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**National Highway
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Administration**

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Crashworthiness Research of Prototype Hydrogen Fuel Cell Vehicles: Task Order 7 Project Report

Appendix B
Electrical Isolation Measurement Plan

DISCLAIMER

TEST PROCEDURE

Organization/Name	Approved Date:	Notes

RECORD OF REVISIONS

Version	Sections Affected	Description of Changes	Date	Approval
0.1	ALL	Initial Draft	3-26-12	
0.2	ALL	Incorporated Improvements after Dry Run	3-30-12	

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1. PURPOSE AND APPLICATION

This document is a test procedure for measuring electrical isolation for crashworthiness research of hydrogen fuel cell vehicles. The purpose of this test procedure is to determine electrical safety based on electrical isolation measurements between the inactive high-voltage sources and the electrical chassis. A safety analyzer will be used to perform the isolation measurements. This test procedure has been developed specifically for crashworthiness research of hydrogen fuel cell vehicles; contract number DTNH22-08-D-00080, Task Order 7. This procedure does not constitute an endorsement or recommendation for use of any particular product or testing method.

2. BACKGROUND

This test procedure is based both on the Federal Motor Vehicle Safety Standard (FMVSS) No. 305 [1], and a test procedure developed in prior work for the National Highway Traffic Safety Administration under this contract: Appendix A of "Electrical Isolation Test Procedure Development and Verification" [2]. FMVSS No. 305, dated July 29, 2011, specifies requirements for protection from harmful electric shock during and after a crash. The procedure specified in FMVSS No. 305 applies to active high-voltage sources, while the high-voltage sources in the vehicles under test will be inactive (the battery will be removed and the hydrogen will be replaced with an inert substitute). This document bridges the gap by providing a method for testing electrical isolation of the inactive high-voltage sources using a safety analyzer.

In order to meet the electrical safety requirements of FMVSS No. 305 S5.3, the electrical isolation between each high-voltage source and the electrical chassis, when determined in accordance with the procedure specified in S7.6 of FMVSS No. 305, must be greater than or equal to:

- 500 ohms/volt for an AC high-voltage source; or
- 500 ohms/volt for a DC high-voltage source without electrical isolation monitoring during vehicle operation; or
- 100 ohms/volt for a DC high-voltage source with electrical isolation monitoring.

The acceptance criteria described above will be used as a point of reference in the discussion of the research results.

FMVSS No. 305 is applicable to passenger cars, and to multipurpose passenger vehicles, trucks, and buses with a gross vehicle weight rating (GVWR) of 4,536 kg or less, that use electrical propulsion components with working voltages greater than 60 volts direct current (VDC) or 30 volts alternating current (VAC), and whose speed, attainable over a distance of 1.6 km on a paved level surface is more than 40 km/h. If the hydrogen fuel cell vehicles under test were manufactured for sale for highway use, they would meet these conditions for applicability.

Testing the electrical isolation between points within a fuel cell coolant loop and each vehicle's chassis is important because the coolant can be a shorting path. Because the coolant in both test vehicles has aged significantly, the coolant has ionized with an increase in electrical conductivity. Unfortunately, a clear method of starting the fuel cell coolant pump and flushing the coolant could not be identified, and coolant loop electrical isolation measurements with the existing aged coolant would not be meaningful.

3. Definitions

Automatic Disconnect
A device that when triggered, conductively separates a high-voltage source from the electric power train or the rest of the electric power train.

Active High-Voltage Source
Any high-voltage source with accessible high-voltage levels from which the electrical isolation of the high-voltage source can be determined with FMVSS 305.

DC Hipot Test
A test used to verify the insulation integrity of a device in order to protect the user from electrical shock. A test voltage is applied and the resulting leakage current is measured, allowing the electrical isolation value to be calculated.

Electrical Chassis
Conductive parts of the vehicle whose electrical potential is taken as reference and which are: (1) conductively linked together, and (2) not high-voltage sources during normal vehicle operation.

Electrical Isolation
The electrical resistance between a high-voltage source and any of the vehicle's electrical chassis divided by the working voltage of the high-voltage source.

Electric Power Train
An assembly of electrically connected components which includes, but is not limited to, electric energy storage/conversion systems and propulsion systems.

High-Voltage Source
Any electric component contained in the electric power train or conductively connected to the electric power train that has a working voltage greater than 30 VAC or 60 VDC.

Inactive High-Voltage Source
Any high-voltage source altered for reasons of safety, cost, or other limitations of vehicle testing such that the inactive source:

- Provides the same electrical isolation to chassis characteristics as the original active source; and
- Produces no voltage levels; and
- Includes any other requirement that allows a safety analyzer to measure isolation resistance representative of the original active high-voltage source.

Examples of inactive high-voltage sources include, but are not limited to: HFCVs without hydrogen or battery packs without battery cells.

Maximum Operating Voltage
Maximum nominal voltage applied by a high-voltage source.

Test Voltage
Voltage set-point for the safety analyzer for a particular high-voltage source.

4. BARRIER CRASH TEST AND VEHICLE DESCRIPTION

The crashes will be patterned after the rear crash test conditions of FMVSS No. 303 [3] and the side dynamic test of FMVSS No. 214 [4]. The research crash test in which this procedure is to be performed is described fully in the Crash Test and Safety Plan [5]. Identifying features and designations of the two crash test vehicles are given below, along with information regarding the high-voltage components of each vehicle.

Both vehicles have a fuel cell under the hood, and both have ballast in the trunk to replace the high-voltage battery, which has been removed. The fuel cells, now no longer useful, had been rated at 250 to 460 VDC, 80 kW. The Li-PB batteries were 152 VDC, 5 A-h capacity.

5. INSTRUMENTATION AND TEST EQUIPMENT

The required test equipment includes a safety analyzer, multimeter, and temperature probes. Figure 1 shows a typical safety analyzer and the requisite wiring for measuring isolation resistance.

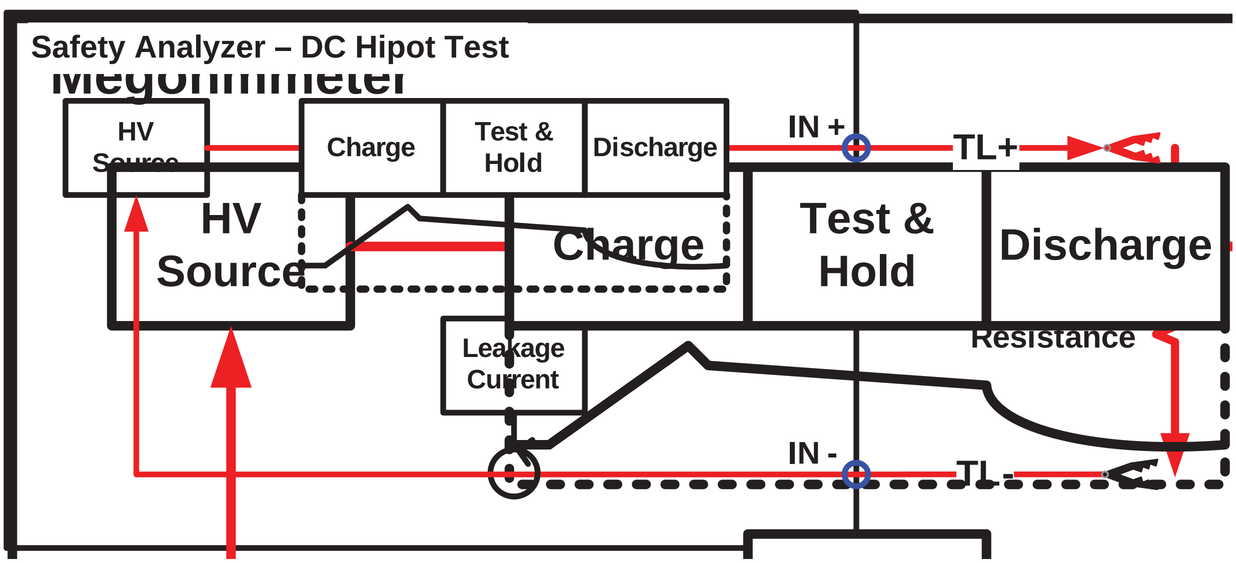

Figure 1. Safety analyzer diagram showing positive and negative test leads, TL+ and TL-

Table 1 is a list of equipment and the corresponding requirements needed to complete the test procedure. The minimum specifications also are listed for each device. Equipment for measuring environmental conditions, such as ambient temperature, is necessary for normalization. Details on the specific test equipment to be used are given in Table 2.

Table 1. Equipment list and minimum specifications

Equipment	Requirement	Minimum Specifications
Safety Analyzer	Test Voltage	> 95% of Maximum Operating Voltage
	Sourced Current Capability	> 10 mA
	Accuracy	< 5% of measurement
	Charge Time*	> 2 seconds
	Dwell Time*	> 3 seconds
	Maximum Line Voltage Present**	< V_{off}
Multimeter	**Ohmmeter**	
	Electrical Resistance	> 1 ohm
	AC and DC voltmeter	
	Internal Impedance	> 10 Mohm
	Maximum Voltage Rating	> 600 volts

NOTE: Comparisons are inclusive.

* The Charge and Dwell Times often are not long enough for all devices to reach the desired test voltage.

** V_{off} is the maximum voltage or DC offset allowed by the instrument at the test points prior to measurement while maintaining the specified accuracy and is below the threshold that the tester would consider to be an energized high-voltage circuit.

Table 2. Test equipment details

Equipment		
Safety Analyzer	Make	Quadtech
	Model	Guardian 5000
	S/N	8288455
	Last Calibration Date	9/27/2007
	Calibration Due Date	9/27/2012
	Sourced Current Capability	20 mA
Multimeter	Make	Fluke
	Model	87-5
	S/N	19510177
	Last Calibration Date	3/29/2012
	Calibration Due Date	3/29/2013
	AC and DC Voltmeter	-
	Internal Impedance	10 Mohm
	Maximum Voltage Rating	1000 volts
	Temperature	-
	Accuracy	1% + 10 °C

6. Electrical Isolation Test Points and Measurement Descriptions

Before being removed, the high-voltage battery was located in the trunk of each vehicle. The schematic shown in Figure 2 illustrates the test points available at the location of the high-voltage battery pack: **DC-1** and **DC-2**. In a normal vehicle configuration, **DC-1** is connected to the positive high-voltage terminal, **HV_BATT+**, and **DC-2** is connected to the negative high-voltage terminal, **HV_BATT-**. Test points **DC-1** and **DC-2** are shown in Figure 3. The electrical chassis connection, **TPGND**, can be made at one of the non-anodized bolts in the trunk, shown in Figure 4. The safety analyzer measures isolation resistances **R1** and **R2**, which are respectively the resistances between the positive and negative battery terminals and the electrical chassis. The dotted lines of **R1** and **R2** indicate that these resistances are not part of the test equipment, but are the isolation resistances under test. As shown in Figure 2, the battery pack system employs automatic disconnects which are physically contained within the battery pack enclosure. FMVSS 305 S7.6.1 states, "For a high-voltage source that has an automatic disconnect that is physically contained within itself, the electrical isolation measurement after the test is made from the side of the automatic disconnect connected to the electric power train or to the rest of the electric power train if the high-voltage source is a component contained in the power train." Therefore, the isolation measurements will be made from the power train side of the automatic disconnects, which is also the only side available after the battery has been removed. This procedure does not determine whether proper disconnections occur, because the vehicle will be in an inactive state and the battery will have been removed.

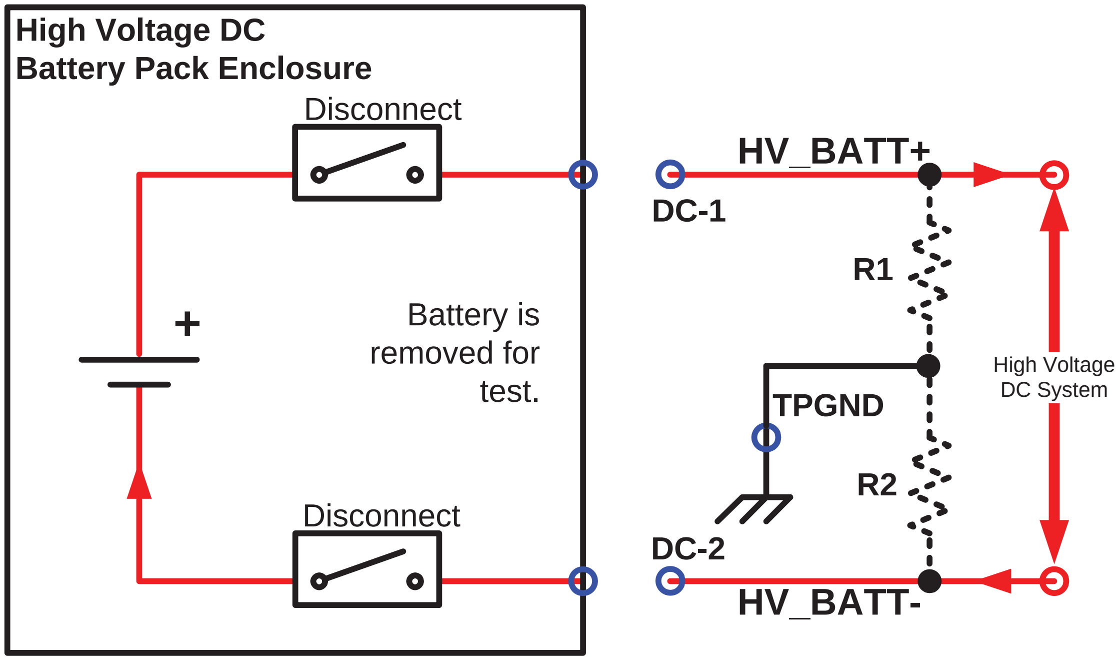

Figure 2. High-voltage battery schematic with marked test points DC-1 and DC-2

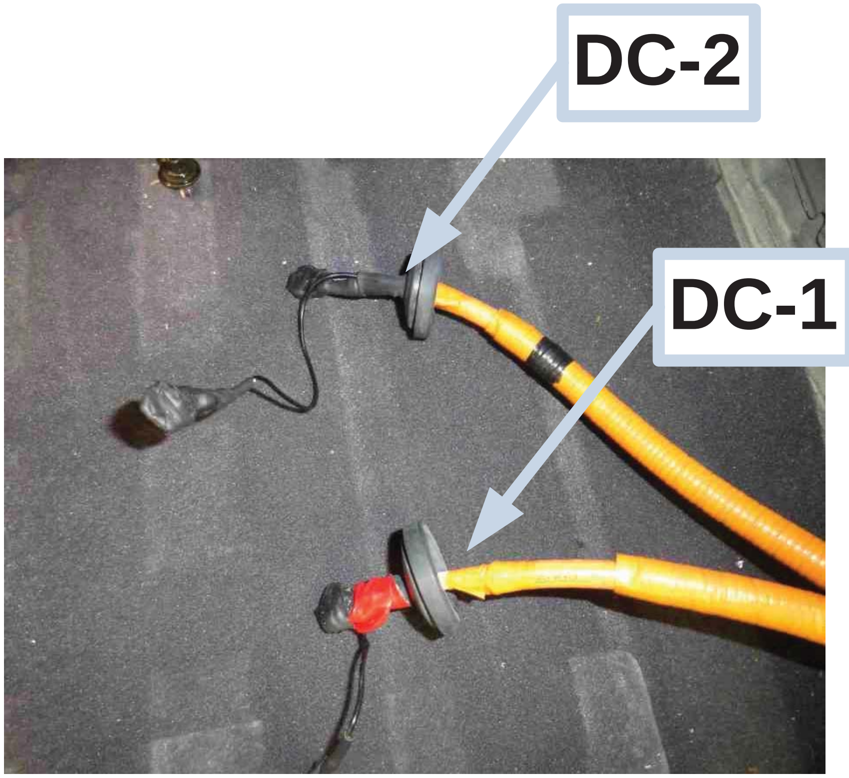

Figure 3. Battery isolation test points DC-1 and DC-2

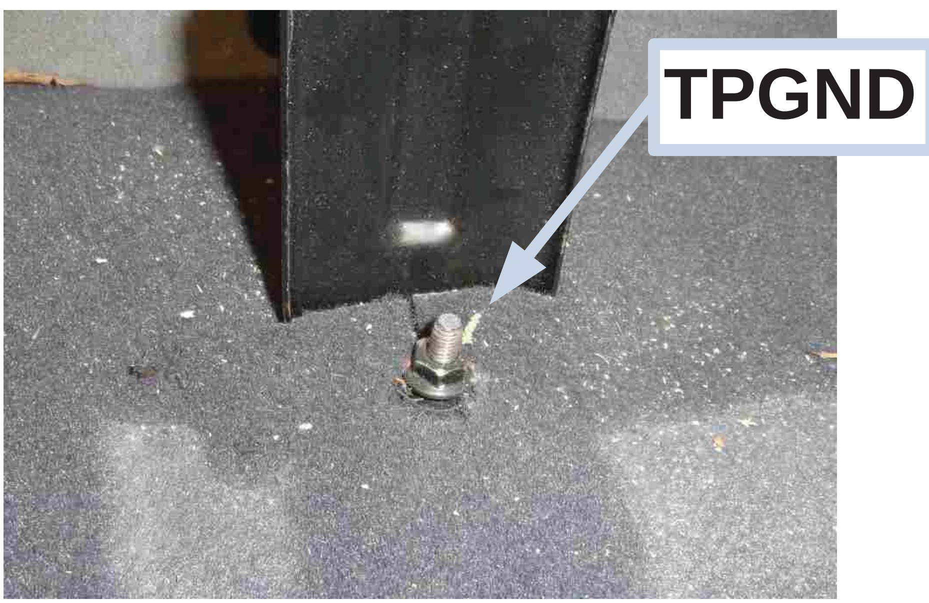

Figure 4. Electrical chassis access point in the trunk

The fuel cell and motor control unit (MCU) test points are found under the hood of each vehicle. The photograph in Figure 5 shows the location of both the MCU enclosure and the high-voltage power distribution (HVPD) enclosure. The DC and AC MCU test points can be accessed by removing the cover of the MCU enclosure. The fuel cell test points are made accessible by removing the cover of the HVPD enclosure. The electrical chassis connection point under the hood can be made at the bolt shown in Figure 6.

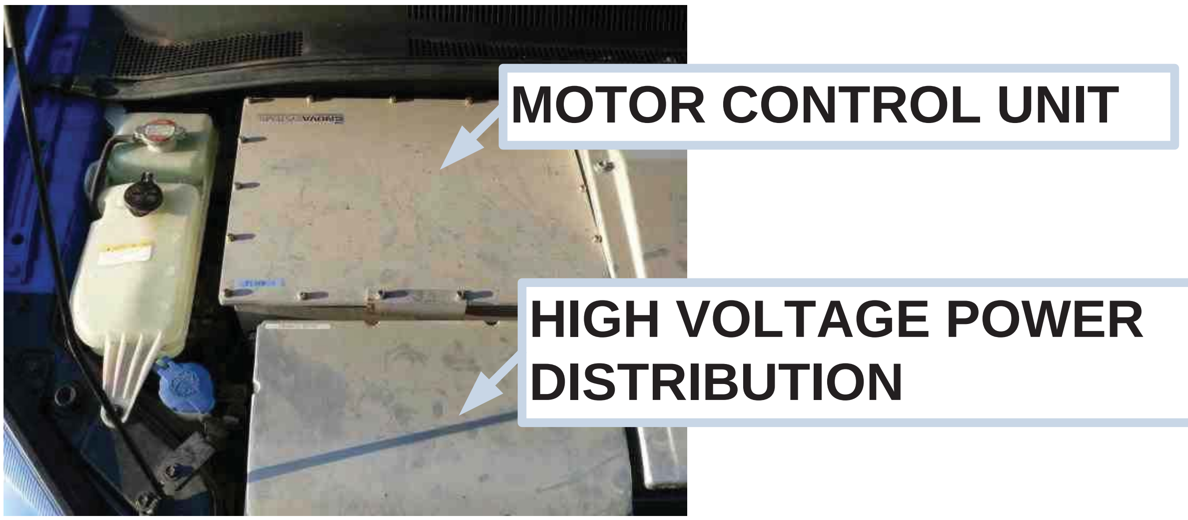

Figure 5. Motor control unit (MCU) and high-voltage power distribution (HVPD) enclosures

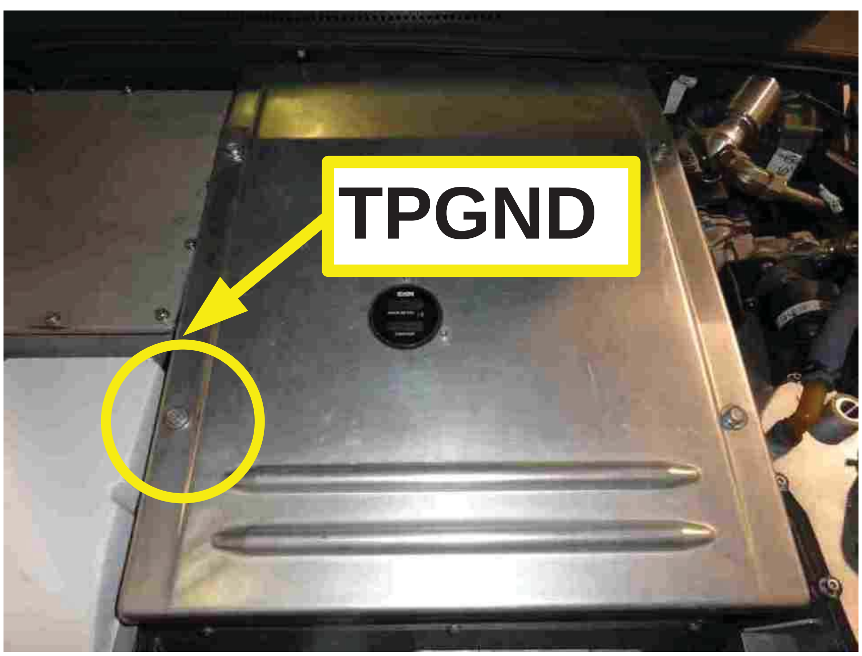

Figure 6. Electrical chassis test point under the hood

The hydrogen fuel cell is located under the hood. The hydrogen has been replaced with helium, so the fuel cell will be inactive and no voltage will be produced during the test. As shown in Figure 7, the test points available from the fuel cell are **DC-5** and **DC-6**. **DC-5** is connected to the positive high-voltage terminal, **HV_FC+**. **DC-6** is connected to the negative high-voltage terminal, **HV_FC-**, and **TPGND** is connected to the electrical chassis. The safety analyzer measures isolation resistances **R5** and **R6**, which are respectively the resistances between the positive and negative fuel cell terminals and the electrical chassis. Figure 7 shows that the fuel cell system employs automatic disconnects which are physically contained within the fuel cell enclosure. In accordance with FMVSS 305 S7.6.1, the isolation measurements will be made from the power train side of the automatic disconnects. This procedure does not determine whether proper disconnections occur, because the propulsion system will not be energized and the high-voltage source side of the automatic disconnect will not be available. Figure 8 is a photograph showing the fuel cell isolation test points, located in the HVPD compartment under the hood. The electrical chassis connection, **TPGND**, is to be made at the bolt shown in Figure 6 on page 8.

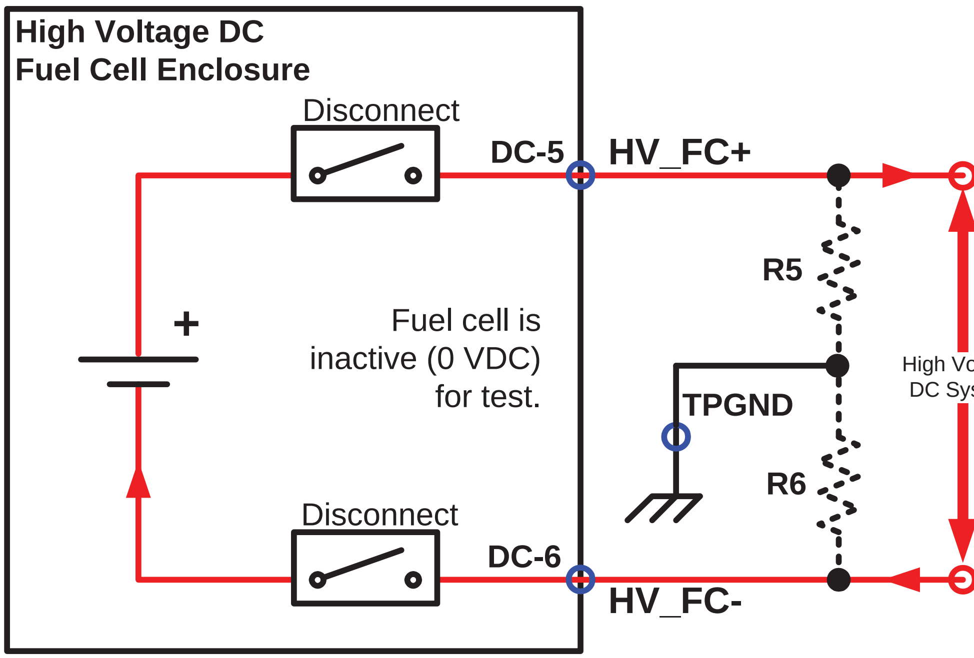

Figure 7. Fuel cell schematic with marked test points DC-5 and DC-6

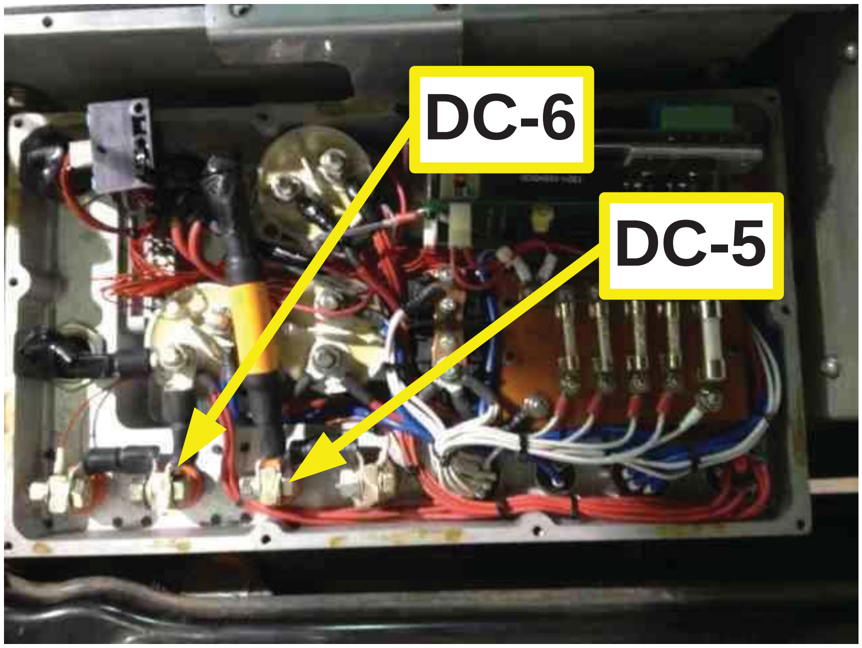

Figure 8. Fuel cell isolation test points DC-5 and DC-6 located in the HVPD compartment under the hood

The MCU enclosure is located under the hood in both vehicles. Figure 9 shows a simple schematic of the high-voltage lines that interface with the MCU. During operation involving energy transfer from the fuel cell and high-voltage battery to the traction motor, the MCU converts high-voltage DC to three-phase AC. The DC test points available at the MCU are **DC-3** and **DC-4**. **DC-3** is connected to the positive high-voltage terminal, **HV_MCU_DC+**. **DC-4** is connected to the negative high-voltage terminal, **HV_MCU_DC-**, and **TPGND** is connected to the electrical chassis. The safety analyzer will be used to measure isolation resistances **R3** and **R4**, which are respectively the resistances between the positive and negative high-voltage terminals and the electrical chassis. The AC test points available at the MCU are **AC-1**, **AC-2**, and **AC-3**, which represent the three phases of the traction motor's electrical drive. The isolation resistances between each line and the electrical chassis are represented in Figure 9 by **R7**, **R8**, and **R9**, and will be measured by performing a DC hipot test with the safety analyzer. The resulting leakage current measurement will provide sufficient information for analysis of insulation resistance. Figure 10 and Figure 11 are photographs showing the DC and AC MCU test points, made accessible by carefully displacing the insulation prior to testing, and located in the MCU compartment under the hood. The electrical chassis connection, **TPGND**, is to be made at the bolt shown in Figure 6 on page 8.

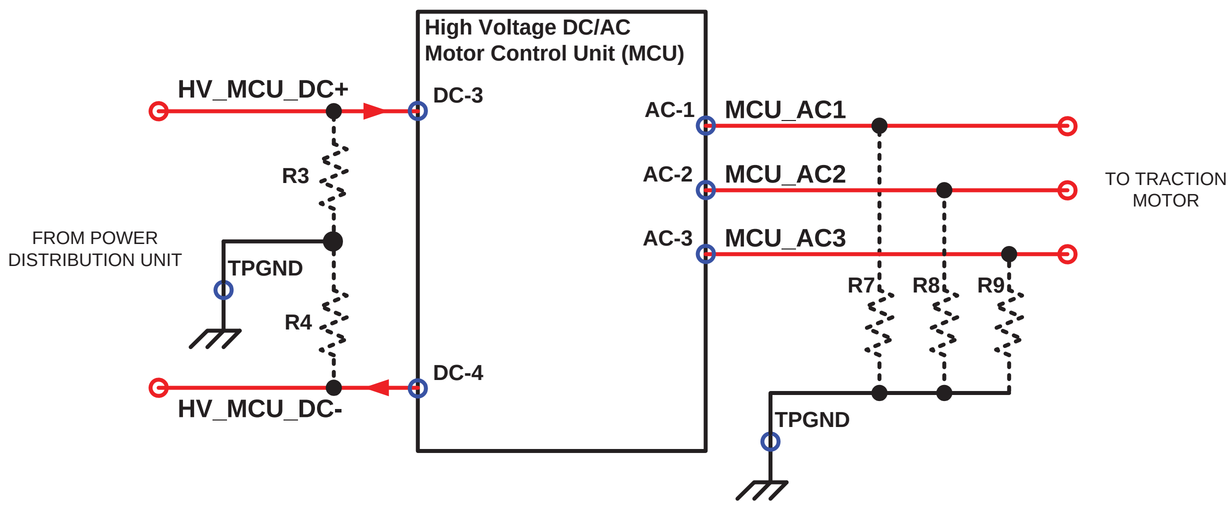

Figure 9. MCU schematic with marked test points: DC-3, DC-4, AC-1, AC-2, and AC-3

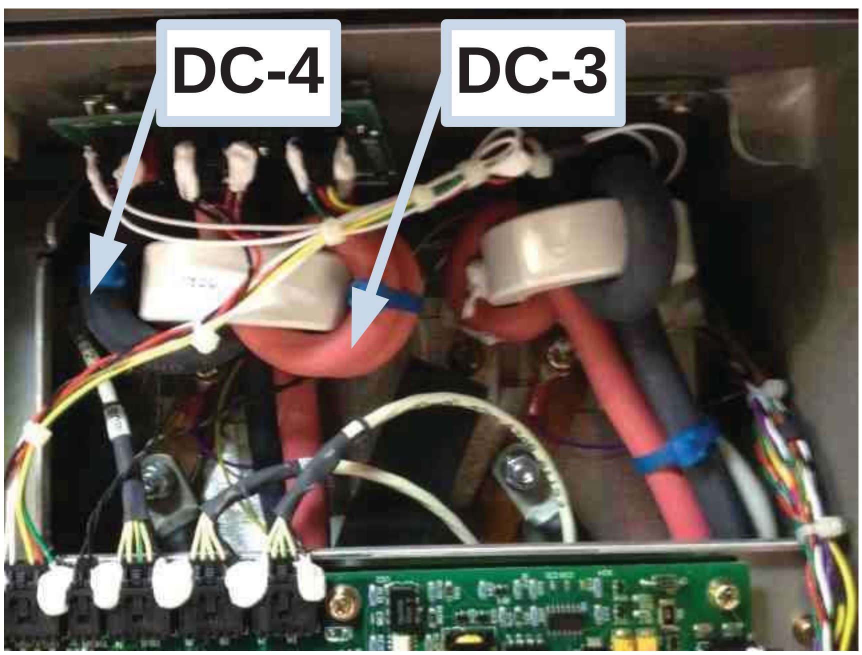

Figure 10. MCU test points DC-3 and DC-4 located in MCU compartment under hood

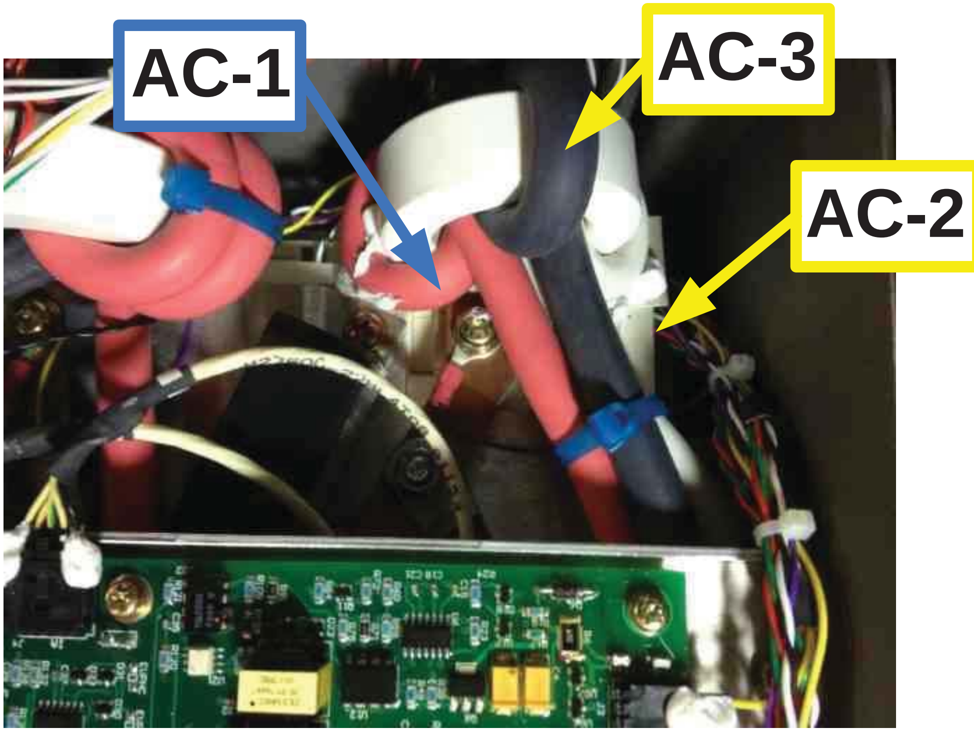

Figure 11. MCU test points AC-1, AC-2, and AC-3 located in MCU compartment under hood

Figure 12 shows the electrical overview of the test setup for one vehicle. The port terminals are referenced in the test procedure for connections with the safety analyzer and multimeter.

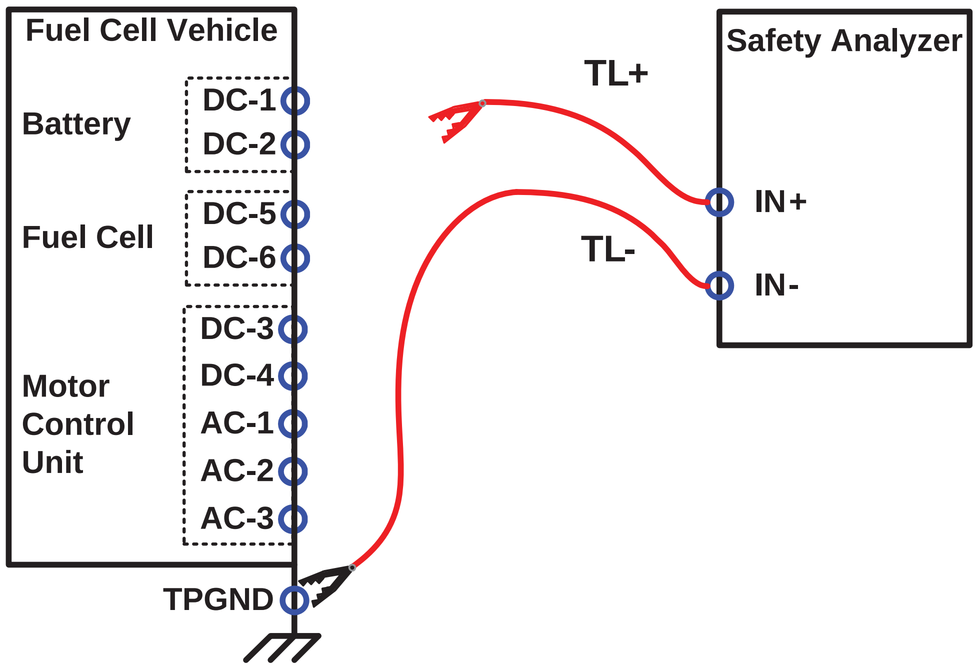

Figure 12. Overview of the test setup for one vehicle

7. Vehicle Preparation and Pre-Test Requirements

It is important to verify that each of the high-voltage sources is inactive for the safety analyzer measurements. For example, to render a hydrogen fuel cell high-voltage source inactive for testing, it is necessary to verify that all hydrogen has been purged from the vehicle and replaced with an approved inert substitute that prohibits the fuel cell from producing a voltage at its terminals. For a future compliance test of a production vehicle following FMVSS No. 305, this step would not be necessary because the procedure is for active high-voltage sources.

NOTE: Some systems can contain residual voltage, thus giving the illusion of an active voltage source. As a result, the tester must determine if the voltage measurements for V_{off} made while disconnected are indicative of a de-energized state and compatible with the selected measurement instrumentation. Failure to do so can result in poor accuracy or a failure to measure isolation.

Each test point shall be prepared prior to testing so that a secure physical connection can be made between the safety analyzer test lead and the test point. The test points shall be located such that they are accessible at the time of the test without requiring excessive effort from the test operator. Battery isolation test points will be made accessible at the time of the test by removing the electrical tape covering the ring terminals of the battery wire harness. MCU isolation test points will be made accessible by displacing 15 mm wide sections of insulation at non-adjacent points. Fuel cell isolation test points are already accessible inside the high-voltage power distribution compartment under the hood.

Several days before the tests, deionized (DI) water shall be added to each vehicle's fuel cell coolant reservoir, ensuring sufficient time for absorption to occur within the fuel cell membranes.

The safety analyzer leads must be zeroed before starting the tests in accordance with the manufacturer's instruction manual. The safety analyzer should be zeroed every time it is powered on and any time the test leads or test parameters are changed.

NOTE: The safety analyzer is a high-voltage device and has the potential to be hazardous to personnel and equipment if used inappropriately. Before using a safety analyzer on any equipment, it is important to verify that the critical components of the system can survive the safety analyzer test. When using a safety analyzer, always follow the best practices and safety guidelines contained within the operator's manual.

8. Test Execution – Pre-impact Electrical Isolation Measurement

For each fuel cell vehicle, the following measurements are required prior to the barrier impact test with no unspecified alterations of test setup between the steps.

A. Preparation

1. *Power-up* the safety analyzer and note the time. The safety analyzer should warm-up for at least 15 minutes before zeroing the device in step 8.
2. *Remove* the MCU and HVPD covers under the hood (shown on page 8, Figure 5), storing the fasteners for later use.
3. *Remove* the electrical tape from the battery test points, DC-1 and DC-2.
4. *Record* the ambient temperature.
5. Put on tested electrical safety gloves; ASTM D120 Class 00 (500 VAC, 750 VDC).

B. Battery Isolation

6. With a multimeter, *confirm* less than **1 volt DC** across

   a. **DC-1 (+)** and **DC-2 (-),**

   b. **DC-1 (+)** and **TPGND,**

   c. **DC-2 (-)** and **TPGND.**

   If voltage is present, consult an electrical engineer before proceeding.

7. Referring to the device instruction manual, *program* the safety analyzer to perform a DC hipot test with the following parameters.

a. Test voltage set to 160 volts DC

b. High current limit set to 20 mA DC

c. No low current limit

d. Arc current limit set to 20 mA DC

e. Test time set to 10 seconds

f. Ramp time set to 5 seconds

8. Once *15 minutes* has passed since the safety analyzer was powered-up, *zero* the safety analyzer, following the device manual's instructions for zeroing with DC hipot test leads.

9. *Connect* the safety analyzer leads as follows.

   a. **TL+** to **DC-1 (+)**

   b. **TL-** to **TPGND**

10. *Trigger* the safety analyzer to perform a DC hipot test, while *recording* the leakage current and test voltage readings.

11. After the test is complete, the readings are recorded, and no high voltage is present, *remove and reconnect* the safety analyzer leads as follows.

   a. **TL+** to **DC-2** (-)

   b. **TL-** to **TPGND**

12. *Trigger* the safety analyzer to perform a DC hipot test, while *recording* the leakage current and test voltage readings.

13. After the test is complete, the readings are recorded, and no high voltage is present, *remove* the safety analyzer leads and *re-wrap* the battery connection points with electrical tape.

C. Fuel Cell Isolation

14. With a multimeter, *confirm* less than 1 volt DC across
   a. **DC-5 (+)** and **DC-6 (-),**
   b. **DC-5 (+)** and **TPGND,**
   c. **DC-6 (-)** and **TPGND.**

   If voltage is present, consult an electrical engineer before proceeding.

15. Referring to the device instruction manual, *program* the safety analyzer to perform a DC hipot test with the following parameters.

    a. Test voltage set to 480 volts DC

    b. High current limit set to 20 mA DC

    c. No low current limit

    d. Arc current limit set to 20 mA DC

    e. Test time set to 20 seconds

    f. Ramp time set to 20 seconds

16. *Zero* the safety analyzer. *Connect* the safety analyzer leads as follows.

    a. **TL+** to **DC-5 (+)**

    b. **TL-** to **TPGND**

17. *Trigger* the safety analyzer to perform a DC hipot test, while *recording* the leakage current and test voltage readings.

18. After the test is complete, the readings are recorded, and no high voltage is present, *remove and reconnect* the safety analyzer leads as follows.

    a. **TL+** to **DC-6 (-)**

    b. **TL-** to **TPGND**

19. *Trigger* the safety analyzer to perform a DC hipot test, while *recording* the leakage current and test voltage readings.

D. Motor Control Unit DC Isolation

20. After the previous test is complete, the readings are recorded, and no high voltage is present, use a multimeter to *verify* less than 1 volt DC across

    a. **DC-3** (red) and **DC-4** (black),

    b. **DC-3** (red) and **TPGND,**

    c. **DC-4** (black) and **TPGND.**

If voltage is present, consult an electrical engineer before proceeding.

21. *Connect* the safety analyzer leads as follows.

a. **TL+** to **DC-3** (red)

b. **TL-** to **TPGND**

22. *Trigger* the safety analyzer to perform a DC hipot test, while *recording* the leakage current and test voltage readings.

23. After the test is complete, the readings are recorded, and no high voltage is present, *remove and reconnect* the safety analyzer leads as follows.

a. **TL+** to **DC-4** (black)

b. **TL-** to **TPGND**

24. *Trigger* the safety analyzer to perform a DC hipot test, while *recording* the leakage current and test voltage readings.

E. Motor Control Unit AC Isolation

25. After the test is complete, the readings are recorded, and no high voltage is present, use a multimeter to *verify* less than 1 volt DC across

a. **AC-1** (red) and **AC-2** (white)

b. **AC-1** (red) and **AC-3** (black)

c. **AC-2** (white) and **AC-3** (black)

d. **AC-1** (red) and **TPGND**

e. **AC-2** (white) and **TPGND**

f. **AC-3** (black) and **TPGND**

If voltage is present, consult an electrical engineer before proceeding.

26. *Connect* the safety analyzer leads as follows.

a. **TL+** to **AC-1** (red)

b. **TL-** to **TPGND**

27. *Trigger* the safety analyzer to perform a DC hipot test, while *recording* the leakage current and test voltage readings.

28. After the test is complete, the readings are recorded, and no high voltage is present, *remove and reconnect* the safety analyzer leads as follows.

a. **TL+** to **AC-2** (white)

b. **TL-** to **TPGND**

29. *Trigger* the safety analyzer to perform a DC hipot test, while *recording* the leakage current and test voltage readings.

30. After the test is complete, the readings are recorded, and no high voltage is present, *remove and reconnect* the safety analyzer leads as follows.

a. **TL+** to **AC-3** (black)

b. **TL-** to **TPGND**

31. *Trigger* the safety analyzer to perform a DC hipot test, while *recording* the leakage current and test voltage readings.

F. Conclusion

32. After the test is complete, the readings are recorded, and no high voltage is present, *remove* all test leads and *power-down* the safety analyzer.

33. *Remove* electrical safety gloves. *Reinstall* the MCU and HVPD covers, if not damaged from the crash.

9. Test Execution – Post-impact Electrical Isolation Measurement

Following the barrier impact tests, steps 1 through 33 of Section 8 are to be repeated for each vehicle to determine the post-impact electrical isolation.

10. Evaluation Criteria

This is a research test. There are no acceptance criteria because it is not a compliance test. However, the acceptance criteria established in FMVSS No. 305 S5.3 [1] and described in the background section will be a point of reference in the discussion of the research results.

11. References

[1] *Electric-Powered Vehicles: Electrolyte Spillage and Electrical Shock Prevention,* Federal Motor Vehicle Safety Standard No. 305, July 29, 2011.

[2] Battelle Memorial Institute, "Electrical Isolation Test Procedure Development and Verification. Prepared for the National Highway Traffic Safety Administration Office of Applied Vehicle Safety Research on Contract No. DTNH22-08-D-00080, Task Order 4," March 24, 2010.

[3] *Fuel system integrity of compressed natural gas vehicles,* Federal Motor Vehicle Safety Standard No. 303, November 24, 1995.

[4] *Side Impact Protection,* Federal Motor Vehicle Safety Standard No. 214, January 06, 2012.

[5] Battelle Memorial Institute, "Crash Test and Safety Plan, Crashworthiness Research of Hydrogen Fuel Cell Vehicles," 2012.

[6] *Laboratory Test Procedure for FMVSS 305, Electric-Powered Vehicles: Electrolyte Spillage and Electrical Shock Protection*, FMVSS Test Procedure TP-305-01, September 11, 2008.

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