Appendix A. ResLab Testing and Calibration Procedure

Fuel Cell Testing and Test Rig Calibration Procedure

Abstract

This procedure is used to calibrate the test system equipment used in the fuel cell testing facility and to provide the procedure for testing fuel cell systems within ResLab. The fuel cell testing facility provides measurements for current, voltage, temperature, mass flow, volumetric flow, pressure and humidity. This document only deals with the calibration of current, voltage and temperature. External calibrations are required for the other measurements. The method of calibration consists of applying a stable current, voltage or temperature to the test system. The scaling coefficients of the test system are then computed by correlating multiple readings from the measuring system with those of a reference measuring system (a DMM for voltage calibrations, a DMM and shunt for current calibrations or a DMM and RTD for temperature calibrations). The readings should adequately cover the required measuring range such that extrapolation from the calibration range is not required during testing.

Written by .... Nathan Coad, ResLab.

Authorised by .... Nigel Wilmot, ResLab.

ResLab

Research Institute for Sustainable Energy

Murdoch University

South Street, Murdoch, WA 6150

ResLab Document ref TP-FC00-T-0001 rev 0

Revision Number	Issue Date	Revision Comment
0	18/05/2006	Released for Use
B	4/04/2006	Final Draft Document
A	14/03/2006	Draft Document

Table of Contents

1 Introduction

1.1 Purpose

These procedures are used to calibrate the fuel cell testing facility for voltage, current and temperature measurements. They also provide a testing procedure for testing fuel cell systems with the fuel cell testing facility.

1.2 Scope

The fuel cell testing facility can be used to monitor the thermal and electrical output from a fuel cell system over a period of time. This requires measurements for current, voltage, temperature, mass flow, volumetric flow, pressure and humidity. This document only deals with the calibration of current, voltage and temperature. External calibrations are required for the other measurements.

The test rig samples the test parameters at a user set frequency (the minimum and typical sample rate is 1 Hz). These samples are then collated over a larger time period (user adjustable in minutes, typically set to 1 minute) and an average is given along with a standard deviation, a maximum and a minimum value for the data set.

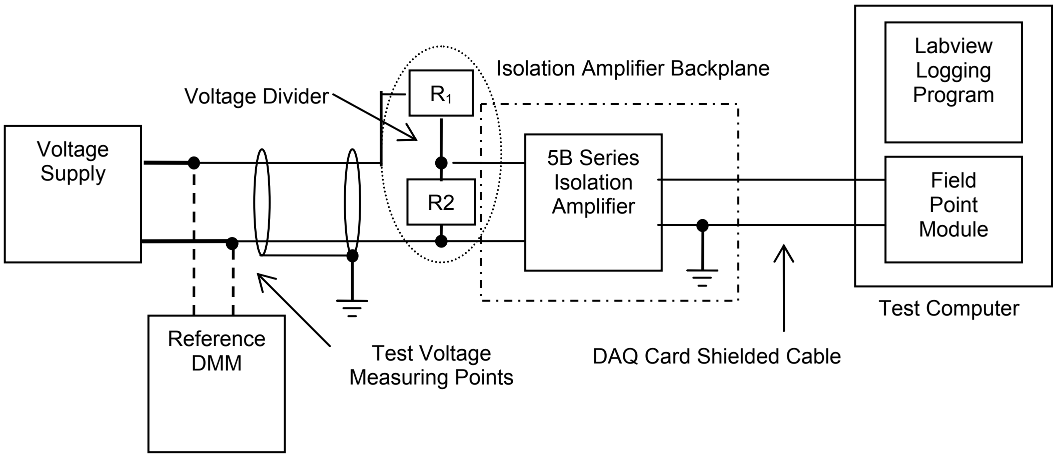
The method of calibration consists of applying a stable voltage, current or temperature to the test system. The scaling coefficients of the test system are then computed by correlating multiple readings from the measuring system with those of a reference test instrument (a DMM for voltage calibrations, a DMM and shunt for current calibrations or a DMM and RTD for temperature calibrations). The readings should adequately cover the required measuring range such that extrapolation from the calibration range is not required during testing.

Testing of a fuel cell system involves running the fuel cell in a constant voltage mode whilst applying a specific loading routine. The control characteristics of the fuel cell system must be carefully enforced to ensure that the system operation is repeatable. Loading is then applied via a 5kW resistive programmable load bank. To obtain this consistent operation and loading the fuel cell must be started, run and tested using the procedure outlined in section 4.2.

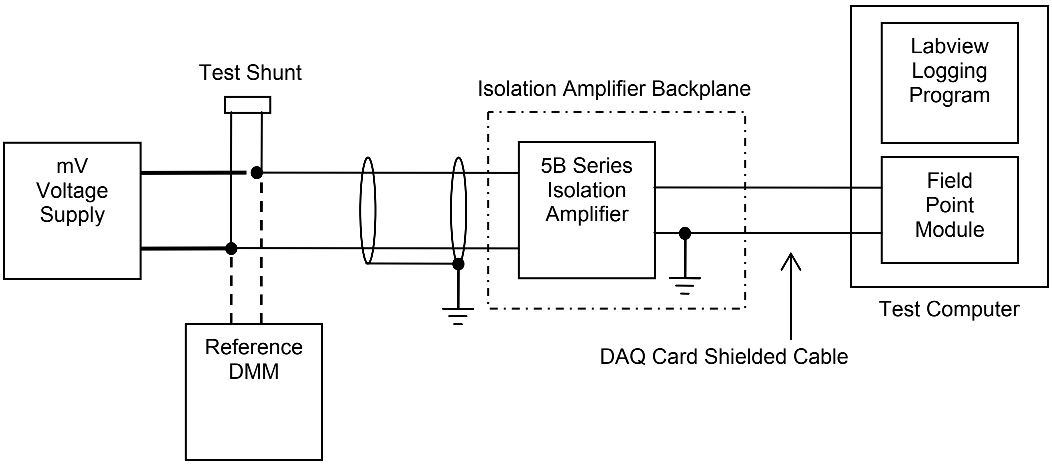
2 Calibration Setup & Equipment

As discussed in section 1, this procedure applies to voltage, current and temperature measurement systems. The calibration setups for these three cases are presented in Figure 1. For actual measurements using this type of system, the reference instruments are not necessary and the signal wires and/or measurement devices are connected to the actual measurement locations.

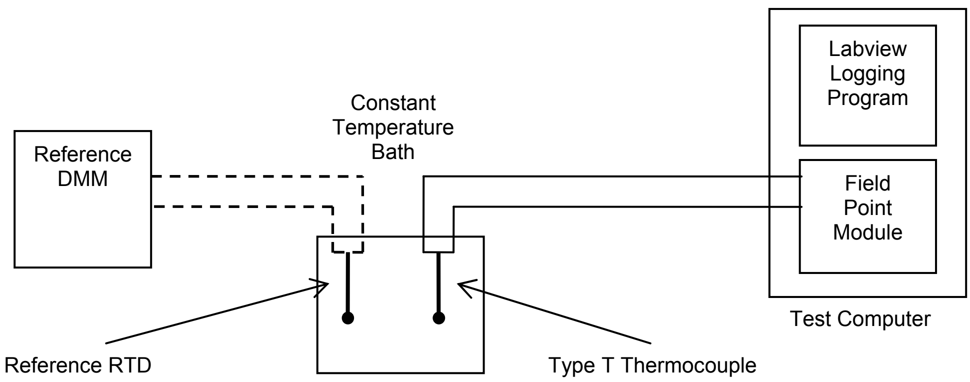
For current calibrations the shunt was not included in the system calibration and was calibrated separately using the ResLab procedure TP-RESL-T-0007 Rev 1 “Calibration Procedures for Current Shunts”.



a) Voltage Calibration Setup



b) Current Calibration Setup



c) Temperature Calibration Setup

Note: The calibration setup including all signal wiring, transducers and equipment from the measuring point to the DAQ module and test computer must be the same as that used for actual testing.

Figure 1 Voltage, Current and Temperature Calibration Setups

2.1 Equipment Required for Calibration

- Agilent 3458A Digital Multimeter, Equipment #MI-MU-0012 (the reference DMM)
- Yokogawa 255A DC Source / Calibrator for voltages up to 100 Volts, Equipment #CAL-AL-0001 (voltage supply)
- Constant Temperature Bath
- Reference RTD, Equipment #TMD-MU-0001
- Reference Current Shunt
- Lab View "FC System Calibration" Program v2.0
- Stop Watch

3 Test Equipment

3.1 Field Point Modules

The fuel cell testing facility uses a National Instruments Field Point system to log all performance data. The Field Point system comprises of a number of different modules, each with their own roles and specifications. Below is a table of the modules used and their role in the logging process. Further information regarding the NI Field Point system can be found at http://sine.ni.com/nips/cds/view/p/lang/en/nid/1206.

Module Model	Measurement	Signal	Resolution	Base Model
FP-1000	Networking Module	N/A	N/A	N/A
FP-AI-110	Voltage	±5VDC (via 5B module)	16 bit	FP-TB-1
	Current	±5VDC (via 5B module)	16 bit	FP-TB-1
	Mass Flow Rate	4 to 20 mA	16 bit	FP-TB-1
	Pressure	4 to 20 mA	16 bit	FP-TB-1
	Temperature and Humidity	0 to 1 VDC via HygroClip probe	16 bit	FP-TB-1
FP-TC-120	Temperature	-20 to 80 mV	16 bit	FP-TB-3
FP-CTR-500	Volumetric Flow Rate	Counter	1 count	FP-TB-1

Table 1: Types of Field Point Modules used in the Fuel Cell Test Facility

The Field Point unit should be calibrated as part of the whole measurement system. Recalibration of the measurement system should be approximately once per year. However, this needs further investigation as the system drift is unknown.

3.2 Isolation Amplifiers

In order to provide isolation between the test circuit and the data acquisition system, Isolation amplifiers are required. These devices provide safety and a common reference for all measured signals. A range of Dataforth 5B series isolation amplifiers are available at ResLab all with an output range of ±5 V. The input ranges available are ±50 mV, ±100 mV, ±5 V, ±10 V, ±20 V and ±40 V in low bandwidth (4 Hz) and wide bandwidth (10 kHz) versions. The use of low bandwidth modules (4 Hz) is required for the fuel cell testing facility due to the DC ripple from the single phase inverter. This means that the ripple will not influence the data taken by the logging system at the 1 Hz sample rate.

Equipment Number	Description
MT-0038A to MT-0039F	±40 V Input, ±5 V Output, Dataforth 5B series isolation amplifier
MT-0039A to MT-0039G	±50 mV Input, ±5 V Output, Dataforth 5B series isolation amplifier

Table 2: List of Isolation Amplifiers Used in the Fuel Cell Testing Facility

3.3 Transducers

3.3.1 Voltage Transducers

Voltage transducers in the form of voltage dividers are required for measurements where the peak voltage exceeds ±40 V. This is due to the available laboratory isolation amplifiers having a maximum input range of ±40 V. The voltage dividers selected for the fuel cell test facility use high precision resistors (±0.1% Ohm) and have a low thermal coefficient (15ppm/degC). The resistor selection was to ensure minimal power dissipation to reduce thermal effects. No specific limit was considered for the selected resistors except that they be WELL below 50% of the specified limit (0.25W limit for selected resistors).

Any measurement channel using a voltage divider must be calibrated as a complete system. This is due to the internal resistance of the 5B isolation amplifier (650 kΩ) slightly affecting the voltage divider relationship as the resistance R_2 (from Figure 1) approaches the 5B resistance. However, low resistor values should not be considered as this will increase the power dissipation and result in additional current measurement error.

All test rig voltage measurements greater than ±40 V are within the 48 VDC system. This system connects the fuel cell to the loading, charging and power conditioning components, which operate within 46 to 57 VDC. Therefore, all of the voltage dividers have been designed to reduce 60 VDC to 40 VDC. The selected values were 100 kΩ for R_1 and 200 kΩ for R_2 (see Figure 1). At 60 VDC this results in a power dissipation of 0.012 W, which is approximately 5% of the design limit.

3.3.2 Current Transducers

The current transducers used are shunt resistors with 50 mV outputs. Most shunts have an input range of ±150 Amps; however there is a ±30 Amp and a ±50 Amp shunt that are also installed. Care must be taken when using other shunts by ensuring that the output of the shunt does not exceed the input range of the isolation amplifiers.

To improve the uncertainties of the current measurements the shunts should not be used to measure currents less than about 5% of their rated capacity. Also, the current shunts should not be allowed to operate at currents greater than 80% of rated capacity for two reasons: one is to prevent thermal degradation over time and the other is to ensure that the current shunt operates within the linear region of its current-resistance characteristic.

Equipment Number	**Description**
CS-0019A to CS-0019F	±150 A Input, ±50 mV Output, Current Shunt
CS-0037A	±30 A Input, ±50 mV Output, Current Shunt
CS-0032	±50 A Input, ±50 mV Output, Current Shunt

Table 3: List of Current Shunts Used Within the Fuel Cell Testing Facility

3.3.3 Thermocouples

The thermocouples used within the fuel cell testing facility are “type T”. These thermocouples can have a valid range of -270 to 400 ^{0}C and have the best accuracy (when compared to other thermocouple types) in the 0 to 200 ^{0}C temperature range. Specific ranges and accuracies depend on the manufacturer.

The thermocouples selected for the test facility have a flexible cable with PVC insulation. The measurement junction is electrically insulated and sheathed within a 3mm stainless steel probe. This allows for insertion into conductive and corrosive fluids.

Figure 2: Thermocouple

4 Procedures

4.1 Voltage, Current and Temperature Calibration

These calibration procedures shall be performed annually or when one of the system components has been replaced. This includes the replacement of a transducer, connection board or a signal wire.

a) Connect the calibration circuit as shown in Figure 1.

   Note: Ensure that all signal cables are as short as possible and that they are shielded or twisted to reduce the effect of noise in the measurements. Shields must be connected to earth. Bear in mind however, that these signal cables must be the same as those used for actual testing.

b) Ensure that ambient temperature is being logged by the test facility logging system.

c) Connect the DMM to the fuel cell testing computer using the GPIB cable. (check that the DMM is in calibration prior to use)

d) Allow the reference DMM to warm up for at least 2 hours and the power supplies for at least 20 minutes.

e) Perform the “ACAL” function on the 3458A DMM before the start of the calibration. This function must be performed at least once every 24 hours, or when the ambient temperature has varied by more than ± 1°C.

f) With NPLC set to 10, measure the DMM offset by shorting the input terminals with the shorting accessory. Note down in the logbook the largest observed offset reading over a period of 2 minutes.

g) Run the fuel cell calibration program “_Top Level FC System Calibration.vi”.

Note: This calibration program was developed for the calibration of all the Field Point channels. As such it logs all data from the Field Point unit and produces a log file in the same manner as the normal testing log. It also logs the readings and statistics from the 3458A DMM and the scaling coefficients saved in the system.

h) Follow the program prompts and fill the information required. The logging parameters, scaling factors and offsets should be set as follows:

   - DMM NPLC = 10
   - DMM No. of Samples = 1
   - DMM Measurement Type = Voltage (voltage and current) or 4W Resistance (temperature).
   - FP Sampling Rate = 1 sample/sec
   - FP Logging Rate = 1 minutes/log (3 minutes is recommended for calibrations).
   - Quadratic scaling factor = 0
   - Linear scaling factor = 1
   - Offset scaling factor = 0

i) Follow the program prompts until it asks you if you want to insert a comment for that reading and click “Yes”. For temperature calibrations only, proceed to step (q).

j) Short all signal wires including the DMM ones to the positive side of the measurement point.

k) In the comment box of the calibration program add the following note: “Noise measurements with minimum input and signals shorted to positive”

l) Click OK on the comment and then click OK to take the readings. When the program prompts you to make another reading click “Yes”. When the program prompts you to insert a comment for that reading click “Yes”.

m) Short all signal wires including the DMM ones to the negative side of the measurement point.

n) In the comment box of the calibration program add the following note: “Noise measurements with minimum input and signals shorted to negative”

o) Repeat step (l).

p) Return the signal wires to the appropriate positive and negative measuring points.

q) In the comment box of the calibration program add a note specifying the measurement point (e.g. “V_g2 setpoint +60 V”, “I_bb setpoint +50 mV”, “Bath Setpoint 0 degC”, etc.). These values are specified in Table 4: Calibration Steps for the Fuel Cell Test Facility.

r) Apply calibration set point to the system and wait until the system is stable. This is approximately 45 seconds for voltage and current calibrations and 20 mins for temperature.

Note: System calibrations should be performed over the range of input values that are expected in testing. Table 4 gives the calibration values within the fuel cell testing facility.

48 VDC system	50 mV shunt	Temperature
+ 60 V	+ 50 mV	0 ^{0}C
- 60 V	- 50 mV	10 ^{0}C
+ 45 V	+ 38 mV	20 ^{0}C
- 45 V	- 38 mV	30 ^{0}C
+ 30 V	+ 25 mV	40 ^{0}C
- 30 V	- 25 mV	50 ^{0}C
+ 15 V	+ 13 mV	60 ^{0}C
- 15 V	- 13 mV	70 ^{0}C
+ 3 V	+ 3 mV	80 ^{0}C
- 3 V	- 3 mV	
+ 0.06 V	+ 1 mV	
- 0.06 V	- 1 mV	

Table 4: Calibration Steps for the Fuel Cell Test Facility

s) Repeat step (l).

t) Increase the calibration step according to Table 4.

u) Repeat steps (q) to (t) until all the readings have been taken.

v) Click OK on the comment and then click OK to take the readings. When the program prompts you to make another reading click “No”. When the program prompts you to end the program click “Yes”.

w) Check that the DMM temperature has not varied by more than 1 degree Celsius and that the ambient temperature has not varied by more than 5 degrees Celsius. If so consider repeating the calibration or make an allowance in the uncertainty.

x) Turn off the power supplies.

y) Note down the ambient temperature in the logbook. Tag this temperature "End of test temperature".

z) End of calibration.

4.2 Fuel Cell Testing Procedure

The testing procedures may differ slightly depending on the fuel cell system being tested. Presented are the two methods used so far.

4.2.1 General

In order to simplify testing and increase repeatability there are a number of factors to consider when devising the testing procedure. Presented below are a number of issues that relate to both AFC and PEM fuel cell systems.

- The fuel cell system will likely have a heating element that warms the system to the operating temperature during a cold start up. To compensate for this the fuel cell system must be started and fully pre-heated prior to the commencement of any testing. This means that the fuel cell internal heater will not be operational during the test and can be therefore removed from the testing scope. If the start up energy is required then a current shunt will need to be installed.

- The fuel cell battery bank (internal or external) must be fully charged prior to the commencement of any testing. This will effectively remove the battery bank from the test (providing that the fuel cell maximum load is not exceeded) and allow the fuel cell system to follow the load profiles more accurately. The fuel cell system should not be run without a battery bank attached unless this is the manufacturer's operating instructions.

- To hasten the battery charge time the fuel cell start-up and pre-heat steps should be undertaken with the battery charger turned on. This results in the batteries being at full charge immediately after start up.

- The fuel cell operating system will have a large impact on how the fuel cell reacts to the load changes during testing. For all testing performed by ResLab, the fuel cell system was operated in a constant voltage mode. This means that the fuel cell will always try to maintain the DC voltage at a set point regardless of the current supplied.

- Prior to running any tests the fuel cell system's maximum sustainable load must be determined. This is necessary so that the automated test is not interrupted by unexpected fuel cell system failure. Many initial tests required repeating due to this. This can be determined by the following:

    i. Firstly, read all of the documentation provided by the manufacturer.

ii. Then, where possible, consult the manufacturer regarding their operating and testing experiences. An in-depth discussion of ResLab's testing objectives is recommended.

iii. Finally, with the fuel cell installed in the testing facility, manually increase the load bank power until the fuel cell voltages become low. (The low voltage should be specified by the fuel cell manufacturer). This loading value can then be used as the peak load profile value. Unfortunately, this method is not infallible so be slightly conservative to account for parasitic losses and DC ripple from the testing system.

- Experience has shown that the steady state maximum load can be higher than the dynamic maximum loading.
- The hydrogen supply must remain at a very constant pressure to obtain satisfactory readings and to ensure that there is no downstream effect on the fuel cell system. The current test rig supply system is relatively stable, but check that the standard deviation of the hydrogen mass flow data is small enough so that it does not significantly impact on the measurement uncertainty.
- Operating the fuel cell system at high loads can result in over temperature problems. Monitor the system temperatures very carefully at high loads.

4.2.2 Steady State Load Profiles

The steady state load profiles are used to obtain the data for calculating the electrical and thermal efficiencies. The main requirement for performing steady state tests is ensuring thermal, mass flow and electrical equilibrium. This will reduce any effects due to these transients allowing for more accurate comparisons to other systems.

At higher loads the heat that is released from the fuel cell system impacts on the ambient temperature in the test area. To minimise this effect the steady state profiles are run in a specific format so that the ambient temperature increase is minimised. This improves the test accuracy as most sensors will experience a level of drift due to temperature change.

The steady state format is to ramp the fuel cell system up to maximum load as fast as possible. Once equilibrium is reached the data is collected and the load will step down one level. This is repeated for all the load steps down to the minimum load. This format reduces the time needed to reach equilibrium and maintains a more consistent ambient temperature.

4.2.3 RAPS Profiles

The RAPS profiles are simulations of Remote Area Power requirements. The values used in the ResLab tests where taken from real systems within the Port Headland region in Western Australia. Two profiles are tested, one is from a remote homestead, and the other is from a small remote community. (Patel M. (2006), Performance Characterisation of Hybrid Photovoltaic Diesel Generator Remote Area Power Supply Systems, Chapter-3. PhD Thesis, Division of Science and Engineering, Murdoch University, Perth, WA, Australia).

As the RAPS profiles are simulations of measured RAPS systems the temperature fluctuations due to heat released from the fuel cell system are unavoidable. In fact, for a true simulation, realistic temperature variations are perhaps even desirable as they are more representative of the actual conditions. However, adequate test rig ventilation must still be ensured so that the ambient conditions remain as steady as possible and the test accuracies are not greatly influenced.

4.2.4 Fuel Cell Testing Methodology

4.2.4.1 Test rig testing procedure for FC system with internal battery system.

1. Turn on the fuel cell container.
2. Open valves on the hydrogen cylinders and piping directly above them.
3. Boot up the fuel cell testing computer and fuel cell interfacing computer.
4. Turn on the instrumentation power supply.
5. Check that the hydrogen control PWM valve is turned on and operating at the correct pressure set-point (for the fuel cell) and control setting (read manufacturer’s manual for details).
6. Slowly turn on the manual valve upstream of PWM valve.
7. Check that the fuel cell breaker is open (near inverter).
8. Turn on external battery bank switch and battery charger.
9. Turn on the inverter and load bank.
10. Connect the FC internal power and start up the fuel cell interface program.
11. Provided that the inverter is operating, close the fuel cell breaker.
12. Start up the FC as per manufacturer’s procedure and ensure it is running correctly.
13. Once the FC is in the run mode, disconnect the external battery bank and turn off the battery charger.
14. Run the LabView GUI “_Top Level _FC Performance Monitoring with Load Profile Simulation.vi” and follow the instructions to start the test profile.
15. Monitor all systems whilst LabView steps through the load profile.
16. When testing has finished, close the LabView GUI.
17. Shut down the fuel cell after it has idled for a few minutes.
18. Turn off the inverter and load bank.
19. Turn on the external battery bank.
20. Turn on the battery charger.

21. Close the manual hydrogen valve near the PWM solenoid.
22. Turn off the instrumentation power supply.
23. Close the valves on the hydrogen cylinders and piping.
24. Once the internal and external battery banks are charged turn off the charger.
25. Open the fuel cell breaker.
26. Disconnect both the battery banks.

4.2.4.2 Test rig start-up procedure for FC system without internal battery system.

1. Start up the fuel cell testing container.
2. Open the valves on the hydrogen cylinders and piping directly above them.
3. Boot up the fuel cell testing computer and fuel cell interfacing computer.
4. Turn on the instrumentation power supply.
5. Check that the hydrogen control PWM valve is active and at the correct set-point.
6. Slowly open the manual valve upstream of PWM valve.
7. Check that the fuel cell breaker is open (near inverter).
8. Turn on the external battery bank switch and the battery charger.
9. Turn on inverter and load bank.
10. Once the inverter is operating, close fuel cell breaker.
11. Start up fuel cell interface program.
12. Start up FC and ensure it is running correctly.
13. Once the FC is in the run mode, turn off the battery charger.
14. Run the LabView GUI "_Top Level _FC Performance Monitoring with Load Profile Simulation.vi" and follow the instructions to start the test profile.
15. Monitor all systems whilst LabView steps through the load profile.
16. When testing has finished, close the LabView GUI.
17. Shut down the fuel cell after it has idled for a few minutes.
18. Open the fuel cell breaker.
19. Turn off the inverter and load bank.

20. Turn on the battery charger.

21. Close the manual hydrogen valve near the PWM solenoid.

22. Turn off the instrumentation power supply.

23. Close the valves on the hydrogen cylinders and piping.

24. Once the external battery bank is charged turn off the charger.

25. Disconnect the battery bank.

5 Uncertainty Analysis

A summary of the calibration uncertainties are presented below. The measurement uncertainties can not be calculated during the calibration stage and shall be presented in the individual test reports.

The uncertainty evaluation and calculations can be viewed in the document "CAL_FC00_T_0001 Calibration Uncertainty Calculations for Fuel Cell Testing".

Table of Calibration Uncertainties

Field	Range	Percentage of Measurement (%)	Additional Uncertainty (±)	Units
Current	0 to 150 Amps	0.09%	0.05	A
Voltage	0 to 60 VDC	0.08%	0.002	V
H2 Mass Flow	full range	2.01%	N/A	kg/s
Air Mass Flow	full range	3.10%	N/A	kg/s
Temperature	0 to 80 degC	N/A	0.36	degC
Volumetric Flow	full range	0.50%	N/A	L/s
Pressure	full range	0.91%	N/A	kPag

Table 5: Summary of Calibration Uncertainty