorting/Oxide Cleanup Study on Ion Tiger UAV Stack

The Protonex stack system utilizes a proprietary stack shorting technique which momentarily creates a low resistance, electrical connection between the positive and negative end plates of the fuel cell, effectively 'shorting' the stack. The effect is a sudden voltage drop as oxygen is immediately consumed, and this process effectively 'cleans' the electrode surface of any reversible degradation cause by platinum oxide formation. In mid-2009, NRL found that this shorting process was causing issue with the motor controller and gear box, as the power is cutoff for approximately 120 msec every 200 sec in the actual system. In turn, HNEI was asked to evaluate the efficiency improvements provided by the shorting process, and what if any effects on mission duration eliminating the shorting process might have. As a starting point, HNEI produced a series of voltage efficiency gains vs. shorting interval at 3 different current levels to provide a baseline understanding of the effect of the shorting process at different power operating ranges of the Ion Tiger Stack under controlled, steady-state conditions. Figure 2-10 presents the results of the steady state study, in terms of the energy gains achieved during a 1 hr profile under constant conditions vs. the shorting interval. The standard system timing was determined to provide approximately a 2% gain, which over a 24 hr mission is quite significant, i.e., 30 minutes. At 30-minute intervals the gains were insignificant, indicating the benefit of the shorting process. Further testing was conducted in the HIL station in dynamic mode evaluating the shorting interval effect when operating under the realistic flight power profile, as well as more complex logic schemes.

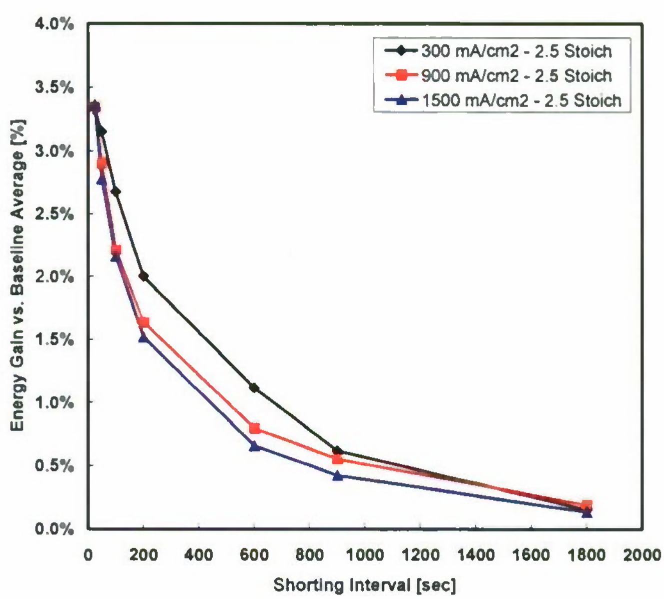


Figure 2-10 Energy Gain vs. Shorting Interval at 300, 900, and 1500 mA/cm^2 Test Levels

3.0 SYSTEM CHARACTERIZATION AND HARDWARE-IN-THE-LOOP

The objective of the Task 2 of the Ion Tiger project involved the following:

1. Characterization of dynamic performance limitations of fuel cell stack under simulated flight conditions and load profiles.
2. Investigation of dynamic operational characteristics of the simulated fuel cell power system and components (balance of plant) during steady state, cyclic and load profiles.
3. Analysis of alternative operations schemes, e.g., fuel control strategies, alternative cooling protocols, hybridization.

The overall strategy of achieving these objectives was to:

1. Develop a Ion Tiger (IT) System simulation to characterize the performance of the stack and balance of plan (BoP) under simulated flight condition, operational strategies and mission load profiles.
2. Use the IT system simulation to characterize the dynamic performance of the system components and overall system using Hardware-in-the-Loop (HiL) methodology and a fast dynamic test station.

Figure 3-1 shows the overview scheme of simulation development and HiL Testing.

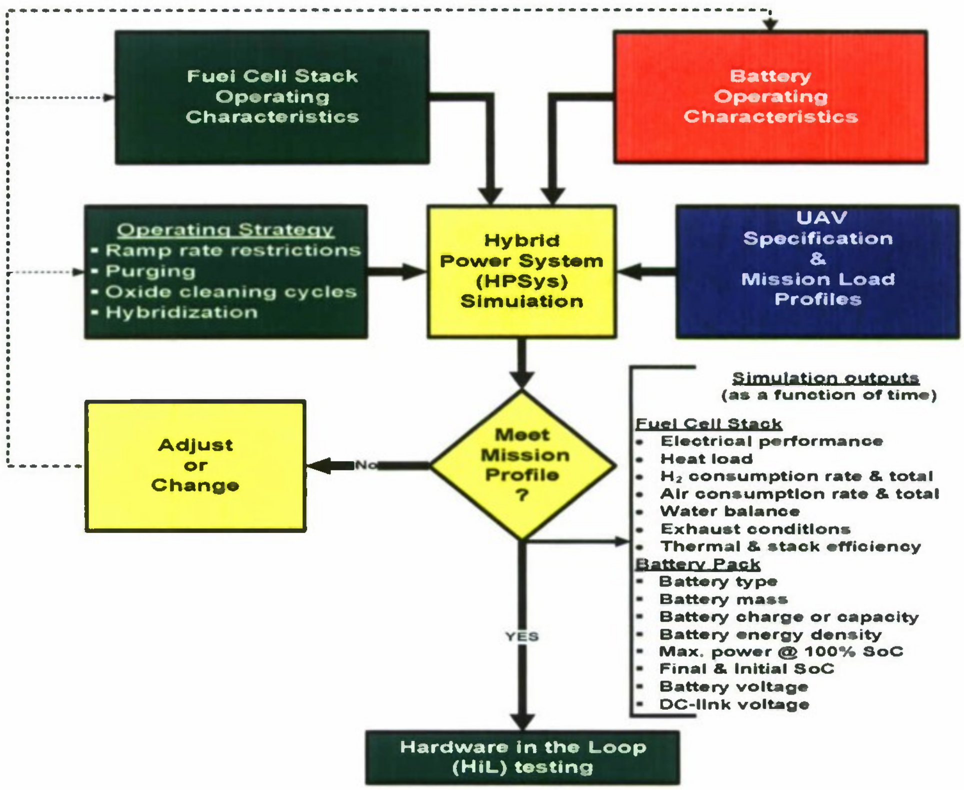


Figure 3-1 Overview scheme of the Simulation development and HiL testing

3.1 Development of the Ion Tiger UAV System Simulation

The main aim of this task was to first develop a simulation of the actual load following (LF) IT UAV system by modeling different sub-system and component of the system such as fuel cell system, emergency/start-up battery, different avionic loads, mission load profiles and overall controller of the system. The LF IT UAV system simulation once developed would also be use in HiL testing to study the dynamic performance of the stack and BoP components under different load profiles and operational strategies. The second task was to develop a Full Hybrid (FH) UAV system simulation with same sub-system and component models, but a different battery types and sizes. The Hybrid UAV simulation was to study the impact of the hybridization on the overall performance and duration of the UAV. Figure 3-2 shows the schematic of the LF IT UAV system.

During the first six months of the project, the individual models of LF IT UAV system were developed in the Matlab/Simulink Environment and initial data used in the models were from the different presentation of the Protonex (IT stack developer) presentation and Ion Tiger specification and schematic (Rev 2.0) documentations. Some of the HNEI existing battery and fuel cell system models and data were used in the simulation since fuel cell system and other system components were still under development and not specified. In June 2008, the first M250 stack 242503 data were incorporated into the PEMFC system model as a look-up data table. The intent was to populate the look-up table with test data as it becomes available. The matrix of data should cover the possible operating envelope of the stack when operating under a mission profile of Ion Tiger UAV. The battery model was also completed and was validated against manufacturing data for a Panasonic (CGR18650D) Lithium Ion Battery. The model was now capable of running in either power, current or voltage mode. A 32-min power profile was also implemented into the simulation and was based on flight data for the battery-powered XFC flight (data from NRL on July 7th 2008).

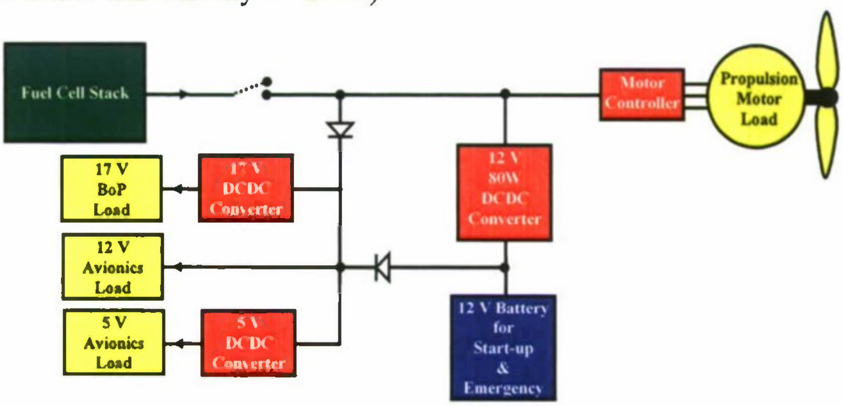


Figure 3-2 Schematic representation of the LF IT UAV System

During the next three months, development of the IT LF UAV system simulation continued with implementation of the following:

1. Ion Tiger Stack (ID PTX242711) steady state matrix of data measure at HNEI as a 4-D Look-up table as function of temperature, RH, and stoich.
2. Air blower model using the Protonex data presented in the month report (July'08).
3. Battery model with charge and discharge characteristics of A123 system high power lithium ion (4S LiPo) cell.
4. A control and operational model which implements the operational strategy by controlling the power from the PEMFC systems and battery pack for a total load power demand that includes power for UAV propulsion, payload, avionics and air blower.
5. Ion Tiger (IT) power profile derived from flight data for a battery-powered XFC flight (data from NRL on July 7th 2008). IT power profile has average power consumption of 296 watts over the 32-minute flight duration.

Figure 3-3 shows the IT UAV System simulation in the Matlab/Simulink Environment. The first simulation results were presented in review meeting in Hawaii in October 2008. Figure 3-4 shows typical examples of results from the simulation.

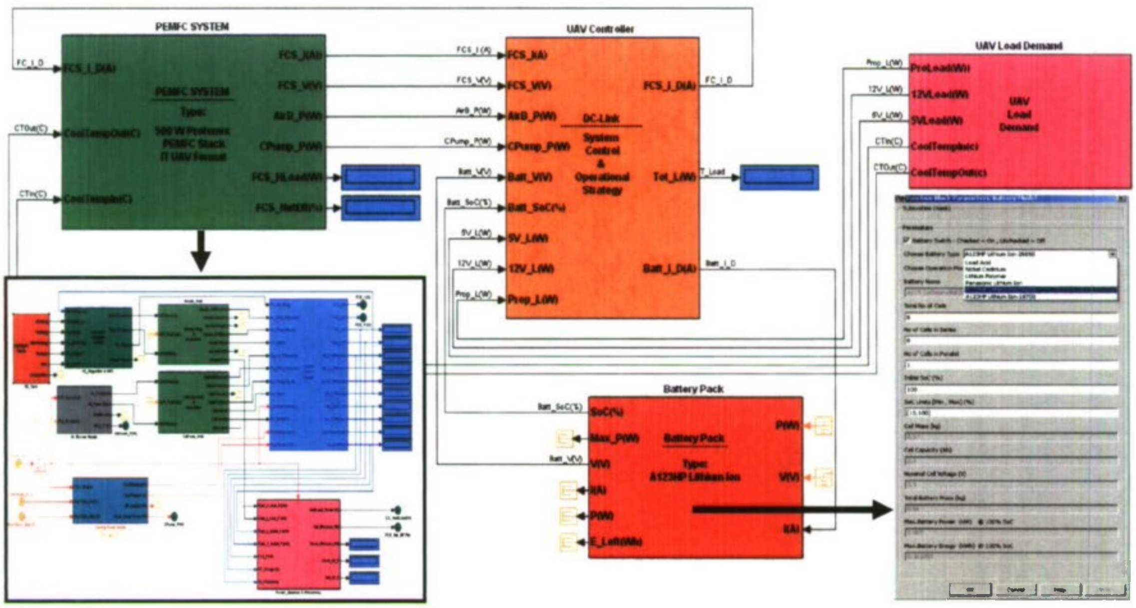


Figure 3-3 IT UAV System simulation in Matlab/Simulink Environment

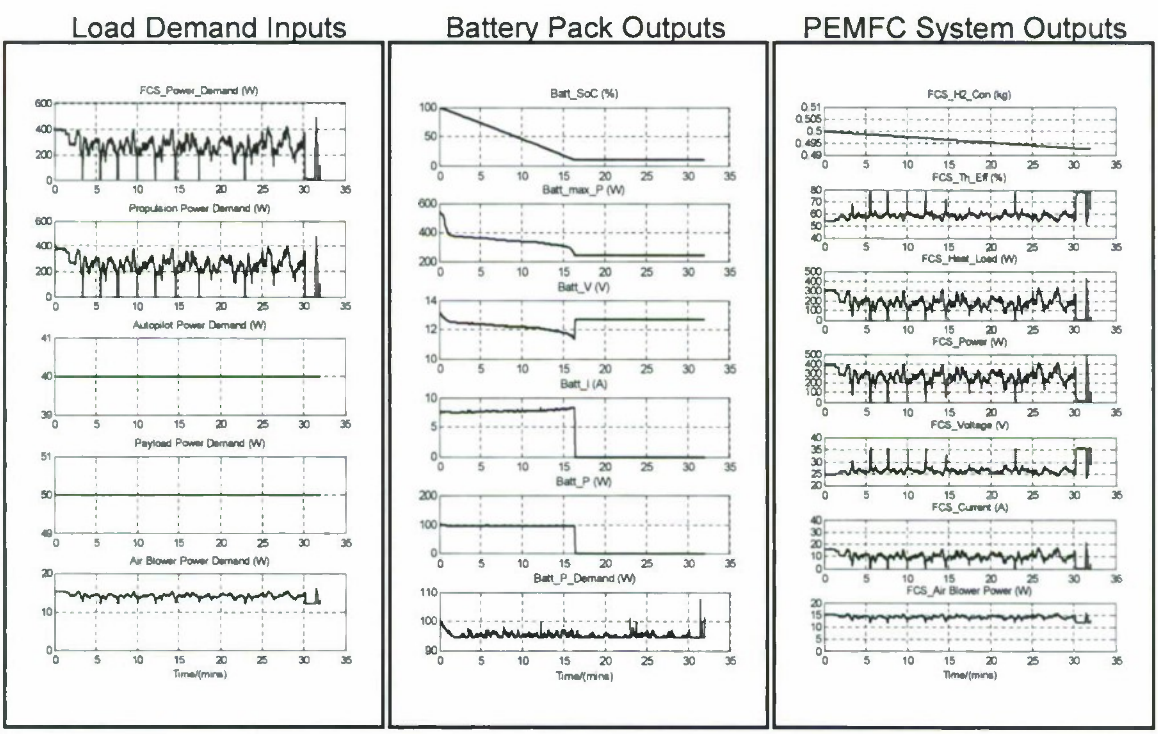


Figure 3-4 LF IT UAV System simulation results under a 32-min mission load profile

3.2 Development of the Hybrid UAV System Simulation & Hybridization Study

The IT LF UAV System simulation and the controller were modified to build a Full Hybrid simulation for the UAV system. Figure 3-5 shows the schematic of the Full Hybrid UAV system.

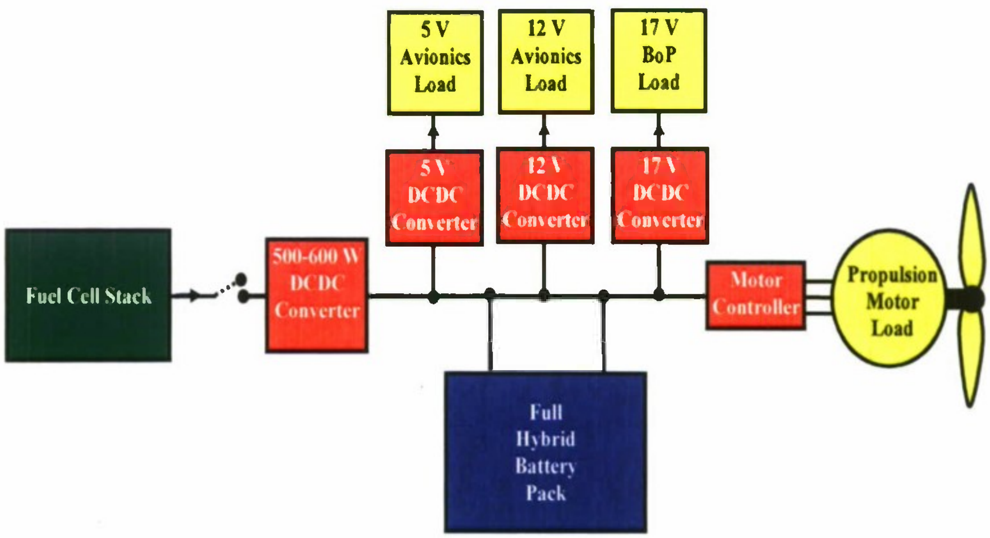


Figure 3-5 Schematic representation of the Full Hybrid UAV System

The objectives of the hybridization study was to analysis the performance and determine the mission duration of a Full Hybrid UAV system with increase in system weight compensated by increase in propulsion power.

For comparison purpose, the mission duration analyses were carried out for both the load following LF IT UAV and Full hybrid UAV systems with following battery packs:

1. Battery Pack with Lithium Ion cell type 26650 (2.3 Ah/3.3 V/70 g/cell).
   a. For LF UAV System = 4 cells in series.
   b. For Hybrid UAV System = 8 cells in series.
2. Battery Pack with Lithium Ion cell type 18700 (0.7 Ah/3.3 V/38 g/cell) (F1 cell).
   a. For LF UAV System = 4 cells in series.
   b. For Hybrid UAV System = 8 cells in series.

Four simulation analyses were carried out with two different UAV systems to determine the mission duration of each system under certain load profiles and compare the difference between two systems. This included the following system simulation analyses:

1. Load Following (LF) IT UAV system with battery pack with Type 26650 cells.
2. Load Following (LF) IT UAV system with battery pack with Type 18700 cells.
3. Full Hybrid (FH) UAV system with battery pack with Type 26650 cells.
4. Full Hybrid (FH) UAV system with battery pack with Type 18700 cells.

The results of this study showed that when comparing the mission duration of a LF IT UAV system and Full Hybrid UAV system at same avionics load and under the same mission profile, than, there was ~ 9.3 % loss in mission duration, which was primary due to penalty of additional battery weight and extra power loss through the DC-DC converter. Figure 3-6 shows the illustration of how this duration loss was calculated for UAV systems with battery pack type 18700.

When comparing the mission duration of a LF IT UAV system and Full Hybrid UAV system at same average system load, we find that there was a 2.2% average increase in mission duration for hybrid systems with different battery technologies. Table 3-1 shows the percentage increase in mission duration for hybrid system with F1 battery pack (Type 18700) as compared to LF IT UAV system at same average system load. The mission duration figures in the white boxes where estimated by curve fitting the other data points. Figure 3-6 also illustrates the calculation of this gain in mission durational at same average system load.

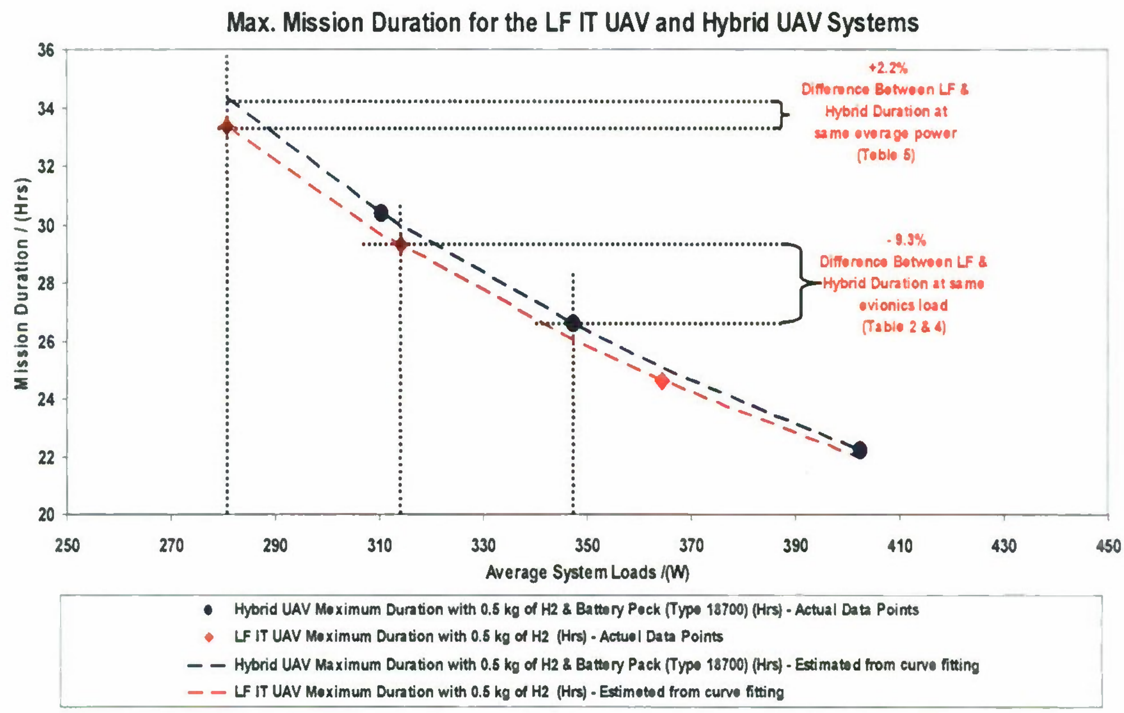


Figure 3-6 Comparison of mission duration between Load Following (LF) IT UAV system and Full Hybrid systems with a Type 18700 (F1) battery pack

Table 3-1 Comparing the mission duration of the LF IT UAV system with Hybrid UAV system at same average system load

Total Average Load	LF IT UAV Maximum Duration with 0.5 kg of H2	Hybrid UAV Maximum Duration with 0.5 kg of H2 & Battery Pack (Type 18700)	% Difference in Mission Duration
(W)	(Hrs)	(Hrs)	%
280.63	33.35	34.35	3.00%
310.48	29.65	30.37	2.44%
314.06	29.34	29.99	2.20%
347.25	26.02	26.60	2.23%
364.30	24.61	25.07	1.86%
402.39	21.91	22.21	1.35%
Average % Increase in Mission duration			2.18%

The final conclusion from the study was that the penalty of removing a H_2 fuel from the system (decreases in fuel tank size) has much more impact on the mission duration (~20%) as compared to compensation via increases in propulsion power (~10% from this hybrid study) at same avionic system load and under same mission profile.

3.3 Hardware-in-the-Loop Dynamic Testing

During the first half of the first year of the project the HNEI dynamic test station used for HiL testing was being upgraded to test stacks which involved installation of a 5 kW, 100 Volts load unit and larger capacity of mass flow controllers. The initial testing of the stack began in early October 2008 and the HiL testing capability was demonstrated to the Ion Tiger team during the review meeting at HNEI in October 2008. The HNEI fast dynamic station was designed in-house and has the following capabilities:

- Dynamic testing on single cells and stacks.
- Single cell operation: 200 cm^2, 200 A, 200 W.
- Stack operation: 100 cm^2, 150 A, 10-100 V, 5 kW.
- Controller response time < 100 ms.
- Real-time simulation of PEMFC applications.
- Potential for rapid prototyping.

The HiL test stand has also multiplex cell monitoring system for measuring individual cell voltage. In addition, it has a serial communication and variable (12, 17, 24,110 Vdc) power and signal points for installing and controlling other potential fuel cell system hardware (e.g., pumps or air blowers).

The fast responding HNEI dynamic test station was used to characterize the dynamic performance of the stack and BoP components of the IT UAV system using the HiL test system operational concept shown in Figure 3-7.

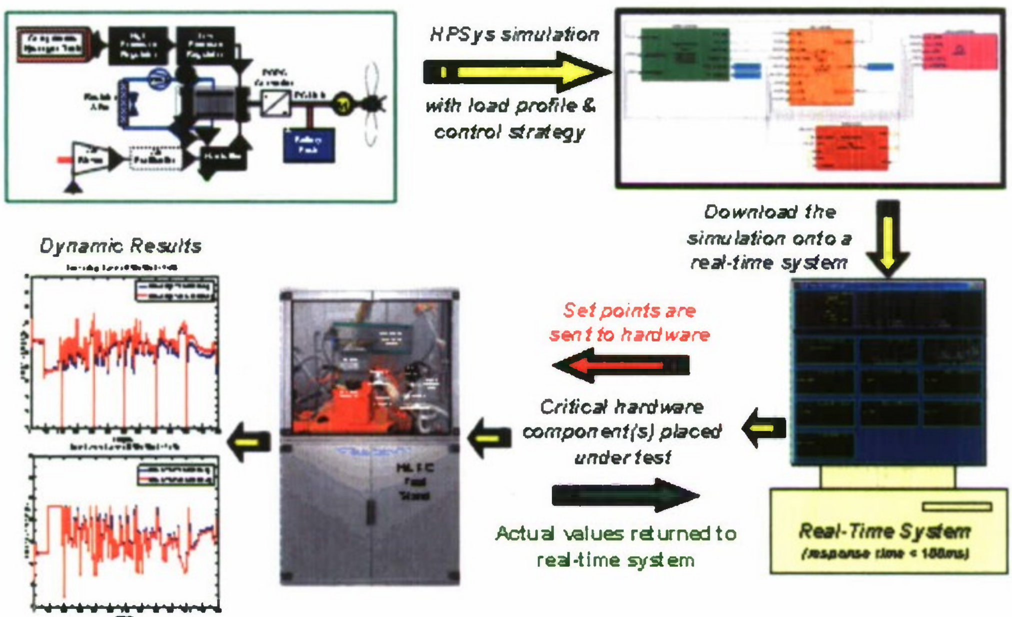


Figure 3-7 HiL Test System Operational Concept

The LF IT UAV System simulation was easily converted to real time simulation and was used in HiL testing with actual system components under realistic dynamic conditions. Initially, the HiL testing was only used to test fuel cell stack hardware, whereby the during the HiL testing the fuel cell stack model was replaced by actual stack and respond of the stack (i.e., stack voltage) was used in the real time simulation of the IT UAV system to calculate the respond of the rest of the simulated system and next step in the simulation and stack demand.

3.3.1 Dynamic characterization of the IT stack and effects of cleaning process under controlled stack conditioning

Once the HiL test station was operational, it was uses to study the effect of oxide cleaning on the Ion Tiger stack performance using a 20-minute Mission Profile and controlled stack conditioning. The stack was operated at temperature of 55 °C, relative humidity of 75% and air stoichiometry of 2.5. Ion Tiger (IT) system shorting process for stack oxide cleaning was implemented on the Hardware-in-the-loop (HiL) test station. The shorting process utilized MOSFET shorting device which short circuits the stack for 120 msec every 200 sec. During the short circuit period oxide layers on the cathode catalyst surface (Pt-OH/Pt-O) are reduced. This oxide cleaning process improves the overall stack voltage which increases the thermal efficiency when under load.

Two HiL tests were performed with an Ion Tiger stack using a LF IT UAV system simulation with a 20-minute mission propulsion profile. The first HiL test was performed with the shorting process for oxide cleaning and the second test without the cleaning process. Figure 3-8 and Figure 3-9 show the result from the HiL test. Figure 3-8 show that the cleaning process has improved the stack voltage over the whole mission profile, especially just after the cleaning process. Figure 3-9 shows the hydrogen consumption for the two mission profiles. This figure shows the advantage of the cleaning process as less hydrogen is consumed during the 20-min mission profile due to increases in stack efficiency. Extrapolating the 20-min profile results for a 24-hour mission leads to a 27.5 min increase in the flight duration. The calculations were as follows:

- Difference in H_2 Consumption between two test = 1.27×10^{-4} kg,
    - Amount of H_2 saved every 20 min or 1.9% saved.
- So, for a 24 hrs mission flight, the H_2 saved is
    - 1.27×10^{-4} kg x 72 = 0.0092 kg.
- H_2 consumption for a 24 hrs flight with the oxide cleaning is
    - $0.0067 \times 72 = 0.4824$ kg.
- So increase in flight duration due to the oxide cleaning process
    - $(0.0092/ 0.4843) \times 24 \times 60 = 27.50$ min,
    - 1.9 % increase in duration.

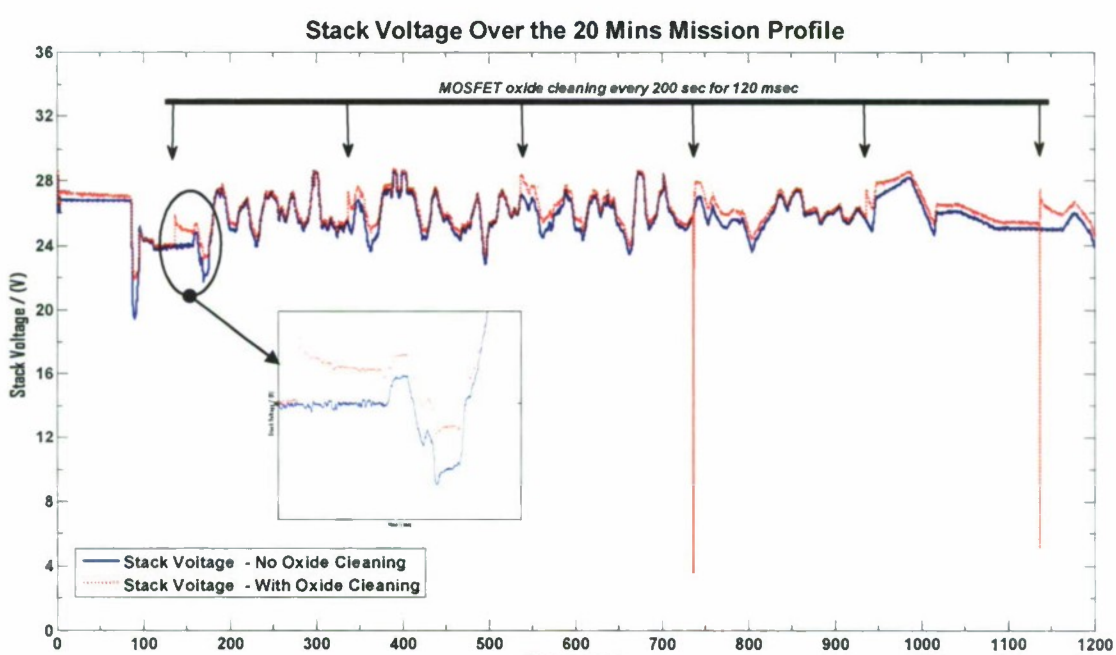


Figure 3-8 Stack voltage with and without the oxide cleaning for the 20-min mission profile using controlled stack conditioning, i.e., test stand air supply

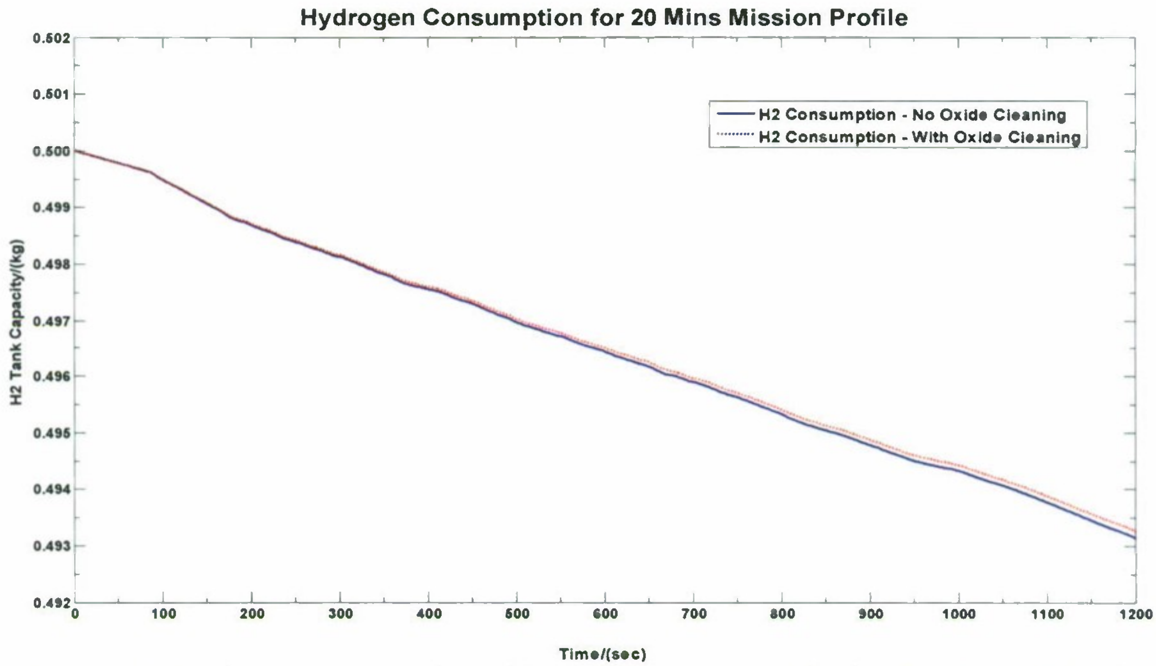


Figure 3-9 Hydrogen consumption with and without the oxide cleaning for the 20-min mission profile using controlled stack conditioning, i.e., test stand air supply

3.3.2 Dynamic characterization of the IT stack and effects of cleaning process with external humidifier and air blower (uncontrolled stack conditioning)

The effect of the oxide cleaning on the Ion Tiger stack performance using a 20-minute Mission Profile using external humidifier and air blower was also performed on the HiL test system. The Ion Tiger (IT) system air blower and external humidifier were implemented on the Hardware-in-the-loop (HiL) test station and were used to supply humidified air to the IT stack. The dry blower air was humidified in the external humidifier using the wet and hot cathode exhaust, prior to being fed into the stack cathode inlet. Figure 3-10 shows the picture of the IT stack, the air blower and external humidifier as implemented in the HiL test station.

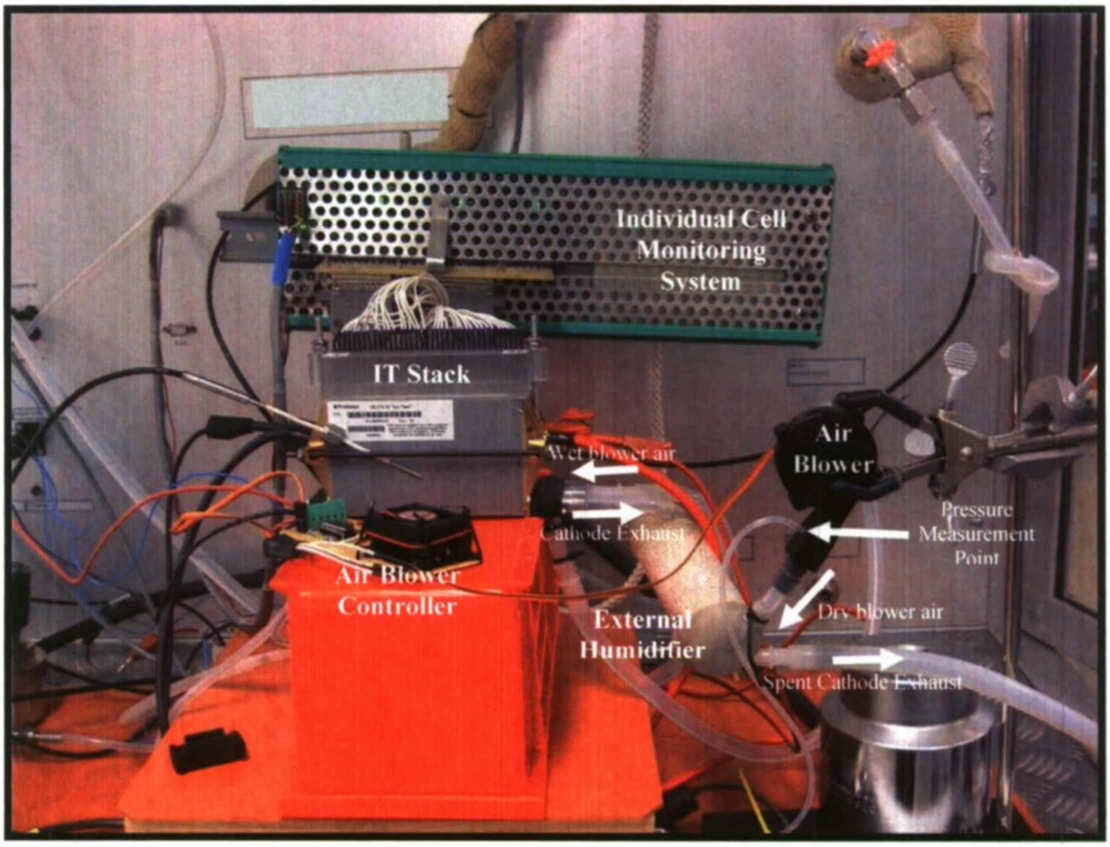


Figure 3-10 IT Stack, Air Blower and External Humidifier implemented in the HiL Test Station

Two HiL tests were performed with an Ion Tiger stack using a LF IT UAV system simulation with a 20-minute mission propulsion profile. The first HiL test was performed without the shorting process for oxide cleaning and the second test with the cleaning process. Figure 3-11 shows the hydrogen consumption for the two tests. This figure shows the advantage of the cleaning process as less hydrogen was consumed during the 20-min mission profile due to increases in stack efficiency. Figure 3-12 shows the stack voltage. As the first shorting event occurred at 200 sec in both tests, there was little difference observed in the voltage for the first 200 sec of the profile. Following the first shorting event, and each subsequent event, the voltage remained higher for the majority of the time. Figure 3-13 shows the stack thermal efficiency for the two tests. The improvement in the stack efficiency due to the cleaning process can be observed in this figure. This increase in stack performance improves the hydrogen utilization and overall system efficiency which results in longer flight duration.

The individual cell monitoring system was also implemented on HiL as diagnostic tool and has the great advantage of monitoring each cell performance during the simulated

UAV flight. Figure 3-14, Figure 3-15, and Figure 3-16 show the examples of the individual cell performance from the end cells, 1 and 36, and the middle cell, 18. The individual cell voltage performance identifies potential stack drying or flooding problem within the stack and would help in preventing stack degradation.

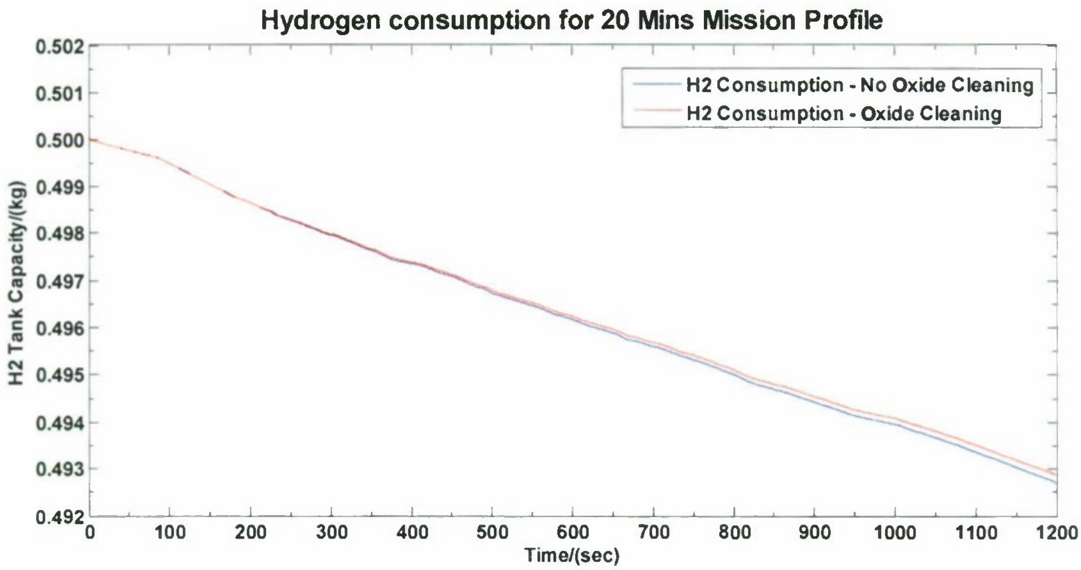


Figure 3-11 Hydrogen consumption with and without the oxide cleaning for the 20-min mission profile using uncontrolled stack conditioning, i.e., IT air supply components

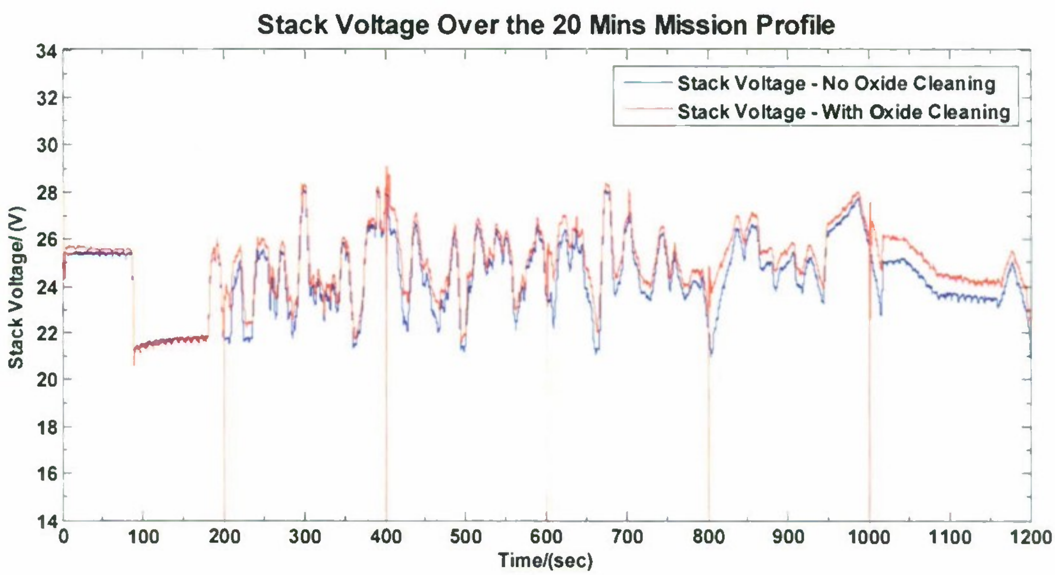


Figure 3-12 Stack voltage with and without the oxide cleaning for the 20-min mission profile using uncontrolled stack conditioning, i.e., IT air supply components

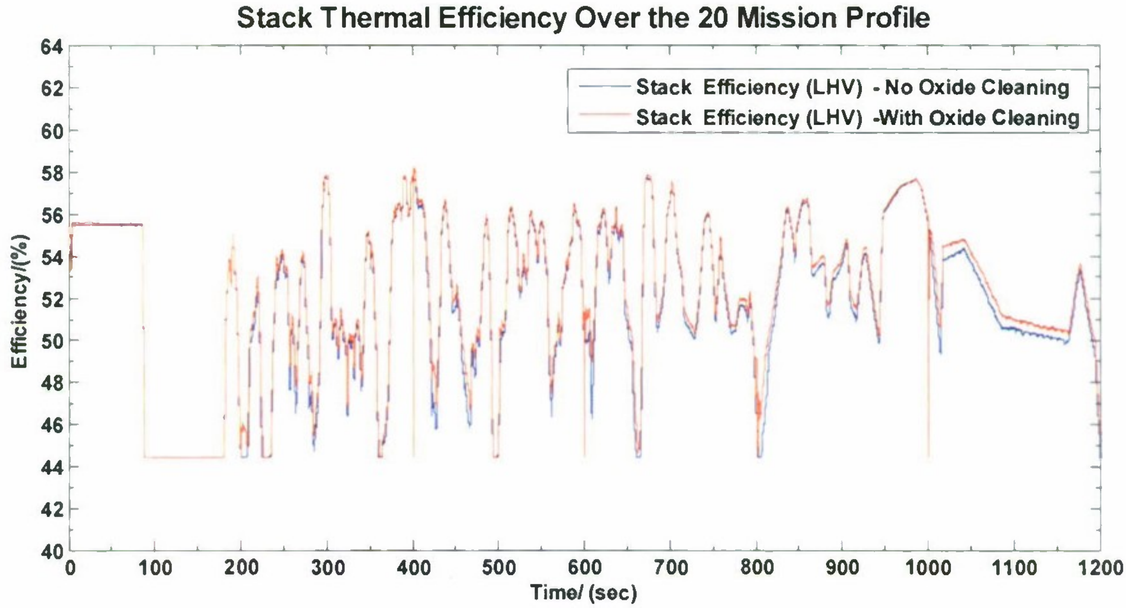


Figure 3-13 Stack thermal efficiency with and without the oxide cleaning for the 20-min using uncontrolled stack conditioning, i.e., IT air supply components

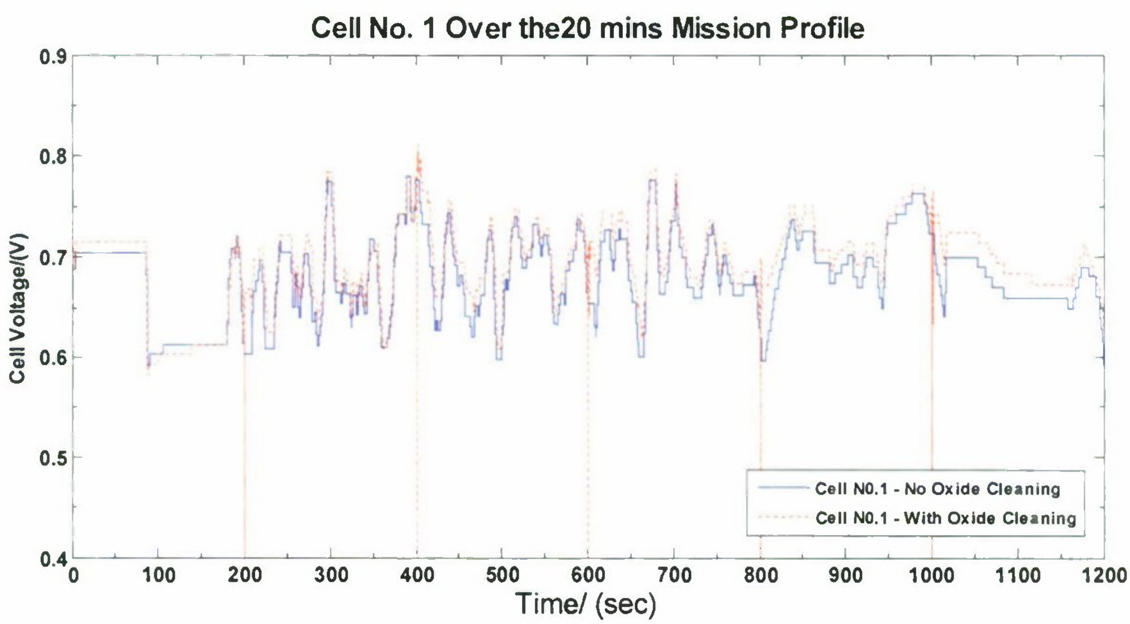


Figure 3-14 Front Cell No. 1 voltages with and without the oxide cleaning for the 20-min mission using uncontrolled stack conditioning, i.e., IT air supply components

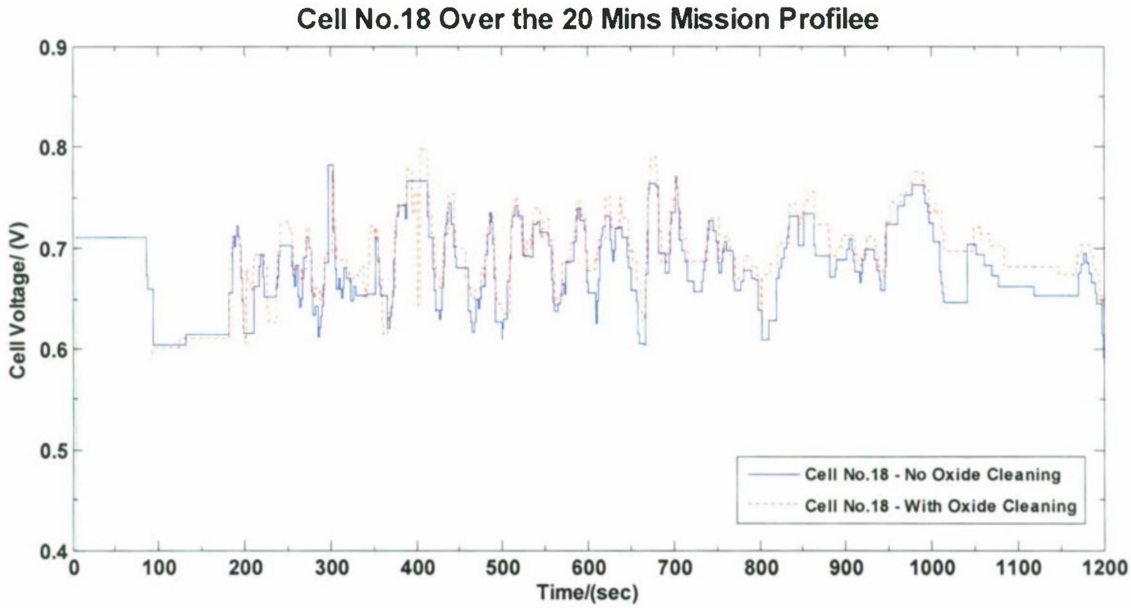


Figure 3-15 Middle Cell No. 18 voltages with and without the oxide cleaning for the 20-min mission profile using uncontrolled stack conditioning, i.e., IT air supply components

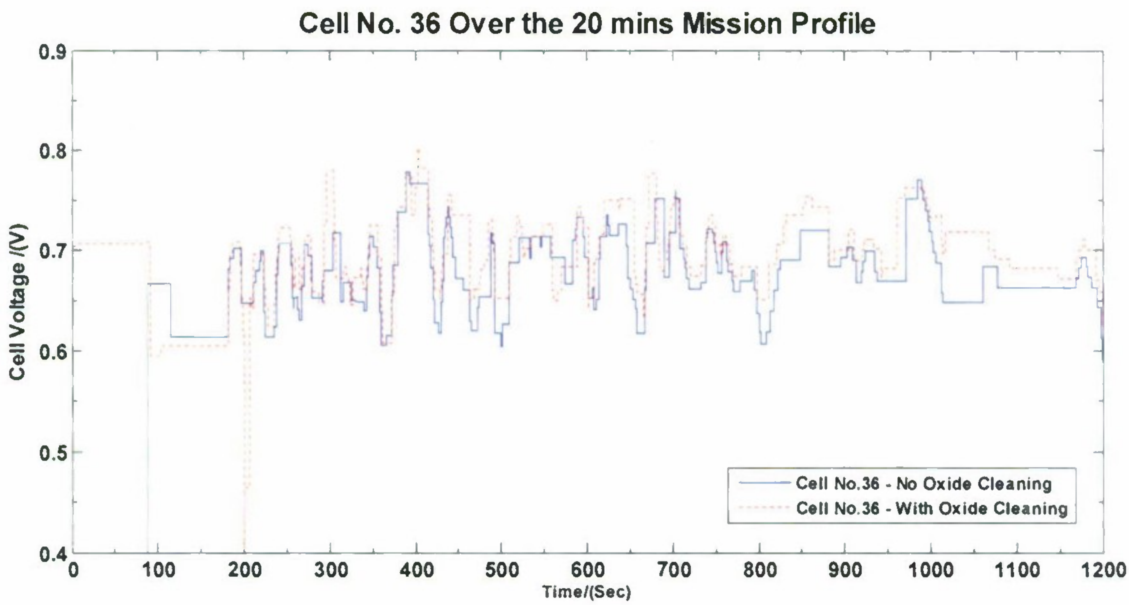


Figure 3-16 End Cell No. 36 voltage with and without the oxide cleaning for the 20-min mission profile using uncontrolled stack conditioning, i.e., IT air supply components