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Hydrogen Fuel Cell Vehicle Fuel System Integrity Research

Electrical Isolation Test Procedure Development and Verification

DISCLAIMER

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EXECUTIVE SUMMARY

The Federal Motor Vehicle Safety Standards (FMVSS) establish minimum levels for vehicle safety, and manufacturers of motor vehicle and equipment items must comply with these standards. The National Highway Traffic Safety Administration (NHTSA) contracted Battelle to develop a procedure for testing electrical isolation on hydrogen fuel cell vehicles (HFCVs) when crash testing without hydrogen. FMVSS 305, *Electric Powered Vehicles: Electrolyte Spillage and Electrical Shock Protection,* requires electrical isolation as the basis for defining electrical safety and for establishing a criterion for the prevention of electrical shock. Enhancement is required to address electrical safety of hydrogen vehicles, particularly when testing without hydrogen onboard the vehicle.

The current electrical isolation test procedure described in FMVSS TP-305-01, *Laboratory Test Procedure for Electric Powered Vehicles: Electrolyte Spillage and Electrical Shock Protection*, uses an active onboard high-voltage power system to determine the electrical safety of the vehicle. FMVSS TP-305-01 is written specifically to require full engagement of the test vehicle’s propulsion system before the crash test. Due to safety concerns, however, some automobile manufacturers and international regulatory bodies are proposing to conduct crash testing of compressed hydrogen vehicles using an inert gas substitute, such as helium. Unlike electric and hybrid electric vehicles, the absence of hydrogen in a hydrogen-fueled vehicle renders the fuel cell inactive, prohibiting the generation of high voltage and preventing the propulsion system from being fully engaged. Consequently, another method for verifying electrical isolation between the high-voltage source(s) and potential human contact points is needed for hydrogen-fueled vehicles if the propulsion system is not engaged fully.

Task Order 4 developed and verified an alternative electrical isolation test procedure for HFCVs with an inactive fuel cell using a megohmmeter or “Megger™,” a piece of test equipment that supplies high voltage and measures the resulting leakage current to the vehicles’ chassis as necessary to verify the isolation. A systematic approach was used to develop the procedure and was initiated with a test requirements review. The review examined the latest standards and literature from industry and regulatory bodies to solidify the requirements for the final test procedure. In addition to current documentation, Battelle received technical insight and guidance from General Motors Corporation (GMC) and Ford Motor Company. The information was compiled and evaluated on the applicability to electrical safety of postcrash HFCV with an inert gas. The test procedure was written to test electrical isolation of an inactive high-voltage source using a megohmmeter. The test instrumentation was selected based on current HFCV power systems and the proposed acceptance criteria. A market survey to find test instrumentation was performed, and the Quad Tech 1855 was selected as a suitable instrument for this effort.

After the proposed acceptance criteria and instrumentation were selected, the detailed procedure steps were outlined. During this phase of the program, the procedure was refined after several trips to the original equipment manufacturers (OEMs). During the OEM visits, the draft procedures were evaluated on several HFCVs for possible test point locations, test sequencing, and safety precautions. These dry runs were essential in order to finalize the test procedure and instrumentation. The final dry-run or procedure verification was performed on a hydrogen fueled Ford Focus and a Chevrolet Equinox at their respective development sites in Michigan. The successful procedure verification was performed to refine further the procedure and to confirm that the detailed steps and instrumentation can accurately test electrical isolation on an inactive fuel cell. Since the HFCVs were not subjected to an actual crash test, a resistor was inserted between the fuel cell power terminals and the chassis to simulate an electrical isolation failure.

Several limitations on the capabilities of the megohmmeter were identified during the development of the procedure. The megohmmeter is an acceptable tool for measuring isolation in accordance with the test procedure; however, the QuadTech 1885 and other commercial available megohmmeters have unique restrictions. The Quadtech 1855 cannot measure isolation accurately between a power source and the chassis if the chassis has a conductive connection to earth ground. Therefore, other types of electrical safety test equipment were evaluated and tested during Task Order 4.

The successful completion of Task Order 4 yielded a verified electrical isolation test procedure utilizing a megohmmeter for testing a HFCV with an inert gas and inactive fuel cell. In addition to this procedure, some additional research activities evaluated the effects of temperature and age on fuel cell coolant and the potential for environmental conditions to alter isolation measurements.

PROJECT REPORT SCOPE

The purpose of the project report is to document the manner in which Battelle applied its subject matter expertise, experience, and facilities to complete Task Order 4, *Electrical Isolation Test Procedure Development and Verification* under the NHTSA Hydrogen Vehicle Fuel System Safety Program. The report describes the discrete steps and results that led to the development and verification of the test procedure and all supporting research.

1.0 INTRODUCTION

Task Order 4 developed a test procedure for conducting postcrash electrical isolation verification for fuel cell vehicles in the absence of onboard hydrogen. Automobile manufacturers are proposing to conduct crash testing of HFCV vehicles using an inert gas substitute during crash testing; this procedure will render the fuel cell inactive. The inactive power source prevents the propulsion system from being fully engaged and from using the current FMVSS Test Procedure (TP)-305-01. Therefore, another method for verifying electrical safety after a crash test, between the high-voltage source(s) and potential human contact points, is needed for hydrogen-fueled vehicles if the propulsion system is not engaged fully. Task Order 4 delivered a verified alternative electrical isolation test procedure for HFCVs with an inactive fuel cell using a megohmmeter or "Megger™," a piece of test equipment that supplies high voltage and measures the resultant leakage current to the vehicles' chassis as necessary to verify the isolation.

The electrical isolation test procedure provides detailed instructions for the setup and step-by-step execution to verify electrical safety. The procedure includes precrash setup and postcrash evaluation; focuses on obtaining test data that can be used to determine if a specific hydrogen fuel cell vehicle meets the electrical isolation performance requirements; presents a uniform testing and data recording format; and suggests requirements for the use of specific equipment for this application. The steps in Figure 1 were executed to develop the final test procedure.

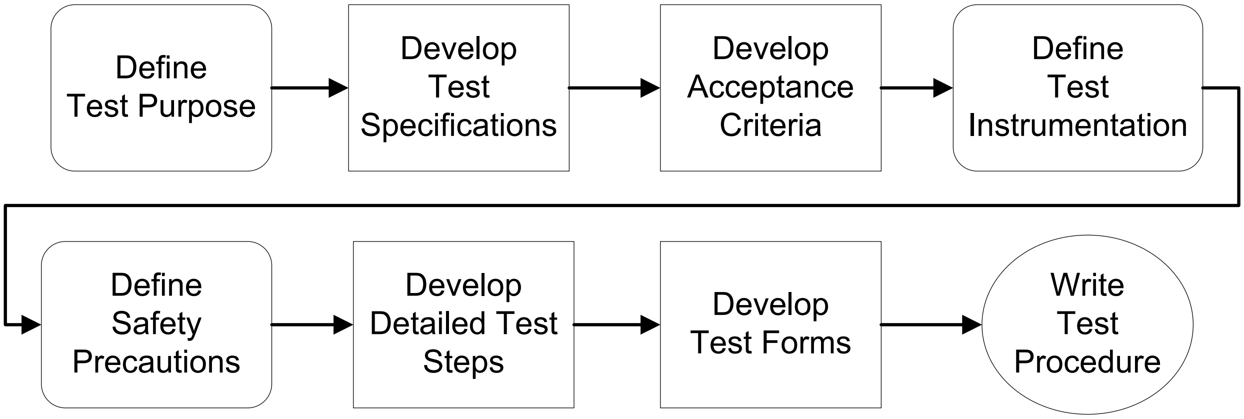

Figure 1. Test procedure development diagram.

The final step in the procedure development is verification. The final draft procedure was performed on an actual HFCV; the results were recorded, capturing a simulated isolation failure. GMC and Ford Motor Company allowed access to a HFCV and provided technical support to execute the megohmmeter measurements.

2.0 TEST PROCEDURE DEVELOPMENT

This section details the development of a test procedure for verifying electrical isolation on inactive fuel cell systems of HFCVs. The development of the test procedure starts with the purpose of developing the procedure. Test requirements are presented next in order to show that this procedure fits within the framework of existing standards and regulations. Proposed acceptance criteria are given, including the development of these criteria based on the instrumentation requirements. Sections on test instrumentation, detailed steps, and data sheets subsequently are included to explain the rationale behind the instruments and the steps used in the procedure. Finally, the compilation of this data into a final procedure is presented.

2.1 Purpose Statement

The purpose of developing this test procedure is to fill a gap in current HFCV test standards and regulations. This gap comes from the desire of automobile manufacturers and test laboratories to crash test HFCVs without hydrogen onboard, primarily due to safety concerns. Instead, the automobile manufacturers and test laboratories prefer to use an inert gas, such as helium, to reduce potential explosive hazards. Currently, the standards and regulations that apply to HFCVs do not address the issue of testing for electrical isolation if the fuel cell is inactive, as is the case with no hydrogen onboard. As shown in the next section of this report, all of the standards and regulations that give procedures for measuring electrical isolation after a crash assume that a power source is present, i.e., with hydrogen in the fuel cell; thus, the aforementioned gap.

Therefore, in order for crash tests to be performed on HFCVs without hydrogen onboard, a procedure must be written to provide an electrical isolation test method. This procedure also must address the criteria that are acceptable for a passing condition. In order to develop this procedure, it is necessary to examine existing standards and regulations in order to obtain guidance for writing the new test procedure and to ensure that the new test details do not violate existing standards and regulations. These issues as well as the documents reviewed are addressed in the next section of this report. The end goal of this report is a test procedure that is acceptable as an expansion or new regulation to the current FMVSS 305.

2.2 Standards and Regulations Review

This section explores the applicability of current standards and regulations to HFCVs without hydrogen onboard. In order to do this, various existing standards and regulations are examined. Section 2.2.1 briefly summarizes the results. Section 2.2.2 presents a more detailed examination with the content of each document broken down into three parts: overview, applicability to HFCVs, and application to HFCVs without hydrogen onboard.

2.2.1 Summary of Results

The following table lists the documents that were identified and found to provide information relevant to fuel cell electrical isolation safety and testing. The documents are listed in the order discussed in Sections 4.2.1 and 4.2.2.

Table 1. Literature used for HFCV test procedure development.

ISO 6469-3: 2001	Electric Road Vehicles – Safety Specifications – Part 3: Protection of Persons against Electrical Hazards
IEC TS 60479-1: 2005-07	Effects of Current on Human Beings and Livestock – Part 1: General Aspects
SAE J2344 June 1998	Guidelines for Electrical Vehicle Safety
SAE J1766 April 2005	Recommended Practice for Electric and Hybrid Electric Vehicle Battery Systems Crash Integrity Testing
ISO 23273-3 2006	Fuel Cell Road Vehicles – Safety Specifications – Part 3: Protection of Persons against Electric Shock
FMVSS 305: Sept 11, 2007 / NHTSA-2007-28517 Notice of Proposed Rulemaking (NPRM)	Electric-Powered Vehicles: Electrolyte Spillage and Electrical Shock Protection
TP-305-01: Sept 11, 2008	Laboratory Test Procedure for FMVSS 305, Electric-Powered Vehicles: Electrolyte Spillage and Electrical Shock Protection
SAE J2578 Jan 2009	Recommended Practice for General Fuel Cell Vehicle Safety

International Standards Organization (ISO), International Electrotechnical Commission (IEC), Society of Automotive Engineers (SAE)

A summary of the results that apply to electrical isolation of HFCVs without hydrogen onboard and electrical isolation test procedures are provided in this section. The first two documents, ISO 6469-3:2001 and IEC TS 60479-1:2005-07, provide the guidance for the lower limit for electrical isolation at which a system can be considered safe for human beings.

ISO 6469-3:2001

ISO 6469-3:2001 establishes that persons should be protected by a minimum insulation resistance of 100 ohms/volt in vehicles with direct current (DC) voltages greater than 60 volts but less than or equal to 1500 volts.

IEC TS 60479-1:2005-07

IEC TS 60479-1:2005-07 provides guidance on the effects of electrical current passing through a human body. This document specifies the relationship between current, voltage, and body impedence as a function of time.

The following documents provide the information that assisted in the test procedure development. The documents show that standards progress from electric vehicles (EVs) to hybrid electric vehicles (HEVs) and fuel cell vehicles (FCVs). Except for one issue, most documents converge. That issue is discussed later in this section.

SAE J2344 June 1998

SAE J2344 June 1998 forms the basis for a later referenced document that is crucial to this report, SAE J2578 January 2009. SAE J2344 June 1998 states that a value of greater than or equal to 500 ohms/volt can be considered electrically isolated. The document also states that a means should be provided to detect degraded electrical isolation and that electrical isolation should be monitored continuously. Although no method is given for performing either task, the groundwork is laid for future documents to expand on these concepts, which is underway.

SAE J1766 April 2005

SAE J1766 April 2005 is one of the primary documents used in this report because of the amount of pertinent information presented therein. In particular, the document states:

- Voltage levels greater than 60 volts DC are defined as high voltage.
- A vehicle can satisfy the electrical isolation requirements of SAE J1766 even if no hydrogen is onboard.
- Passing criteria for electrical isolation are at least 100 ohms/volt for a DC high-voltage bus that is not connected to an external power source and is monitored continuously during operation.
- Fuel cells are expected to maintain an electrical isolation of at least 125 ohms/volt with aged coolant.

The document also presents a procedure for measuring electrical isolation although the procedure is not applicable to the case of no hydrogen onboard.

ISO 23273-3 2006

ISO 23273-3 2006 states that the isolation resistance must be at least 100 ohms/volt or 10 mA for each class B circuit. The document also lists points to be taken into account if measuring electrical isolation. This list includes disconnecting some circuits, measuring all parts of the system, disconnecting cables, and leaving various piping connected for the measurements. All of these points are valuable inputs for the test procedure.

FMVSS 305: September 11, 2007 / NHTSA-2007-28517 NPRM

FMVSS 305: September 11, 2007 / NHTSA-2007-28517 NPRM is geared to insuring public safety with respect to EVs, HEVs, and FCVs. As such, the information in this proposed regulation is crucial to this report. This proposal states:

- Electrical isolation is the electrical resistance between the vehicle high-voltage source and any vehicle conductive structure.
- A high-voltage source is an electrical power-generating device or an energy storage device that produced levels equal to or greater than 60 volts DC.
- At least 125 ohms/volt isolation is required for DC high-voltage systems to pass the electrical isolation test after a crash.

- At least 5 seconds should pass after the crash before an electrical isolation measurement is made.
- Sections S7.1 and S7.2, pertaining to energy storage device state and vehicle conditions, respectively, must be satisfied.

An electrical isolation test procedure is presented in Section S7.6, but does not apply to an HFCV without hydrogen onboard. However, the test procedure does provide valuable information for this report and the development of a test procedure.

TP 305-01: September 11, 2008

TP 305-01: September 11, 2008 provides the test procedure for FMVSS 305, but does not apply directly to HFCVs without hydrogen onboard. However, TP 305-01: September 11, 2008 does provide both precrash and postcrash test procedures that are useful templates for developing the test procedure discussed in this report.

SAE J2578 January 2009

SAE J2578 January 2009 provides considerable pertinent information for the test procedure development and establishes that:

- FMVSS 305 must be consulted.
- Electrical disconnects will actuate in a crash and can be used for ensuring electrical isolation per SAE J1766.
- The electrical system can be tested without fuel onboard.
- Isolation tests should be conducted through a range of environmental conditions.
- Isolation measurements should be conducted downstream of an enclosed isolation device and on both sides of an external isolation device.
- Any onboard energy storage device can be disconnected for the test.
- Fuel cell system can be shut down for the test.
- All electrical circuits that are not under test or that can be damaged can be removed from the circuit.
- Test voltage can be an externally applied DC voltage at least equal to the maximum open circuit voltage of the fuel cell.

This single document provides the greatest amount of material for this report due the depth of the information presented.

As mentioned earlier, the major documents regarding electrical isolation, FMVSS 305 and SAE J2578/SAE J1766, have not converged on an important point, the acceptable value for electrical isolation on the HFCV DC bus. FMVSS 305 lists 125 ohms/volt; SAE J2578/J1766 indicates 100 ohms/volt. Regardless, for the purpose of the test procedure presented in this report, a value of 100 ohms/volt is used for high-voltage DC sources that require a greater current output capability for the test instrumentation. This value will guarantee that the instrumentation will measure successfully the inactive high voltage power source to either the 100 or 125 ohms/volt limit.

By combining all of the above information, a test procedure can be generated for electrical isolation and does not violate the existing standards and regulations. In particular, the existing documents specifically state that it is permissible to test for electrical isolation without hydrogen onboard, but do not provide a procedure for doing so. That gap is filled by the proposed test procedure.

Section 2.2.2 presents an overview for each of the Standards and Regulations discussed in this section as well as a breakdown of their applicability to HFCVs and, in particular, their application to HFCVs without hydrogen onboard.

2.2.2 Standards and Regulations

2.2.2.1 ISO 6469-3:2001 Electric Road Vehicles – Safety Specifications Part 3: Protection of Persons against Electric Hazards

2.2.2.1.1 Overview

As stated in the scope of ISO 6469-3:2001, "This part of ISO 6469 specifies requirements for the protection of persons against electrical hazards on exclusively battery-powered electric road vehicles (passenger cars and light commercial vehicles) when the vehicles are not connected to an external power supply. It is applicable only if the maximum working voltage of an on-board electrical circuit is lower than 1000 volts AC, or 1500 volts DC or lower…" ISO 6469-3:2001 specifies voltage classes of electric circuits, protection against electrical hazards, and protection against water effects. Appendices specify the hose and spray nozzles for various tests.

2.2.2.1.2 Applicability to HFCVs

Even though ISO 6469-3:2001 concerns battery-powered electric road vehicles, many of the safety aspects also apply to HFCVs. In particular, Section 5.2 states that, "Persons shall be protected against any electrical hazard resulting from direct contact to live parts of any voltage class B electrical circuits." The specification defines, in Section 5.1, voltage class B as a DC voltage of greater than 60 volts, but less than or equal to 1500 volts and an AC voltage of greater than 25 volts, but less than or equal to 1000 volts. In Section 6.2.3, the specification also provides that the minimum insulation resistance should be 100 ohms/volt.

2.2.2.1.3 Application to HFCVs without Hydrogen Onboard

The primary contribution of ISO 6469-3:2001 to this report is its confirmation of the subsequently discussed SAE J1766 Apr 2005 Recommended Practice. The portion of the ISO specification that is used as reference is the 100 ohms/volt value.

2.2.2.2 IEC TS 60479-1:2005-07 Effects of Current on Human Beings and Livestock Part 1: General Aspects

2.2.2.2.1 Overview

As stated in the introduction of IEC TS 60479-1:2005-07, "This technical specification provides basic guidance on the effects of shock current on human beings and livestock, for use in the establishment of electrical safety requirements. This technical specification applies to the threshold of ventricular fibrillation which is the main cause of deaths by electric current." This document establishes an electric current safety baseline. In fact, the major sections of this document, Chapter 4 – Electrical Impedance of the Human Body, Chapter 5 – Effects of Sinusoidal Alternating Current (AC) in the Range of 15 Hz to 100 Hz, and Chapter 6 – Effects of Direct Current, seek to establish this baseline for a variety of scenarios.

2.2.2.2.2 Applicability to HFCVs

IEC TS 60479-1:2005-07 applies to electrical safety in HFCVs because of the combination of human beings and a high-voltage DC electrical bus being present in the same vehicle. In particular, Figure 2 from IEC TS 60479-1:2005-07 shows the location of the time/current zones in a typical human body. These zones relate to the expected physiological effects in a human being for combinations of time and current. As quoted from IEC TS 60479-1:2005-07:

DC-1: Slight pricking sensation possible when making, breaking, or rapidly altering current flow;

DC-2: Involuntary muscular contractions likely especially when making, breaking, or rapidly altering current flow, but usually no harmful electrical physiological effects;

DC-3: Strong involuntary muscular reactions and reversible disturbances of formation and conduction of impulses in the heart can occur, increasing with current magnitude and time. Usually no organic damage to be expected; and

DC-4: Patho-physiological effects can occur such as cardiac arrest, breathing arrest, and burns or other cellular damage. Probability of ventricular fibrillation increasing with current magnitude and time.

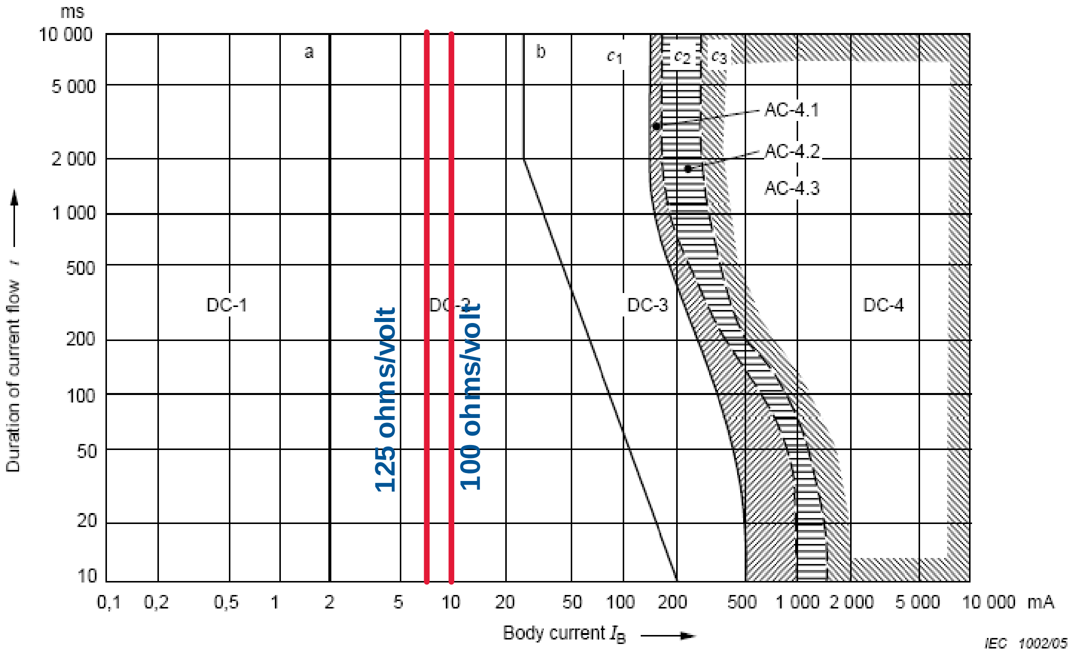

Figure 2. Conventional time/current zones of effects of DC currents on persons for a longitudinal upward current path (IEC TS 60479-1: 2005-07) with 100 ohms/volt and 125 ohms/volt references added.

Standards reviewed in this research identify 100 and 125 ohms/volt isolation limits. These limits have been drawn on Figure 2 for reference.

2.2.2.2.3 Application to HFCVs without Hydrogen Onboard

Because the electrical current safety baselines established by the specification are the same if hydrogen is onboard or not, the portion of the specification listed above also applies to HFCVs without hydrogen onboard. To summarize, the portion of IEC TS 60479-1:2005-07 that is relevant to this report is that both the 100 ohms/volt and 125 ohms/volt lines are expected to cause no harmful electrical physiological effects on human beings. Thus, any electrical isolation reading of 100 ohms/volt or greater in a DC system can be expected safe for humans.

2.2.2.3 SAE J2344 June 1998 Guidelines for Electric Vehicle Safety

2.2.2.3.1 Overview

The purpose of this document was to provide a starting point for developing and/or modifying Standards and Regulations to incorporate information relating to, at the time, new EVs. The foreword of SAE J2344 June 1998 states, “With the onset of new electric propulsion and charging systems…new safety design parameters will need to be provided to vehicle developers. This SAE Information Report is a first attempt to formalize a list of important safety items for vehicle developers. Automotive manufacturers, insurance companies, the repair industry, and first responders groups will need to work together to update this document as more data becomes available.”

The document covers a wide range of topics including:

- Electric Vehicle Crashworthiness
- Single Point Failure
- Electrical Safety
- Fault Monitoring
- Hazardous Liquid Leakage
- Hazardous Gas Leakage
- Vehicle Immersion
- Electromagnetic Compatibility (EMC) and Electrical Transient
- Safety Labeling.

However, this document has been supplanted by newer, more complete standards and regulations such as SAE J2578 January 2009. In spite of this fact, several items of interest in this report are covered in the next section.

2.2.2.3.2 Applicability to HFCVs

One item of SAE J2344 June 1998 that is of interest to HFCVs is the reference to SAE J1766 in Section 4.1, "Crashworthiness guidelines for EVs are contained in SAE J1766." This statement is of interest because SAE J1766, albeit updated since 1998, still is used as a primary reference for this report and is discussed later. Many other elements of this report have been expanded on and are included in SAE J2578, also a primary reference for this report.

2.2.2.3.3 Application to HFCVs without Hydrogen Onboard

Again, the primary contribution of SAE J2344 June 1998 to this report is as the basis for one of the primary reference documents used, SAE J2578 January 2009. Three areas in particular are mentioned in SAE J2344 June 1998 and apply to this report:

1. A definition of electrical isolation is presented in Section 3.7 as, "…the electrical resistance between the vehicle traction battery high-voltage system and any vehicle conductive structure. A value greater than or equal to 500 ohms/volt at the maximum battery pack working voltage…isolation is measured from both the positive and negative battery terminals relative to the vehicle conductive structure."
2. Section 4.3, Electric Safety, states that, "Under normal operating conditions, adequate electrical isolation is achieved through physical separation means such as the use of insulated wire, enclosures, or other barriers to direct contact. There are conditions or events that can occur outside normal operation that can cause this protection to be degraded. Some means should be provided to detect degraded isolation or loss of separation…" This statement, although not presenting a solution to the problem, declares that a method for detecting degraded electrical isolation is necessary.
3. In Section 4.3.1.1.2, the document points out that, "It is desirable to monitor the degree of electrical isolation between traction battery voltage and vehicle conducting structures." This statement is the basis for continuous monitoring of electrical isolation.

2.2.2.4 SAE J1766 April 2005 Recommended Practice for Electric and Hybrid Electric Vehicle Battery Systems Crash Integrity Testing

2.2.2.4.1 Overview

As stated in the foreword of SAE J1766 April 2005, "This SAE Recommended Practice describes methods for evaluating the vehicle high-voltage system performance when subjected to various FMVSS crash test procedures. It addresses battery retention, electrical isolation, and electrolyte spillage. It is intended to provide electric, fuel cell, and hybrid vehicle designers with recommended tests and performance criteria relating to electric, fuel cell, and hybrid vehicles."

The electrical conditions under which this Recommended Practice applies are stated in the scope section of SAE J1766 April 2005: "This SAE Recommended Practice is applicable to all Electric, Fuel Cell, and Hybrid vehicle designs that are comprised of at least one voltage bus with a nominal voltage greater than or equal to 60 volts DC or 30 volts AC." The purpose of SAE J1766 April 2005 defines high voltage in Section 3.4.4 as "…voltage levels greater than 30 volts AC or 60 volts DC."

The physical vehicle conditions under which this Recommended Practice applies are stated in the scope section of SAE J1766 April 2005: "The vehicles covered in this document are electric, fuel cell, and hybrid vehicles with a gross vehicle weight of 4536 kg (10,000 lb) or less and whose speed is attainable in 1.6 km on a paved level surface is more than 40 km/h."

Section 4 of SAE J1766 April 2005 pertains to the actual technical requirements for the Recommended Practice. In particular, Sections 4.1 through 4.3 deal with the preparation for, aftermath of, and the actual crash test. Section 4.3 states that "Electric, fuel cell, and hybrid vehicles shall meet the performance criteria established in Section 4.4 and tested to the following crash procedures…" Section 4.4 details the performance criteria that the vehicle must meet in order to pass the test. Section 4.4.1 is concerned with electrolyte spillage after the crash, including identification of the spillage as well as the cases of spillage inside and outside the passenger compartment. Section 4.4.2 deals with energy storage system retention after the crash. Section 4.4.3 pertains to electrical limits after the crash, including voltage, isolation, and energy. A statement in the Results portion at the end of SAE J1766 Apr 2005 reads that "A vehicle meets the requirements of this recommended practice if it satisfies one or more of the voltage, electrical isolation, or energy provisions described above."

2.2.2.4.2 Applicability to HFCVs

SAE J1766 April 2005 is directly applicable to HFCVs. However, hydrogen leakage after a crash is not covered in this Recommended Practice and could be added under Section 4.4 as an additional performance criteria with electrolyte spillage, energy storage system retention, and electrical limits. SAE J2578 January 2009 addresses this issue as well as the replacement of hydrogen with helium for crash tests.

2.2.2.4.3 Application to HFCVs without Hydrogen Onboard

For the purposes of this report, Sections 4.1 through 4.3 of SAE J1766 April 2005 deal with the preparation for, aftermath of, and the actual crash test itself and are not applicable. Also, Sections 4.4.1 and 4.4.2 concerning electrolyte spillage and energy storage system retention do not apply directly to this report. Likewise, certain portions of Section 4.4.3 pertaining to electrical limits do not apply since no hydrogen is onboard the crash vehicle, i.e., specifically, Section 4.4.3.1 dealing with voltage and Section 4.4.3.3 pertaining to energy. However, Section 4.4.3.2 relates to isolation after the crash and provides information that proved useful in developing the test procedure presented in this report.

The overview section of SAE J1766 April 2005 stated that “A vehicle meets the requirements of this recommended practice if it satisfies one or more of the voltage, electrical isolation, or energy provisions described above.” Therefore, developing a test procedure to meet Section 4.4.3.2 isolation will satisfy this Recommended Practice in spite of no hydrogen onboard. Appendix A of SAE J1766 April 2005 gives an example procedure for measuring isolation; however, this procedure assumes the presence of a power generating device to drive the high voltage which will not be the case if no hydrogen is onboard.

Section 4.4.3.2 states “The isolation between any high-voltage bus and the vehicle conducting structure after the crash shall meet one of the following criteria, as applicable. It is understood that during a crash, electrical isolation can be lost momentarily provided that it is subsequently restored.” Sections 4.4.3.2.1 and 4.4.3.2.2 give the two criteria, one of which must be met.

Section 4.4.3.2.1 gives a passing criteria of “At least 500 ohms/volt if the high-voltage bus is:

- AC high voltage or
- DC high-voltage bus that can be connected to the electrical grid (e.g., for charging) or
- Not continuously monitored during operation for electrical isolation.”

Section 3.2 of SAE J1766 April 2005 defines *continuously monitored* as “includes a digital sampling or analog measurement system that provides warning.” For the purposes of this report, none of these three conditions applies. Then Section 4.4.3.2.2 gives a passing criteria of “At least 100 ohms/volt if the high-voltage bus is:

- DC high voltage and
- DC high-voltage bus that does not connect to the electrical grid or other off board AC electrical source and
- Continuously monitored during operation for electrical isolation.”

These criteria are applicable to the test report, assuming that the electrical isolation of the high-voltage bus is monitored continuously during operation.

For reference, the rationale behind the selection of 100 ohms/volt is given in Section 1.5 of SAE J1766 April 2005: “It is expected that fuel cells will maintain an isolation of 125 ohms/volt with aged coolant. With the remaining high-voltage system maintaining an isolation of 500 ohms/volt, the total high-voltage system isolation shall not be less than 100 ohms/volt (125 ohms/volt + 1/500 ohms/volt = 1/100 ohms/volt).” The document continues by explaining that “the requirement for EVs was conservatively set to 500 ohms per volt based on safety characteristics of AC systems.” Another statement adds that the 100 ohms/volt number is consistent with ISO 6469-3 and IEC curves for allowable AC and DC.

To summarize, the portions of SAE J1766 April 2005 that are relevant to this report are as follows:

1. High voltage is defined as voltage levels greater than 30 volts AC or 60 volts DC.
2. A vehicle will meet the requirements of SAE J1766 April 2005 by satisfying the electrical isolation provisions within this Recommended Practice, even if no hydrogen is onboard.
3. The passing criteria for electrical isolation are given as at least 500 ohms/volt if the high-voltage bus is:
    a. DC high-voltage bus that can be connected to the electrical grid or
    b. AC high voltage or
    c. Not continuously monitored for electrical isolation during operation.
4. The passing criteria for electrical isolation is given as at least 100 ohms/volt if the high-voltage bus is:
    a. DC high voltage and
    b. DC high-voltage bus that doesn't connect to an external AC electrical source and
    c. Continuously monitored for electrical isolation during operation.
5. Aged coolant in fuel cells are expected to lower isolation to a level not below 125 ohms/volt.
6. A procedure for measuring isolation is given in Appendix A, but is not applicable to this report. The procedure assumes the presence of a power generating device, which is not the case with no hydrogen onboard.

2.2.2.5 ISO 23273-3 2006 Fuel Cell Road Vehicles – Safety Specifications Part 3: Protection of Persons against Electric Shock

2.2.2.5.1 Overview

As stated in the scope section of ISO 23273-3:2006, "This part of ISO 23273 specifies the essential requirements of fuel cell vehicles (FCV) for the protection of persons and the environment inside and outside the vehicles against electric shock. This part of ISO 23273 applies only to onboard electrical circuits with working voltages between 25 volts AC and 1000 volts AC or 60 volts DC and 1500 volts DC respectively."

The document contains sections relating to:

- Section 4 – Environmental and Operational Conditions
- Section 5 – Voltage Classes of Electric Circuits
- Section 6 – Marking
- Section 7 – Measures for the Protection of Persons against Electric Shock
- Section 8 – Test Methods and Requirements for the Protection Measures against Electric Shock.

Various SAE documents are referenced throughout to provide the reader with more detail.

2.2.2.5.2 Applicability to HFCVs

This ISO document has been developed specifically for FCVs and is applicable directly to HFCVs.

2.2.2.5.3 Application to HFCVs without Hydrogen Onboard

Several portions of ISO 23273-3:2006 are useful for this report. Specifically, one portion of Section 7 states that, "Hazards of electric shock can occur when electric current passes through the human body (see IEC 60479-1). Such body current shall not exceed 10 mA continuously, which corresponds to 100 ohms/volt minimum resistance…" This statement gives another data point for setting the measurement threshold.

Another portion of the document providing valuable information is Section 8.2.2. This section, concerning insulation resistance measurement of the balance of fuel cell power systems, states that "For the measurement of the insulation resistance between the balance of power system…circuits and their conductive parts, the electric power sources of these circuits (fuel cell stacks, traction batteries) shall be disconnected at their terminals and the live parts disconnected from the electric chassis, if the circuits are chassis-connected." This information can be used in developing the test procedure for this report.

Similarly, Section 8.2.3 on insulation resistance measurement of the electric power sources the documents states, "For the measurement of the insulation resistance of the fuel cell stack, the entire mechanical structure of the fuel cell system (including the cooling system with its cooling medium) shall be considered. Prior to the measurement, stop power generation after operation at maximum output according to the manufacturer's specification. Discharge the voltage across the fuel cell stack power terminals. Disconnect all cables from the fuel cell stack power terminals, and all other cables from other electric terminals of the fuel cell stack. All cooling pipes, fuel pipes, air pipes shall remain connected." Although not directly application to HFCVs without hydrogen onboard, these instructions can help to shape the test procedure being developed.

To summarize, the important information in the document related to this report is:

1. Isolation resistance should be at least 100 ohms/volt.
2. ISO 23273 suggests that for measuring isolation resistance, the electric power sources of these circuits should be disconnected at their terminals and the live parts disconnected from the electric chassis if the circuits are chassis-connected.
3. ISO 23273 suggests that for measuring isolation resistance, the entire mechanical structure of the fuel cell system (including the cooling system with its cooling medium) should be considered.
4. All cables from the fuel cell stack power terminals and all other cables from other electric terminals of the fuel cell stack should be disconnected when measuring isolation resistance.
5. All cooling pipes, fuel pipes, and air pipes should stay connected when measuring isolation resistance.

2.2.2.6 FMVSS 305: September 11, 2007 / NHTSA-2007-28517 NPRM Electric-Powered Vehicles: Electrolyte Spillage and Electrical Shock Protection

2.2.2.6.1 Overview

The information used in this section of the report is a combination of the FMVSS 305: September 27, 2000 release, updated with amendments from 2001, 2004, and 2007, as well as the information in the 2007 proposed rule changes in which the NHTSA states, "Based on concern that the agency's standard on electric-powered vehicles, as currently written, may inadvertently hinder the development of fuel cell vehicles in the United States, NHTSA is proposing to amend the electrical safety requirements of FMVSS No. 305, Electric-Powered Vehicles: Electrolyte Spillage and Electrical Shock Protection." Therefore, the information in this section assumes that the proposed rule changes listed in the October 9, 2007 document are adopted.

As stated in Section S1 of FMVSS 305, "This standard specifies requirements for limitation of electrolyte spillage, retention of energy storage devices, and protection from harmful electric shock during and after a crash." The application section, Section S3, of the Regulation states that, "This standard applies to passenger cars and to multipurpose passenger vehicles, trucks, and buses that have a gross vehicle weight rating (GVWR) of 4536 kg or less, that use more than 60 volts DC or 30 volts AC of electricity as propulsion power, and whose speed attainable over a distance of 1.6 km on a paved level surface is more than 40 km/h."

The general requirements section of FMVSS 305, Section S5, contains subsections relating to:

- Section S5.1 – Electrolyte Spillage
- Section S5.2 – Energy Storage Device Retention
- Section S5.3 – Electrical Safety.

Section S5 also states that, "Each vehicle to which this standard applies, when tested according to S6 under the condition of S7, must meet the requirements of S5.1, S5.2, and S5.3."

Section S6 lists test requirements, with specific types of tests listed as:

- Section S6.1 – Frontal Barrier Crash
- Section S6.2 – Rear Moving Barrier Impact
- Section S6.3 – Side Moving Deformable Barrier Impact
- Section S6.4 – Post-Impact Test Static Rollover.

All four of these tests specifically state that the requirements of S5.1, S5.2, S5.3, and S5.4 must be met.

Section S7 gives the test conditions to be used as follows, "When the vehicle is tested according to S6, the requirements of S5 must be determined by the conditions specified in S7.1 through S7.6.7." These sections are:

- Section S7.1 – Energy Storage Device State of Charge
- Section S7.2 – Vehicle Conditions
- Section S7.3 – Static Rollover Test Conditions

- Section S7.4 – Rear Moving Barrier Impact Test Conditions
- Section S7.5 – Side Moving Deformable Barrier Impact Test Conditions
- Section S7.6 – Electrical Isolation Test Procedure.

Multiple figures are included with Section S7 for reference.

2.2.2.6.2 Applicability to HFCVs

FMVSS 305 is applicable directly to HFCVs. This standard contains some of the most up-to-date requirements information for HFCVs.

2.2.2.6.3 Application to HFCVs without Hydrogen Onboard

Several portions of FMVSS 305 are directly applicable to this report. First, Section S4 contains two definitions that are particularly useful:

- Electrical Isolation – "Electrical isolation means the electrical resistance between the vehicle high-voltage source and any vehicle conductive structure."
- High-Voltage Source – "High-voltage source means any item that produces voltage levels equal to or greater than 30 volts AC or 60 volts DC."

Although these terms are defined in other documents, FMVSS 305 defines these terms for regulatory purposes.

As mentioned in the overview, Section S5 requires that, "Each vehicle to which this standard applies, when tested according to S6 under the condition of S7, must meet the requirements of S5.1, S5.2, and S5.3." S5.1 and S5.2, electrolyte spillage and energy storage device retention, respectively, do not apply to this report. However, S5.3 pertaining to electrical safety is directly applicable.

Section S5.3 requires that, "After each test, electrical isolation and energy between any high-voltage source and the vehicle chassis electricity-conducting structure must meet the following:

1. For AC high-voltage systems, electrical isolation is not less than 500 ohms/volt, or
2. For DC high-voltage systems, electrical isolation is not less than 125 ohms/volt."

Another portion of FMVSS 305 that is useful for this report is in Section S7 and states that, "All measurements for calculating electrical isolation…will be made after a minimum of 5 seconds immediately after the test specified in S6." Section S7 also adds that, "When the vehicle is tested according to S6, the requirements of S5 must be determined by the conditions specified in S7.1 through S7.6.7." Furthermore, Section S7.6 contains the electrical isolation test procedure and directs, "In addition to the conditions of S7.1 and S7.2, the conditions in S7.6.1 through S7.6.7 apply to the measuring of electrical isolation specified in S5.3."

Section S7.1 deals with energy storage device state of charge and states, "The energy storage device is at the level specified in the following notations, as appropriate:

1. At the maximum state of charge recommended by the manufacturer, as stated in the vehicle operator's manual or on a label that is permanently affixed to the vehicle

2. If the manufacturer has made no recommendation, at a state of charge of not less than 95 percent of the maximum capacity of the energy storage device
3. If the energy storage device(s) are rechargeable only by an energy source on the vehicle, at any state of charge within the normal operating voltage, as defined by the vehicle manufacturer."

Section S7.2 deals with vehicle conditions and states that "The switch or device that provides power from the high-voltage system to the propulsion motor(s) is in the activated position or the ready-to-drive position.

- S7.2.1 The parking brake is disengaged and the transmission, if any, is in the neutral position. In a test conducted under S6.3, the parking brake is set.
- S7.2.2 Tires are inflated to the manufacturer's specifications.
- S7.2.3 The vehicle, including test devices and instrumentation, is loaded as follows."

Returning to Section S7.6, the electrical isolation test procedure, the directions in S7.6.1 through S7.6.7 assume that the high-voltage system is powered. Not being the case for an HFCV with no hydrogen onboard, this section does not apply to the report.

To summarize, the portions of FMVSS 305 relevant to this report are:

1. Electrical isolation means the electrical resistance between the vehicle high-voltage source and any vehicle conductive structure.
2. High-voltage source means any item that produces voltage levels equal to or greater than 30 volts AC or 60 volts DC.
3. Each vehicle to which FMVSS 305 applies, when tested according to Section S6 under the condition of Section S7, must meet the requirements of electrical isolation in Section S5.3.
4. Section S5.3 requires that after each crash test, the electrical isolation between any high-voltage source and the vehicle chassis electricity-conducting structure must be not less than 500 ohms/volt for AC high-voltage systems and not less than 125 ohms/volt for DC high-voltage systems.
5. Section S7 states that electrical isolation measurements will be made after a minimum of 5 seconds after the test specified in S6.
6. Section S7 states that if a vehicle is tested according to S6, the requirements listed in S5 must be determined by S7.1 through S7.6.7.
7. Sections S7.1 and S7.2 must be satisfied for electrical isolation tests.
8. The electrical isolation test procedure listed in Section S7.6 does not apply to the case of an HFCV without hydrogen onboard because the assumption is that the high-voltage system is powered.

2.2.2.7 TP-305-01: September 11, 2008 Laboratory Test Procedure for FMVSS 305, Electric-Powered Vehicles: Electrolyte Spillage and Electrical Shock Protection

2.2.2.7.1 Overview

TP-305-01: September 11, 2008 defines its purpose as, “This document is a laboratory test procedure provided by the NHTSA, Office of Vehicle Safety Compliance (OVSC) for the purpose of presenting guidelines for a uniform testing data and information recording format, and providing suggestions for the use of specific equipment and procedures for contracted testing laboratories. The data correspond to specific requirements of the FMVSS. The OVSC test procedures include requirements that are general in scope to provide flexibility for contracted laboratories to perform compliance testing and are not intended to limit or restrain a contractor from developing or utilizing any testing techniques or equipment which will assist in procuring the required compliance test data.” Thus, this document is the test procedure for the previously discussed FMVSS 305.

2.2.2.7.2 Applicability to HFCVs

Just as FMVSS 305 was applicable to HFVCs, the information in this test procedure also appears to be applicable to the testing of HFVCs.

2.2.2.7.3 Application to HFCVs without Hydrogen Onboard

As some portions of FMVSS 305 were directly applicable to this report, some portions of TP 305-01: September 11, 2008 are also applicable. In particular, under the general requirements section, Section 2, the procedure states that, “When tested to the procedures contained herein, each vehicle to which the standard applies shall not:…Fail to maintain an electrical isolation of no less than 500 ohms/volt between the propulsion battery system and the vehicle’s electricity-conducting structure”. This statement indicates that the proposed FMVSS 305 limit of 125 ohms/volt for DC high-voltage has not been incorporated into TP 305-01: September 11, 2008.

Section 12.4, concerning electrical isolation baseline measurement during pretest requirements, gives valuable information on performing the current test procedure; such data can be incorporated into the test procedure proposed in this report. Likewise, Section 13.2, pertaining to electrical isolation compliance measurement postcrash, provides an outline for developing a test procedure.

2.2.2.8 SAE J2578 January 2009 Recommended Practice for General Fuel Cell Vehicle Safety

2.2.2.8.1 Overview

As stated in the scope section of SAE J2578 Jan 2009, “This SAE Recommended Practice identifies and defines the preferred technical guidelines relating to the safe integration of fuel cell system, the hydrogen fuel storage and handling systems as defined and specified in SAE J2579, and electrical systems into the overall FCV. This document relates to the overall design, construction, operation, and maintenance of fuel cell vehicles.” The document’s content subsequently is identified further by the statement, “The purpose of this document is to provide mechanical and electrical system safety guidelines, safety criteria and methodologies that should be considered when designing FCVs for use on public roads."

One of the benefits of SAE J2578 Jan 2009 is the large list of the publications related to FCVs. In particular, Section 2 of the document provides a list of documents and their titles, including 11 SAE publications, 1 American National Standards Institute (ANSI) publication, 3 FMVSS standards, 2 Canadian Motor Vehicle Safely Standards (CMVSS) documents, 4 IEC publications, 1 ISO publication, 6 Underwriters Laboratories, Inc. (UL) publications, 1 Deutche Wissenschaftliche Gesellschaft fur Erdol, Erdgas und Kohle (DGMK) report, 1 Electric Power Research Institute (EPRI) report, and 1 National Fire Protection Association (NFPA) standard which are used as references for SAE J2578 January 2009. In addition, 30 SAE publications, 3 ANSI publications, 3 Comite Internationale Special des Perturbations Radioelectrotechnique (CISPR) publications, 5 IEC publications, 17 ISO publications, 1 Federal Communication Commission (FCC) rule, l Canadian/Canadian Standards Association (CAN/CSA) document, 1 CSA document, 1 Institute for Computational Engineering and Sciences (ICES) document, 2 NFPA documents, and 1 Ballard report are listed for information only. This large number of referencess provides an excellent source for finding documents related to FCVs. The following section, Section 3, gives a large number of relevant FCV definitions.

Section 4 of SAE J2578 January 2009 provides the technical systems safety guidelines for the Recommended Practice. In particular, the subsections under Section 4 concern the following topics:

- Section 4.1 – General Vehicle Safety
- Section 4.2 – Fuel System Safety
- Section 4.3 – Fuel Cell System Safety
- Section 4.4 – Electrical System Safety
- Section 4.5 – Mechanical Safety
- Section 4.6 – Fail-Safe Procedures
- Section 4.7 – Safety Labeling.

Each of these sections, with the exception of Section 4.7, is divided into smaller subsections.

Section 5 of SAE J2578 January 2009 pertains to the operation of the fuel cell vehicle and contains information on the following topics:

- Section 5.1 – Owner's Guide or Manual
- Section 5.2 – Normal Vehicle Discharges
- Section 5.3 – Inadvertent or Inappropriate Operation of the Vehicle
- Section 5.4 – Byproducts.

Section 6, a short section, deals with emergency response and contains a simple list of information that the fuel cell vehicle manufacturer should have available for emergency responders. Section 7, another small section, pertains to maintenance.

The appendices of SAE J2578 January 2009 contain potentially valuable information relating to test methods and vehicle construction. The topics covered are:

- Appendix A – Postcrash Criteria for Compressed Hydrogen Systems
- Appendix B – Guidance for Conducting High-Voltage Tests
- Appendix C – Guidance for Conducting Discharge Evaluations into Spaces Surrounding Vehicles
- Appendix D – Guidance for Conducting Local Exhaust Flammability and Toxicity Evaluations of Vehicle Discharges
- Appendix E – Guidance for the Packaging of Hydrogen Systems Including Pressure Relieve Device Requirement Documents (PRDs), Shields, and Flow Barriers.

These appendices comprise approximately half of the Recommended Practice and contain charts, notes, and step-by-step procedures.

2.2.2.8.2 Applicability to HFCVs

SAE J2578 January 2009 is directly applicable to HFCVs. In fact, this Recommended Practice has some of the most up-to-date information on HFCVs, relative to the other Recommended Practices and Standards examined.

2.2.2.8.3 Application to HFCVs without Hydrogen Onboard

For the purposes of this report, the portions of SAE J2578 January 2009 that provide reference material and definitions, Sections 2 and 3, do not apply except for the valuable general information therein. Likewise, Sections 5 through 7, pertaining to operation, emergency response, and maintenance, respectively, do not apply. Also, large parts of Section 4 and the appendices do not apply. However, portions of Section 4, technical systems safety guidelines, and Appendix B, guidance for conducting high-voltage tests, are applicable to this report.

Section 4.1.3 of SAE J2578 January 2009 states that, “Crashworthiness guidelines for FCVs should meet applicable government regulatory requirements. In the U.S., use the applicable FMVSS…See 4.6.2 for crash response. Fuel system and electrical integrity can be tested simultaneously or separately. If performed separately, electrical integrity testing can be performed with a partial or no fuel inventory.” This information is reinforced in Section 4.1.3.2 on electrical integrity; this section declares, “Postcrash electrical requirements for fuel cell vehicles are addressed in SAE J1766. See also 4.6.2.” Several aspects of Section 4.1.3 proved useful in this task by pointing out the following items:

1. The relevant FMVSS must be consulted.
2. Section 4.6.2 of this Recommended Practice pertains to crash response.
3. Electrical system integrity testing can be performed separately and with no fuel inventory.

The relevant FMVSS was determined to be FMVSS 305 and is discussed later in this report.

Section 4.6.2 of SAE J2578 January 2009 deals with the response to a crash and states that, “If detected by crash sensors, the automatic fuel shutoff(s) and electrical disconnect(s) should be actuated, if appropriate. The electrical disconnect can also be used for assuring that the electrical isolation required by SAE J1766 is maintained after a crash…” The important thing covered in this section is the assumption that the electrical disconnect(s) will be actuated in a crash and that these electrical disconnect(s) can be used for ensuring electrical isolation, as per SAE 1766.

Section 4.4, Electrical System Safety, also has some pertinent details. In particular, Section 4.4.3.1 on high-voltage isolation states, "The isolation resistance when measured from any DC bus to the electrically-conductive chassis should be at least 100 ohms/volt (by itself) and when measured from any AC bus to the electrically-conductive chassis should be at least 500 ohms/volt (by itself)." This Recommended Practice also discusses DC and AC conductively connected circuits. However, this discussion is out of scope for this report because no AC sources are expected to be present in an HFCV after a crash.

Appendix B.1 of SAE J2578 January 2009 provides guidance for conducting a high-voltage isolation test. The reason for the isolation test is stated simply as, "The high-voltage isolation test should be conducted on high-voltage systems to ensure that, if there is inadvertent contact with a single high-voltage rail and the vehicle chassis, a person is not exposed to harmful electric shock due to a circuit created by low electrical isolation resistance to the vehicle chassis..." The Appendix continues to explain that, "The objective of the 500 ohms/volt and 100 ohms/volt requirements is to ensure that the current passing through the body of a person (accidentally or inadvertently) touching a single electrical bus does not exceed 2 mA AC and 10 mA total DC, respectively, due to a single failure. The purpose of the testing is to ensure that the isolation of DC and AC circuits meets the requirements defined in 4.4.3.1." These statements establish both the reason for the isolation test and the reason for the ohms/volt limits selected as passing criteria for the test. Section 4.4.3.1 was mentioned above and simply lists the 500 and 100 ohms/volt criteria. The appendix also state that, "The test can be performed on the entire system at one time, or on individual assemblies with appropriate analytical adjustments to determine the isolation resistance (to current flow through the body if a person touches any point of the high-voltage system)." This statement establishes the degree of freedom that exists for developing the measurement technique presented in this report. The appendix explains more about AC systems, but this material is not relevant to the discussion presented here because no AC source will be present after a crash, as established earlier in this section.

The procedure presented in Appendix B.1 begins with the statement, "The general approach is to measure the isolation resistance (ohms) between the various sections of the high-voltage bus and the conductive chassis (ground) under a condensing condition, and then calculate the isolation (ohms/volt) at the maximum working voltage(s) of the system." The statement precedes the actual procedure and establishes the guidelines for the test. Highlights relevant to this report are quoted from the procedure:

1. "Any on-board energy storage device (e.g., traction battery, auxiliary battery) complying with 4.4.10.1, 4.4.10.2, and 4.4.10.4 can be disconnected for this test.
2. The fuel cell system can be shut down for testing.
3. Both sides of electrical circuits not under test (such as low voltage circuits) should be connected to the vehicle conductive structure (chassis) at a common point. If some electronic components connected between the vehicle conductive structure and the live part cannot withstand the test voltage, they should be disconnected from the test electrical circuit. Printed wiring assemblies and other electronic-circuit components that can be damaged by application of the test potential or that short-circuit the test potential should

be removed, disconnected, or otherwise rendered inoperative before the tests are made. Semiconductor devices in the unit can be individually shunted before the test is made to avoid destroying them in the case of a malfunction elsewhere in the circuits.

4. The test voltage for isolation resistance measurements “can be an externally applied DC voltage. The test voltage selected for fuel cell systems should be at least the maximum open circuit voltage of the fuel cell stack…”

To summarize, the portions of SAE J2578 January 2009 that appear relevant to this report are:

1. FMVSS 305 must be consulted.
2. If electrical disconnect(s) are actuated in a crash, these electrical disconnect(s) can be used for ensuring electrical isolation per SAE J1766.
3. The electrical system integrity testing can be performed separately and with no fuel inventory.
4. Any isolation tests should be conducted throughout a range of environmental conditions, including condensation.
5. If a device is used to isolate high voltage within a finger-roof, rigid barrier/enclosure and if the isolation device is located within the barrier, the voltage or energy measurements should performed downstream of the isolating device. Alternatively, if the isolating device is located external to the barrier, voltage or energy measurements should be performed on both sides of the isolating device.
6. Any onboard energy storage device can be disconnected for the test.
7. The fuel cell system can be shut down for testing.
8. Both sides of electrical circuits not under test should be connected to the vehicle conductive structure at a common point, and any electronic components that can be damaged by the test can be disconnected from the circuit or shunted.
9. The test voltage for isolation resistance measurements can be an externally applied DC voltage of a value at least equal to the maximum open circuit voltage of the fuel cell stack.

2.3 Acceptance Criteria

After an extensive literature review, the following proposed acceptance criteria were created and used in the test procedure. The acceptance criteria, 100 ohms/volt, was selected to increase the current capacity requirements for the test instrumentation and not to imply that 100 ohms/volt is the acceptable limit for high-voltage DC sources in HFCVs.

To satisfy postcrash electrical safety, the high-voltage source is required to maintain a minimum level of electrical isolation from the vehicle chassis. If applicable, disconnects must be shown to have opened properly as a result of a crash in order to consider the remaining high-voltage components disconnected from high-voltage sources and therefore electrically safe. If any high-voltage components of the system would be powered due to the lack of disconnects or otherwise, then the high-voltage electrical isolation requirements must be met at those high-voltage components as well as sources: greater than 100 ohms/volt for high-voltage DC (60 volts DC) and greater than 500 ohms/volt for high-voltage AC (30 volts AC).

2.4 Test Instrumentation

The megohmmeter is a member of a broad class of measurement instruments referred to as ohmmeters, which are designed to measure electrical resistance. Ohmmeter instruments have the common characteristic of basing their measurement technique on the relationships among voltage, current, and resistance as defined by Ohm's law. Ohm's law states that the current through a conductor is proportional to the voltage across it and inversely proportional to its resistance. Three equivalent expressions representing Ohm's law are shown in Figure 3.

$$I = V/R,\ V = IR,\ R = V/I$$

Figure 3. Three expressions representing Ohm's law.

The operation of the ohmmeter is based on the Ohm's law expression defining resistance as the ratio of voltage and current, R = V/I. Figure 4 shows the resistance, voltage, and current parameters associated with any conductor of electrical current.

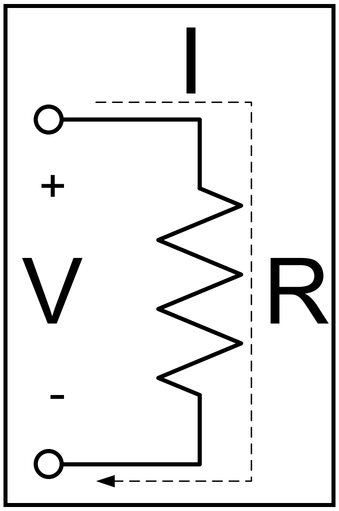

Figure 4. Voltage (V), current (I), and resistance (R) of a conductor.

R represents the electrical resistance of the conductor, and I, the electrical current flowing through the conductor. Voltage V is produced across the conductor resulting from the flow of current through the resistance, and an ohmmeter determines the value of this resistance by either providing a voltage and measuring the resulting current or by providing a current and measuring the resulting voltage.

The typical ohmmeter routinely found in electronics laboratories is designed to measure the resistance of low voltage electrical circuit components found in industrial, medical, and consumer electronic equipment, such as machinery, power tools, computers, patient monitors, and household appliances. Ohmmeters designed for these applications commonly are used to measure the winding resistance of electric motors, to check for open and short circuit conditions in electrical wiring, and to check the polarity of semiconductor diodes within electronic circuits. Therefore, this type of ohmmeter operates by applying a DC voltage of a few hundred millivolts to measure resistance in the range of approximately 1Ω to a few megohms ($10^6\Omega$). Since the ohmmeter operates by applying a voltage or current to a device under test (DUT), any externally applied voltage or current can disrupt its measurement and possibly can cause damage to the instrument; thus, it is imperative that the DUT be inactive and fully de-energized before the ohmmeter measurement is made.

The megohmmeter is a specialized version of an ohmmeter and is used primarily to test the resistance of electrical wiring insulation, which is referred to as insulation resistance (IR) and is not to be confused with the V= IR form of Ohm's law. The megohmmeter instrument performs an IR test by applying a high DC voltage to the DUT and then measuring the resulting current, referred to as leakage current, which flows through the wiring and its associated insulation. This current is dependent on the value of voltage applied, the value of resistance, and also the value of any capacitance, either as capacitive components within with the DUT or as parasitic capacitance associated with electrical wiring to the DUT.

Leakage current is comprised of three distinct current components: conductive, capacitive, and polarization. These three components together make up the total leakage current that determines the value of the insulation resistance measured by the megohmmeter. The conductive current component is that current that flows normally through any conductive material found between layers of insulation, such as the current that flows through the adjacent wires within a cable subjected to an insulation resistance measurement or the current that flows through a wire within the DUT connected to ground. This primary leakage current is evaluated for isolation resistance measurements.

The capacitive current component is an exponentially varying current that results from the application of a DC voltage to the capacitance found within the measurement circuit. The duration of the capacitive current component can be very low, as occurs in a circuit with a very low value of capacitance such as parasitic wiring capacitance, or can be quite long, as occurs when voltage is applied to a capacitive component within the DUT. As a result, it is necessary to allow sufficient time for the leakage current to stabilize while making an insulation resistance measurement.

The flow of the polarization component of leakage current results from the polarization of the dielectric material used to form electrical insulation. This time-varying current typically has a high value for a few seconds and then slowly decreases to zero. The duration of the polarization current can be very short in the case of low capacitance and can be much longer in the case of high capacitance. As with the capacitive current, it is necessary to allow sufficient time for the polarization current to stabilize while making an insulation resistance measurement.

Wiring insulation typically has a very high value of resistance in order to provide sufficient electrical safety over a wide range of operating voltage; thus, the megohmmeter is designed to measure a much higher range of resistance than a typical ohmmeter. A megohmmeter typically applies a DC voltage within the range of 250 volts DC to 5000 volts DC to measure resistance within the range of 10 KΩ ($10^3\Omega$) to 1 PΩ ($10^{15}\Omega$). As with any ohmmeter, the megohmmeter resistance measurement can be compromised by any externally applied voltage or current; thus, the DUT must be inactive and completely discharged to take an accurate measurement and to avoid potential damage to the instrument. The megohmmeter applies only to DC voltage if performing an insulation resistance measurement. Thus, when the megohmmeter is used to perform an insulation resistance measurement in an AC system, the measurement result, though useful for the evaluation of electrical safety, cannot be representative of the actual AC system.

The megohmmeter commonly is used to determine the applied voltage if an insulator undergoes insulation breakdown or dielectric breakdown as illustrated in Figure 5.

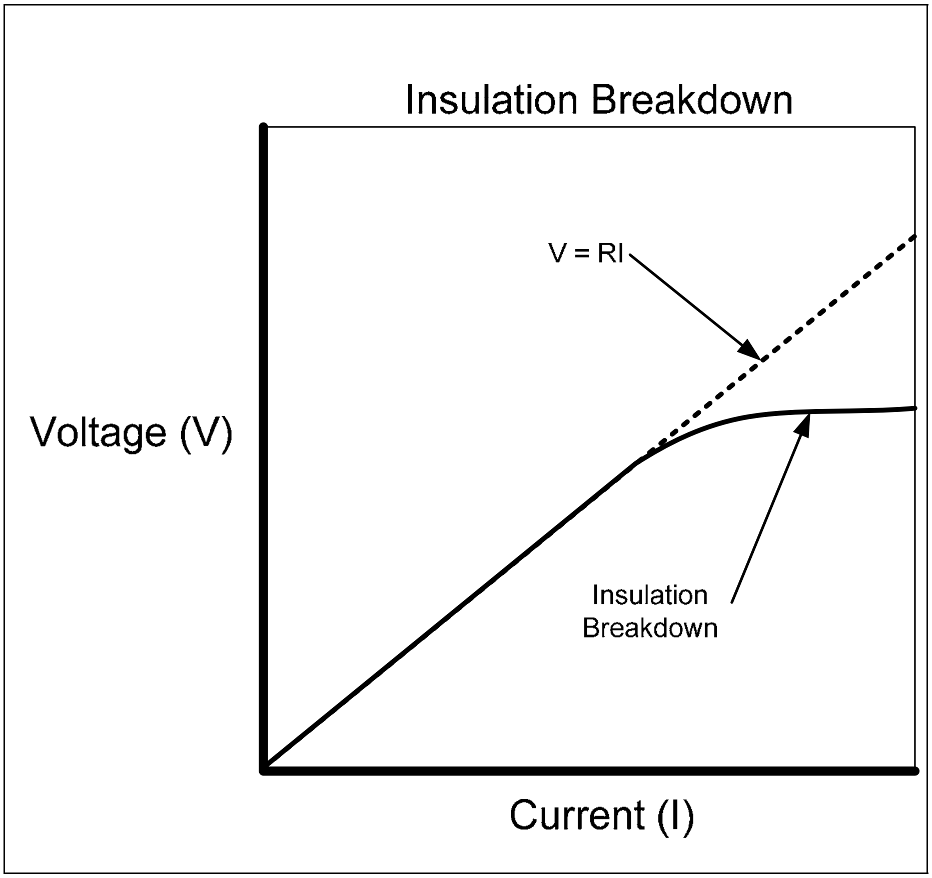

Figure 5. Insulation breakdown.

The dashed line in the figure represents the ideal linear resistance of a perfect insulator; any small incremental increase in applied voltage results in a proportional small incremental increase in current as defined by the slope of the line defining the relationship between voltage and current, V=RI, which is resistance. The solid line represents the nonlinear effect of insulation breakdown, which begins at the point where a small incremental increase in applied voltage results in a larger, nonlinear increase in current. This breakdown effect continues as the applied voltage is increased incrementally until the insulator completely fails, allowing a very high current flow. This insulation breakdown characteristic creates an electrical safety hazard. Obviously, a human coming into contact with an active high voltage conductor or circuit, operating in insulation breakdown, is exposed to a dangerous shock hazard that can result in injury or death.

Battelle performed a market survey of commercially available megohmmeters, shown in Table 2, in order to identify those instruments applicable to the evaluation of FCV electrical safety during NHTSA crash testing. The first step of the survey was to identify the megohmmeter performance characteristics required for measuring the insulation resistance of vehicle electrical systems which can be compromised due to structural deformation resulting from the forces encountered during the execution of the NHTSA crash test. A compromised electrical system can exhibit an increase in leakage current if subjected to an applied voltage because damage to wiring insulation or the protective enclosures of electrical components partially exposes wire conductors, causing dielectric breakdown to be exhibited at reduced levels of applied voltage. The R=V/I form of Ohm's law defines insulation resistance as the ratio of applied voltage to the resulting leakage current; this ratio can show that an increased flow of leakage current at a reduced value of applied voltage does result in a reduced value of insulation resistance and a corresponding reduction of electrical isolation.

Electrical isolation is determined from the value of insulation resistance at an applied voltage and is expressed in units of ohms/volt. Leakage current can be defined as the ratio of applied voltage to measured insulation resistance using the I=V/R form of Ohm's law which expresses current as volts/ohm or amperes and showing that leakage current is the inverse of electrical isolation. This result is used to determine the value of current that must be supplied by a megohmmeter instrument during an insulation resistance measurement. An electrical isolation value defined to be 100 ohms/volt corresponds to leakage current of 0.01 volts/ohm or is more commonly referred to as 10 mA. The leakage current and isolation resistance are inversely proportional; if the ohms/volt value is increased, the leakage current decreases. Thus, to measure the insulation resistance of an electrical system exhibiting electrical isolation of 100 ohms/volt, a megohmmeter must be capable of supplying 10 mA of current. It is desirable in practice to have 50 percent excess current capacity to provide sufficient measurement resolution for determining accurately the electrical isolation both above and below the limit of 100 ohms/volt. This desire for measurement resolution defines the minimum desirable source current as 15 mA.

Battelle found that megohmmeter instruments can be separated into two distinct classes based on the type of power source utilized for operation: battery powered and AC line powered. The majority of megohmmeter instruments commercially available are battery-powered units. These units are used widely because of their small size, light weight, and internal energy source, allowing them to be handheld and readily portable. However, these units can be operated only

Table 2. Megohmmeter market survey results.

Manufacturer	Model	Test Voltage Range	Resistance Range	Accuracy	Current
Fluke	1550B	250-1000, 50V increments	0-1Tohm	<200K unspecified; 200k-5GOhm 3%	2mA
	1507	50, 100, 250, 500, 1000	10k-10Gohm	3%	1mA
	1587	50, 100, 250, 500, 1000	10k-100Mohm	3%	1mA
Megger	MIT410	50, 100, 250, 500, 1000	100Gohm	3%	2mA
	MIT520	50-1000, 10V increments	10k to 15Tohm	20%	3mA
	MIT1020	50-1000, 10V increments	10k to 35Tohm	20%	3mA
	MJ358	100V	0.1Ω - 2000MΩ	+40%, -0% max	2 mA
		250V, 500V, 1000V		+30%, -0% max	2 mA
Gossen Metrawatt	Metriso 500D	500V	30k-3Gohm	5%	<2mA
	Metriso 1000D	100, 500, 1000	100k-400Mohm	5%	<2mA
AEMC	1035	50, 100, 250, 500	20k-2Gohm @ 100V; 50k-20Gohm @250V	3%	<3mA
	1050	50, 100, 250, 500, 1000	4k-400Gohm @ 100V; 10k-1Tohm @250V	5%	<6mA
	1026	250, 500, 1000	1k-4Tohm	3%	
	1030	250V	50kΩ - 2000MΩ	< 40MΩ ±3% ± 3 cts > 40MΩ ±3% ± 2 cts	3 mA
		500V	100kΩ - 2000MΩ		
Agilent	4339B	0.1 to 1000	1k - 1.6*10^16	> ~1%	60 fA to 100 uA
	4349B		1k - 10^15	> ~1%	1 pA to 100 uA
Hotek	1863	50V, 100V	50 kΩ to 2 TΩ	~±3%	2 mA
		200V, 250V, 500V	500 kΩ to 20 TΩ		
Amprobe	AMB-5 KVD	100-500V (Programmable)	100kΩ - 500GΩ	±20% + 10dgt	3 mA
		1000-5000V (Programmable)			1.4 mA
Keithley	6517A	2 to 200	2M to 200T		1fA - 20mA
QuadTech	**1855**	**1-650V, 0.1V increments**	**10-99.99Gohm**	**1.7%@200V 2mA**	**0.5mA-150mA**
	1865	100-1000V	1k - 100Tohm	[0.45%+{(Rx/Vx)(0.0005 FS + 2pA)+30/Rx)100]	<2mA
	1868	10-1000V, 1V increments	10k-1Pohm	2%	1p-1mA
Sefelec	1501	1-1500V, 1V increments	4K to 2P	0.2% of reading + 0.1% or range	9mA
Danbridge	DB620	10-1000V, 1V increments	10K to 1P	2%	1p-1mA

for a few hours before their internal batteries need to be recharged. Battery-powered megohmmeters typically provide a range of test voltages from a few volts DC to 1000 volts DC at test currents up to 6 mA and typically offer measurement accuracies of 3 to 5 percent. Battelle found that none of the commercially available battery-powered instruments could supply a test current approaching the minimum desired value of 15 mA.

AC line-powered units typically conform to the 19-inch, rack-mount enclosure standard commonly used within the electronic instrumentation industry. These units are intended to be operated as a modular unit within of a rack of automatic test equipment (ATE) or as a laboratory bench-top unit. Since these units are powered by AC mains, their designs include AC to DC power converters that necessitate their being inherently larger and heavier than their battery-powered counterparts, but provide the instruments the potential to source higher test currents. Battelle identified a single AC line-powered unit meeting the 15 mA minimum test current: the Quad Tech 1855, shown in Figure 6. The instrument is capable of supplying test current levels up to 20 mA.

Figure 6. QuadTech 1855

Visits to both GMC and Ford revealed that the automobile industry commonly used battery-powered megohmeters to determine the electrical isolation of vehicles not subjected to NHTSA crash testing. This practice works very well due to the high values of electrical isolation inherent in the uncompromised electrical systems of production-representative FVCs that exhibit very low leakage currents of typically 1 mA or less. As stated above, determining the electrical safety of a vehicle having a compromised electrical system resulting from NHTSA crash testing requires an instrument capable of delivering test current levels of at least 15 mA to characterize accurately the electrical isolation values above and below 100 ohms/volt, including values as low as 67 ohms/volt. Battelle selected the Quad Tech 1855 megohmmeter as a result of this survey; it was the only commercially available instrument capable of delivering the desired 15 mA of test current. This instrument is an AC line-powered laboratory bench-top unit, conforming to the 19-inch enclosure standard. The Quad Tech 1855 is intuitive to setup and use; its user interface has easy-to-navigate menus, enabling the user to configure quickly the instrument for making insulation resistance measurements.

Battelle traveled to both GMC and Ford to dry-run the preliminary megohmmeter-based test procedure in order to verify the application of the Quad Tech 1855 instrument. Both GMC and Ford previously had used a handheld, battery-powered megohmmeter during their electrical isolation measurements, and Battelle was interested in comparing test data measured with the Quad Tech 1855 AC line-powered instrument with test data measured with a battery-powered instrument. The measurements obtained with both instruments during testing at GMC exhibited a very high correlation, but the measurements at Ford showed a discrepancy that was attributed to the Quad Tech 1855. Further investigation revealed an electrical grounding issue, referred to as a ground loop, which created a significant source of error if using the Quad Tech 1855 instrument for performing the test procedure.

The measurement error was determined on a prototype design of a Ford vehicle available for testing. It was necessary to elevate the vehicle on a hydraulic lift to provide physical access to the electrical connectors on its underside. Unavoidably, the hydraulic lift came into direct contact with the lifting points on the vehicle chassis, creating a direct connection to earth ground potential through the metal structure of the lift. The presence of this ground loop did not affect the measurements obtained with the handheld instrument used by Ford because battery-powered equipment inherently is isolated from the building safety ground as no connection exists to the building electrical distribution system. However, in the case of the Quad Tech 1855 AC line-powered instrument, a connection to the building electrical distribution system provided the necessary power source and created the ground loop between the measurement ground reference and the building safety ground. This grounded device scenario placed a very low impedance on the output of the Quad Tech1855 test voltage supply, resulting in an over-current condition. This condition overloaded the test voltage supply, resulting in significant measurement error.

Battelle contacted application engineers at Quad Tech to discuss this phenomenon; this technical interchange revealed that the Quad Tech 1855 instrument was not designed to operate with grounded devices. With this information, Battelle determined that the megohmmeter selection criteria for AC line-powered instruments must include operation with a grounded device.

Battelle subsequently re-evaluated the meghommeter selection criteria to ensure that the 15 mA minimum test current requirement was not overly conservative, thus excluding some of the available commercial instruments. As such, Battelle considered performing the megohmmeter test at reduced voltage for the purpose of relaxing the test current requirement. The I=V/R form of Ohm’s law shows that for a fixed value of resistance, a reduction in voltage results in a proportional reduction in current. The megohmmeter survey showed that if the current requirement could be relaxed sufficiently, the use of a battery-powered instrument possibly could eliminate the measurement error caused by a grounded device. However, the test procedure was designed to capture an electrical isolation failure at full operating voltage due to the possibility of the barrier crash test degrading electrical insulation and reducing the voltage level for insulation breakdown. This reduction in the breakdown voltage point of failure can be identified only by testing with a megohmmeter operating at or near full operating voltage. Therefore, it remains necessary to maintain the test voltage at full operating voltage, thus re-enforcing the need for the 15 mA current requirement.

The megohmmeter is used for the measurement of insulation resistance, but other types of measurements can be desirable for demonstrating electrical safety: AC hipot, DC hipot, leakage current, and ground bond measurements. A safety tester is a measurement instrument capable of performing multiple types of electrical measurements, both AC and DC; regulatory agencies, such as UL, ISO, and IEC, routinely require the use of this instrument. These agencies generally do not consider DC testing equivalent to AC testing, and a safety tester is capable of testing both DC and AC systems. A safety tester also can be referred to as a hipot tester; the term hipot is an abbreviation for high potential testing. Hipot testing verifies the electrical safety of a device by stressing its electrical wiring insulation at voltage levels much higher than those that occur during normal operation and is a proven method for revealing the existence of compromised electrical wiring insulation prone to premature failure during normal operation. Hipot testing commonly is performed as part of production testing in order to verify the electrical safety of each and every production unit; a safety tester is capable of performing hipot tests using high levels of either AC or DC voltage.

In addition to performing AC and DC hipot tests, safety tester instruments are also capable of performing the DC insulation resistance and leakage current measurement tests performed by a megohmmeter. For this reason, Battelle also considered the use of a safety tester as a means for verifying electrical safety. Battelle again consulted the application engineers at Quad Tech who recommended a Quad Tech Guardian 500 VA safety tester, shown in Figure 7, that can supply the necessary 15 mA of test current and operate with grounded devices. For expediency, Battelle ordered a Guardian 500 VA evaluation unit and subjected the instrument to full voltage and near15 mA current measurement conditions with a grounded device. The results of this performance evaluation showed that the Guardian 500 VA was an acceptable instrument for determining electrical isolation testing during NHTSA crash testing due to its ability to supply 15 mA of test current to a grounded device.

Figure 7. QuadTech Guardian 500 VA.

Battelle returned to both GMC and Ford with a revised test procedure to verify the ability of the Quad Tech 1855 megohmmeter to perform accurately the electrical isolation test on a grounded device when isolated from building safety ground and to verify that the Guardian 500 VA is an acceptable alternative measurement instrument to a megohmmeter. For thoroughness, verification tests were performed with each instrument under conditions exhibiting electrical isolation both above and below the 100 ohms/volt limit.

During the GMC verification testing, the vehicle remained on the concrete floor in the test garage, and its tires provided electrical isolation from earth ground, allowing the Quad Tech 1855 to be used without any additional electrical isolation. The verification testing at Ford again required elevating the vehicle on a hydraulic lift for electrical connector access, which presented a grounded device to each measurement instrument. The Quad Tech 1855 instrument was isolated from earth ground by using a modified power cord with a disconnected safety ground terminal. This arrangement created a potential shock hazard and is not recommended for normal use. However, while performing measurements with the Quad Tech 1855, the test operator was outfitted with high-voltage insulating gloves for protection from electrical shock. Since the Guardian 500 VA is specified to operate with grounded devices, no modification or additional safety precautions were necessary.

The data collected with the Quad Tech 1855 during the Ford visit confirmed that the measurement error observed during the previous visit was caused by operating the Quad Tech 1855 on a grounded device. Additionally, the data collected with the Guardian 500 VA showed a high degree of correlation with the data collected with the Quad Tech 1855, verifying that the Guardian 500 VA is an acceptable alternative to a megohmmeter. In actuality, the use of the Guardian 500 VA can be preferable for not requiring any special consideration for testing grounded devices.

2.5 Test Sequence Development

The step-by-step instructions to verify electrical isolation, including precrash setup and postcrash evaluation, were developed in a detailed manner. The steps began with analyzing the general block diagram of a typical HFCV power system as shown in

Figure 8. The potential high-voltage sources are the fuel cell, battery, and ultra-capacitors as indicated by the orange outlines. Current FCV designs are integrating either a battery or ultra-capacitors to provide additional power during surge and start-up periods, but not both. Therefore, the block diagram below would contain only one of these sources. Additionally, current high-voltage FCV sources are all DC, and the research did not reveal any plans for incorporating AC fuel cell sources.

After evaluating the GM Equinox and Ford Focus FCVs with respect to this Task Order, the general block diagram can be simplified to include only the high-voltage sources, high-voltage regulator, and the high- voltage bus. The regulator is referred to as a bidirectional DC to DC converter and connects the fuel cell, high-voltage battery, and the power system bus. In both of these vehicle designs, the fuel cell operates at a higher potential voltage as compared to the battery. The bidirectional converter decreases the fuel cell voltage to charge the battery during and increases the output voltage of the battery if the vehicle requires this source. The bidirectional converter is the key component that permits the vehicle to operate the electric traction motor during all operational conditions. Figure 9 represents the simplified HFCV block diagram including these key components.

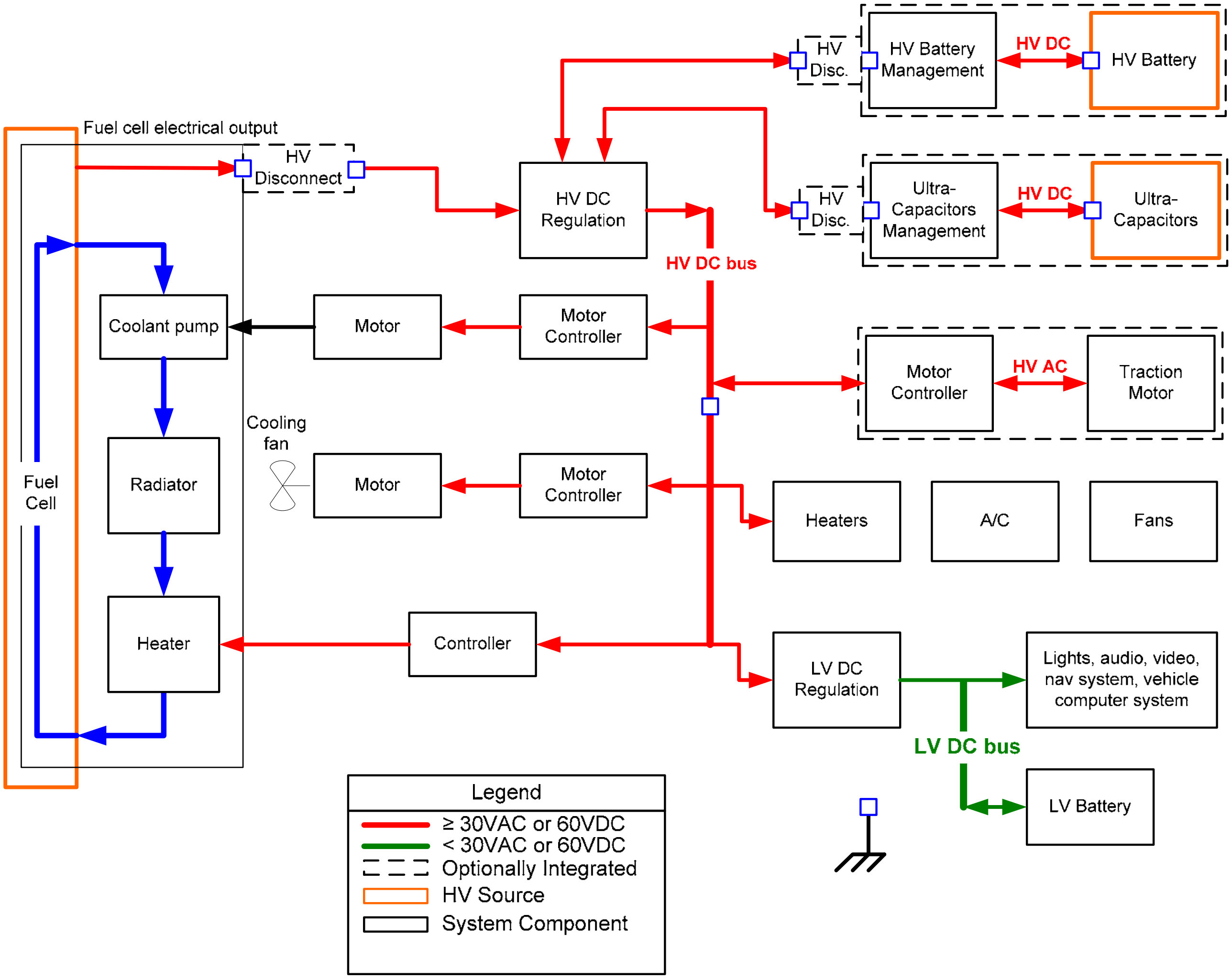

Figure 8. General block diagram for an HFCV with test points and disconnects.

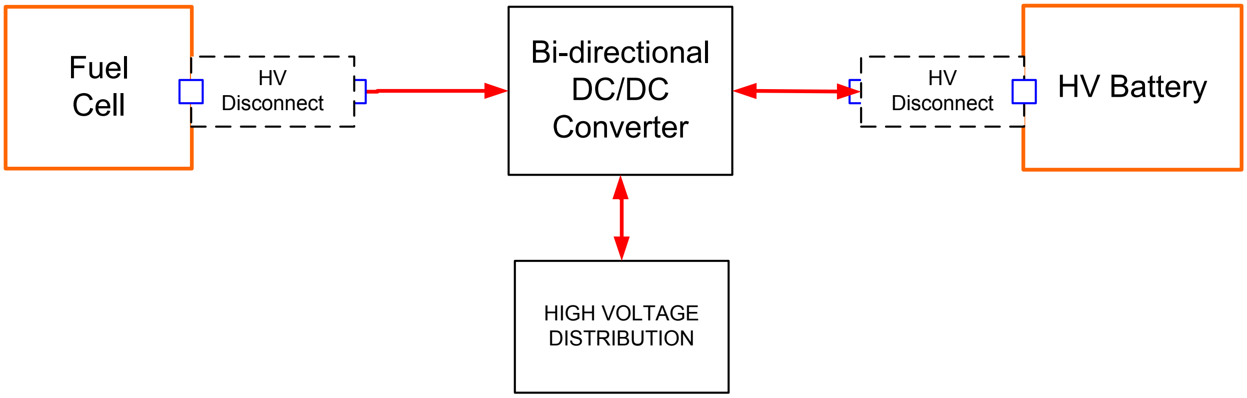

Figure 9. Simplified HFCV power system diagram.

When evaluating the simplified figure for procedural test point locations, the electrical safety disconnects required significant attention. Currently, the test procedure associated with FMVSS 305 and TP-305-01 only requires access to the traction motor side (bidirectional DC/DC converter side in Figure 9) of the disconnects postcrash if the disconnects are contained physically within the high-voltage source system. Not requiring access to the source side of the disconnects eliminates the need for the OEM or test house to penetrate a protective enclosure for test purposes. However, the disconnect functionality can be evaluated by the presence of voltage before and the absence of voltage after the crash test. This functionality is accomplished by TP-305-01 requiring the vehicle to be in a ready-to-drive, propulsion-system-engaged state for the precrash measurements, guaranteeing that the disconnects are closed and voltage is present. During the crash, the disconnects are designed to open and remove the high-voltage supply from the vehicle power system; this functionality is verified by checking for voltage after the event. When the high voltage is not present and disconnects are opened, the car is considered electrically safe; if the disconnects are not open and high voltage is present, the procedure will continue to measure isolation resistance and determine safety.

The unique challenge for this procedure is focusing on a high-voltage fuel cell fueled with an inert gas, i.e., helium. The inert gas renders the fuel cell inactive, and the source will not produce high voltage before or after the crash event; therefore, a new procedure was needed. The ability of the procedure to verify that the disconnects have opened is dependent on access to both sides of the safety disconnects. Furthermore, the coolant loop is a major source of possible fuel cell leakage current to the vehicle chassis and can be tested only if the fuel cell terminals are available precrash and postcrash. Figure 10 describes the potential shock hazard associated with the coolant loop. Current design of the coolant loop and coolant fluid on the GM and Ford vehicles does not permit excessive conductivity, path for leakage current, to fail or even approach the isolation limit; however, the loop could be compromised during a crash event and lower the isolation value. Therefore, not only should the fuel cell side of the disconnects be accessible and tested to determine contact state, but also testing the isolation value of the fuel cell postcrash is important. Including the measurement of the inactive fuel cell isolation precrash and postcrash is an essential step incorporated into the procedure to verify electrical safety based on isolation resistance.

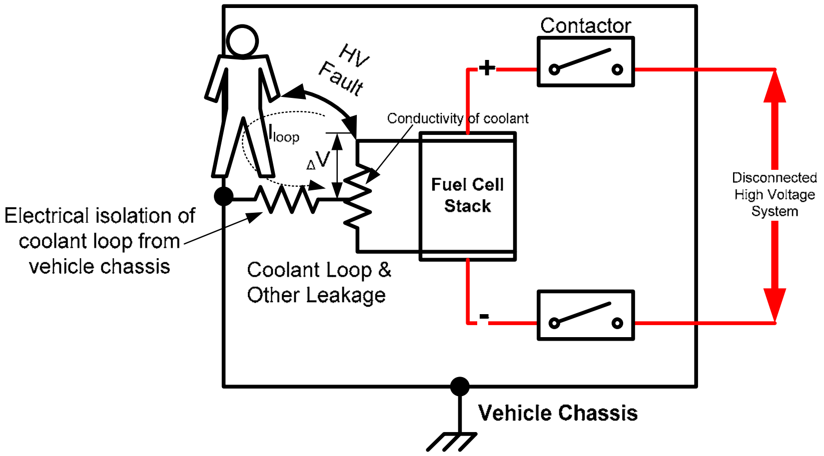

Figure 10. Potential shock hazard from fuel cell and coolant loop.

The test point determination is the key component to creating the detailed steps for the procedure. The procedure was written to accommodate an inactive source with and without disconnects. If the source does not contain disconnects, only two test points (TP1 and TP2) are required to execute the procedure. When the inactive source contains safety disconnects, two additional test points (TP3 and TP4) are incorporated into the procedure. These test points are required to verify the opened or closed state of the disconnects precrash and postcrash. R+ and R- represent the equivalent resistance of the positive and negative portions of the high voltage system, and IR is the isolation resistance of the high voltage source. The steps and use of the megohmmeter are written to test any inactive source; however, the requirement for the additional test points located on the source side of the disconnects are derived from the need to test an inactive fuel cell. The locations of the test points are detailed in Figure 11 and 12.

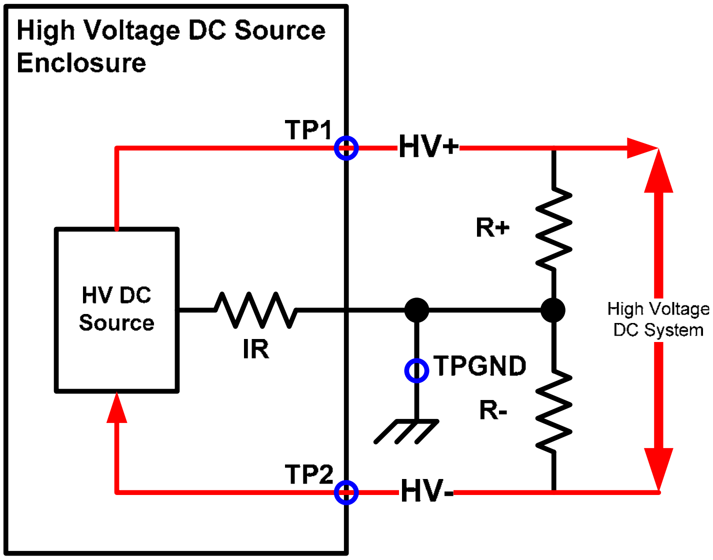

Figure 11. Test points for source without disconnects.

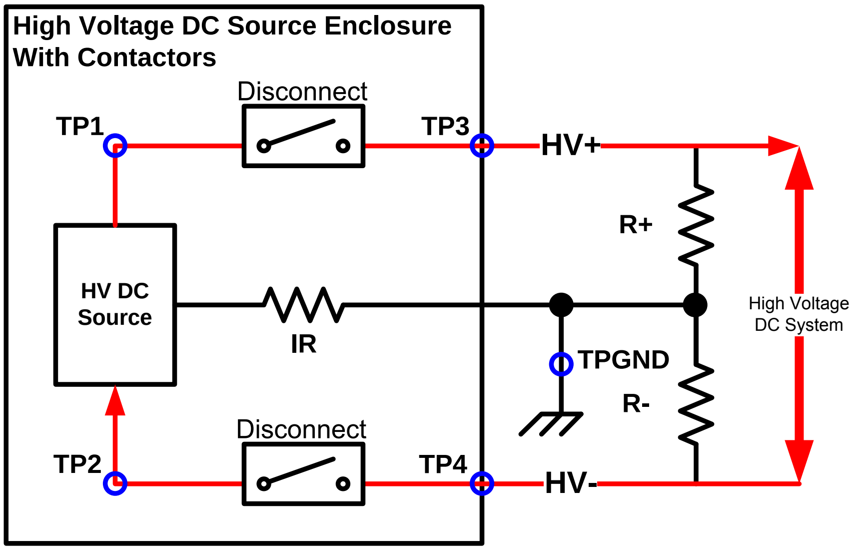

Figure 12. Test points for source with disconnects.

Once the test points were identified, the test sequence was developed. The initial draft of the procedure was organized to perform the precrash and postcrash measurements in the same manner. The procedure was written to divert to the current test procedure for FMVSS 305 and TP-305-01 when a high-voltage source is found to be active. The first draft of the procedure was performed at GMC and Ford to assist with procedure refinement. Two significant alterations were made to the original draft procedure:

- The procedure first evaluates the source for the presence of high voltage.
- The procedure was modified to facilitate a clear and defined approach to measuring and recording the required values.

Verifying the presence of high voltage permits the tester to establish a safe test environment and to determine if a need exists to transition to TP-305-01. The procedure was modified mainly for clarity and to establish procedural breaks between each measurement. The tester then can proceed through the procedure in an easy-to-follow, step-by-step method.

One of the first steps of the procedure, before attaching the megohmmeter, is connecting TP1 and TP2, the fuel cell positive and negative terminals. This step is slightly different if comparing the technique to the current TP-305-01 procedure that measures each leg of the high-voltage source independently. Based on current fuel cell design, if the source is inactive with no hydrogen onboard, an internal low resistance connection exists between the positive and negative terminals. Shorting the terminals together in the procedure forces a known connection, and the resulting measurement is the parallel equivalent of the fuel cell isolation from chassis. The original draft procedure for the verification stage of this effort incorporated the same connection of TP3 and TP4 before the precrash megohmmeter measurement of the high-voltage bus. The final procedure altered this approach to measure both the positive and negative legs of the high-voltage bus in order to be consistent with TP-305-01; however, the values measured via TP3 and TP4 of the high voltage system using a megohmmeter will not equal the values recorded if TP-305-01 was executed on the same system in a powered state. The discrepancies are addressed in the Additional Analysis portion of Section 4. The final procedural steps can be evaluated in the test procedure, Appendix A.

2.6 Data Sheets

The test datasheets are similar to those included in the current TP-305-01 and were created to capture the results from the step-by-step procedure. The procedure requires four datasheets to capture relevant vehicle information, instrumentation details, and precrash and postcrash measurements. Datasheet 1, titled Test Vehicle Specifications, captures information about the vehicle under test, ranging from vehicle identification number (VIN) to propulsion system details. The next datasheet captures pretest data specific to the test vehicle. The tester documents everything from the test weight of the vehicle to the location of test points for the chassis. This datasheet describes in detail the type of propulsion system, i.e. fuel cell, and the nominal working voltage range that is used to setup the megohmmeter.

Datasheets 3 and 4 capture precrash and postcrash information and results. The datasheets were constructed to capture the test instrumentation details and setup before actual measurements are attempted. The datasheet values were setup to match the detailed steps of the procedure; for every measurement made in the procedure, a dedicated location exists to record the values. If the vehicle under test contains more than one inactive source, the tester performs the measurement and completes Datasheets 3 and 4 for each source. Each datasheet contains a location for the tester to note comments or observations that occur during each phase of the test procedure. The datasheets are crucial to documenting and establishing the electrical isolation measurement and the vehicle electrical safety postcrash. Samples of the datasheets can be found in Appendix B.

2.7 Final Test Procedure

The final verified procedure, Appendix A, was the focus of Task Order 4. The final procedure describes in detail the instrumentation and steps required to evaluate the electrical isolation measurements of an inactive vehicle high-voltage source using a megohmmeter. Using the systematic approach discussed in the Introduction, the final test procedure was developed. Starting with the test requirements and researching the applicability of standards, regulations, and other research literature to electrical isolation measurement to HFCV led to narrowing the results to a detailed acceptance criterion. HFCV power system designs were analyzed to determine the test point locations. The lack of hydrogen during testing and the inactive fuel cell provided an interesting problem and required source and traction side access of the safety electrical disconnects.

After the test points were identified, detailed test steps were constructed to provide a safe and consistent verification of a high-voltage source isolation from chassis. The first draft of the procedure was followed by performing the dry-runs at both GMC and Ford and was modified to correct errors and increase clarity. Based on this evaluation and peer reviews, the final procedure was written and used for the verification portion of the program.

During the verification, discussed in Section 5, the final procedure incorporated two additional changes. The first was the establishment of the parameter V_{off}. When the vehicle is in a de-energized state, residual voltage is present giving the illusion of an active low-voltage source when measuring the inactive high-voltage source. The voltage level originally was expected to be lower than 1 volt, but during the test at GMC the measured values were above this threshold. However, the voltage was sufficiently low and the megohmmeter could perform an accurate resistance measurement. The procedure was modified to indicate that the tester or OEM is responsible for determining if the voltage measurements for $\mathbf{V_{off}}$ are indicative of a de-energized state and compatible with the selected measurement instrumentation.

3.0 TEST PROCEDURE VERIFICATION

The primary objective of Task 5 was to validate detecting an isolation failure mode caused by a vehicle crash of the HFCV with the megohmmeter test procedure by conducting on-site demonstrations with OEM HFCVs. The verification was conducted at the GMC Milford Proving Grounds in Michigan using a 2009 Chevrolet Equinox HFCV. The second demonstration was conducted at the Ford Motor Company Dearborn Michigan Facility using a 2004 Ford Focus HFCV.

To support the test procedure verification, Battelle created a test plan to simulate an electrical isolation failure mode of a HFCV for the megohmmeter. Battelle analyzed the relationship between the test voltage and source leakage current requirements of the acceptance criteria and calculated the correct resistance value to insert between the fuel cell and vehicle chassis in order to simulate an isolation failure below 100 ohms/volt.

The complete test report is contained in Appendix C and describes in detail the events that occurred at both the GMC and Ford verification events. The final procedure was executed on a GM Chevrolet Equinox and a Ford Focus. To simulate a failed isolation condition, a resistor was placed between the fuel cell and the chassis during the postcrash test portion of the procedure. The purpose of the resistor was to force the isolation to drop below the 100 ohms/volt acceptance criteria.

The safety features of the vehicles incorporated disconnects between the high-voltage output of the fuel cell and the remaining power system of the vehicle. These disconnects were designed to remain open when the car is turned off and open in an event of a crash (similar to the air bag). Therefore, when the procedure test points were accessible, the disconnects were always opened, simulating a potential postcrash state. The test points required by the procedure for the Equinox are shown in Figure 13. In the event of a real crash test, these test points will be accessible via an external interface port. These extra safety precautions did not permit testing the fuel cell while connected to the high voltage bus with the megohmmeter.

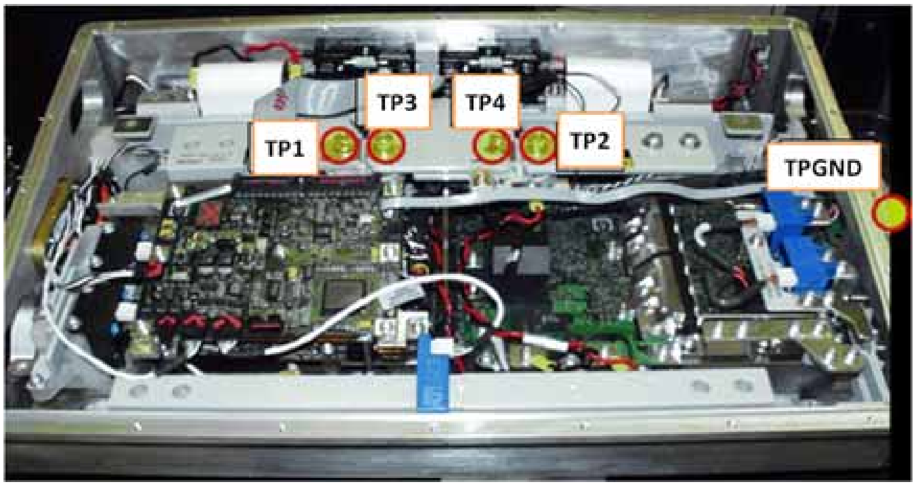

Figure 13. GM Chevrolet Equinox test point locations.

The test instrumentation was programmed to apply the nominal maximum working voltage of both vehicles. Two different pieces of equipment were used to measure isolation values. First, the megohmmeter, QuadTech 1855, was used to perform the procedure as written. Next, a safety analyzer repeated the measurements. The procedure was not designed to support the safety tester results because the information is given in volts and leakage current vs. resistance (ohms) from the megohmmeter. However, utilizing Ohms law (voltage = current x resistance), the matching resistance can be determined easily. The precrash and postcrash (simulated) isolation results on the GM Chevrolet Equinox and Ford Focus are shown in Table 3.

Table 3. Procedure verification results.

		Equinox		Focus	
		Megohmmeter	**Safety Tester**	**Megohmmeter**	**Safety Tester**
Precrash	Fuel Cell	1073 ohms/volt	1000 ohms/volt	3158 ohms/volt	3325 ohms/volt
	HV Bus	437 ohms/volt	371 ohms/volt	629 ohms/volt	625 ohms/volt
Postcrash	Fuel Cell	82 ohms/volt	81 ohms/volt	77 ohms/volt	75 ohms/volt
	HV Bus	440 ohms/volt	410 ohms/volt	Not tested	Not tested

The megohmmeter procedure was able to detect the failed isolation between the chassis and the high-voltage source. The safety tester also was able to detect the failure mode. As expected, the HV bus measurements did not fall below the acceptance criteria because the inserted resistor did not have an effect on this side of the disconnects. The procedure verification using a megohmmeter was successful, and a few minor changes were made to the procedure based on verifications at GMC and Ford. The most significant modification was the addition of the parameter V_{off}. V_{off} is the relationship between the residual voltage remaining on the high-voltage source and the capabilities of the megohmmeter. The voltage V_{off} must be low enough for the megohmmeter to perform an accurate measurement. A safety analyzer used during the verification showed that another instrument can perform a similar function, but the procedure was not written to use this instrument. The successful verification demonstrates the ability of a megohmmeter to measure isolation failures of an inactive fuel cell and its applicability to performing assessment of a postcrash HFCV with an inert fuel.

4.0 ADDITIONAL ANALYSIS

4.1 High Voltage Bus Measurement Discrepancies

Battelle and Ford engineers performed electrical isolation tests on a prototype Ford fuel cell vehicle, first using the SAE J1766 test method and then the using proposed megohmmeter test method. When the respective results were compared, some discrepancies were identified. The purpose of this brief is to provide a qualitative analysis describing some of the causes of these measurement discrepancies.

Figure 14 is a simplified block diagram representing the design of a DC to DC converter which is likely be found in a fuel cell vehicle. The front end of the converter is comprised of an input filter, a linear power regulator, the control circuits, and the magnetics and power conversion electronics. The purpose of the linear power regulator is to provide startup power to operate the control circuits during the initialization of the converter. When power is first applied to the converter, the linear power converter provides the DC power necessary to enable the control circuits to start the power conversion electronics and to begin the DC to DC conversion. The converter design feeds a portion of its output to the control circuits to provide the necessary operating power once the converter is operating, essentially replacing the linear regulator, to maximize the overall power conversion efficiency.

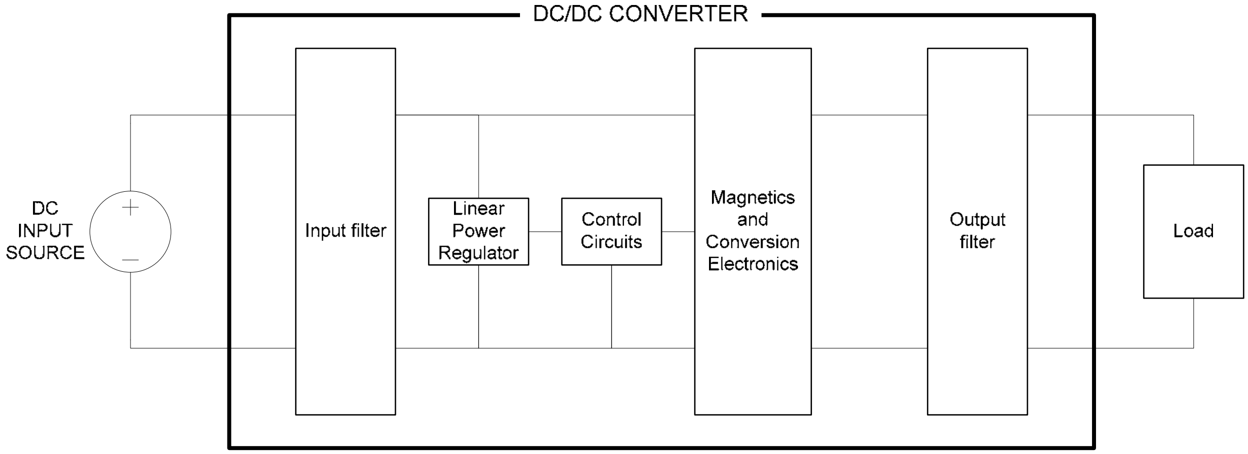

Figure 14. DC to DC converter block diagram.

Connecting the megohmmeter to the input of the converter to perform a differential resistance measurement using a test voltage amplitude near the nominal operating voltage of the DC power bus can create an unstable operating condition which can result in an erroneous resistance measurement. This situation can occur if the test voltage output of the megohmmeter powers the linear power regulator and allows the power conversion electronics to begin operation and deliver power to load. The power capacity of the megohmmeter test voltage output cannot supply the source current necessary to sustain converter operation; thus, the megohmmeter test voltage amplitude will drop quickly below the nominal bus voltage level. The reduced bus voltage will cause the DC to DC converter to discontinue operation and will reduce the load on the megohmmeter test voltage output, allowing the test voltage amplitude to return the nominal bus voltage level. Once this situation occurs, the cycle will repeat, resulting in an erroneous resistance measurement.

If the megohmmeter test voltage is reduced below the nominal operating voltage of the DC power bus, the linear power regulator and control circuits will be nonoperational. A differential resistance measurement in this scenario will not include any significant load from the power conversion electronics and will only measure the DC resistance of the input filter and the converter inputs circuits, both of which are likely very high. The resulting DC resistance measurement is expected to differ substantially from the results obtained utilizing the SAE J1766 method; the SAE J1766 test method is performed under full power with the DC to DC converter fully operational. The average input current will be much greater when the converter is operating, so the ratio of voltage to current (V/I) will be much less using the SAE J1766 method compared to the result obtained with the megohmmeter.

The discrepancy between the SAE J1766 and the megohmmeter results can be analyzed further by a closer examination of the input power filter shown in Figure 15. This filter contains a differential filter capacitor from line to line, common mode filter capacitors from each line to the filter case, and a common mode choke from input to output. The filter case is likely to be electrically bonded to the vehicle chassis; as a result, the common mode filter capacitors become electrically connected to the vehicle chassis. During a DC measurement with the megohmmeter, the power converter will be nonoperational; no AC current will flow through the input line filter, only DC current. The capacitors will exhibit very high impedance at DC and can be approximated with open circuits; likewise, the inductors will exhibit very low impedance at DC and can be approximated with short circuits. These results allow the input line filter to be approximated by the DC equivalent circuit shown in Figure 16.

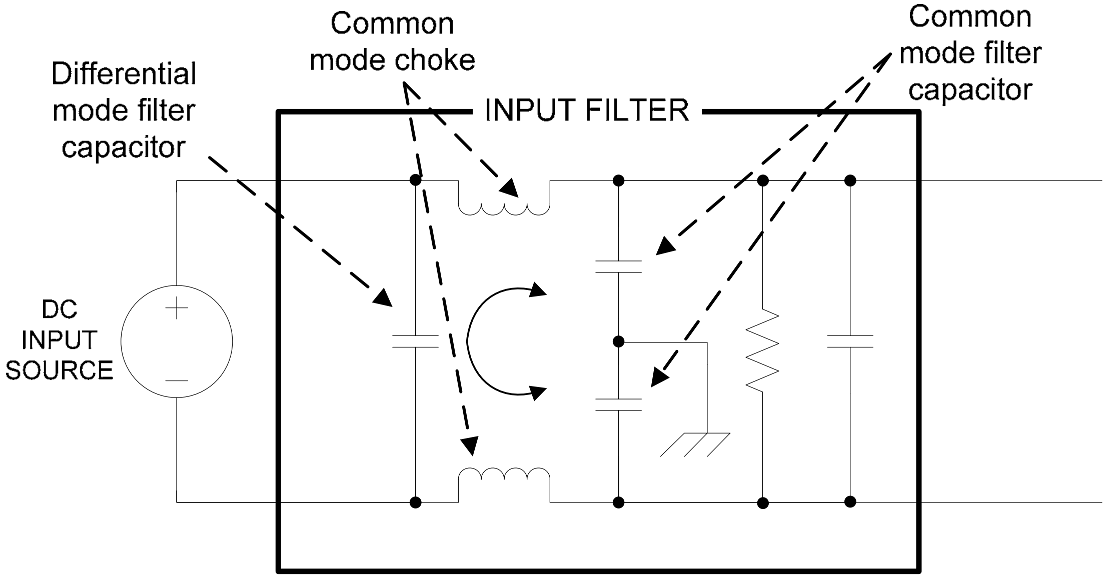

Figure 15. Input power filter.

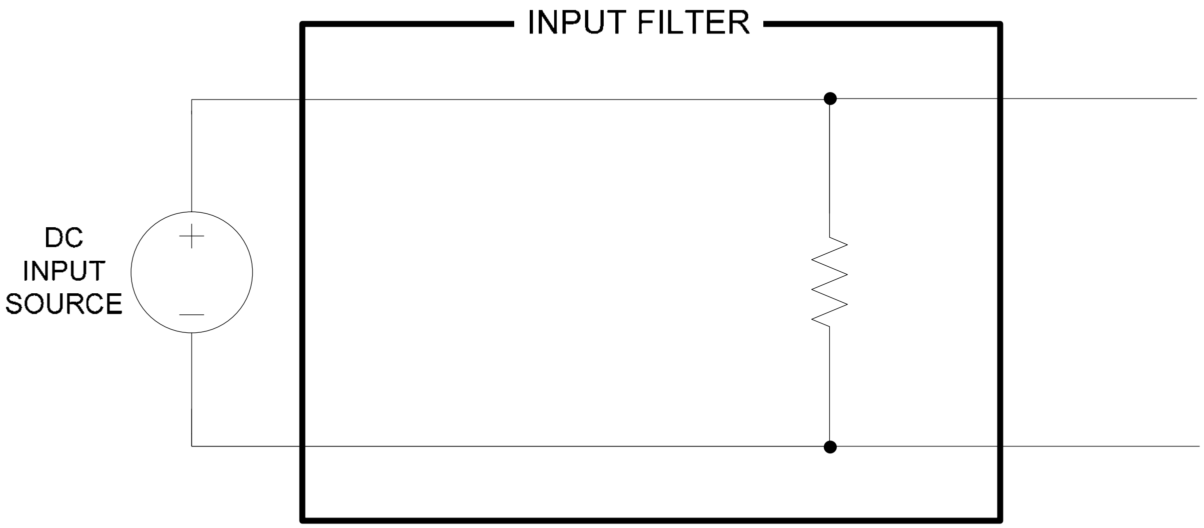

Figure 16. Input power filter DC equivalent circuit.

The DC equivalent circuit of the input power filter has no path to the vehicle chassis; as a result of the megohmmeter DC measurement, a very high resistance measurement to the vehicle chassis is expected. The only steady-state current that flows is the leakage current flowing through electrical insulation. Since the SAE J1766 measurement technique utilizes full DC bus voltage, the power converter will be operating and AC current will be flowing through the circuit elements of the input line filter. The impedance of the circuit elements is a function of frequency and, therefore, is dependent on the operating frequency of the power converter. The magnitude of the circuit element impedances can be approximated by resistance values at the operating frequency of the converter, resulting in the AC equivalent circuit shown in Figure 17.

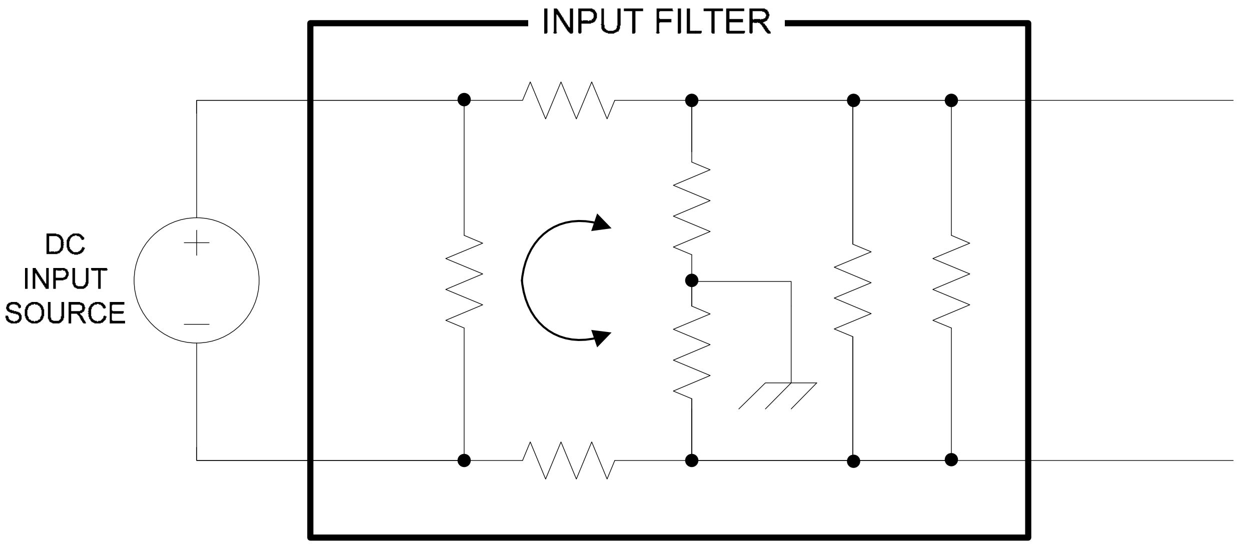

Figure 17. Input power filter AC equivalent circuit.

The AC equivalent circuit of the input power filter has a conductive path to the vehicle chassis through the common mode choke and the common mode filter capacitors. The common mode choke is chosen for high impedance at the operating frequency of the converter to block the AC switching currents of the power converter from conducting onto the DC bus of the vehicle. The differential filter capacitors are chosen for low impedance at the operating frequency to conduct AC switching currents away from the DC bus. These AC currents will result in an average operating current to vehicle chassis during the SAE J1766 measurement method which is greater than the average current flowing during the megohmmeter resistance measurement. The ratio of voltage to current (V/I) will again be less using the SAE J1766 method than using the megohmmeter method. The conclusion is reached that the electrical isolation value determined with the megohmmeter method will be greater than the electrical isolation value determined with the SAE J1766 method.

4.2 Fuel Cell Coolant Conductivity Testing

Battelle was tasked to develop and validate the Electrical Isolation Test Procedure using a Megohmmeter for HFCVs for the NHTSA, Office of Applied Vehicle Safety Research (OAVSR). The performance requirements specify leakage to the limitation of electrolyte spillage, retention of propulsion batteries, and electrical isolation of the vehicle chassis from the high-voltage system in the postcrash state.

HFCVs are cooled as are standard vehicles with a radiator, hoses, and coolant. The possible coolant for HFCV is an engine coolant concentrate called Glysantin. Glysantin is based on ethylene glycol and contains a hybrid corrosion inhibitor package with salts of organic acids and silicates. Because of these properties, the coolant exhibits a very low electrical conductivity. The coolant flows through the fuel cells (across the plates) and back to the radiator to be cooled. The radiator is tied to the chassis electrically and thermally. The purpose of the Electrical Isolation Test Procedure using a Megohmmeter is to test leakage current to the chassis. The HFCV coolant loop typically is referred to as the high-temperature loop. Battelle's task was to understand the current conduction mechanisms of the high-temperature loop to ensure accuracy and applicability with the megohmmeter.

OEMs used deionized water as the coolant during initial HFCV designs due to its properties of being electrically nonconductive. But in practical use, Glysantin has low conductivity and doesn't freeze in cold temperatures. The concern about Glysantin was the coolant conductivity directly related to temperature and its application to effective and practical electrical safety. The Electrical Isolation Test Procedure using a Megohmmeter was performed with fuel cells filled with an inert gas, rendering the fuel cells inactive. By conducting this test with inactive fuel cells at pretests and posttests, the HFCV is not at maximum operating temperature and the results of electrical isolation to the chassis can be skewed. This study was to characterize the relationship of the Glysantin conductivity as a function of temperature.

It was necessary to develop the test procedure properly, so instrumentation and hardware such as conductivity probes, general chemistry labware, and a fixture for the megohmmeter probes were assembled as shown in Figure 18. Battelle obtained unused Glysantin FC 20 coolant from an onsite fuel cell laboratory and conducted conductivity vs. temperature tests, shown in Figure 19.

Figure 18. Temperature conductivity test setup.

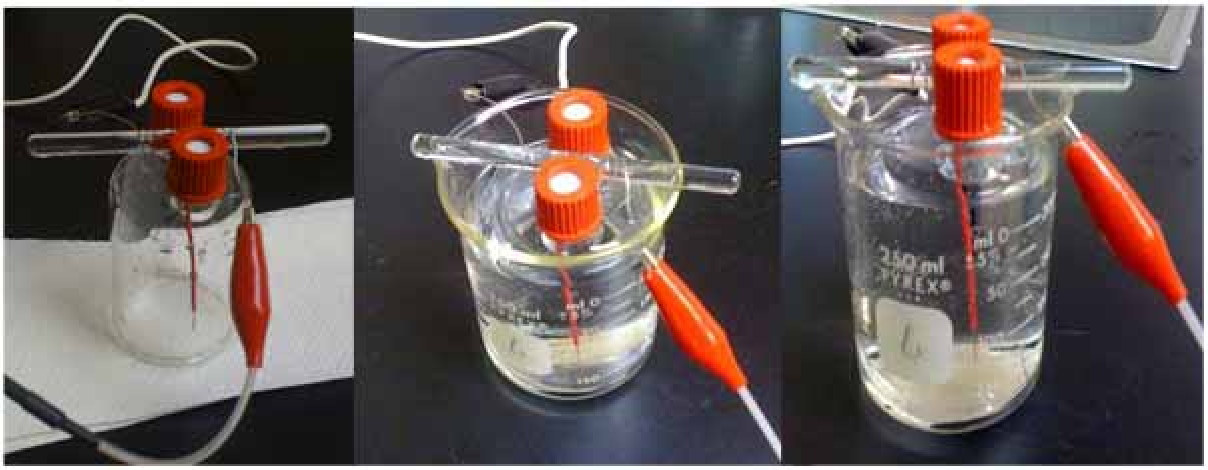

Figure 19. Glass electrode for megohmmeter.

The results of this test showed that in an ambient pressure environment, the high-temperature fuel cell coolant, Glysantin, has a linear relationship between temperature (°C) and conductivity (µS/cm or µS). From 25 °C to 100 °C, the coolant's conductivity increased by a factor of 4.

Predicting Conductivity:

- **G(T) = G(Tcal) (1 + alpha (T - Tcal))**
- **G(T)** is conductivity at temperature **T**
- **Tcal** is the temperature of calibration
- **alpha** is temperature coefficient of solution at **Tcal.**

Thus, the effective isolation resistance is decreased by a factor of 4 at 100 °C and is confirmed with both a conductivity sensor and the megohmmeter. Figure 20 describes the Glysantin insulation resistance results when measured with a megohmmeter at different temperatures.

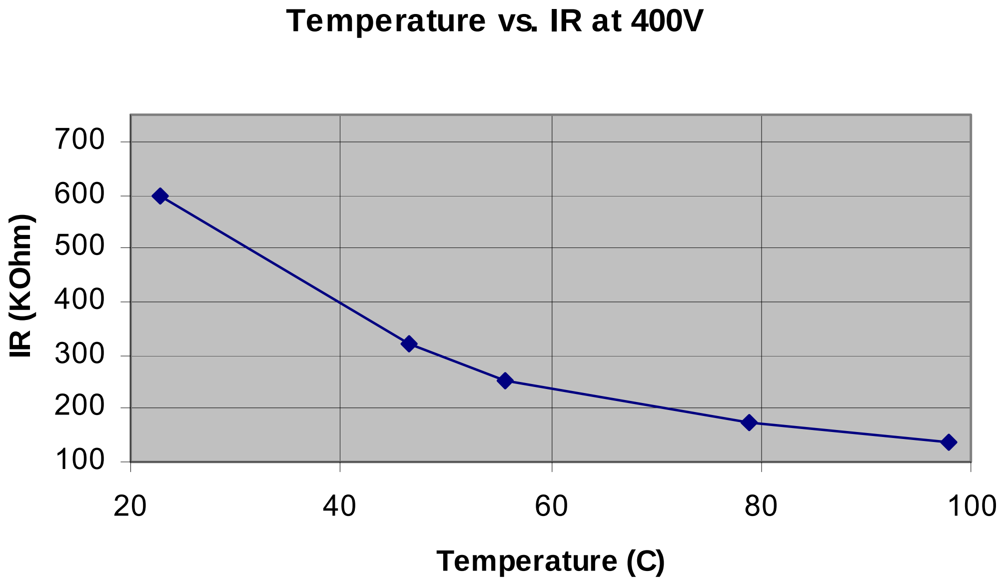

Figure 20. Glysantin megohmmeter results at increasing temperatures.

Battelle presented the findings to NHTSA and identified a need to conduct further research on the effects of aging and temperature on a HFCV's coolant conductivity. As the coolant flows through the exchange system and is in contact with the fuel cell, rubber hoses, pumps, etc., ions are added into the coolant through leaching, degradation, and/or corrosion processes, thus increasing conductivity. The HFCV utilizes an on-board, mixed-bed ion exchange resin filter to maintain low conductivity of the coolant by removing leached or produced ions as the fuel cell coolant moves throughout the filter exchange system. This filter system reduces the effects of coolant aging process.

The OEMs provided Battelle with aged fuel cell coolant for experiments to identify the temperature effects of aging on the conductivity of the fuel cell coolant. Ford provided a sample of new Glysantin and a sample that was over 6 months old with 638.0 recorded hours of operation. During initial testing at ambient conditions, the coolant demonstrated a conductivity of 2.75µS. As test temperature increased, so did the conductivity; at the same rate as the initial test, the coolant's conductivity increased by a factor of 4 as shown in Figure 21. When the aged coolant from Ford was tested, the coolant demonstrated less conductivity (1.5 µS) than the new coolant. As test temperature increased, so did the conductivity, but not at same rate as for the initial test. The coolant conductivity increased by a factor of 3 as displayed in Figure 22. The Ford HFCV uses an ion exchange resin filter to maintain low conductivity of the coolant, and this use appears to be successful. The history/lineage of the Ford aged HFCV coolant sample and ion exchange resin filter is unknown.

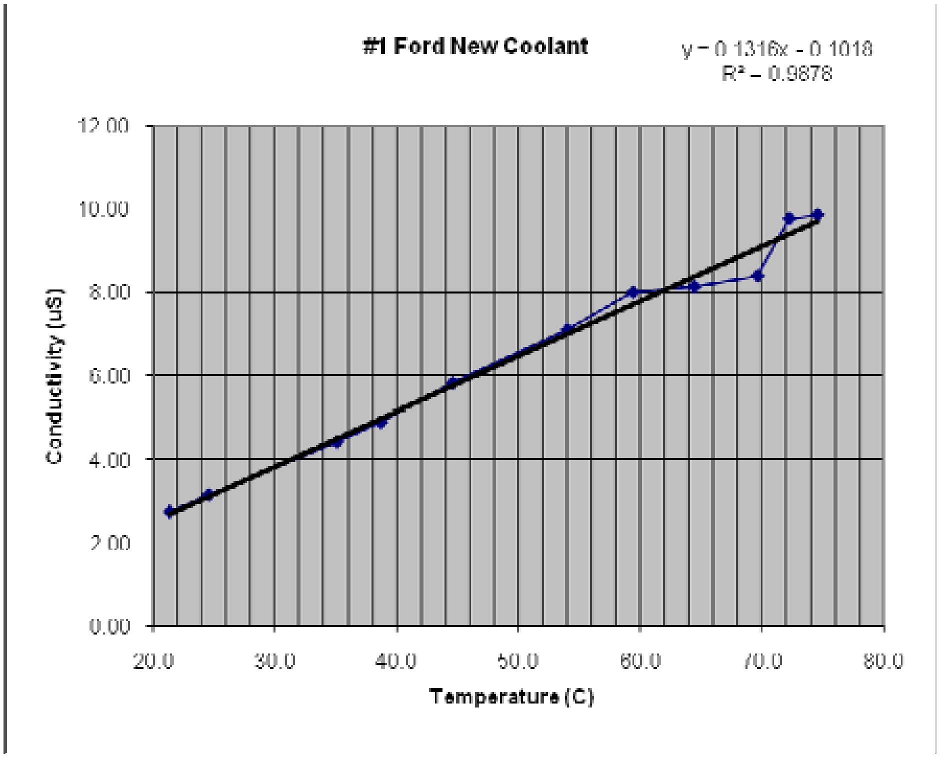

Figure 21. New Glysantin sample from Ford results at increasing temperatures.

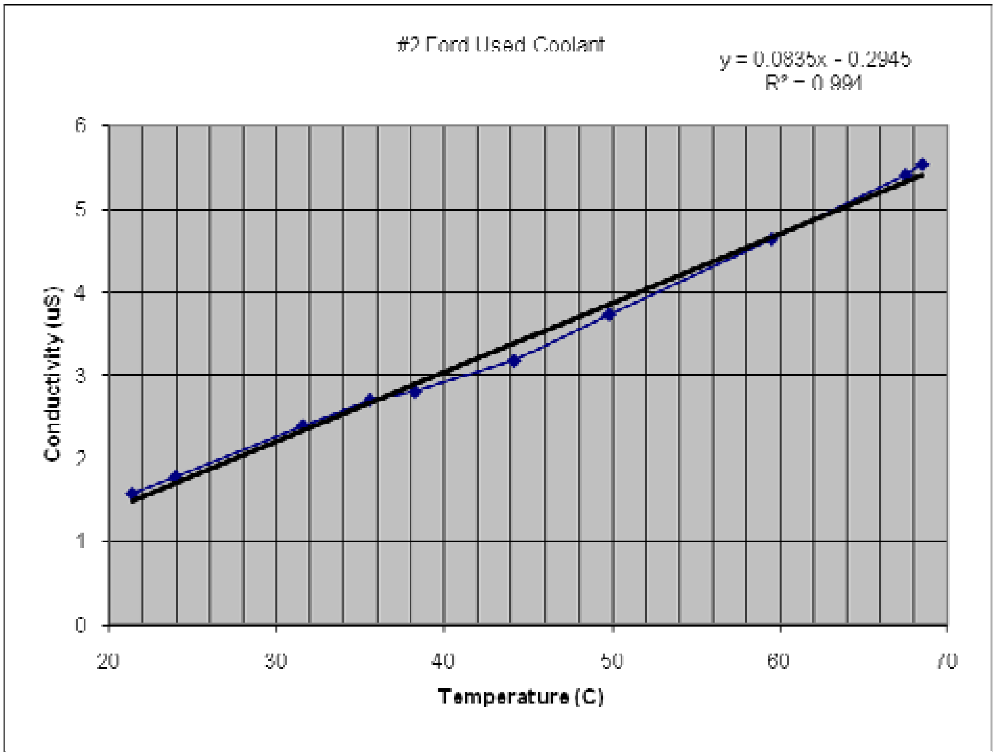

Figure 22. Aged Glysantin sample from Ford results at increasing temperatures.

GMC also provided a sample of Glysantin that was over 6 months old and in use for approximately 3900 miles. Prior to providing a coolant sample, GMC measurement of the coolant conductivity at the end of July was 14 µS. The temperature at the time of measurement was not recorded. Initial testing at ambient conditions of this coolant demonstrated an initial high conductivity of 9.67 µS, shown in Figure 23. As test temperature increased, so did the conductivity at the same rate as the initial test; the coolant's conductivity increased at a factor of 4. At 75 °C, the aged coolant conductivity was 34.1µS. GMC did not provide a new sample of Glysantin for comparison testing. Prior to initiating this study, testing of the coolant conductivity was performed on the GMC HFCV show vehicle and an engineering test vehicle. The show vehicle coolant had 600 miles of operation and was approximately 1 year old. The coolant conductivity measured 2.3 µS at ambient conditions. The engineering test vehicle coolant also had 600 miles of operation since last coolant flush and resin filter change. The coolant conductivity measured 9.0 µS after being driven. Temperature of the coolant at the time of measurement was not provided.

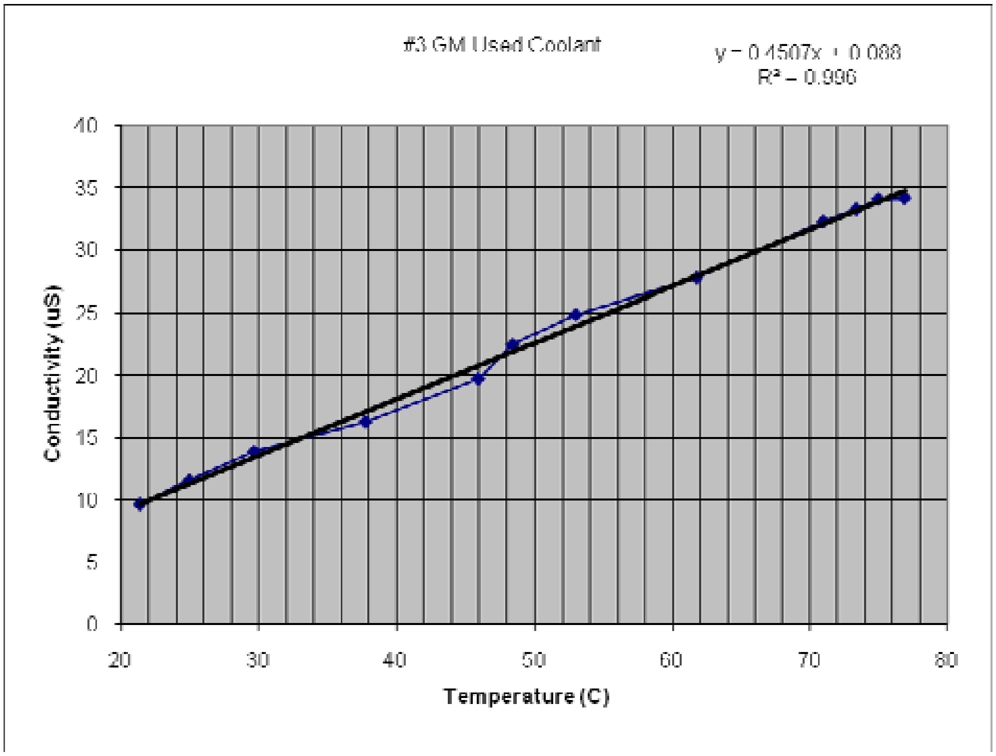

Figure 23. Aged Glysantin sample from General Motors results at increasing temperatures.

This study was to characterize the relationship of the Glysantin conductivity over temperature and to use these results to support the validation of the Electrical Isolation Test Procedure using a Megohmmeter.

Battelle understands the current conduction mechanisms of the coolant loop, but needs to gather more data to develop a “correction factor” to guarantee accuracy and applicability with the megohmmeter. Early testing of the Electrical Isolation Test Procedure most likely would be with new coolant at ambient conditions. A correction factor investigation is needed if the coolant was new but at temperature or if the coolant was aged and at temperature.

5.0 CONCLUSION

The successful completion of Task Order 4 yielded a verified test procedure to measure electrical isolation using a megohmmeter on an HFCV. Initiating the task by evaluating current regulatory documents, specifications, and literature assisted in defining the gap associated with crash testing an HFCV with an inert gas. The gap existed only in the procedure to perform the measurement with an inactive fuel cell and not in the test requirements and acceptance criteria. The proposed acceptable isolation limits are 100 ohms/volt for DC systems greater than 60 volts and 500 ohms/volt for AC systems greater than 30 volts. The 100 ohms/volt value was selected to require a maximum current capacity requirement for the test instrumentation; therefore, the instrument could measure values greater than or equal to 100 ohms/volt. Even though current and near-term designs do not include extremely high-voltage systems, i.e., 1000 volts or greater, NHTSA can consider placing an upper limit on the AC and DC voltage requirements for electrical isolation.

After the proposed acceptance criteria were established, a search for a suitable megohmmeter began and the result was the QuadTech 1855. Many megohmmeters are commercially available; however, many of these instruments could not measure the amount of leakage current required to detect an isolation failure below 100 ohms/volt at current fuel cell operating voltages. The QuadTech 1855 met the instrumentation requirements established by the procedure and can measure accurately the electrical isolation of an inactive fuel cell and high-voltage bus. A limitation for the QuadTech 1855 was detected during a dry-run of the procedure; i.e., the device could not perform accurately if the vehicle chassis had a low resistance connection to earth ground. Because of this deficiency, a safety tester, QuadTech Guardian 5000, was procured. The safety tester performs in a similar manner to a megohmmeter, but reports a leakage current and test voltage values instead of resistance. These devices are more expensive, but include additional functionality, i.e., outputting AC test voltages, and can perform measurements if the vehicle chassis is connected to earth ground.

The final test procedure was written to support the use of the megohmmeter and to provide detailed testing steps to sequence the operator through the measurements. The fuel cell coolant loop and an inactive source altered the approach to measuring for electrical safety when compared to the current TP-305-01. Access to the high-voltage source side, in addition to the traction motor side, of the safety disconnects now is required by this procedure. The additional test points provide the ability to verify that the disconnects have opened and to measure the isolation of the fuel cell high-voltage source, including the coolant loop effects. The datasheets augment this procedure and provide a concise location to record all vehicle-related information and test results. The final procedure was validated by executing the step-by-step instructions on two different HFCVs, a Chevrolet Equinox and a Ford Focus. Since the OEMs would not permit an actual crash event, an isolation failure was simulated by inserting a resistor to force the measurement to drop below 100 ohms/volt. The megohmmeter procedure was able to detect the failed isolation between the chassis and the high-voltage source. The safety tester also was able to detect the failure mode. Slight modifications were made to the procedure after the verification tests, and the updated test procedure is provided in Appendix A.

6.0 RECOMMENDATION FOR FUTURE WORK

During this effort, Battelle performed a brief experiment to determine the relationship between the fuel cell coolant conductivity and temperature. The coolant is a major source of leakage current from the fuel cell stack to the vehicle chassis; if a vehicle is crash tested with an inactive fuel cell, this coolant likely will be at room temperature. The results of the experiment show conductivity of the coolant increases with temperature; therefore, the isolation value decreases. Further studies are needed to evaluate the impact of the coolant temperature increase on an actual HFCV during an isolation measurement.

REFERENCES

SAE J2578, *Recommended Practice for General Fuel Cell Vehicle Safety*. January 2009.

SAE J1766. *Recommended Practice for Electric and Hybrid Vehicle Battery Systems Crash Integrity Testing.* Revised April 2005.

SAE J2344, *Guidelines for Electrical Vehicle Safety*, June 1998.

Federal Motor Vehicle Safety Standard No. 305. *Electric-Powered Vehicles: Eelectrolyte Spillage and Electrical Shock Protection.*

TP-305-01 Laboratory Test Procedure for FMVSS 305. *Electric-Powered Vehicles: Eelectrolyte Spillage and Electrical Shock Protection*

NHTSA-2007-28517 Notice of Public Rulemaking (NPRM) FMVSS 305. *Electric-Powered Vehicles: Electrolyte Spillage and Electrical Shock Protection.*

IEC 60479. *Effects of Current on Human Beings and Livestock.*

ISO 6469-3: 2001, *Electric Road Vehicles – Safety Specifications – Part 3: Protection of Persons against Electrical Hazards.*

ISO 23273-3: 2006, *Fuel Cell Road Vehicles – Safety Specifications – Part 3: Protection of Persons against Electric Shock.*

Taylor, T.A., E.J. Sullivan, J.A. Myers, and D.R. Stephens. *Electrical Isolation Test Procedure for Hydrogen Fuel Cell Vehicles,* Draft Report to NHTSA, November 2007.

Appendix A

Test Procedure

Electrical Isolation Test Procedure Using a Megohmmeter

Prepared by:

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Prepared for:

National Highway Traffic Safety Administration
Office of Applied Vehicle Safety Research
Washington, DC

Contract No. DTNH22-08-D-00080 Task Order 4

TEST PROCEDURE

Organization/Name	Approved Date:	Notes

RECORD OF REVISIONS

Version	Sections Affected	Description of Changes	Date	Approval
0.1	ALL	Initial Draft		

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PURPOSE AND APPLICATION

This document is a test procedure for measuring electrical isolation using a megohmmeter provided by Battelle to the National Highway Traffic Safety Administration (NHTSA), Office of Applied Vehicle Safety Research (OAVSR). The test procedure presents guidelines for uniform testing data and information recording format and provides suggestions for the use of specific equipment and procedures. The data correspond to specific requirements of the Federal Motor Vehicle Safety Standard(s) (FMVSS). The test procedure includes requirements that are general in scope, providing flexibility to perform testing. The procedures are not intended to limit or restrain NHTSA from developing or utilizing any testing techniques or equipment which will assist in procuring the required test data. These test procedures do not constitute an endorsement or recommendation for use of any particular product or testing method.

The purpose of this test procedure is to determine electrical safety based on electrical isolation measurements between the inactive high-voltage sources and the vehicle chassis using a megohmmeter. This test procedure augments the current procedure for FMVSS 305 – Electric-Powered Vehicles: Electrolyte Spillage and Electrical Shock Protection or can be integrated into a new standard. For active high-voltage systems, the latest FMVSS 305 test procedure, the TP-305-01 (2008), is used to measure electrical isolation. For vehicles with inactive high-voltage sources, such as a Hydrogen Fuel Cell Vehicle (HFCV) without hydrogen, a megohmmeter can be used according to this procedure to determine electrical isolation.

GENERAL REQUIREMENTS

Section 7.6 of FMVSS No. 305, dated September 11, 2007, specifies test procedure requirements for electrical isolation of the chassis from active high-voltage sources during the crash event. The procedure in the cited standard applies to the active high-voltage sources of vehicles that use electricity as propulsion power. This procedure extends the cited standard to ensure the safety of newly emerging electric vehicles for which a high-voltage direct-current (DC) source is inactive during the test. Alternating-current (AC) sources are not considered in this megohmmeter procedure. For the circumstances and requirements prescribed herein, this electrical test procedure takes precedence over the legacy test procedure described in FMVSS 305.

APPLICABILITY

The standard is applicable to passenger cars, multipurpose passenger vehicles, trucks, and buses with a gross vehicle weight rating (GVWR) of 4536 kg or less that use more than 30 nominal volts AC or 60 nominal volts DC of electricity and whose speed, attainable in 1.6 km on a paved level surface, is more than 40 km/h.

STANDARD REQUIREMENTS

When tested to the procedures contained herein, each vehicle to which the standard applies can:

- Maintain an electrical isolation of no less than 500 ohms/volt between the high-voltage AC sources and the vehicle's electricity-conducting structure
- Maintain an electrical isolation of no less than 100 ohms/volt between the high-voltage DC sources and the vehicle's electricity-conducting structure.

APPLICABLE BARRIER TESTS

The vehicles are be tested to the requirements of FMVSS 305, or related Electrical Safety Standard for High-Voltage Vehicles, in conjunction with testing to FMVSS Nos. 208, 214 (dynamic side impact requirements) and/or FMVSS 301 (frontal or rear impact requirements). Table 1 indicates the governing barrier tests that are utilized if testing to other dynamic standards. The vehicle must be able to meet the requirements of this standard for any of the governing barrier tests. Also, the test facility must be adequate for conducting the governing barrier tests prescribed in dynamic test listed above.

Table 1. Governing barrier tests.

Type of Test	Applicable FMVSS	Description	Requirement
Frontal Rigid Barrier	208	Any single rigid barrier crash at any speed up to and including 48 km/h in a line of travel perpendicular to the barrier face or at any angle between +/- 30 degrees from the line of travel perpendicular to the barrier face	305 S5.1, S5.2, and S5.3
Side Moving Deformable Barrier	214 Dynamic	Any single moving deformable barrier crash at any speed up to and including 54 km/h, side impact	
Rear Deformable Barrier	301 (Optional)	Any single moving deformable barrier crash at any speed up to and including 80 km/hr, rear impact with 70% overlap toward either side of the vehicle (passenger car, multiple passenger vehicle, truck, or bus under 4,536 kg GVWR (10,000 pounds)	

METRIC SYSTEM OF MEASUREMENT

Section 5164 of the Omnibus Trade and Competitiveness Act (Pub. L. 100-418) establishes that the metric system of measurement is the preferred system of weights and measures for trade and commerce in the U.S. Executive Order 12770 directs federal agencies to comply with the Act by converting regulatory standards to the metric system after September 30, 1992. In a final rule published on March 15, 1990 (60 FR 13639), NHTSA completed the first phase of metrication, converting English measurements in several regulatory standards to the metric system. Since then, metrication has been applied to other regulatory standards (63 FR 28912).

Accordingly, the NHTSA Office of Vehicle Safety Compliance (OVSC) laboratory test procedures include revisions to comply with governmental directives in using the metric system. Regulatory standards converted to metric units are required to use metric measurements in the test procedures; whereas standards using English units are allowed to use English measurements or to use English measurements in combination with metric equivalents in parentheses. For any testing equipment that is not available for direct measurement in metric units, the test laboratory can calculate the metric equivalent by means of a conversion factor carried out to at least five significant digits before rounding consistent with the specified metric requirement.

All final compliance test reports are required to include metric measurements for standards using metrication.

NOTE: The methodology for rounding measurement in test reports can be made in accordance with the standard ASTM E29-06b, "Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications."

DEFINITIONS

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.

Governing Barrier Test Procedure
OVSC Test Procedures for FMVSS Nos. 208, 214D, or 301 per Table 1. Each of these procedures is available on the agency website: www.NHTSA.dot.gov

High Voltage
Any voltage greater than 30 volts of AC or 60 volts of DC or continuous current.

High-Voltage Component
Any device in a high-voltage system that operates at high voltage, but requires an electrical connection to a high-voltage source in order for high voltage to be present.

High-Voltage Source
Any device in a high-voltage system that generates or stores energy and produces high-voltage levels. Examples of high-voltage sources include, but are not limited to: E batteries, fuel cells, ultra-capacitors, flywheels.

High-Voltage System
Any electrically connected set of devices which receives, generates, or otherwise utilizes high voltage.

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 megohmmeter safely and accurately 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 a high-voltage system, source, or component while the vehicle is in use.

Test Voltage
Chosen voltage set-point for the megohmmeter for a particular high-voltage system, source, or component.

Unloaded Vehicle Weight (UVW)
Weight of a vehicle with maximum capacity of all fluids necessary for operation of the vehicle, but without cargo, occupants, or accessories that ordinarily are removed from the vehicle when not in use. (571.3)

Vehicle Capacity Weight (VCW)
Rated cargo and luggage load plus 68 kg times the vehicle's designated seating capacity (571.110, S3). Vehicle Capacity Weight for school buses follow the calculation contained within the governing barrier test procedure.

INSTRUMENTATION AND TEST EQUIPMENT

Measurement Interface

Measurements throughout this test must be made quickly and safely. To ensure these requirements are met, the testing laboratory must devise, for Contracting Officer's Technical Representative (COTR) approval, a test interface port or other device to facilitate these measurements.

Measurement and interface requirements are:

- All measurements must be recorded upon connection to the interface port.
- The test interface port equipment must be easily accessible from the exterior of the vehicle.

- The test interface must provide connections to high-voltage sources and chassis ground; for high-voltage DC sources, this requirement entails connections to the high-voltage positive and negative terminals and chassis ground.
- The mounting of this test interface port must be configured so that no movement, interference, or damage can result to it from a barrier crash test.
- The test interface port must incorporate a fuse and any other necessary safety device or procedure to protect the data measurement and recording equipment from damage and to protect test technicians from electrical hazards.

A terminal block or circuit board is recommended as a means of providing an external interface.

The following is an example quoted from Transport Canada document, *Test Procedures, Frontal Impact 208-212-301F-305F, No. 03-002:*

> “This kit is composed of a PVC box compliant with the electrical code and containing insulated banana connectors that allow the measuring equipment to be connected for the verification of the standard. A warning light indicates the presence of voltage inside the box. A shielded cable with three conductors, 20 feet in length and capable of supporting 600 volts, connects the box to the vehicle’s electrical system. This cable is covered with orange-colored mechanical protection (similar to the hybrid vehicle high-voltage identification code). The box is protected by a 0.5-amp fuse.”

Test Instrumentation

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

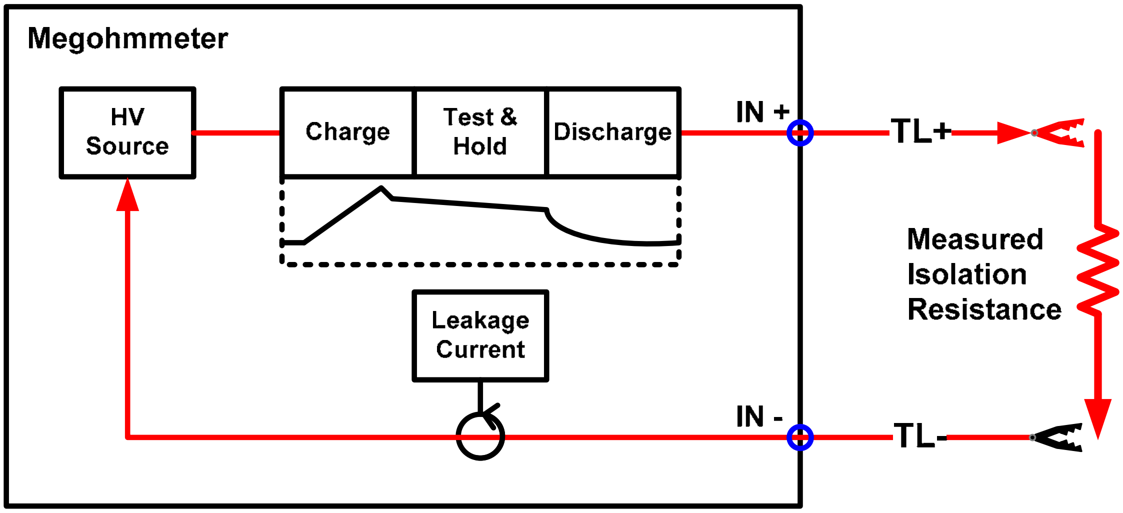

Figure 1. Diagram of a megohmmeter with positive and negative test leads, TL+ and TL-, respectively.

Table 2 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 fuel cell coolant and ambient temperatures, are necessary for normalization.

Table 2. Equipment list and minimum specifications.

Equipment	Requirement	Minimum Specifications
Megohmmeter	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.

PRETEST REQUIREMENTS

The megohmmeter leads must be zeroed according to the manufacture's instruction manual. Typically, the megohmmeter should be zeroed every time the megohmmeter is powered on and any time contact leads are connected or changed.

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

VEHICLE INSTRUMENTATION

The vehicle must be equipped with an interface port that provides electrical connections to each of the high-voltage sources, as described in the **Measurement Interface** Section.

For a high-voltage source without disconnects, Figure 2 illustrates the test points available on the interface port: **TP1**, **TP2**, and **TPGND**. **TP1** is connected to the positive high-voltage terminal, **HV+**. **TP2** is connected to the negative high-voltage terminal, **HV-**, and **TPGND,** to the vehicle chassis ground. **IR** is the isolation resistance between the high-voltage source and the vehicle chassis. The megohmmeter measures the combined effects of **R+**, **R-**, and **IR**.

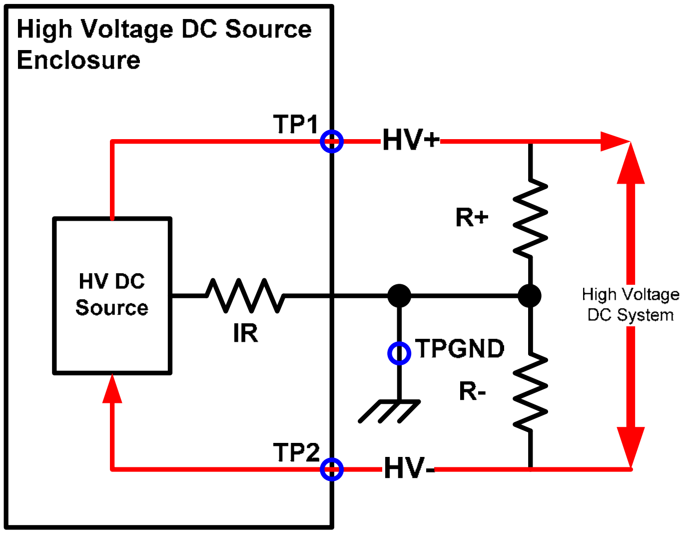

Figure 2. High-voltage source with marked test points providing direct access to the high-voltage terminals.

As shown in Figure 3, some high-voltage systems employ safety disconnects to separate the high-voltage sources from the rest of the system in the event of a crash, thus removing the high voltage from the remainder of the system. If the high-voltage source is inactive during the measurement stages of the FMVSS 305 tests, all four test points plus ground must be wired to the interface port, regardless if the disconnects are integrated into the high-voltage source enclosure. Figure 3 shows the electrical test points that must be connected to measure electrical isolation and to determine that proper disconnections occur.

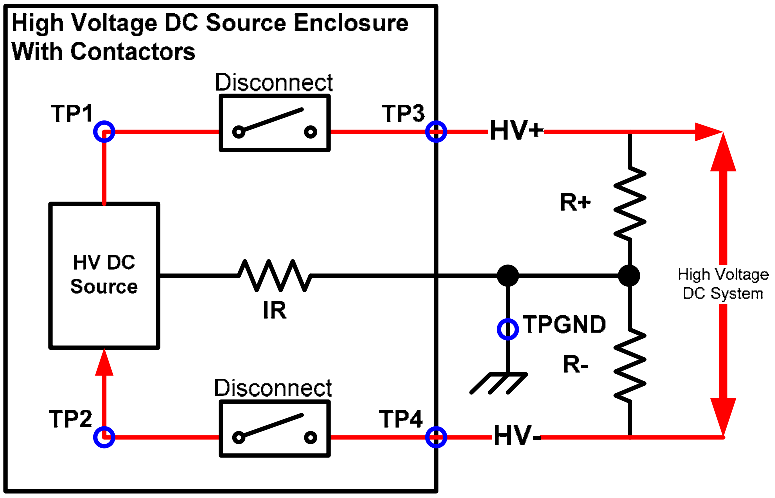

Figure 3. High-voltage source with marked test points having direct access to the high-voltage terminals.

Figure 4 shows the electrical overview of a single high-voltage source connected to the interface port. The port terminals are referenced in the test procedure for connections with the megohmmeter and multimeter.

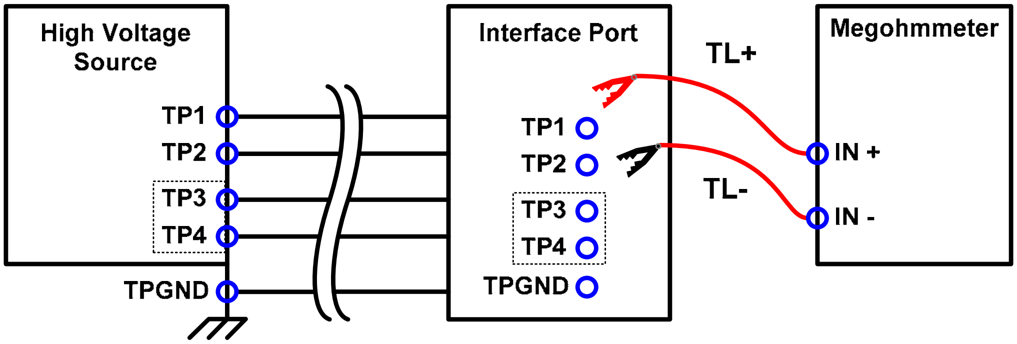

Figure 4. Overview of the test setup for one high-voltage source.

TEST VEHICLE PREPARATION

Measurements must be made with propulsion energy storage system connected to the vehicle propulsion system and the vehicle in the “ready-to-drive” (propulsion motor(s) activated) position.

It is important to verify that each of the high-voltage sources to be tested is inactive for the megohmmeter measurements. For example, to render a HFC 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 voltage.

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 $V_{\mathbf{off}}$ 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.

The interface port that provides access to the appropriate test points for the high-voltage source(s) of the test vehicle must be installed.

The vehicle's safety systems should operate in states that emulate the nominal conditions of a running vehicle. For example, high-voltage disconnects should be closed for impact tests.

PREIMPACT ELECTRICAL ISOLATION MEASUREMENT

For each high-voltage source instrumented on the interface port, the following measurements are required prior to the barrier impact test with no alterations of test setup between the steps.

1. With a voltmeter, *verify* less than $\mathbf{V_{off}}$ across
   TP1 and **TP2**,
   TP1 and **TPGND**,
   TP2 and **TPGND**.
   If voltage is present, *discontinue* this procedure and use FMVSS 305 to determine electrical isolation resistance and voltage, either **R1** and **V1** or **R2** and **V2**.

2. *Record* ambient and, if applicable, fuel cell coolant *temperatures*.

3. If the high voltage source has disconnects, with a voltmeter *verify* less than $\mathbf{V_{off}}$ across
   TP3 and **TP4**,
   TP3 and **TPGND**,
   TP4 and **TPGND**.
   If the voltages are less than a volt, with an ohmmeter *verify* closed *electrical continuity* from
   TP1 to **TP3**,
   TP2 to **TP4**.

4. Select the settings for the megohmmeter according to Table 2 and the high voltage source.

5. *Connect* **TP1** to **TP2**.
   Connect the megohmmeter leads
   TL+ to **TP1**,
   TL- to **TPGND**.
   Trigger the megohmmeter to acquire the *isolation resistance* from the shorted terminals of the *high voltage source*, **TP1** and **TP2**, to chassis ground, **TPGND**.

If the high voltage source has disconnects and were verified open in Step 3,
connect the megohmmeter leads
TL+ to **TP3**,
TL- to **TPGND**.
Trigger the megohmmeter to acquire the *isolation resistance* from the positive terminal of the *high voltage bus* **TP3** to chassis ground **TPGND**.

6. If the high voltage source has disconnects and were verified open in Step 3,
   Connect the megohmmeter leads
   TL- to **TP4**,
   TL+ to **TPGND**.
   Trigger the megohmmeter to acquire the *isolation resistance* from the negative terminal of the *high voltage bus* **TP4** to chassis ground **TPGND**.

TEST EXECUTION – POSTIMPACT ELECTRICAL ISOLATION MEASUREMENT

The following steps are to be made after the barrier impact test for each high voltage source. With a voltmeter, *verify* less than $\mathbf{V_{off}}$ across
TP1 and **TP2**,
TP1 and **TPGND**,
TP2 and **TPGND**.
If voltage is present, *discontinue* this procedure and use FMVSS 305 to determine electrical isolation resistance and voltage, either **R1** and **V1** or **R2** and **V2**.

A. *Record* ambient and, if applicable, fuel cell coolant *temperatures*.

B. If the high voltage source has disconnects, with a voltmeter *verify* less than $\mathbf{V_{off}}$ across
TP3 and **TP4**,
TP3 and **TPGND**,
TP4 and **TPGND**.
If the voltages are less than $\mathbf{V_{off}}$, with an ohmmeter *verify* open *electrical continuity* from
TP1 to **TP3**,
TP2 to **TP4**.

C. Select the settings for the megohmmeter according to Table 2 and the high voltage source.

D. *Connect* **TP1** to **TP2**.
Connect the megohmmeter leads
TL+ to **TP1**,
TL- to **TPGND**.
Trigger the megohmmeter to acquire the *isolation resistance* from the shorted terminals of the *high voltage source*, **TP1** and **TP2**, to chassis ground, **TPGND**.

E. If the high voltage source has disconnects and were verified open in Step C,
Connect the megohmmeter leads
TL+ to **TP3**,
TL- to **TPGND**.
Trigger the megohmmeter to acquire the *isolation resistance* from the positive terminal of the *high voltage bus* **TP3** to chassis ground **TPGND**.

F. If the high voltage source has disconnects and were verified open in Step C,
Connect the megohmmeter leads
TL- to **TP4**,
TL+ to **TPGND**.
Trigger the megohmmeter to acquire the *isolation resistance* from the negative terminal of the *high voltage bus* **TP4** to chassis ground **TPGND**.

ACCEPTANCE CRITERIA

To satisfy postcrash electrical safety, the high-voltage source must maintain a minimum level of electrical isolation from the vehicle chassis. If applicable, disconnects must be shown to have opened properly as a result of a crash in order to consider the remaining high-voltage components disconnected from high-voltage sources and, therefore, electrically safe. If any high-voltage components of the system are powered due to the lack of disconnects or otherwise, then the high-voltage electrical isolation requirements must be met at those high-voltage components as well as sources: i.e., greater than 100 ohms/volt for high-voltage DC (above 60 volts DC) and greater than 500 ohms/volt for high-voltage AC (above 30 volts AC).

NOTE: In Figures 2 and 3, the resistances, **R+** and **R-** electrically approximate the combined effects for both conductors of a high-voltage component to chassis ground. The measurements performed within this procedure can be affected by many design-specific factors not accounted for in Figures 2 and 3. R+ and R-, when measured in the inactive state with a megohmmeter, will not equal values if the measurement was taken in an active state, i.e., TP-305-01. Therefore, some circuit analysis will be necessary to calculate the effective isolation resistance from the measurement data so that a valid comparison can be made to the results of the legacy procedure in FMVSS TP-305-01 2005 performed on the same, but active high-voltage source.

Appendix B

Test Procedure Datasheets

Data Sheet No. 1
Test Vehicle Specifications

TEST VEHICLE INFORMATION

Year/Make/Model/Body Style ____________________
NHTSA No.:_______; Color:____________; Date Received:___________
Odometer Reading: _______miles
Selling Dealer:____________________
& Address:____________________

DATA FROM VEHICLE'S CERTIFICATION LABEL:

Vehicle Manufactured By:____________________
Date of Manufacture: ____________
VIN: ________________________
GVWR:_____kg. ; GAWR-Front:______kg. ; GAWR-Rear:___kg.

DATA FROM VEHICLE'S TIRE PLACARD & SIDEWALL:

Location of Placard on Vehicle:____________________
Recommended Tire Size:____________________
Recommended Cold Tire Pressure: Front:___kPa; Rear:____kPa
Size of Tires on Test Vehicle:____________________
Type of Spare Tire:____________________

VEHICLE CAPACITY DATA:

Type of front Seat (s): ____________________
Number of Occupants: Front =_____; Rear =_____;Total =____________
    G. VEHICLE CAPACITY WEIGHT (VCW) = ___________________
    H. Number of Occupants x 68 kg.= _______kg.
RATED CARGO AND LUGGAGE WEIGHT (RCLW) [A-B]:_________kg
Maximum RCLW used in testing a truck, MPV, or bus is 136 kg.
RCLW-School Bus (If Applicable)= ___________________kg

ELECTRIC VEHICLE PROPULSION SYSTEM

Type of Electric Vehicle (Electric/Fuel Cell/Hybrid/Other):____________________
Propulsion Energy Storage System Type:____________________
Nominal Voltage:__________V;
Physical Location of Automatic Propulsion Battery Disconnect:
____
Auxiliary Energy Storage System Type:____________________
Propulsion Fuel Cell Type:____________________
Nominal Fuel Cell Voltage:________V;
Physical Location of Automatic Propulsion Fuel Cell Disconnect:
____

RECORDED BY:____________________________DATE:__________________

APPROVED BY:____________________________DATE:__________________

Data Sheet No. 2
Pre-Test Data

Vehicle:________________________ NHTSA No.: __________________

CALCULATION OF TARGET TEST WEIGHT (TTW)

- Unloaded Vehicle Weight (UVW) =________________kg.
- Rated Cargo & Luggage Weight (RCLW) =__________kg.
- Weight of Part 572 Dummies = ______kg.

TARGET TEST WEIGHT = 1+2+3=____________kg.

As Tested

Test Weight of Vehicle,_____Dummies and_______kg of Cargo Weight

TOTAL TEST WEIGHT =________kg

Measured Cold Tire Pressure @ Total test Weight:
Front:________kPa; Rear:__________kPa

PROPULSION BATTERY SYSTEM DATA:
(COTR supplied data)
Electrolyte Fluid Type:____
Electrolyte Fluid Specific Gravity:______________________________________
Electrolyte Fluid Kinematic Viscosity:________________________centistokes
Electrolyte Fluid Color:____
Propulsion Battery Coolant Type, Color, Specific Gravity (if applicable):
____
Location of Battery Modules:

☐ Inside Passenger Compartment:
☐ Outside Passenger Compartment:

Propulsion Battery State of Charge:

☐ Maximum State of Charge: ____________
Test Voltage
(No less than 95% of Maximum State of Charge): ____________

OR

☐ Range of Normal Operating Voltage:___________
Test Voltage
(Within Normal Operative Voltage Range): ____________

PROPULSION FUEL CELL SYSTEM DATA:
(COTR supplied data)

Type:____

Propulsion Fuel Cell Coolant Type, Color, Specific Gravity (if applicable):

____

Location of Fuel Cell Modules:

☐ Inside Passenger Compartment:
☐ Outside Passenger Compartment:

VEHICLE CHASSIS GROUND POINT(S) LOCATION(S):

Details of Vehicle Chassis Ground Point(s) & Location(s) [Supply photographs as appropriate]:

____
____
____
____
____

OTHER HIGH VOLTAGE ENERGY STORAGE SYSTEM:

Details of Propulsion System Components [Supply photographs as appropriate]:

____
____
____
____

Comments: ____________________________________
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RECORDED BY:_________________________DATE:______________

APPROVED BY:_________________________DATE:______________

Data Sheet No. 3
Pre-Impact Electrical Isolation Measurements & Calculations

Vehicle:________________________ NHTSA No.:__________________________

MEGOHMMETER INFORMATION:

Make:_____________; Model:_________________; S/N:__________________________

Last Calibration Date:_______________________________

Test Voltage (**Vt**):___________V; Dwell Time:__________sec; Charge Time:_________sec

TEMPERATURE SENSOR INFORMATION

Make:_____________; Model:_________________; S/N:__________________________

MULTIMETER INFORMATION:

Make:_____________; Model:_________________; S/N:__________________________

Internal Impedance Value:_________MΩ Maximum Voltage Rating:_______________V

Measurement Accuracy:__________% Last Calibration Date:__________________

Maximum Nominal Working Voltage for the Vehicle (**Vmax**):______________________V

HIGH VOLTAGE SYSTEM TO VEHICLE CHASSIS

High Voltage Source (Fuel Cell, Battery, Ultra-Capacitors, other): ___________________

A. Verify the voltages from

TP1 to **TP2** = ____________V
TP1 to **TPGND** = ____________V
TP2 to **TPGND** = ____________V

- NOTE: If the voltages are not zero do not continue with the megohmmeter measurement.

Did the procedure transition to FMVSS 305: (YES / NO)

Use FMVSS 305 to determine electrical isolation resistance and voltage, either **R1** and **V1** or **R2** and **V2**.

Ri1 = ____________Ω **V1** = ____________V
Ri2 = ____________Ω **V2** = ____________V

ENVIROMENTAL MEASUREMENTS

B. Ambient Temperature = ________________C;
Fuel Cell Coolant Temperature = _________C;

HIGH VOLTAGE SYSTEM TO VEHICLE CHASSIS ELECTRICAL ISOLATION

State of High Voltage Source Disconnects

C. Does the High Voltage Source employ disconnects: (YES / NO)

Verify the voltages from

TP3 to **TP4** = ____________V
TP3 to **TPGND** = ____________V
TP4 to **TPGND** = ____________V

If the voltages are zero, verify closed electrical continuity from

TP1 to **TP3** = ____________Ω
TP2 to **TP4** = ____________Ω

Megohmmeter Settings

D. Settings for the megohmmeter:

Test Voltage = ____________V
Charge Time = ____________s
Dwell Time = ____________s

Other Settings:____
____
____
____

High Voltage Source Electrical Isolation Measurement

E. Measure raw isolation resistance from the shorted terminals of the high voltage source, **TP1** and **TP2**, to chassis ground, **TPGND**.

HVS Ri = ________________Ω

High Voltage Bus Electrical Isolation Measurement

F. If the high voltage source has disconnects and were verified open in step C., measure raw isolation resistance from the positive terminal of the high voltage bus **TP3** to chassis ground **TPGND**.

HVB+ Ri = ______________Ω Time:_______minutes _____s

G. If the high voltage source has disconnects and were verified open in step C., measure raw isolation resistance from the negative terminal of the high voltage bus **TP4** to chassis ground **TPGND**.

HVB- Ri = ______________Ω Time:_______minutes _____s

Isolation resistances normalized to the test voltage (**Vt**):

HVS Ri/Vt = ______________Ω/V (Electrical Isolation Value)
HVB+ Ri/Vt = ______________Ω/V (HVB Electrical Isolation Value)
HVB- Ri/Vt = ______________Ω/V (HVB Electrical Isolation Value)

H. Does the vehicle maintain an electrical isolation of no less than 100 Ohms/Volt between the inactive high voltage DC source and the vehicle's electricity-conducting structure:
(YES / NO (Fail) / NA)

Comments:____
____
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RECORDED BY:______________________________DATE:_______________
APPROVED BY:______________________________DATE:_______________

Data Sheet No. 4
Post-Impact Electrical Isolation Measurements and Calculations

Vehicle:________________________ NHTSA No.:__________________________

MEGOHMMETER INFORMATION:

Make:_____________; Model:_________________; S/N:__________________________

Last Calibration Date:_______________________________

Test Voltage (**Vt**):___________V; Dwell Time:__________sec; Charge Time:_________sec

TEMPERATURE SENSOR INFORMATION

Make:_____________; Model:_________________; S/N:__________________________

MULTIMETER INFORMATION:

Make:_____________; Model:_________________; S/N:__________________________

Internal Impedance Value:_________MΩ Maximum Voltage Rating:_______________V

Measurement Accuracy:__________% Last Calibration Date:__________________

Maximum Nominal Working Voltage for the Vehicle (**Vmax**):______________________V

HIGH-VOLTAGE SYSTEM TO VEHICLE CHASSIS

High-Voltage Source (Fuel Cell, Battery, Ultra-Capacitors, other): ___________________

A. Verify the voltages from

TP1 to **TP2** = ____________V Time:_______minutes _____s
TP1 to **TPGND** = ____________V Time:_______minutes _____s
TP2 to **TPGND** = ____________V Time:_______minutes _____s

- **NOTE:** If the voltage measurement is not zero volts, do not continue with the megohmmeter measurement.

Did the procedure transition to FMVSS 305: (YES / NO)

Use FMVSS 305 to determine electrical isolation resistance and voltage, either **R1** and **V1** or **R2** and **V2**.

Ri1 = ____________Ω **V1** = ____________V
Ri2 = ____________Ω **V2** = ____________V

ENVIROMENTAL MEASUREMENTS

B. Ambient Temperature = ________________C Time:_______minutes _____s
Fuel Cell Coolant Temperature = _________C Time:_______minutes _____s

HIGH-VOLTAGE SYSTEM TO VEHICLE CHASSIS ELECTRICAL ISOLATION

High-Voltage Source Quick Disconnects

C. Does the High-Voltage Source employ disconnects: (YES / NO)
Verify the voltages from
TP3 to **TP4** = ____________V Time:_______minutes _____s
TP3 to **TPGND** = ____________V Time:_______minutes _____s
TP4 to **TPGND** = ____________V Time:_______minutes _____s

If the voltages are zero, verify open electrical continuity from
TP1 to **TP3** = ____________Ω Time:_______minutes _____s
TP2 to **TP4** = ____________Ω Time:_______minutes _____s

Megohmmeter Settings

D. Settings for the megohmmeter:
Test Voltage = ____________V
Charge Time = ____________s
Dwell Time = ____________s

Other Settings:____
____
____
____

High-Voltage Source Electrical Isolation Measurement

E. Measure raw isolation resistance from the shorted terminals of the high-voltage source, **TP1** and **TP2**, to chassis ground, **TPGND**.
HVS Ri = _______________Ω Time:_______minutes _____s

High-Voltage Bus Electrical Isolation Measurement

F. If the high-voltage source has disconnects and were verified open in step C., measure raw isolation resistance from the positive terminal of the high-voltage bus **TP3** to chassis ground **TPGND**.
HVB+ Ri = ______________Ω Time:_______minutes _____s

G. If the high-voltage source has disconnects and were verified open in step C., measure raw isolation resistance from the negative terminal of the high-voltage bus **TP4** to chassis ground **TPGND**.
HVB- Ri = ______________Ω Time:_______minutes _____s

Isolation resistances normalized to the test voltage (**Vt**):

HVS Ri/Vt = ______________Ω/V (Electrical Isolation Value)
HVB+ Ri/Vt = ______________Ω/V (HVB Electrical Isolation Value)
HVB- Ri/Vt = ______________Ω/V (HVB Electrical Isolation Value)

H. Does the vehicle maintain an electrical isolation of no less than 100 ohms/volt between the high-voltage DC sources and the vehicle's electricity-conducting structure:
(YES / NO (Fail) / NA)

I. Is fuel cell coolant spillage visible on human accessible areas of the vehicle?
(YES / NO / NA)

Comments:____
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RECORDED BY:____DATE:___________________

APPROVED BY:____DATE:___________________

Appendix C

Test Procedure Verification Report

Report Number 305-BMI-09-001

Electrical Isolation Test Procedure Using a Megohmmeter Validation Report

Ford Motor Company Corporation	General Motors
2004 Ford Focus Sedan	2009 Chevrolet Equinox
NHSTA No.___________	NHSTA No.___________

Prepared by:
Battelle Memorial Institute
505 King Avenue
Columbus, OH 43201

Prepared for

National Highway Traffic Safety Administration
Office of Applied Vehicle Safety Research
Washington, DC

Contract No. DTNH22-08-D-00080 Task Order 4

10 September 2009

Executive Summary

Battelle was tasked to develop and validate the Electrical Isolation Test Procedure using a Megohmmeter for Hydrogen Fuel Cell Vehicles (HFCVs) for the National Highway Traffic Safety Administration (NHTSA), Office of Applied Vehicle Safety Research (OAVSR).

Battelle conducted on-site demonstrations with Original Equipment Manufacturers (OEMs) HFCVs. The demonstrations were conducted at the General Motors Corporation (GMC) Milford Proving Grounds, Milford, Michigan, using a 2009 Chevy Equinox HFCV on June 24, 2009 and at the Ford Motor Company, Dearborn, Michigan, Facility using a 2004 Ford Focus HFCV.

The demonstrations at the OEMs were successful in measuring the electrical isolation failure condition utilizing a megohmmeter, validating the applicability of a safety tester, collecting logistics information for executing the procedure, data collection, and general test procedure execution.

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1.0 Purpose of Test

The primary objective of the task was to validate the isolation failure mode caused by a vehicle crash of the Hydrogen Fuel Cell Vehicle (HFCV) with the megohmmeter test procedure by conducting on-site demonstrations with Original Equipment Manufacturers (OEMs) HFCVs.

The first demonstration was conducted at the General Motors Corporation (GMC) Milford Proving Grounds, Milford, Michigan, using a 2009 Chevy Equinox HFCV on June 24, 2009. The second demonstration was conducted the following day at the Ford Motor Company, Dearborn, Michigan, Facility, using a 2004 Ford Focus HFCV.

2.0 Test Procedure and Discussion Results

2.1 Test Procedure Development

The NHTSA Office of Vehicle Safety Compliance (OVSC) provides guidelines for uniform testing processes through the requirements of Federal Motor Vehicle Safety Standards (FMVSS). FMVSS No. 305 specifies performance requirements for limitation of electrolyte spillage, retention of propulsion batteries, and electrical isolation of the vehicle chassis from the high-voltage system during a crash event. This test procedure was written specifically to test the electrical isolation of the vehicle chassis from the high-voltage system utilizing a megohmmeter.

The proposed vehicle electrical isolation requirements must:

- Maintain an electrical isolation of no less than 500 ohms/volt between the high-voltage AC sources and the vehicle's electricity-conducting structure
- Maintain an electrical isolation of no less than 100 ohms/volt between the high-voltage DC sources and the vehicle's electricity-conducting structure.

These requirements are applicable to passenger cars, multipurpose passenger vehicles, trucks, and buses with a gross vehicle weight rating (GVWR) of 4536 kg or less; use more than 30 nominal volts alternating current (AC) or 60 nominal volts direct current (DC) of electricity; and whose speed, attainable in 1.6 km on a paved level surface, is more than 40 km/h.

Under a previous contract with NHSTA, the rationale and concept of testing the electrical isolation using a megohmmeter were proposed. This effort was to develop the test procedure and to confirm the successful electrical isolation of the failure mode.

2.2 Test Procedure Verification

Battelle created a test plan to simulate an electrical isolation failure mode of an HFCV for the megohmmeter test procedure verification. Battelle also analyzed the relationship between the test voltage and source leakage current requirements of the acceptance criteria, calculated the correct resistance value to insert between the fuel cell and the vehicle chassis, and simulated an isolation failure below 100 ohms/volt.

Access to the Chevrolet Equinox fuel cell test points was located in the engine compartment under the hood. When measuring the voltage between the high-voltage sources and vehicle chassis, Battelle found that if the vehicle is in a deenergized state, residual voltage is present, giving the illusion of an active low-voltage source when measuring the inactive high-voltage source. The voltage level originally was expected to be lower than 1 volt, but during the GM test, the measured values were above this threshold. However, the voltage was low enough for the megohmmeter to perform an accurate resistance measurement.

The procedure was modified to indicate that the tester or OEM is responsible to determine if the voltage measurements for $\mathbf{V_{off}}$ made while disconnected are indicative of a de-energized state and compatible with the selected measurement instrumentation.

When the dry run of the draft Electrical Isolation Test Procedure using a megohmmeter was performed on the Ford Focus HFCV at the Dearborn Test Facility, access to the Focus fuel cell test points was located in the undercarriage of the vehicle. To obtain access to the test points, the vehicle was placed on a vehicle lift. The procedure was followed, but the megohmmeter failed to acquire isolation measurements.

Battelle evaluated the test procedure, the test data, and the overall test setup and determined that the vehicle chassis was no longer isolated from earth ground, thus causing the data to be skewed. When the Ford Focus was suspended on the lift via the vehicle chassis, the vehicle ground path was going through the lift to the building. The megohmmeter also was powered using a building outlet. The vehicle chassis and megohmmeter now shared the same ground. This configuration caused the megohmmeter to form a ground loop during certain tests and failed to acquire accurate isolation measurements.

Battelle identified and characterized the megohmmeter ground loop issue and determined that a resistive connection from the device under test to earth ground greater than 200 ohms on the positive (+) voltage test lead would allow the QuadTech 1855 megohmmeter to perform within specification. When characterizing the megohmmeter, the results indicated that the Ford vehicle's chassis had approximately a 2 ohm connection to earth ground.

Though the megohmmeter measurements are applicable in the HFCV crash scenario, a hipot tester or safety analyzer can be better suited to both meeting the requirements of the test procedure and determining overall electrical safety. Battelle evaluated an alternative test instrument, the Quadtech Guardian 500 safety tester, relevant to the requirements of the test procedure, and determined that the safety tester functioned normally during the Ford measurements and eliminated the ground loop.

The test was rerun at Ford using the megohmmeter with a modified power connection. The ground pin of the megohmmeter's power cable was disconnected from the building ground, effectively floating the chassis of the megohmmeter. The floating chassis of a test instrument necessitated the use of insulating rubber gloves during operation to protect the operator from a potential shock hazard. The results of this configuration confirmed successful electrical isolation of the failure mode.

The test procedure was repeated using the Quadtech Guardian 500 safety tester. The safety tester test results are presented in current and voltage instead of resistance and voltage as the megohmmeter provides. The safety tester required a longer charge time to reach full voltage, was capable of testing grounded systems, and could output an AC test voltage. The safety tester results were unaffected as long as the instrument's grounded test lead was connected to the grounded chassis. The results of this configuration also confirmed successful electrical isolation of the failure mode.

The tests at the OEMs were successful in measuring the electrical isolation failure condition, validating the applicability of a safety tester, and collecting logistics information for executing the procedure, data collection, and general test procedure execution.

3.0 Test Data

3.1 GM Chevrolet Equinox Test Results

The electrical isolation test procedure using a megohmmeter was designed to measure the isolation between the fuel cell and vehicle chassis postcrash test of an HFCV with an inactive fuel cell. GMC provided access to their Fuel Cell Equinox, but would not permit a real crash test. Even though a crash test was not performed, the procedure could be executed and validated. The Equinox design permitted access underneath the hood to the test points described in the test procedure, as shown in Figure 1. The test procedure was written to require the OEM to incorporate a measurement interface to facilitate the test instrumentation connections. This interface was not required on the Equinox because the test points were easily accessible under the vehicle's hood and a removable cover.

Figure 1. GM Equinox test point access.

The safety features of the Equinox incorporated disconnects between the high-voltage output of the fuel cell and the remaining power system of the vehicle. These disconnects were designed to remain open if the car is turned off, open in an event of a crash (similar to the air bag), and open if the protective cover is removed. Therefore, when the procedure test points were accessible, the disconnects always were opened, simulating a potential crash event.

To simulate a failed isolation condition, a resistor was placed between the fuel cell and chassis. The resistor was inserted during the postcrash test portion of the procedure. The goal of the resistor was to force the isolation to drop below the 100 ohms/volt acceptance criteria. The test instrumentation was programmed to apply a voltage of 440 volts to match the nominal maximum working voltage of the Equinox. Two different pieces of equipment were used to measure isolation values. First, the megohmmeter, QuadTech 1855, was used to perform the procedure as written. Next, a safety analyzer repeated the measurements. The procedure was not designed to support the safety tester results because the information is given in volts and leakage current vs. resistance (ohms) from the megohmmeter. However, utilizing Ohms law, the matching resistance can be determined easily. The pretest results on the GM Chevrolet Equinox are shown in Table 1. The fuel cell passes the proposed100 ohms/volt requirement with 1072.5 ohms/volt. The megohmmeter was connected to the fuel cell test points as shown in Figure 2. The test points were accessible under the protective cover, providing access to both sides of the disconnects: the fuel cell high-voltage power output and the high-voltage bus.

Table 1. GM Chevrolet Equinox precrash readings.

Location	Megohmmeter		Safety Tester			
	Reading	Ohms/Volt	Current	Voltage	Ohms	Ohms/Volt
Fuel Cell	471.3 kOhms	1072.5	1.0 mA	440	440 kOhms	1000
HV Bus	192.5 kOhms	437.5	2.7 mA	440	163 kOhms	370.5

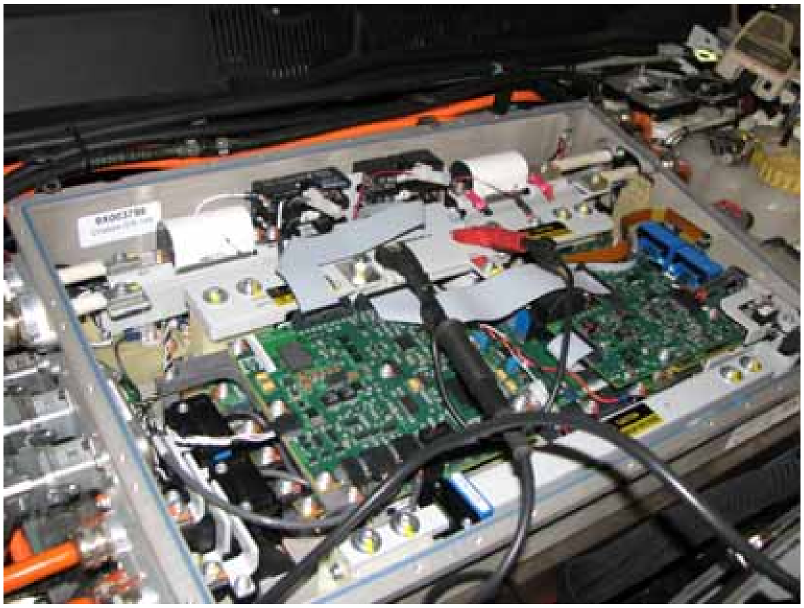


Figure 2. Megohmmeter Equinox connections.

Next, the isolation failure resistance was inserted between the fuel cell and the vehicle chassis. Again, this resistor simulated a potential failure from a crash test causing the isolation resistance to drop below the allowable threshold. The key results are shown in Table 2.

Table 2. GM Chevrolet Equinox postcrash (simulated) readings.

Location	Megohmmeter		Safety Tester			
	Reading	Ohms/Volt	Current	Voltage	Ohms	Ohms/Volt
Fuel Cell	35.93 kOhms	81.66	10.1 mA	361	35.74 kOhms	81.22
HV Bus	193.4 kOhms	439.5	2.4 mA	434	180.8 kOhms	410.1

As shown in Table 2, the isolation resistance for the fuel cell dropped to a failed 81.22 ohms/volt measurement. The megohmmeter procedure was able to detect the failed isolation between the chassis and the high-voltage source. Additionally, the safety tester was able to detect the failure mode. The HV bus measurements did not change as expected because the inserted resistor did not have an effect on this side of the disconnects.

3.2 Ford Focus HFCV Test Results

The same test procedure was performed on the Ford Focus HFCV. The Focus vehicle design located the fuel cell and electrical connections underneath the vehicle as shown in Figure 3. To access the test points required for the procedure, the vehicle was lifted on a hoist, and the enclosure cover was removed. The safety disconnects, similar to the GM design discussed above, were exposed with the enclosure cover removed. Thus, access was provided to both the fuel cell and the high-voltage bus side of the disconnects. The pretest portion of the procedure was performed, and the results are displayed in Table 3. The megohmmeter and safety analyzer were programmed to apply a test voltage equal to the maximum nominal working voltage, 380 volts DC.

Figure 3. Ford Focus fuel cell (blue box) and electronic/disconnects enclosure.

Table 3. Ford precrash results.

Location	Megohmmeter		Safety Tester			
	Reading	Ohms/Volt	Current	Voltage	Ohms	Ohms/Volt
Fuel Cell	1.2 MOhm	3158	0.3 mA	379	1.26 MOhm	3325
HV Bus	239 kOhm	629	1.6 mA	379	237 kOhm	625

Next, the isolation failure resistor (29.9 kOhm) was inserted between the fuel cell and the vehicle chassis. Again, this resistor simulated a potential failure from a crash test, causing the isolation resistance to drop below the allowable threshold. The key results are shown in Table 4.

Table 4. Ford postcrash (simulated) reading.

Location	Megohmmeter		Safety Tester			
	Reading	Ohms/Volt	Current	Voltage	Ohms	Ohms/Volt
Fuel Cell	29.1 kOhm	76.6	10.3 mA	292	28.4 kOhm	74.7
HV Bus	--	--	--	--	--	--

A failed isolation resistance measurement of 77 ohms/volt was recorded between the fuel cell and vehicle chassis. Again, the megohmmeter procedure was able to detect the failed isolation of the crashed (simulated) vehicle. Furthermore, the safety tester was able to detect the failure mode. The HV bus measurement was not recorded due to time constraints, but the values were not expected to change.

4.0 Test Equipment List and Calibration Information

4.1 Test Equipment List

The minimum specifications for the test equipment are provided in Table 5.

Table 5. Minimum specifications for test equipment.

Equipment	Requirement	Minimum Specifications
Megohmmeter	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

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

4.2 Equipment Used and Calibration Dates

Table 6 lists the test equipment used and the calibration dates for the equipment.

Table 6. Test equipment and calibration dates.

Equipment	Manufacturer	Model	Serial Number	Calibration Date
Megohmmeter	Quadtech	1855	08451440	12/23/2008
Safety Tester	Quadtech Guardian	G500V	7132045	06/08/2009
Temperature Sensor	Oakton	ION 200	101275	N/A
Multimeter	Fluke	87V	N/A	12/15/2008

5.0 Photographs

5.1 2009 Chevrolet Equinox HVFC

A photograph of the 2009 Chevrolet Equinox HVFC is shown in Figure 4.

Figure 4. Photograph of the 2009 Chevrolet Equinox HFCV provided by GMC.

5.2 2004 Ford Focus Sedan HVFC

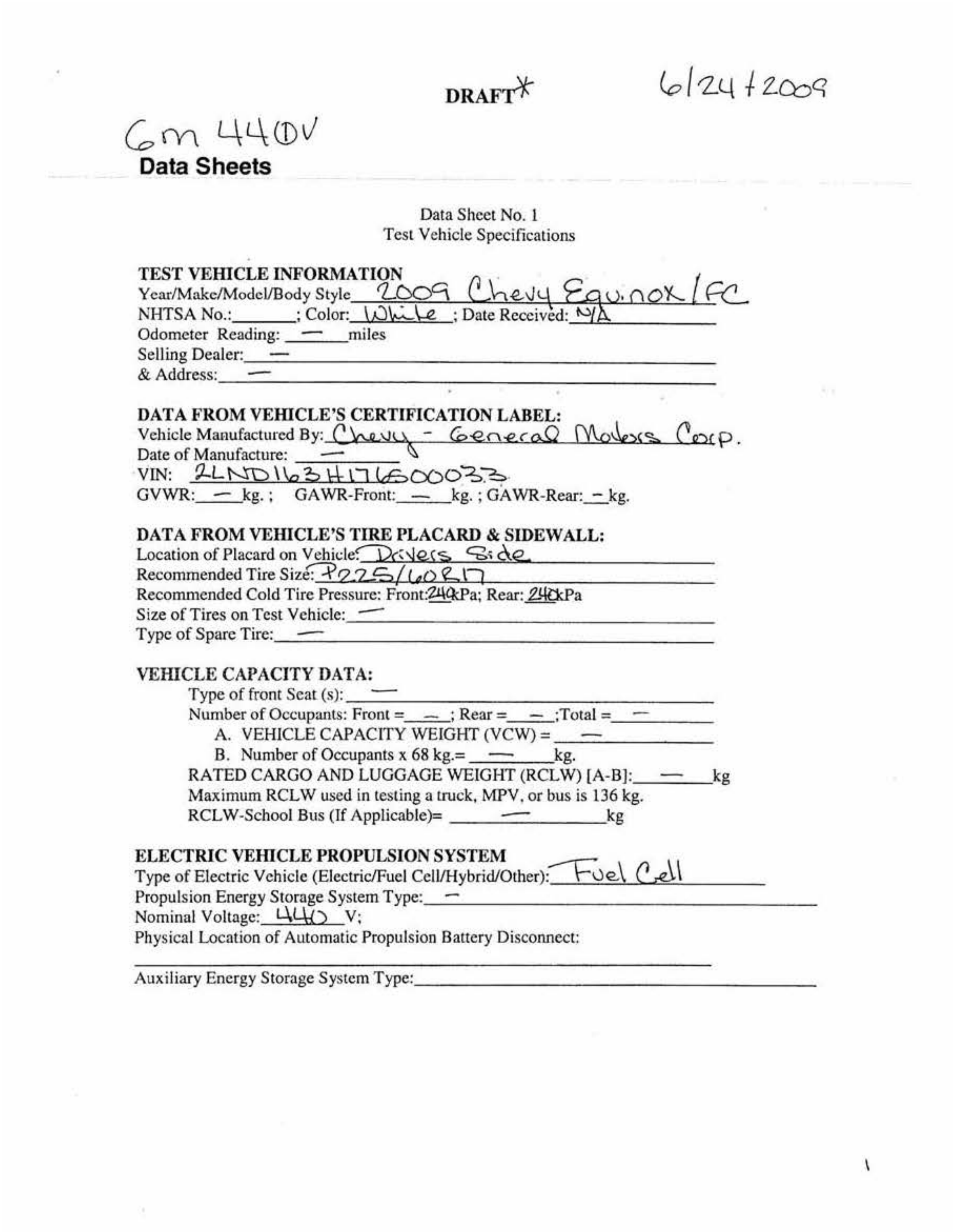
A photograph of the 2004 Ford Focus Sedan HVFC is the subject of Figure 5.

Figure 5. Photograph of the 2004 Ford Focus HFCV furnished by green.autoblog.com.

6.0 Test Data

6.1 2009 Chevrolet Equinox

Test data relative to the 2009 Chevrolet Equinox were gathered on data sheets during the validation of the test procedure. A set of these data sheets follow.



DRAFT*

6/24/2009

Gm 440V

Data Sheets

Data Sheet No. 1
Test Vehicle Specifications

TEST VEHICLE INFORMATION

Year/Make/Model/Body Style 2009 Chevy Equinox/FC
NHTSA No.:_______; Color: White; Date Received: N/A
Odometer Reading: — miles
Selling Dealer: —
& Address: —

DATA FROM VEHICLE'S CERTIFICATION LABEL:

Vehicle Manufactured By: Chevy - General Motors Corp.
Date of Manufacture: —
VIN: 2LND163H17600033
GVWR: — kg. ; GAWR-Front: — kg. ; GAWR-Rear: — kg.

DATA FROM VEHICLE'S TIRE PLACARD & SIDEWALL:

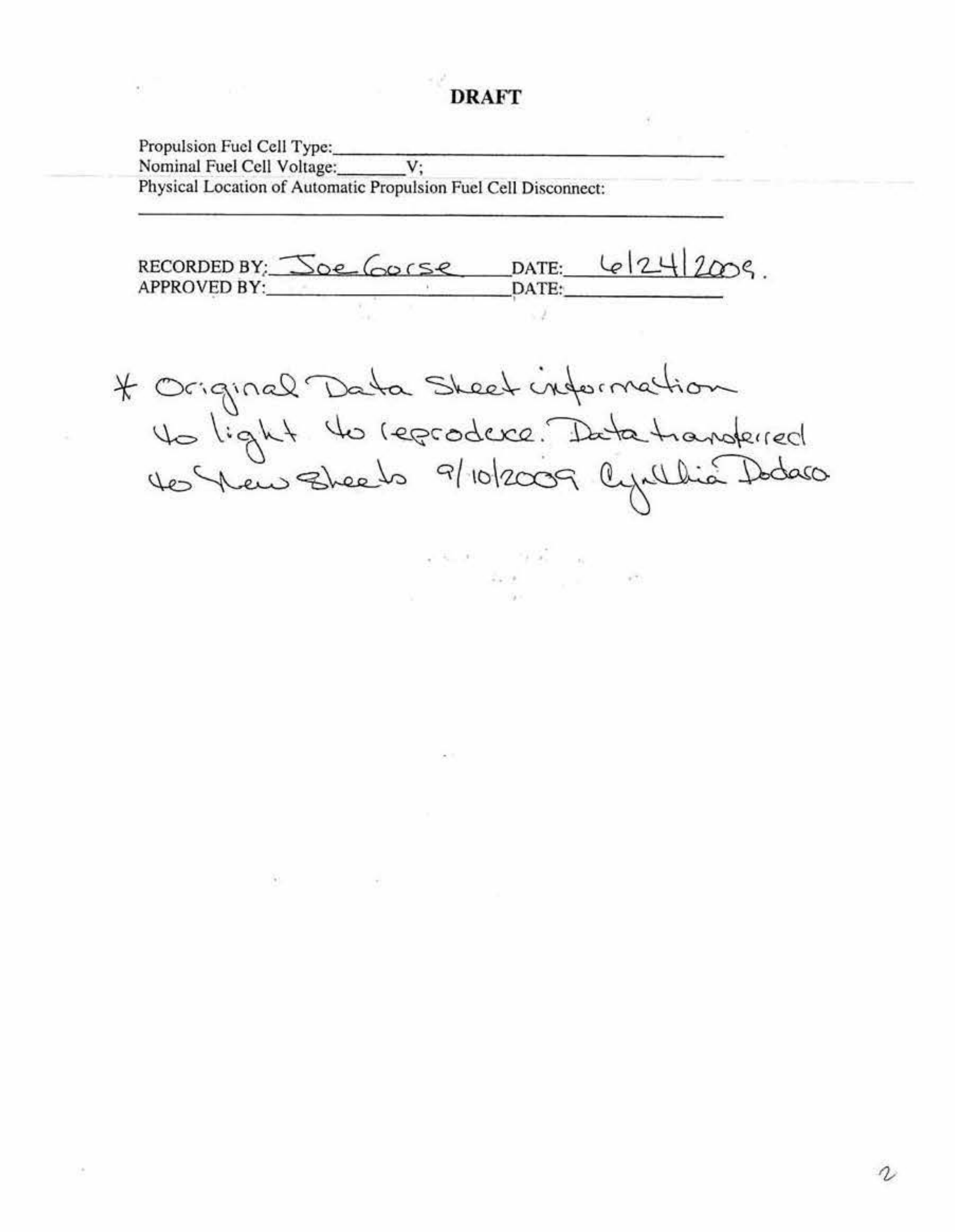
Location of Placard on Vehicle: Drivers Side
Recommended Tire Size: P225/60R17
Recommended Cold Tire Pressure: Front: 240 kPa; Rear: 240 kPa
Size of Tires on Test Vehicle: —
Type of Spare Tire: —

VEHICLE CAPACITY DATA:

Type of front Seat (s): —
Number of Occupants: Front = —; Rear = —; Total = —
A. VEHICLE CAPACITY WEIGHT (VCW) = —
B. Number of Occupants x 68 kg.= — kg.
RATED CARGO AND LUGGAGE WEIGHT (RCLW) [A-B]: — kg
Maximum RCLW used in testing a truck, MPV, or bus is 136 kg.
RCLW-School Bus (If Applicable)= — kg

ELECTRIC VEHICLE PROPULSION SYSTEM

Type of Electric Vehicle (Electric/Fuel Cell/Hybrid/Other): Fuel Cell
Propulsion Energy Storage System Type: —
Nominal Voltage: 440 V;
Physical Location of Automatic Propulsion Battery Disconnect:
____
Auxiliary Energy Storage System Type:____________________



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Propulsion Fuel Cell Type:____________________________________

Nominal Fuel Cell Voltage:________V;

Physical Location of Automatic Propulsion Fuel Cell Disconnect:

____

RECORDED BY: Joe Gorse DATE: 6/24/2009.

APPROVED BY:________________________DATE:________________

* Original Data Sheet information to light to reproduce. Data transferred to New Sheets 9/10/2009 Cynthia Dodaro

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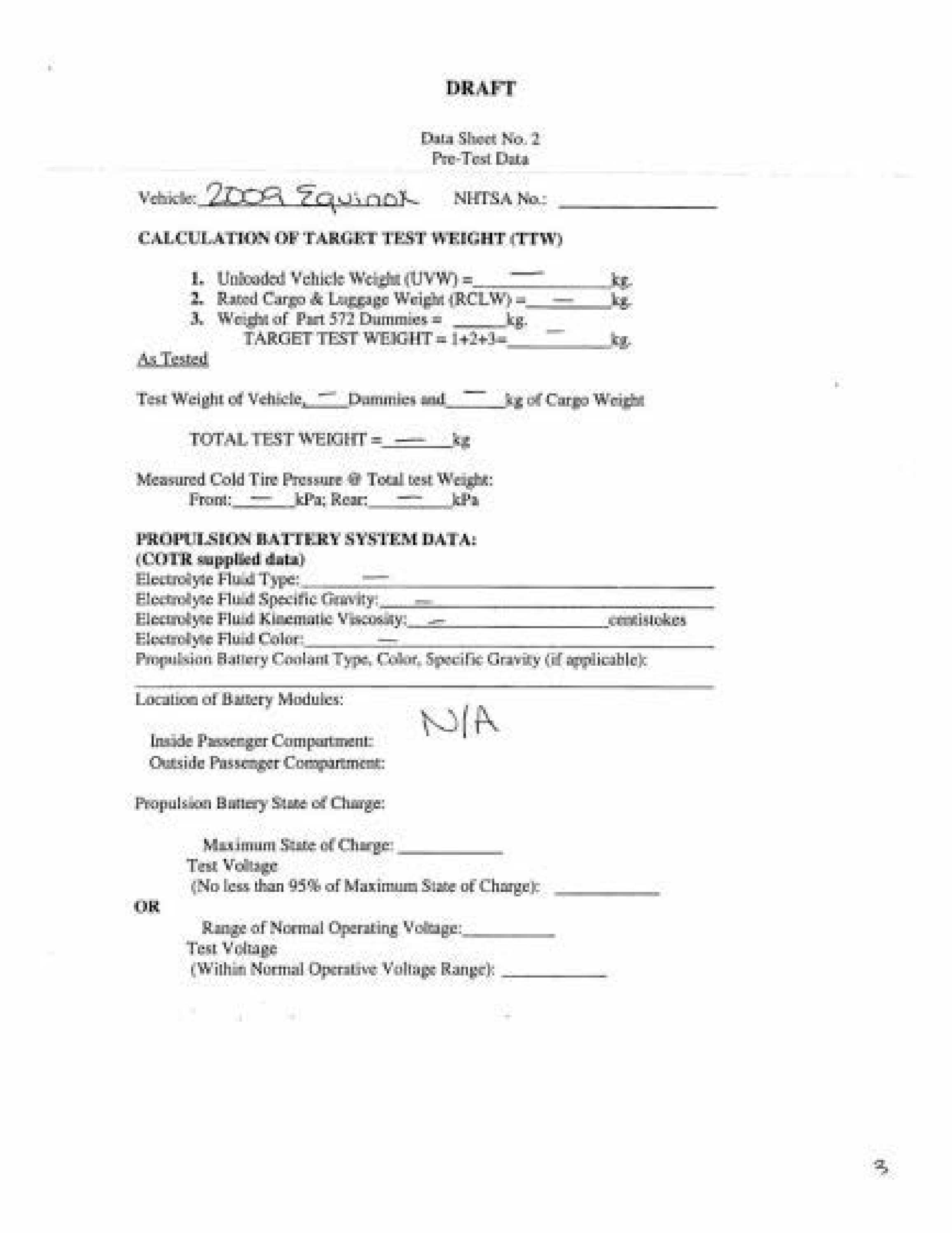

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Data Sheet No. 2
Pre-Test Data

Vehicle: 2009 Equinox NHTSA No.: ______________

CALCULATION OF TARGET TEST WEIGHT (TTW)

1. Unloaded Vehicle Weight (UVW) =____—______kg.
2. Rated Cargo & Luggage Weight (RCLW) =___—____kg.
3. Weight of Part 572 Dummies = _____kg. —

TARGET TEST WEIGHT = 1+2+3=__________kg.

As Tested

Test Weight of Vehicle,__—__Dummies and___—___kg of Cargo Weight

TOTAL TEST WEIGHT =__—__kg

Measured Cold Tire Pressure @ Total test Weight:
Front:__—__kPa; Rear:___—___kPa

PROPULSION BATTERY SYSTEM DATA:
(COTR supplied data)
Electrolyte Fluid Type:______—______________________________
Electrolyte Fluid Specific Gravity:____—_________________________
Electrolyte Fluid Kinematic Viscosity:__—________________centistokes
Electrolyte Fluid Color:________—_________________________
Propulsion Battery Coolant Type, Color, Specific Gravity (if applicable):
____

Location of Battery Modules:

Inside Passenger Compartment: N/A
Outside Passenger Compartment:

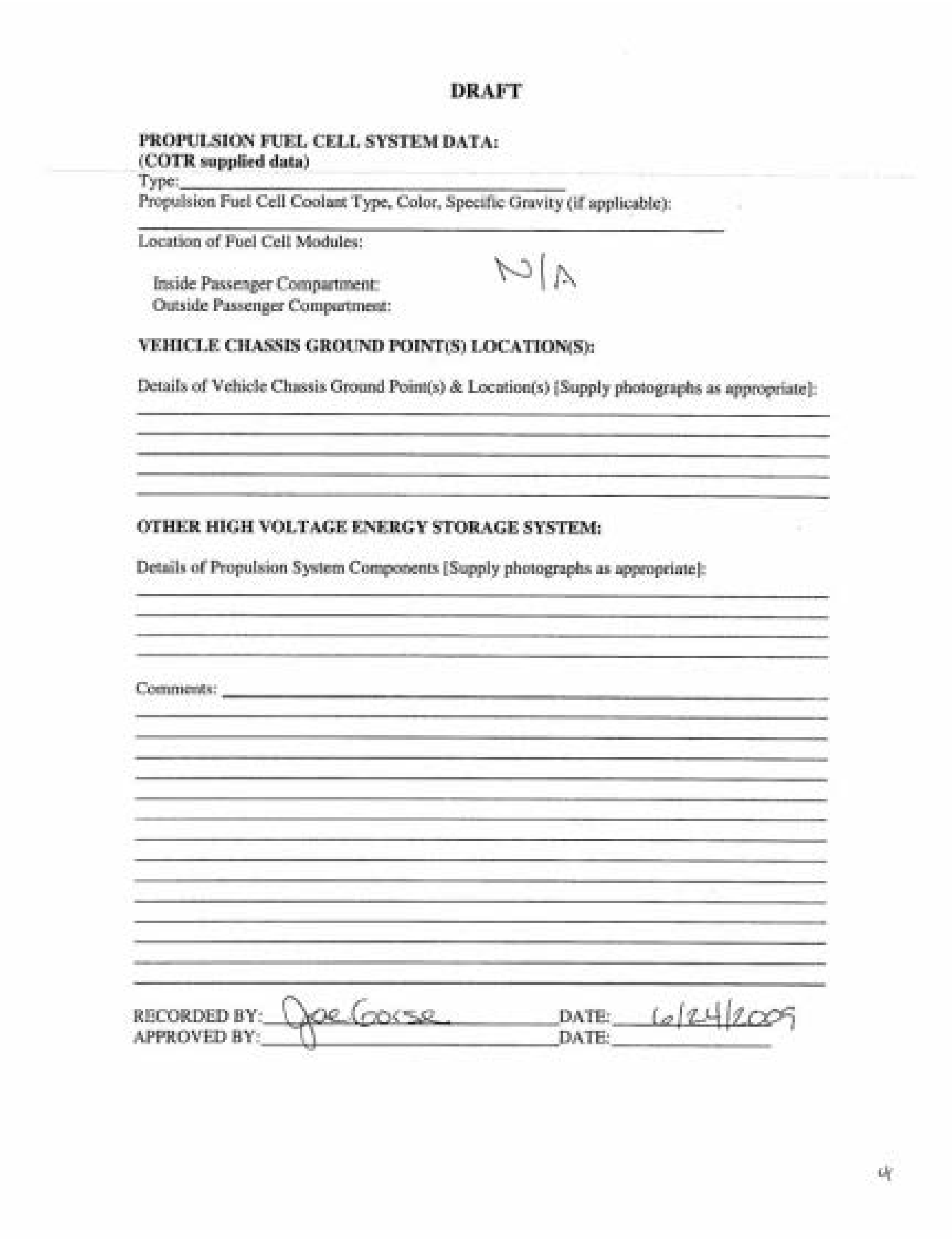
Propulsion Battery State of Charge:

Maximum State of Charge: __________
Test Voltage
(No less than 95% of Maximum State of Charge): __________

OR

Range of Normal Operating Voltage:_________
Test Voltage
(Within Normal Operative Voltage Range): __________

3



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PROPULSION FUEL CELL SYSTEM DATA:
(COTR supplied data)

Type:____

Propulsion Fuel Cell Coolant Type, Color, Specific Gravity (if applicable):

Location of Fuel Cell Modules:

Inside Passenger Compartment: N/A
Outside Passenger Compartment:

VEHICLE CHASSIS GROUND POINT(S) LOCATION(S):

Details of Vehicle Chassis Ground Point(s) & Location(s) [Supply photographs as appropriate]:

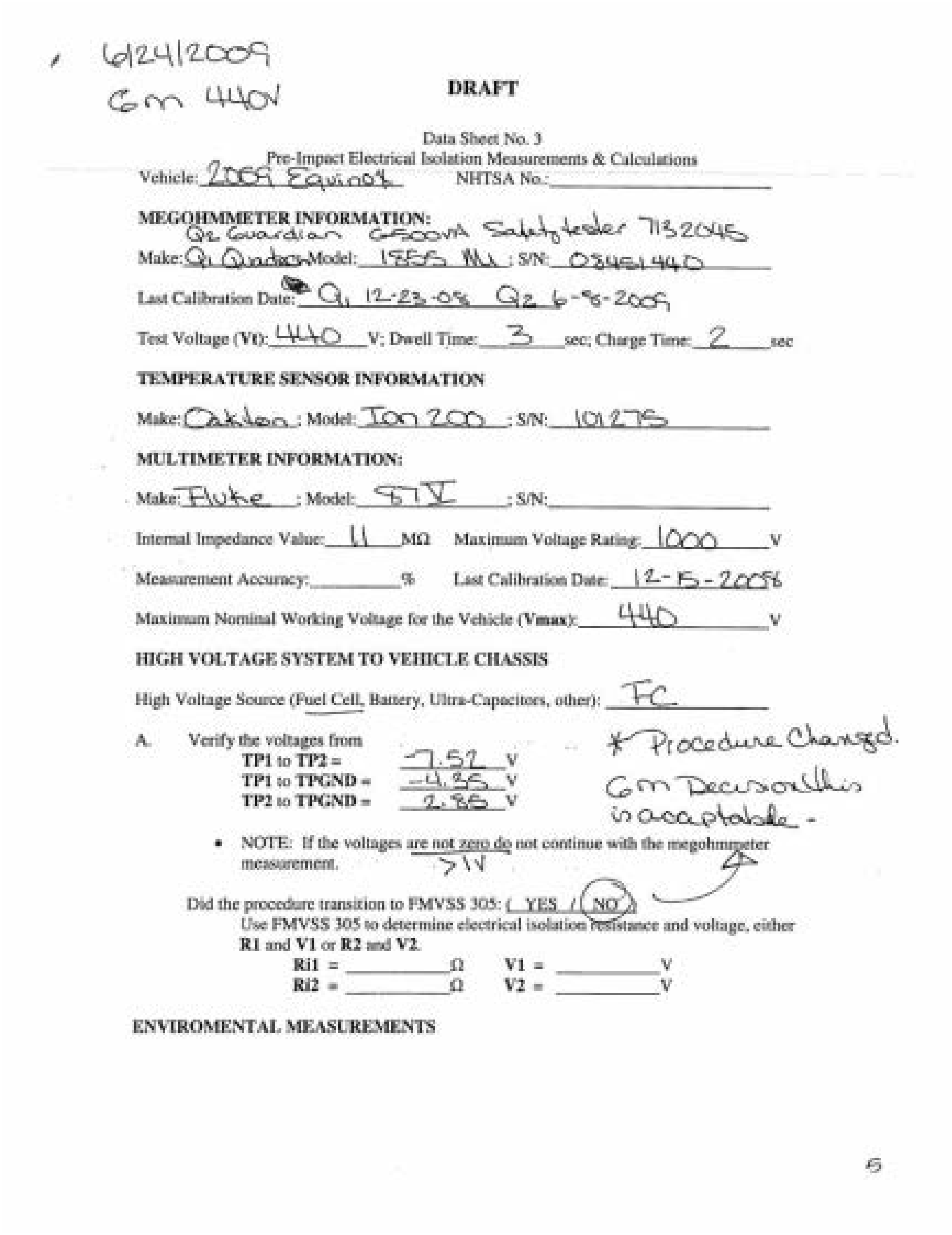
OTHER HIGH VOLTAGE ENERGY STORAGE SYSTEM:

Details of Propulsion System Components [Supply photographs as appropriate]:

Comments:

RECORDED BY: Joe Gorse DATE: 6/24/2009
APPROVED BY:____________________ DATE:__________

4



6/24/2009
GM 440V

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Data Sheet No. 3
Pre-Impact Electrical Isolation Measurements & Calculations

Vehicle: 2009 Equinox NHTSA No.:__________

MEGOHMMETER INFORMATION:
Q2 Guardian G500VA Safety tester 7132045
Make: Q1 Quadtech Model: 1855 MI ; S/N: 03451440

Last Calibration Date: Q1 12-23-08 Q2 6-8-2009

Test Voltage (Vt): 440 V; Dwell Time: 3 sec; Charge Time: 2 sec

TEMPERATURE SENSOR INFORMATION

Make: Oakton ; Model: Ion 200 ; S/N: 101275

MULTIMETER INFORMATION:

Make: Fluke ; Model: 87V ; S/N:__________

Internal Impedance Value: 11 MΩ Maximum Voltage Rating: 1000 V

Measurement Accuracy:______ % Last Calibration Date: 12-15-2008

Maximum Nominal Working Voltage for the Vehicle (**Vmax**): 440 V

HIGH VOLTAGE SYSTEM TO VEHICLE CHASSIS

High Voltage Source (Fuel Cell, Battery, Ultra-Capacitors, other): FC

A. Verify the voltages from
TP1 to **TP2** = -7.52 V
TP1 to **TPGND** = -4.35 V
TP2 to **TPGND** = 2.85 V

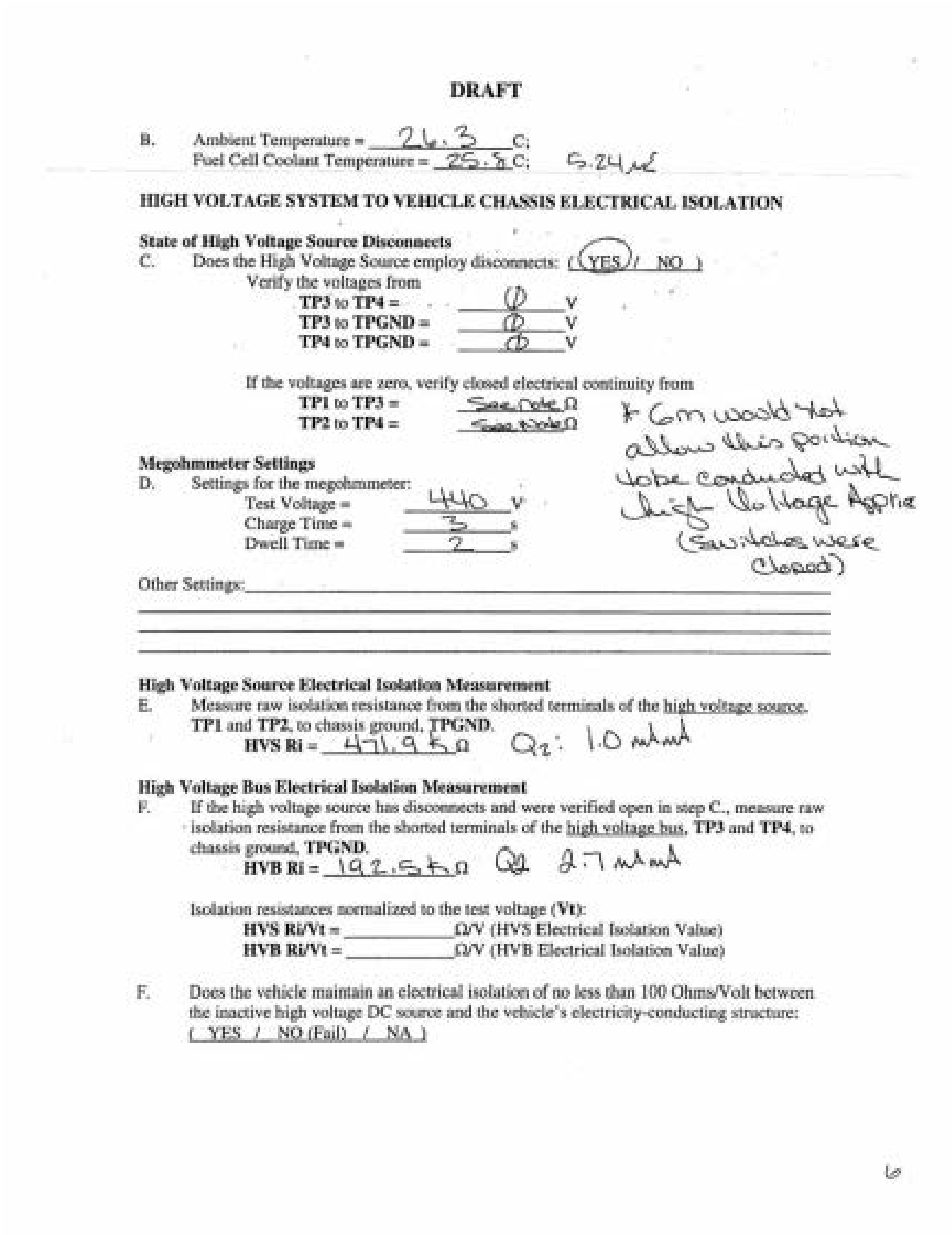
* Procedure Changed.
GM Decision this is acceptable -

- NOTE: If the voltages are not zero do not continue with the megohmmeter measurement.
>1V

Did the procedure transition to FMVSS 305: (YES / [✓ NO])
Use FMVSS 305 to determine electrical isolation resistance and voltage, either **R1** and **V1** or **R2** and **V2**.
Ri1 = ________ Ω **V1** = ________ V
Ri2 = ________ Ω **V2** = ________ V

ENVIROMENTAL MEASUREMENTS

5



DRAFT

B. Ambient Temperature = 26.3 C;
Fuel Cell Coolant Temperature = 25.8 C; 5.24ul

HIGH VOLTAGE SYSTEM TO VEHICLE CHASSIS ELECTRICAL ISOLATION

State of High Voltage Source Disconnects

C. Does the High Voltage Source employ disconnects: ([✓ YES] / NO)

Verify the voltages from
TP3 to **TP4** = 0 V
TP3 to **TPGND** = 0 V
TP4 to **TPGND** = 0 V

If the voltages are zero, verify closed electrical continuity from
TP1 to **TP3** = See note Ω
TP2 to **TP4** = See Note Ω

* GM would not allow this portion to be conducted with High Voltage Applie (Switches were Closed)

Megohmmeter Settings

D. Settings for the megohmmeter:
Test Voltage = 440 V
Charge Time = 3 s
Dwell Time = 2 s

Other Settings:____

High Voltage Source Electrical Isolation Measurement

E. Measure raw isolation resistance from the shorted terminals of the high voltage source, **TP1** and **TP2**, to chassis ground, **TPGND**.
HVS Ri = 471.9 kΩ Q2: 1.0 mA

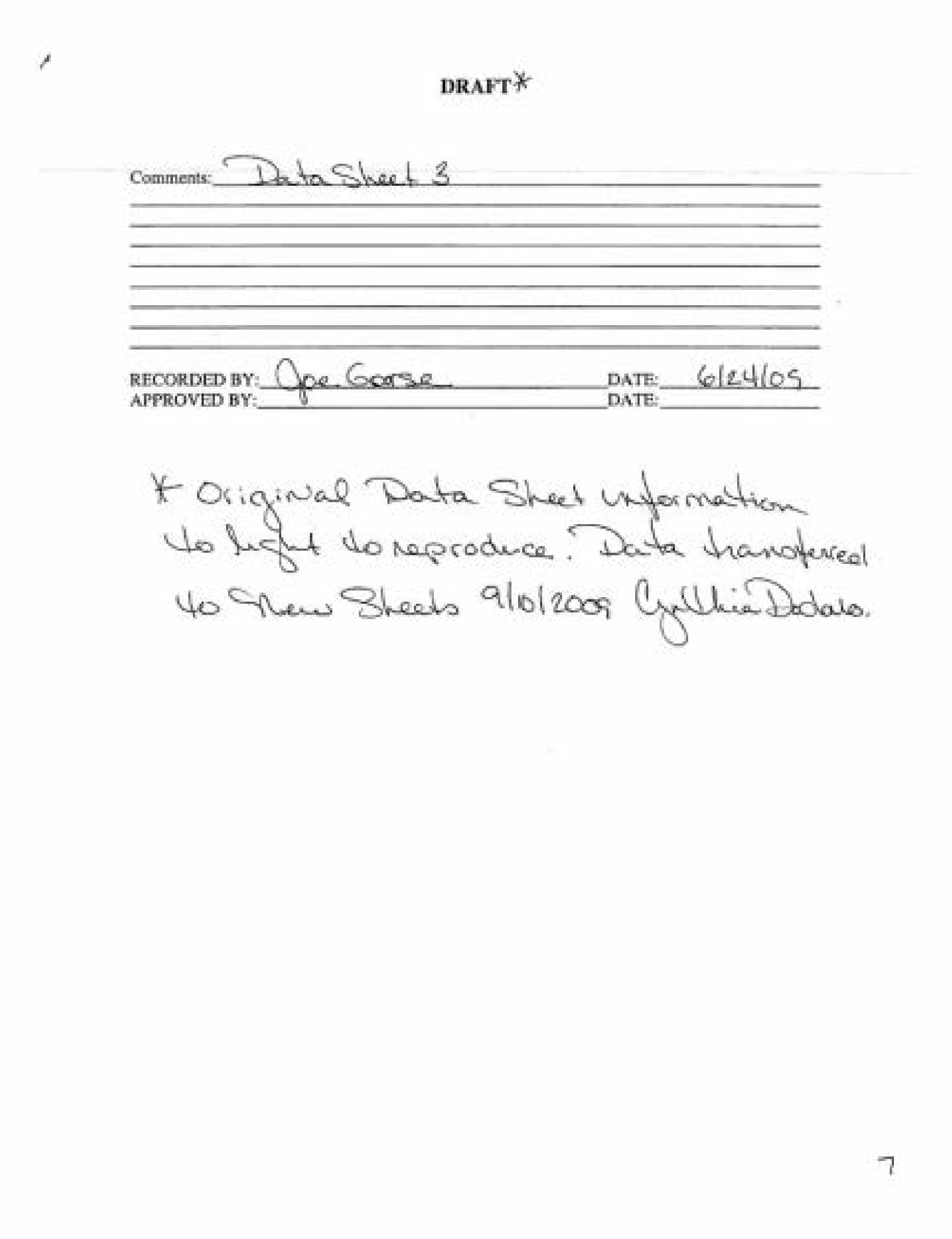
High Voltage Bus Electrical Isolation Measurement

F. If the high voltage source has disconnects and were verified open in step C., measure raw isolation resistance from the shorted terminals of the high voltage bus, **TP3** and **TP4**, to chassis ground, **TPGND**.
HVB Ri = 192.5 kΩ Q2 2.7 mA

Isolation resistances normalized to the test voltage (**Vt**):
HVS Ri/Vt = __________Ω/V (HVS Electrical Isolation Value)
HVB Ri/Vt = __________Ω/V (HVB Electrical Isolation Value)

F. Does the vehicle maintain an electrical isolation of no less than 100 Ohms/Volt between the inactive high voltage DC source and the vehicle's electricity-conducting structure:
(YES / NO (Fail) / NA)

6



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Comments: Data Sheet 3

RECORDED BY: Joe Gorse DATE: 6/24/05

APPROVED BY: DATE:

* Original Data Sheet information to light to reproduce. Data transferred to New Sheets 9/10/2009 Cynthia Dodaro.

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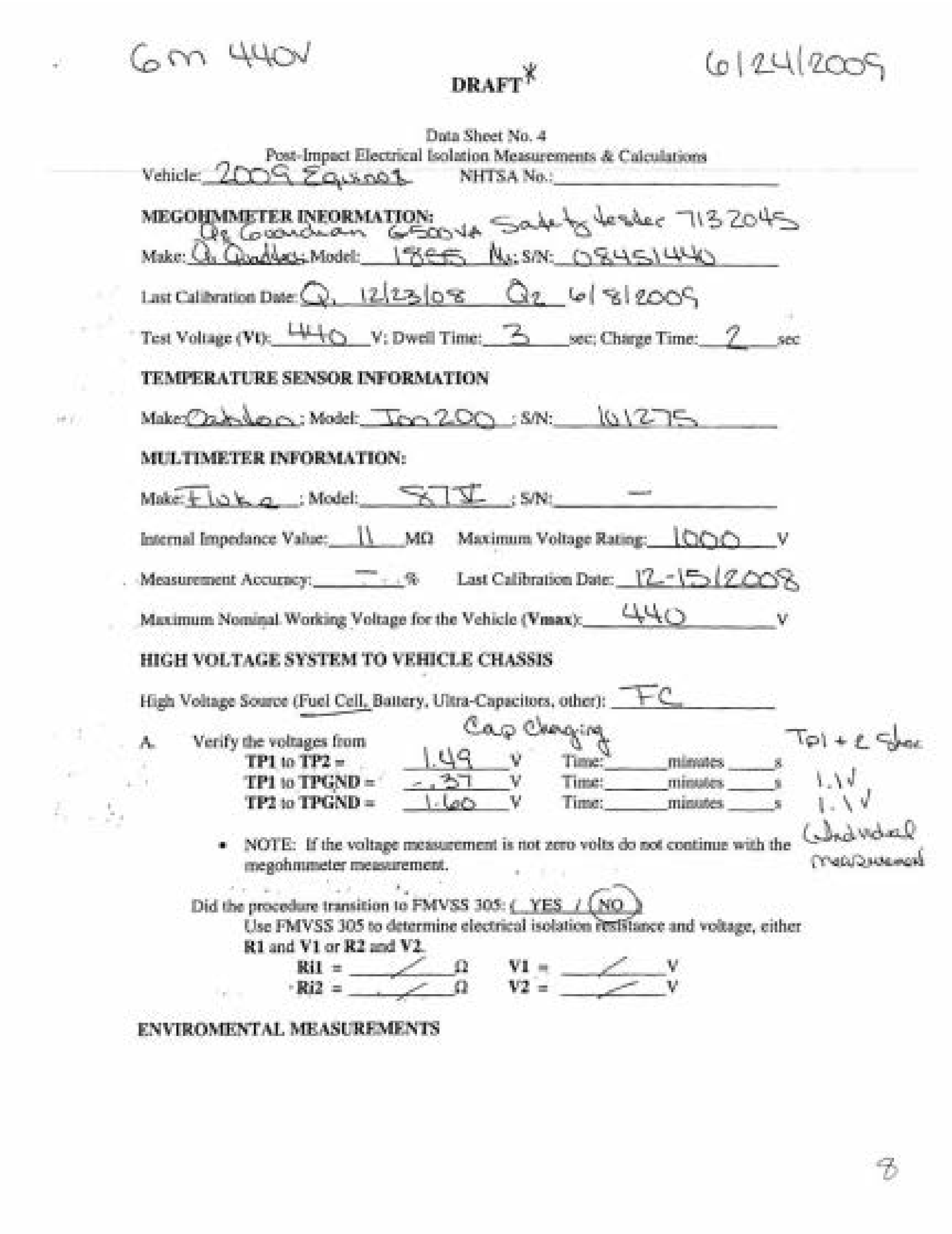

Gm 440V

6/24/2009

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Data Sheet No. 4

Post-Impact Electrical Isolation Measurements & Calculations

Vehicle: 2009 Equinox NHTSA No.: ________

MEGOHMMETER INFORMATION: Q2 Guardian 6500VA Safety tester 7132045

Make: Q1 QuadTech; Model: 1865 Q2; S/N: 08451440

Last Calibration Date: Q1 12/23/08 Q2 6/18/2009

Test Voltage (Vt): 440 V; Dwell Time: 3 sec; Charge Time: 2 sec

TEMPERATURE SENSOR INFORMATION

Make: Oakton; Model: Ion 200; S/N: 101275

MULTIMETER INFORMATION:

Make: Fluke; Model: 87V; S/N: —

Internal Impedance Value: 11 MΩ Maximum Voltage Rating: 1000 V

Measurement Accuracy: — % Last Calibration Date: 12-15/2008

Maximum Nominal Working Voltage for the Vehicle (**Vmax**): 440 V

HIGH VOLTAGE SYSTEM TO VEHICLE CHASSIS

High Voltage Source (Fuel Cell, Battery, Ultra-Capacitors, other): FC

A. Verify the voltages from Cap Charging TP1 + E Shoe

TP1 to TP2 = 1.49 V Time: ____ minutes ____ s

TP1 to TPGND = -.37 V Time: ____ minutes ____ s 1.1V

TP2 to TPGND = 1.60 V Time: ____ minutes ____ s 1.1V

Individual measurement

- NOTE: If the voltage measurement is not zero volts do not continue with the megohmmeter measurement.

Did the procedure transition to FMVSS 305: (YES / [✓ NO])

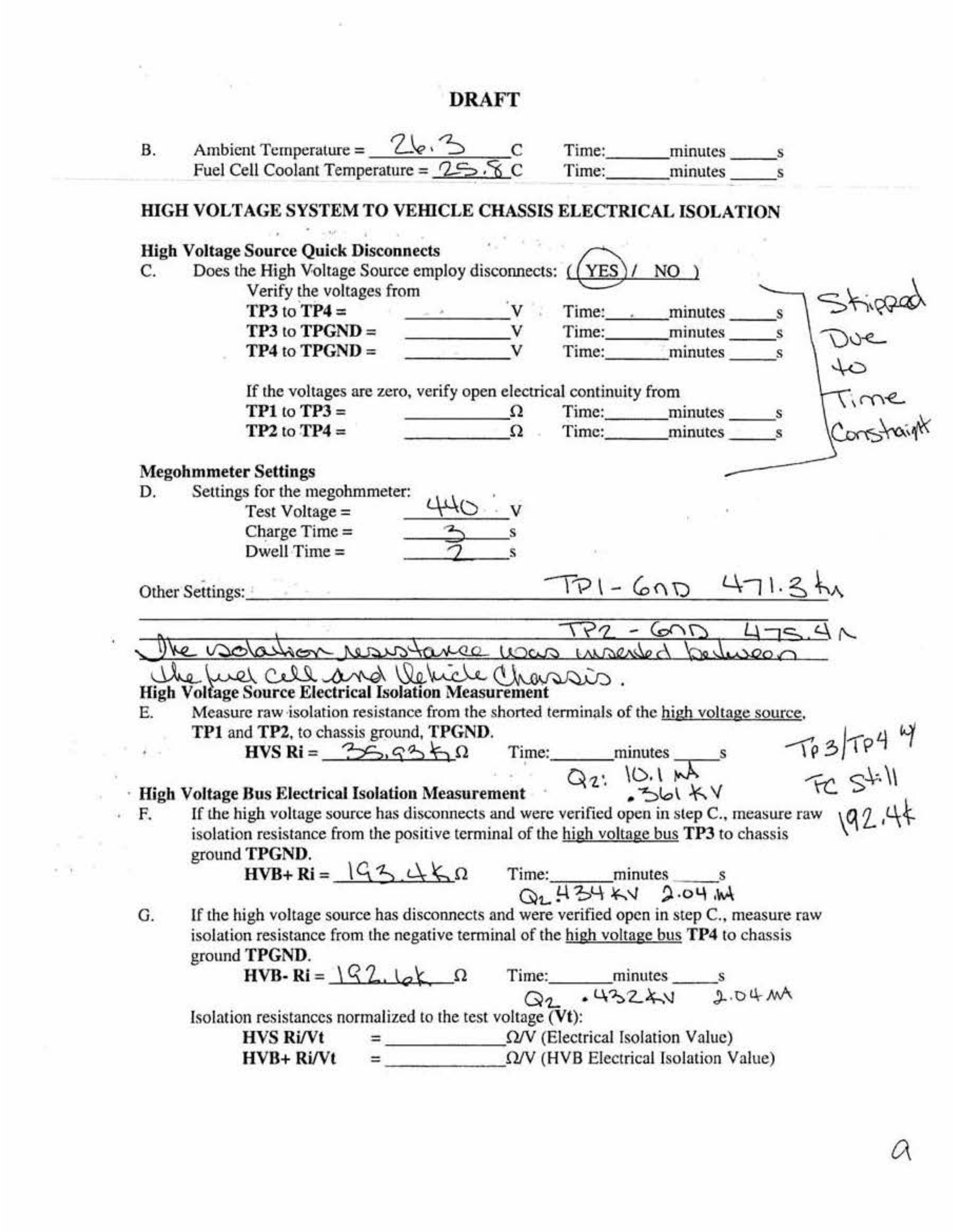
Use FMVSS 305 to determine electrical isolation resistance and voltage, either **R1** and **V1** or **R2** and **V2**.

Ri1 = / Ω **V1** = / V

Ri2 = / Ω **V2** = / V

ENVIROMENTAL MEASUREMENTS

8



DRAFT

B. Ambient Temperature = 26.3 C Time:_______minutes _____s
Fuel Cell Coolant Temperature = 25.8 C Time:_______minutes _____s

HIGH VOLTAGE SYSTEM TO VEHICLE CHASSIS ELECTRICAL ISOLATION

High Voltage Source Quick Disconnects

C. Does the High Voltage Source employ disconnects: ([✓ YES] / NO)

Verify the voltages from

TP3 to **TP4** = ___________V Time:_______minutes _____s
TP3 to **TPGND** = ___________V Time:_______minutes _____s
TP4 to **TPGND** = ___________V Time:_______minutes _____s

If the voltages are zero, verify open electrical continuity from

TP1 to **TP3** = ___________Ω Time:_______minutes _____s
TP2 to **TP4** = ___________Ω Time:_______minutes _____s

Skipped Due to Time Constraint

Megohmmeter Settings

D. Settings for the megohmmeter:

Test Voltage = 440 V
Charge Time = 3 s
Dwell Time = 2 s

Other Settings: TP1 - GND 471.3 kΩ
TP2 - GND 475.4 Ω
The isolation resistance was inserted between the fuel cell and vehicle chassis.

High Voltage Source Electrical Isolation Measurement

E. Measure raw isolation resistance from the shorted terminals of the <u>high voltage source</u>, **TP1** and **TP2**, to chassis ground, **TPGND**.

HVS Ri = 35,93 kΩ Time:_______minutes _____s
Q2: 10.1 mA
.361 kV

TP3/TP4 w/ FC still 192.4k

High Voltage Bus Electrical Isolation Measurement

F. If the high voltage source has disconnects and were verified open in step C., measure raw isolation resistance from the positive terminal of the <u>high voltage bus</u> **TP3** to chassis ground **TPGND**.

HVB+ Ri = 193.4kΩ Time:_______minutes _____s
Q2 .434 kV 2.04 mA

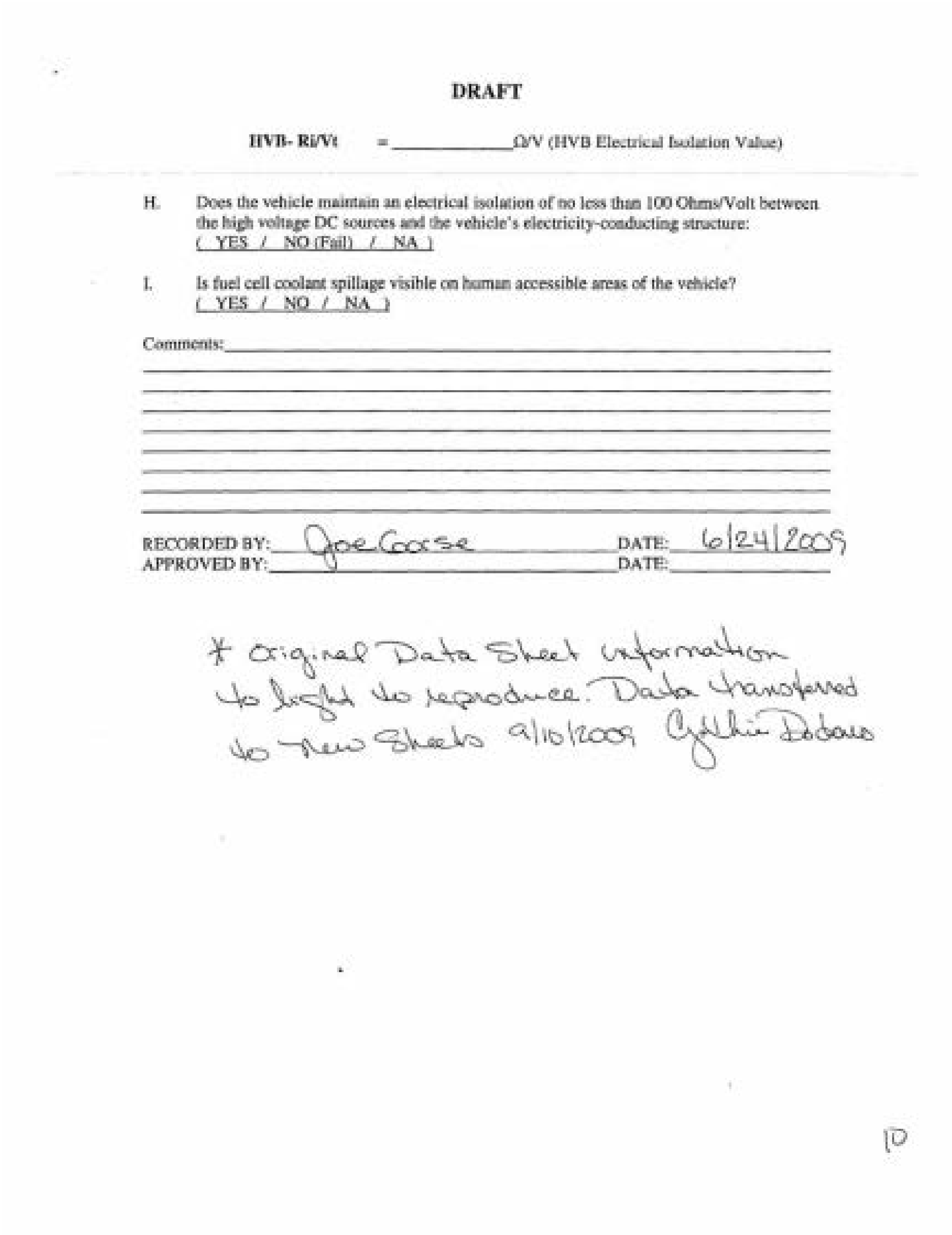
G. If the high voltage source has disconnects and were verified open in step C., measure raw isolation resistance from the negative terminal of the <u>high voltage bus</u> **TP4** to chassis ground **TPGND**.

HVB- Ri = 192.6k Ω Time:_______minutes _____s
Q2 .432kV 2.04 mA

Isolation resistances normalized to the test voltage (**Vt**):

HVS Ri/Vt = _____________Ω/V (Electrical Isolation Value)
HVB+ Ri/Vt = _____________Ω/V (HVB Electrical Isolation Value)

a



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HVB- Ri/Vt = ____________Ω/V (HVB Electrical Isolation Value)

H. Does the vehicle maintain an electrical isolation of no less than 100 Ohms/Volt between the high voltage DC sources and the vehicle's electricity-conducting structure:
(YES / NO (Fail) / NA)

I. Is fuel cell coolant spillage visible on human accessible areas of the vehicle?
(YES / NO / NA)

Comments:____

RECORDED BY: Joe Coarse DATE: 6/24/2009
APPROVED BY:____________________ DATE:__________

* Original Data Sheet information to light to reproduce. Data transferred to new Sheets 9/10/2009 Cynthia Dobans

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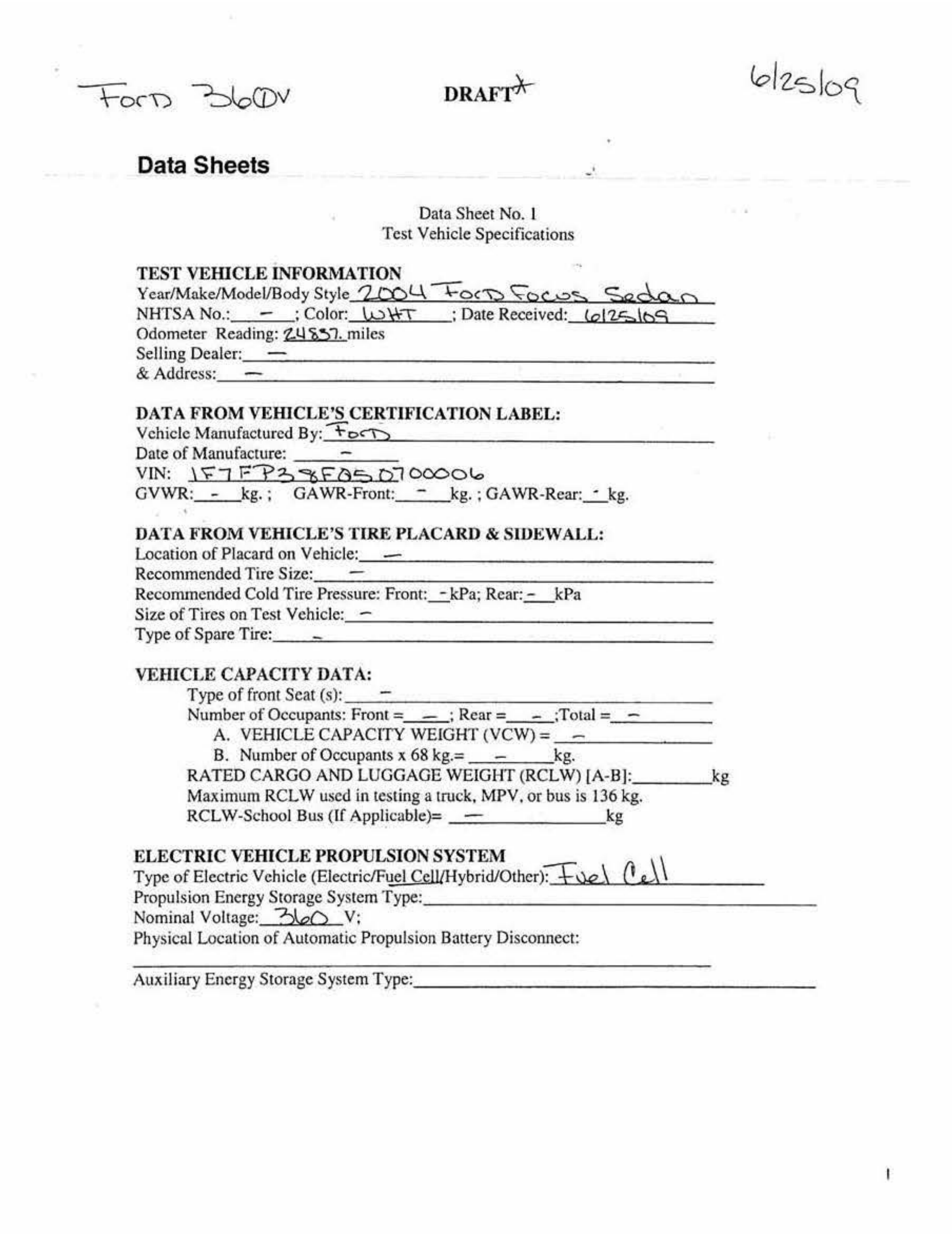
6.2 2004 Ford Focus Sedan

Test data relative to the 2004 Ford Focus Sedan were gathered on data sheets during the validation of the test procedure. A set of these data sheets follow.



Ford 360V

DRAFT*

6/25/09

Data Sheets

Data Sheet No. 1
Test Vehicle Specifications

TEST VEHICLE INFORMATION

Year/Make/Model/Body Style 2004 Ford Focus Sedan
NHTSA No.: – ; Color: WHT ; Date Received: 6/25/09
Odometer Reading: 24857. miles
Selling Dealer: –
& Address: –

DATA FROM VEHICLE'S CERTIFICATION LABEL:

Vehicle Manufactured By: Ford
Date of Manufacture: –
VIN: 1F7FP38F05D700006
GVWR: - kg. ; GAWR-Front: - kg. ; GAWR-Rear: - kg.

DATA FROM VEHICLE'S TIRE PLACARD & SIDEWALL:

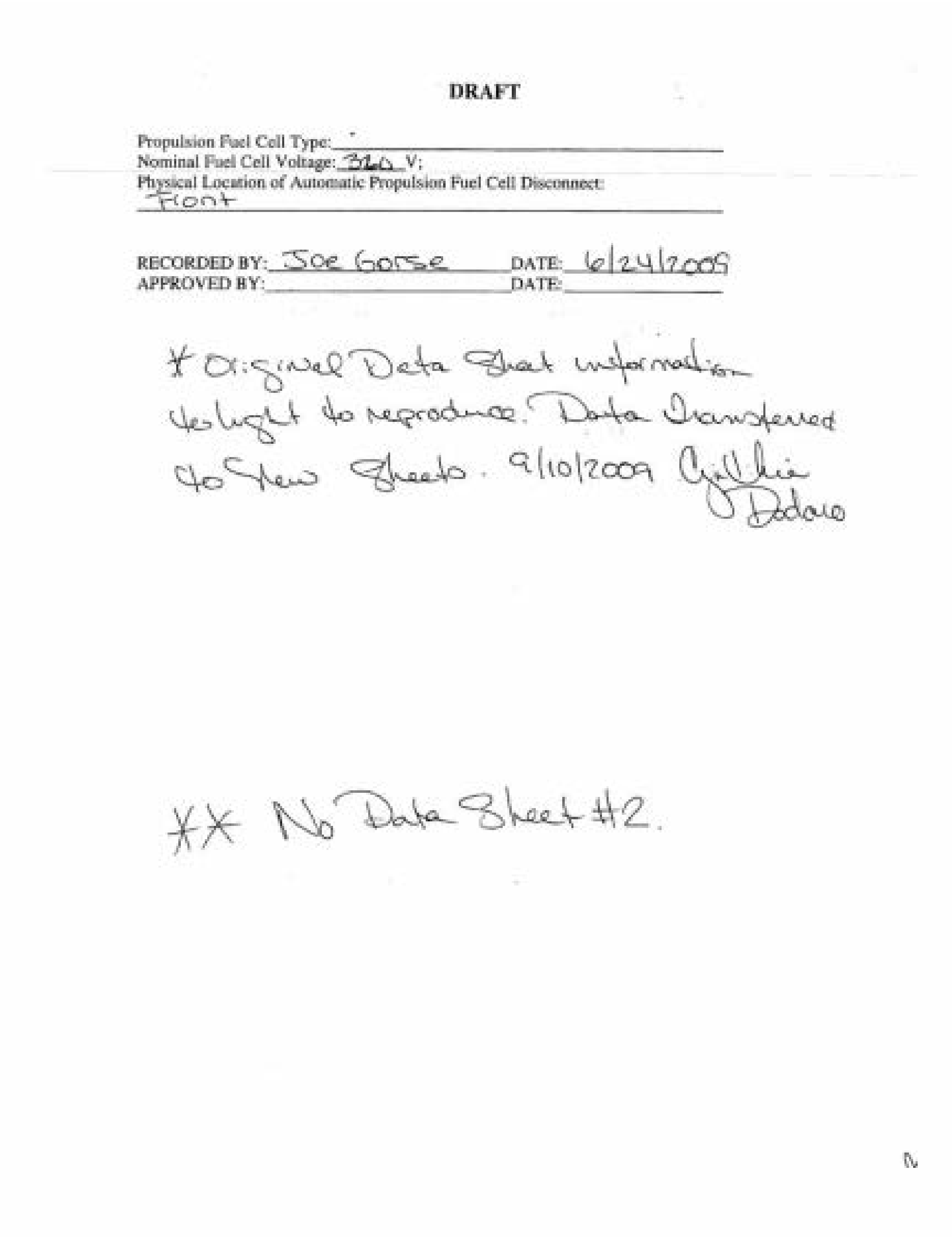
Location of Placard on Vehicle: –
Recommended Tire Size: –
Recommended Cold Tire Pressure: Front: - kPa; Rear: - kPa
Size of Tires on Test Vehicle: –
Type of Spare Tire: –

VEHICLE CAPACITY DATA:

Type of front Seat (s): –
Number of Occupants: Front = – ; Rear = – ;Total = –
A. VEHICLE CAPACITY WEIGHT (VCW) = –
B. Number of Occupants x 68 kg.= – kg.
RATED CARGO AND LUGGAGE WEIGHT (RCLW) [A-B]:_________kg
Maximum RCLW used in testing a truck, MPV, or bus is 136 kg.
RCLW-School Bus (If Applicable)= – kg

ELECTRIC VEHICLE PROPULSION SYSTEM

Type of Electric Vehicle (Electric/Fuel Cell/Hybrid/Other): Fuel Cell
Propulsion Energy Storage System Type:_________________
Nominal Voltage: 360 V;
Physical Location of Automatic Propulsion Battery Disconnect:
____
Auxiliary Energy Storage System Type:_________________



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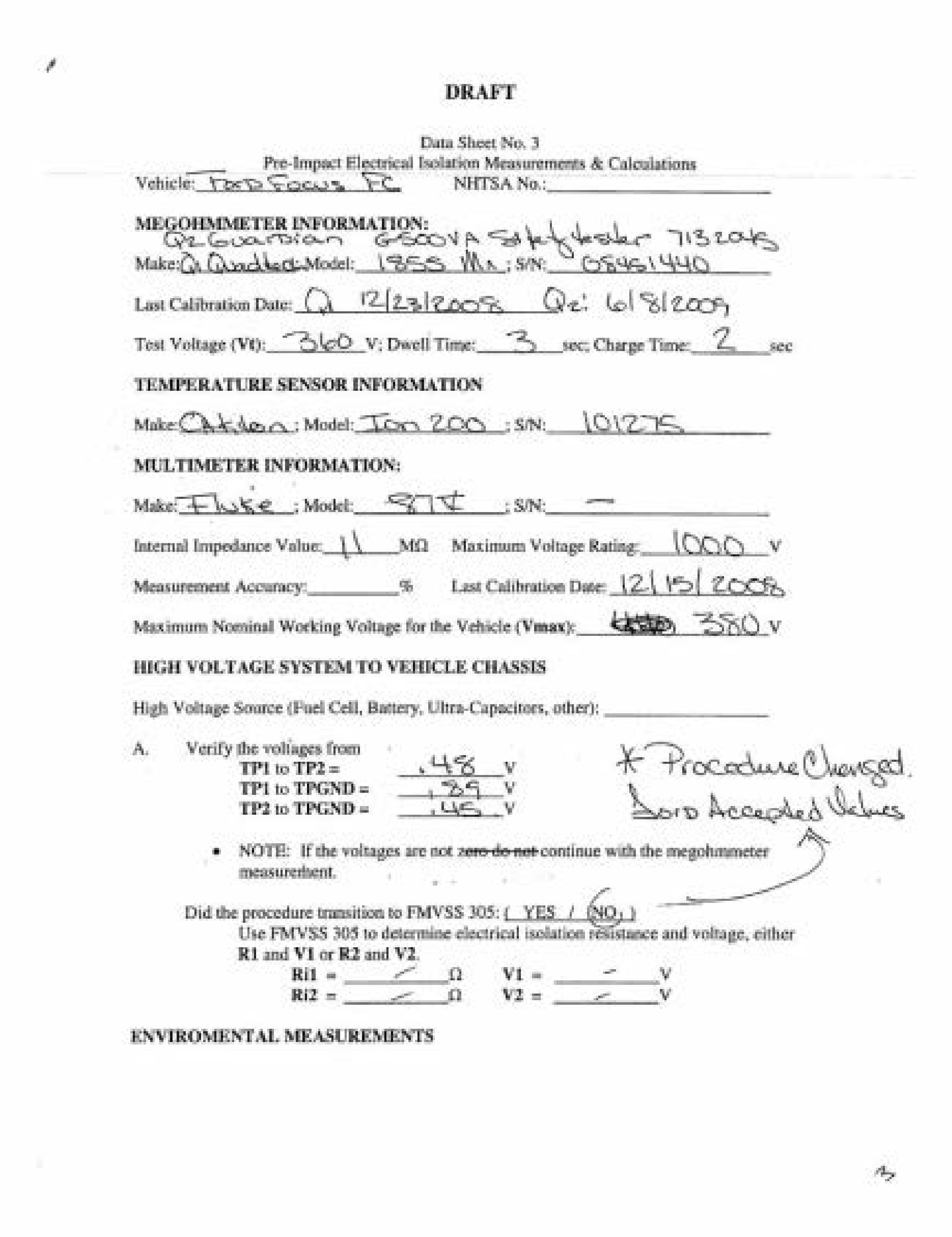
Propulsion Fuel Cell Type:
Nominal Fuel Cell Voltage: 360 V;
Physical Location of Automatic Propulsion Fuel Cell Disconnect:
Front

RECORDED BY: Joe Gorse DATE: 6/24/2009
APPROVED BY: DATE:

* Original Data Sheet information too light to reproduce. Data transferred to new sheets. 9/10/2009 Cynthia Dodaro

** No Data Sheet #2.



DRAFT

Data Sheet No. 3
Pre-Impact Electrical Isolation Measurements & Calculations

Vehicle: Ford Focus FC NHTSA No.:

MEGOHMMETER INFORMATION:
Q2 Guardian G500VA Safetytester 713206
Make: Q1 Quadtech Model: 1855 Mx ; S/N: 08451440

Last Calibration Date: Q1 12/23/2008 Q2: 6/8/2009

Test Voltage (Vt): 360 V; Dwell Time: 3 sec; Charge Time: 2 sec

TEMPERATURE SENSOR INFORMATION

Make: Oakton ; Model: Ion 200 ; S/N: 101275

MULTIMETER INFORMATION:

Make: Fluke ; Model: 87V ; S/N: –

Internal Impedance Value: 11 MΩ Maximum Voltage Rating: 1000 V

Measurement Accuracy: ______ % Last Calibration Date: 12/15/2008

Maximum Nominal Working Voltage for the Vehicle (**Vmax**): [illegible] 380 V

HIGH VOLTAGE SYSTEM TO VEHICLE CHASSIS

High Voltage Source (Fuel Cell, Battery, Ultra-Capacitors, other): ______

A. Verify the voltages from
TP1 to **TP2** = .48 V
TP1 to **TPGND** = .39 V
TP2 to **TPGND** = .45 V

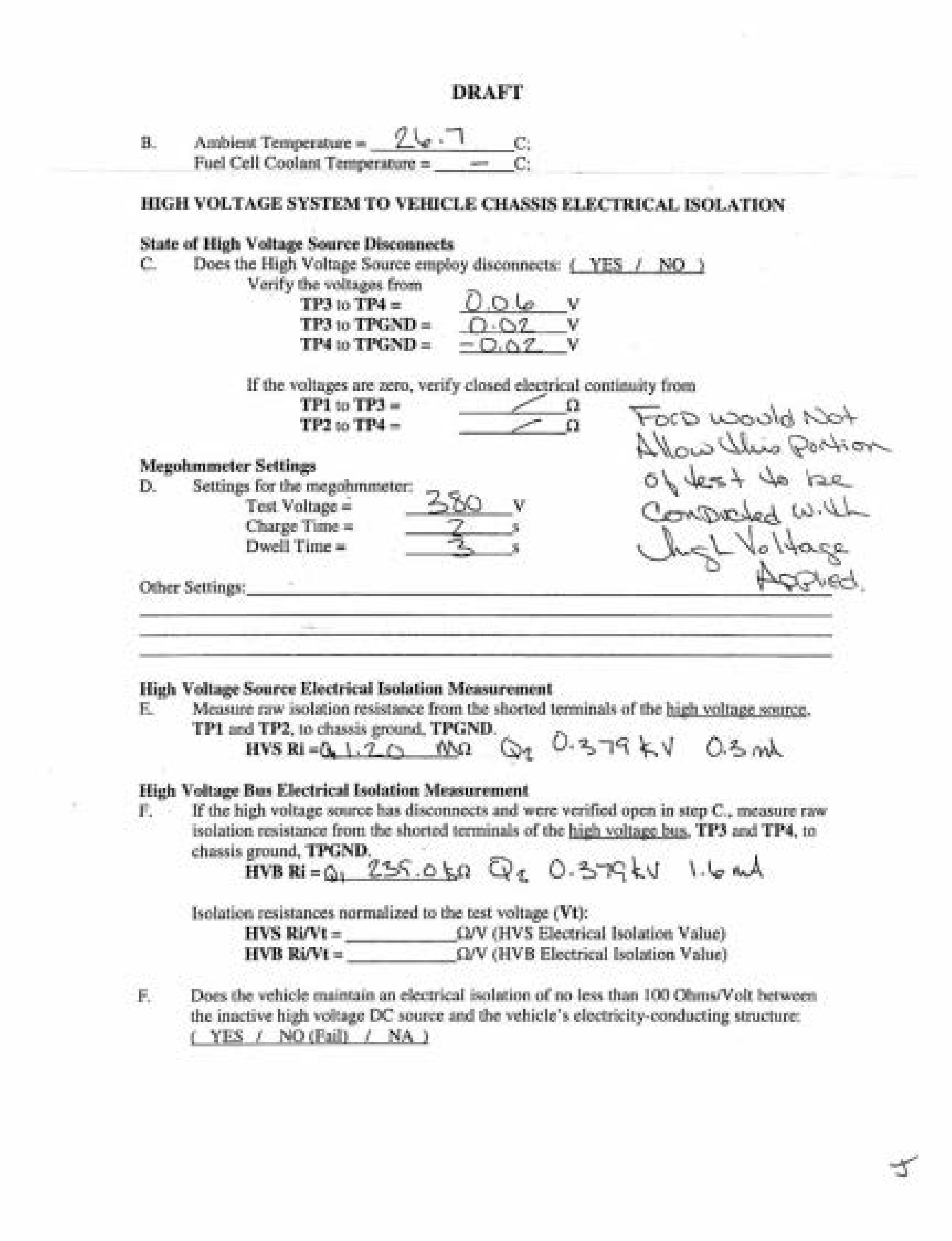
* Procedure Changed.
Zero Accepted Values

- NOTE: If the voltages are not ~~zero do not~~ continue with the megohmmeter measurement.

Did the procedure transition to FMVSS 305: (YES / [✓ NO])
Use FMVSS 305 to determine electrical isolation resistance and voltage, either **R1** and **V1** or **R2** and **V2**.
Ri1 = – Ω **V1** = – V
Ri2 = – Ω **V2** = – V

ENVIROMENTAL MEASUREMENTS

3



DRAFT

B. Ambient Temperature = 26.7 C;
Fuel Cell Coolant Temperature = — C;

HIGH VOLTAGE SYSTEM TO VEHICLE CHASSIS ELECTRICAL ISOLATION

State of High Voltage Source Disconnects

C. Does the High Voltage Source employ disconnects: (YES / NO)

Verify the voltages from
TP3 to **TP4** = 0.06 V
TP3 to **TPGND** = 0.02 V
TP4 to **TPGND** = -0.02 V

If the voltages are zero, verify closed electrical continuity from
TP1 to **TP3** = ______ Ω
TP2 to **TP4** = ______ Ω

Ford would Not Allow this Portion of test to be Conducted with High Voltage Applied.

Megohmmeter Settings

D. Settings for the megohmmeter:
Test Voltage = 380 V
Charge Time = 2 s
Dwell Time = 3 s

Other Settings: ______

High Voltage Source Electrical Isolation Measurement

E. Measure raw isolation resistance from the shorted terminals of the high voltage source, **TP1** and **TP2**, to chassis ground, **TPGND**.
HVS Ri = Q_1 1.20 MΩ Q_2 0.379 kV 0.3 mA

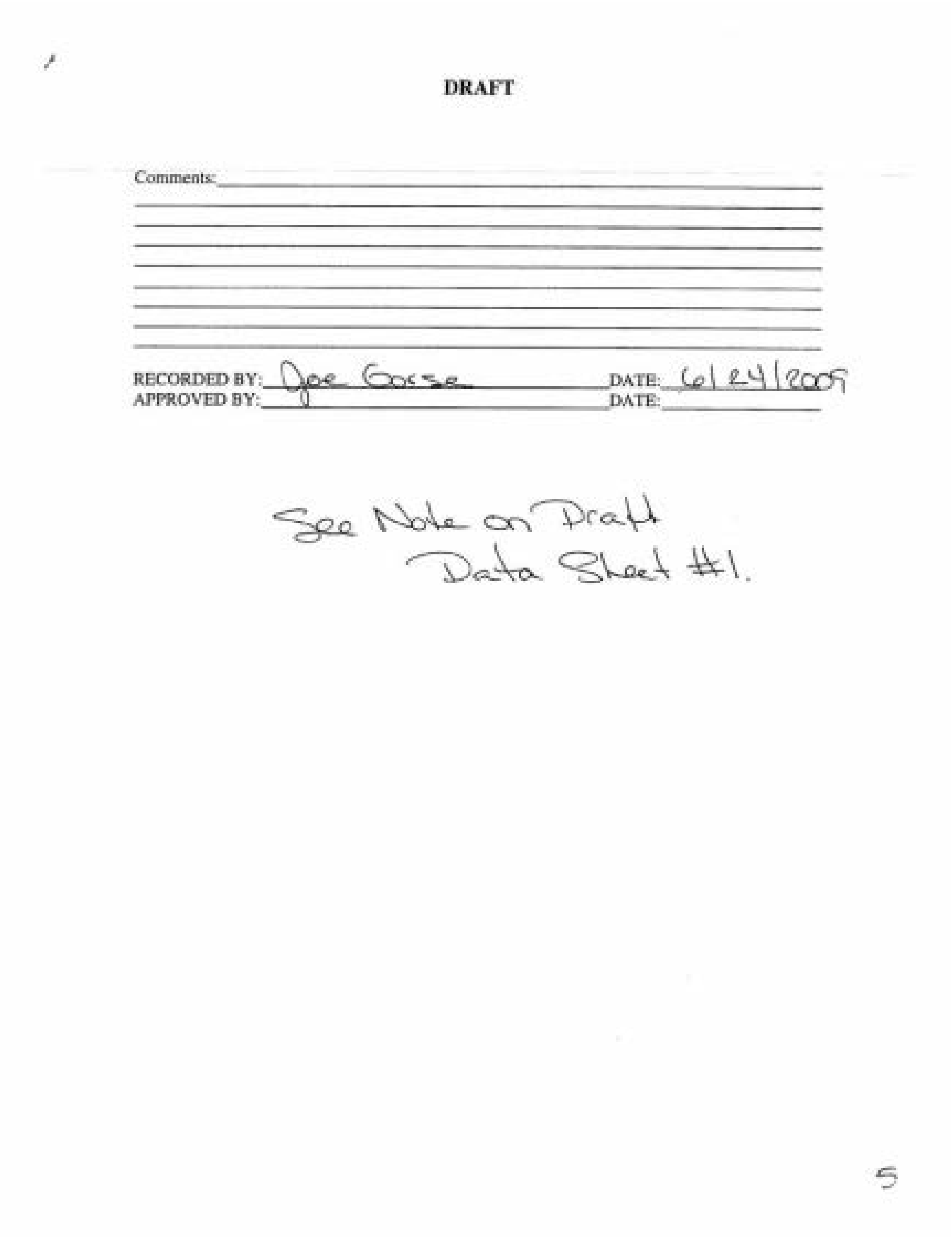
High Voltage Bus Electrical Isolation Measurement

F. If the high voltage source has disconnects and were verified open in step C., measure raw isolation resistance from the shorted terminals of the high voltage bus, **TP3** and **TP4**, to chassis ground, **TPGND**.
HVB Ri = Q_1 235.0 kΩ Q_2 0.379 kV 1.6 mA

Isolation resistances normalized to the test voltage (**Vt**):
HVS Ri/Vt = ______ Ω/V (HVS Electrical Isolation Value)
HVB Ri/Vt = ______ Ω/V (HVB Electrical Isolation Value)

F. Does the vehicle maintain an electrical isolation of no less than 100 Ohms/Volt between the inactive high voltage DC source and the vehicle's electricity-conducting structure:
(YES / NO (Fail) / NA)

J



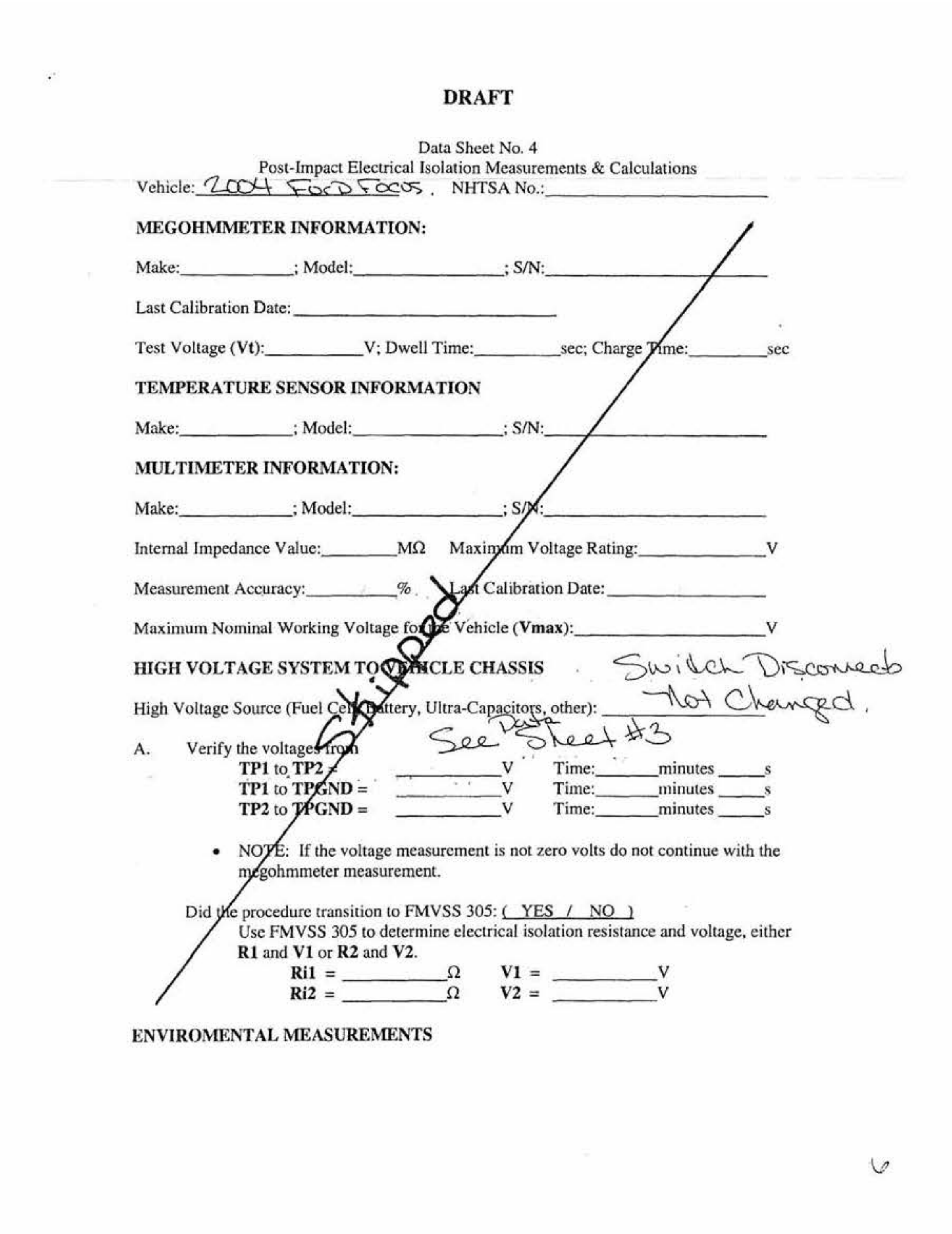
DRAFT

Comments:

RECORDED BY: Joe Gorse DATE: 6/24/2009
APPROVED BY: DATE:

See Note on Draft
Data Sheet #1.

5



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Data Sheet No. 4
Post-Impact Electrical Isolation Measurements & Calculations

Vehicle: 2004 Ford Focus . NHTSA No.:____________

MEGOHMMETER INFORMATION:

Make:________; Model:__________; S/N:____________

Last Calibration Date:______________

Test Voltage (**Vt**):________V; Dwell Time:________sec; Charge Time:________sec

TEMPERATURE SENSOR INFORMATION

Make:________; Model:__________; S/N:____________

MULTIMETER INFORMATION:

Make:________; Model:__________; S/N:____________

Internal Impedance Value:________MΩ Maximum Voltage Rating:__________V

Measurement Accuracy:________% Last Calibration Date:__________

Maximum Nominal Working Voltage for the Vehicle (**Vmax**):____________V

Skipped

HIGH VOLTAGE SYSTEM TO VEHICLE CHASSIS Switch Disconnect Not Changed.

High Voltage Source (Fuel Cell, Battery, Ultra-Capacitors, other): ____________

See Data Sheet #3

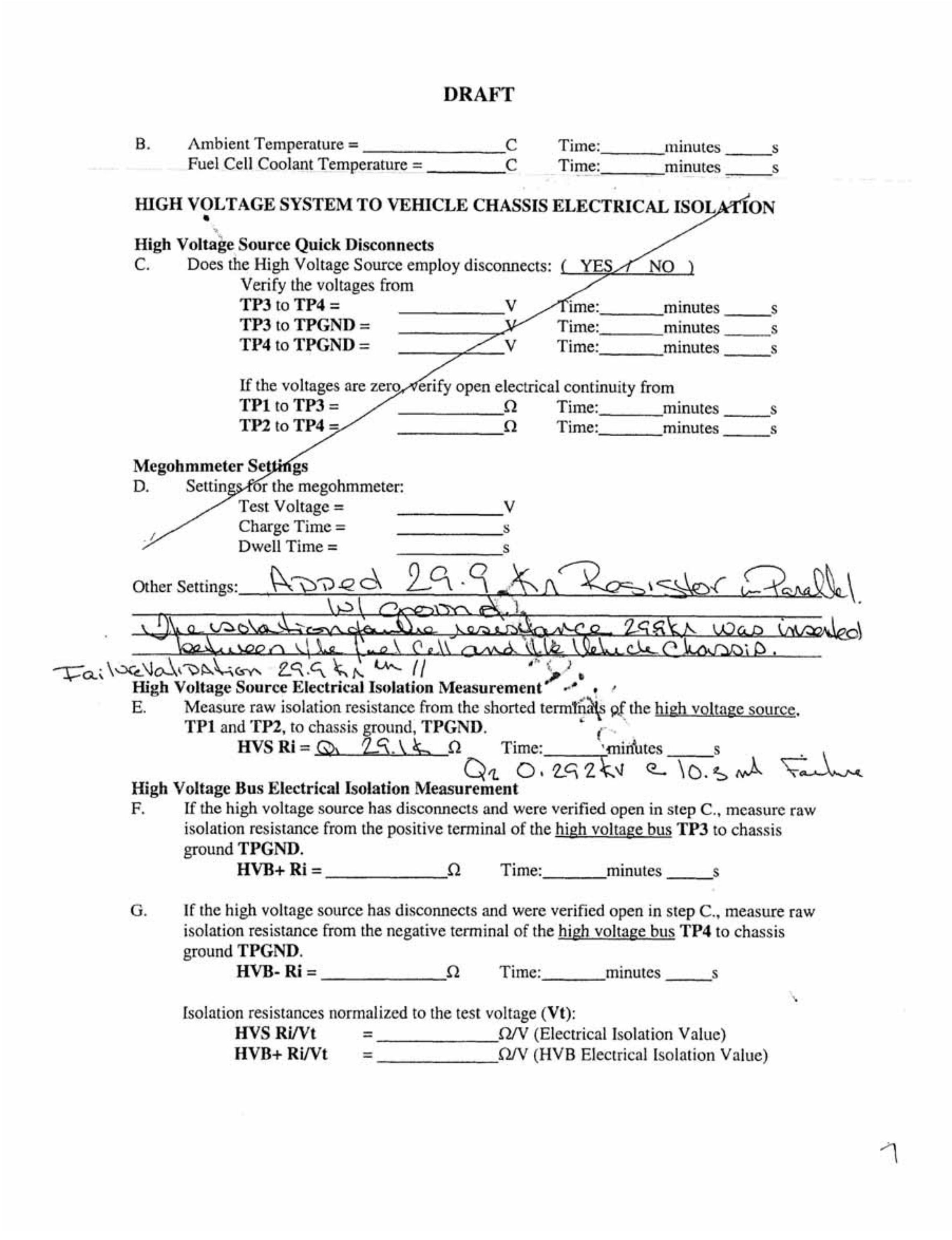
A. Verify the voltages from

TP1 to **TP2** = ________V Time:______minutes ______s
TP1 to **TPGND** = ________V Time:______minutes ______s
TP2 to **TPGND** = ________V Time:______minutes ______s

- NOTE: If the voltage measurement is not zero volts do not continue with the megohmmeter measurement.

Did the procedure transition to FMVSS 305: (YES / NO)
Use FMVSS 305 to determine electrical isolation resistance and voltage, either **R1** and **V1** or **R2** and **V2**.
Ri1 = ________Ω **V1** = ________V
Ri2 = ________Ω **V2** = ________V

ENVIROMENTAL MEASUREMENTS



DRAFT

B. Ambient Temperature = ________________C Time:_______minutes _____s
Fuel Cell Coolant Temperature = _________C Time:_______minutes _____s

HIGH VOLTAGE SYSTEM TO VEHICLE CHASSIS ELECTRICAL ISOLATION

High Voltage Source Quick Disconnects

C. Does the High Voltage Source employ disconnects: (YES / NO)

Verify the voltages from

TP3 to **TP4** = ____________V Time:_______minutes _____s
TP3 to **TPGND** = ____________V Time:_______minutes _____s
TP4 to **TPGND** = ____________V Time:_______minutes _____s

If the voltages are zero, verify open electrical continuity from

TP1 to **TP3** = ____________Ω Time:_______minutes _____s
TP2 to **TP4** = ____________Ω Time:_______minutes _____s

Megohmmeter Settings

D. Settings for the megohmmeter:

Test Voltage = ____________V
Charge Time = ____________s
Dwell Time = ____________s

Other Settings: Added 29.9 kΩ Resistor in Parallel. w/ ground.
The isolation fault resistance 29.9kΩ was inserted between the fuel cell and the vehicle chassis.

FailureValidation 29.9 kΩ in //

High Voltage Source Electrical Isolation Measurement

E. Measure raw isolation resistance from the shorted terminals of the high voltage source, **TP1** and **TP2**, to chassis ground, **TPGND**.

HVS Ri = Q1 29.1k Ω Time:_______minutes _____s

Q2 0.292kV @ 10.3 mA Failure

High Voltage Bus Electrical Isolation Measurement

F. If the high voltage source has disconnects and were verified open in step C., measure raw isolation resistance from the positive terminal of the high voltage bus **TP3** to chassis ground **TPGND**.

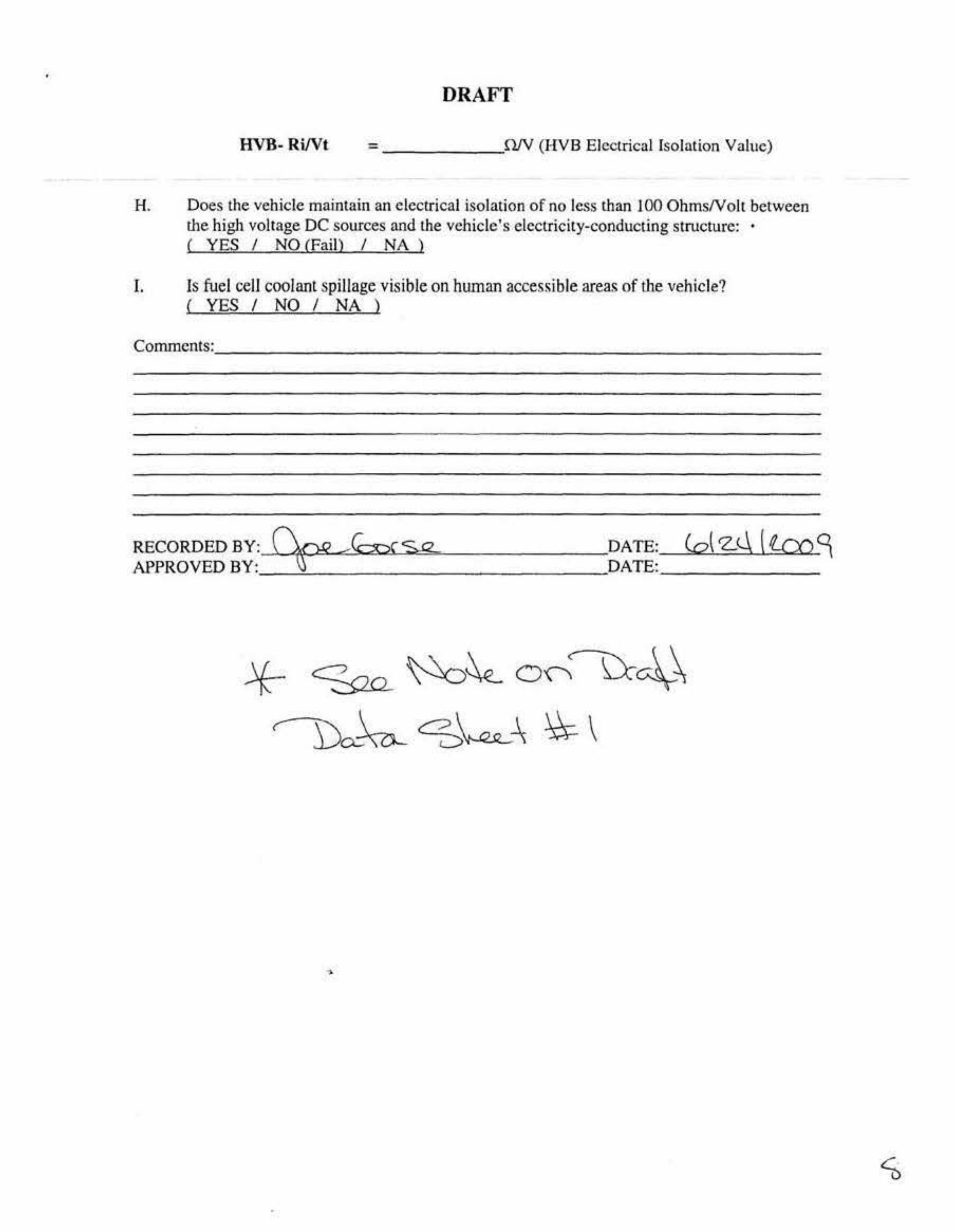
HVB+ Ri = ______________Ω Time:_______minutes _____s

G. If the high voltage source has disconnects and were verified open in step C., measure raw isolation resistance from the negative terminal of the high voltage bus **TP4** to chassis ground **TPGND**.

HVB- Ri = ______________Ω Time:_______minutes _____s

Isolation resistances normalized to the test voltage (**Vt**):

HVS Ri/Vt = _____________Ω/V (Electrical Isolation Value)
HVB+ Ri/Vt = _____________Ω/V (HVB Electrical Isolation Value)



DRAFT

HVB- Ri/Vt = ____________Ω/V (HVB Electrical Isolation Value)

H. Does the vehicle maintain an electrical isolation of no less than 100 Ohms/Volt between the high voltage DC sources and the vehicle's electricity-conducting structure: •
(YES / NO (Fail) / NA)

I. Is fuel cell coolant spillage visible on human accessible areas of the vehicle?
(YES / NO / NA)

Comments:____________________

RECORDED BY: Joe Gorse DATE: 6/24/2009
APPROVED BY:____________ DATE:____________

* See Note on Draft Data Sheet #1

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U.S. Department
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**National Highway
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