SAE International

SURFACE
VEHICLE
RECOMMENDED
PRACTICE

SAE J1645 OCT2011

Issued 1994-02
Revised 2011-10

Superseding J1645 AUG2006

# (R) Fuel Systems and Components - Electrostatic Charge Mitigation

## RATIONALE

This 2011 version of SAE Recommended Practice J1645 includes some editorial updates of the August, 2006 publication MAIN TEXT based on new or corrected information. The APPENDICES have been completely reorganized and in some cases significantly revised in order to provide more coherent information regarding this complex subject. The reasons for the update of the APPENDICES were a significant amount of new information about testing procedures and acceptance criteria. Incorporating these areas of improved information caused changes so numerous that they cannot be individually noted. This version of J1645 replaces the previous version.

## TABLE OF CONTENTS

---

**TO PLACE A DOCUMENT ORDER:** **Tel: 877-606-7323 (inside USA and Canada)**
**Tel: +1 724-776-4970 (outside USA)**
**Fax: 724-776-0790**
**Email: CustomerService@sae.org**
SAE WEB ADDRESS: http://www.sae.org

**SAE values your input. To provide feedback on this Technical Report, please visit http://www.sae.org/technical/standards/J1645_201110**

# 1. SCOPE

This SAE Surface Vehicle Recommended Practice deals with electrostatic charge phenomena that may occur in automotive fuel systems and applies to the following:

- Fuels that are in a liquid state at ambient temperatures and atmospheric pressures and are contained in vehicle fuel tanks that operate at or near atmospheric pressure. This includes gasoline and diesel fuels as well as their blends with additives such as alcohols, esters and ethers whether the additives are petroleum based or bio-fuel based.
- The group of components that comprise the fuel system (in contact and not in contact with fuels).
- Other components in proximity to the fuel system that may be affected by electrostatic fields caused by the fuel system.
- Electrostatic phenomena that arise from or are affected by the following aspects of vehicle or fuel system operation:
  - Flowing fuel in the fuel delivery system
  - Flowing fuel being dispensed to the vehicle while it is being fueled

## 1.1 Basic Approach

This recommended practice provides two approaches that may be used separately or collectively to ensure that there is no likelihood of adverse consequences resulting from electrostatic phenomena:

a) Recommendations for materials, components and subsystems to be used in conjunction with resistance, resistivity and dissipation time tests, noting that this is the conservative approach and may result in unnecessary use of these designs and materials for some specific applications. See Section 4.1.

b) Recommendations for the limits on electrical charge accumulation and transfer – with an indication of the advanced tests and analyses that must be conducted, noting that these tests and analyses require specialist personnel with the appropriate knowledge, experience, test equipment and testing environment. See Section 4.2.

# 2. REFERENCES

## 2.1 Applicable Publications

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest version of SAE publications shall apply.

### 2.1.1 SAE Publication

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

SAE J1681 Gasoline, Alcohol, and Diesel Fuel Surrogates for Material Testing

### 2.1.2 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

| | |
|---|---|
| ASTM D 257 | Standard Test Method for DC Resistance or Conductance of Insulating Materials |
| ASTM D 4496 | Standard Test Method for DC Resistance or Conductance of Moderately Conductive Materials (October 30, 1987) |
| ASTM D 991 | Standard Test Method for Rubber Property—Volume Resistance of Electrically Conductive and Antistatic Products |
| ASTM D 2624-02 | Standard Test Method for Electric Conductivity of Aviation and Distillate Fuels |

### 2.1.3 European Committee for Electrotechnical Standardization (CENELEC) Publications

Available from Cenelec Standards Inspections Ltd., Unit 22 Apex Business Village, Northumberland Business Park, Newcastle Upon Tyne NE23 7BF, United Kingdom, Tel: 44-0191-2502005, email: info@cenelec.com.

| | |
|---|---|
| CLC/TR 50404 | Electrostatics—Code of practice for the avoidance of hazards due to static electricity |

### 2.1.4 International Electrotechnical Commission (IEC) Publications

Available from International Electrotechnical Commission, 3, rue de Verambe, P.O. Box 131, 1211 Geneva 20, Switzerland, Tel: +41-22-919-02-11, www.iec.ch.

| | |
|---|---|
| IEC 60079-0 | Electrical apparatus for explosive atmospheres |
| IEC 93 | Methods of test for volume resistivity and surface resistivity of solid electrical insulating materials |
| IEC 61340-2-1 | Electrostatics Part 2-1: Measurement methods—Ability of materials to dissipate static electric charge |
| IEC 61340-2-3 | Electrostatics Part 2-3: Methods of test for determining the resistance and resistivity of solid planar materials to avoid electrostatic charge accumulation |
| IEC 60243-2 | Electric strength of insulating materials—Test methods—Part 2: Additional requirements for tests using direct voltage |

### 2.1.5 Military Specification

Available from the Document Automation and Production Service (DAPS), Building 4/D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6257, http://assist.daps.dla.mil/quicksearch/.

| | |
|---|---|
| MIL-STD-3010 | Method 4046.1—Antistatic Properties of Materials |

### 2.1.6 API Publications

Available from American Petroleum Institute, 1220 L Street NW, Washington, DC 20005-4070, Tel: 202-682-8000, www.api.org.

| | |
|---|---|
| 88-1-461 | Potential Fire Hazards of Lowering Gasoline Volatility |

API RP 2003, 7th ed., Jan 2008Protection Against Ignitions Arising Out of Static, Lightning, and Stray Currents

### 2.1.7 NFPA Publication

Available from the National Fire Protection Association, 1 Batterymarch Park, Quincy, MA 02169-7471, Tel: 617-770-3000, www.nfpa.org.

| | |
|---|---|
| NFPA77 | Recommended Practice on Static Electricity 2000 Edition |

### 2.1.8 Electrostatic Discharge Association (ESDA) Publications

Available from Electrostatic Discharge Association, 7900 Turin Road, Building 3, Rome, NY 13440-2069, Tel: 315-339-6937, www.esda.org.

| | |
|---|---|
| ESDA Adv.1.0 | Glossary of Terms (1994 publication) |
| ESD STM 11.11 | Surface Resistance Measurement of Static Dissipative Planar Materials (2006 publication) |
| ESD STM11.12-2000 | Volume Resistance Measurements of Static Dissipative Planar Materials (2000 publication) |
| ESD TR 02-99 | High Resistance Ohmmeters—Voltage Measurements |

## 2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this document; they mainly provide background information.

### 2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

| | |
|---|---|
| SAE J2044 | Quick Connect Coupling Specification for Liquid Fuel and Vapor/Emissions Systems |
| SAE J2045 | Performance Requirements for Fuel System Tubing Assemblies |
| SAE J2260 | Nonmetallic Fuel System Tubing with One or More Layers |

### 2.2.2 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

| | |
|---|---|
| ASTM D 150 | Test Methods for A-C Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulating Materials |
| ASTM D 2679 | Electrostatic Charge |
| ASTM D 3509 | Electrostatic Field Strength Due to Surface Charges |
| ASTM D 4470 | Standard Test Method for Static Electrification |
| ASTM D 4865 | Standard Guide for Generation and Dissipation of Static Electricity in Petroleum Fuel Systems |

### 2.2.3 Military Specification

Available from the Document Automation and Production Service (DAPS), Building 4/D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6257, http://assist.daps.dla.mil/quicksearch/.

MIL-PRF-81705DBarrier Materials, Flexible, Electrostatic, Free, Heat Sealable

### 2.2.4 Underwriters Laboratory (UL) Publication

Available from Underwriters Laboratories Inc., 333 Pfingsten Road, Northbrook, IL 60062-2096, Tel: 847-272-8800, www.ul.com.

| | |
|---|---|
| UL 330 | Hose and Hose Assemblies for Dispensing Flammable Liquids |

### 2.2.5 DIN Publication

Available from Deutsches Institut für Normung e.V., Burggrafenstrasse 6, 10787 Berlin, Germany, www.din.de.

DIN 53-486/VDE 030 Part 8/4 75 (April, 1975) VDE Specifications for Electrical Tests on Insulating Materials: Evaluation of Electrostatic Behavior

### 2.2.6 Other Publications - Detailed Background

C. B. Shepherd Jr., Standard calibration fuels, WADC Technical Report 52-331, Wright Air Development Center, Ohio (1952)

Journal of Research Article (Oct-Dec, 1965) - Electric Currents and Potentials Arising from the Flow of Charged Liquid Hydrocarbons through Short Pipes

ISO 3915-1981 (E) - Plastics - Measurement of Resistivity of Conductive Plastics

IEEE Transactions on Electrical Insulation Volume 23, No. 1 (ISSN 0018-9367) (February, 1988)—Electrical Insulation and Breakdown in Vacuum

IEEE Transactions on Electrical Insulation Volume 23, No. 1 (ISSN 0018-9367) (February, 1988)—Flow Electrification in Electrical Power Apparatus

Naval Research Laboratory Report 8021—Pro Static Agents in Jet Fuels (August 16, 1976)

Coordinating Research Council—Electrostatic Discharge in the Fuel Systems of Gasoline Powered Vehicles in North America (Paper by Ron Tharby, Nov., 1990)

ESSO Research and Engineering Company—Charging Tendency Test (April 9, 1959)

Naval Research Laboratory Report 8484—Generation of Electrostatic Charge in Fuel Handling Systems: A Literature Survey (September 24, 1981)

January, 1988 issue of Plant/Operations Progress Magazine—Collection of articles on aspects of electrostatic charge concerns arising in handling chemicals

Research Studies Press, Inc., John Wiley & Sons—Electrostatic Hazards in the Petroleum Industry by W. M. Bustin and W. G. Dukek

Analysis of "Flow Electrification in Fuel Distribution Systems" by J. C. Dean, G. H. Williams, and J. DeGiovann—IEEE Transactions on Industry Applications, vol. 29, No 3, pp 132-138, 1993

DGMK Project 508—Avoidance of Ignition of Gasoline/Air Mixture During Refueling of Motor Vehicles at Filling Stations—DGMK German Society for Petroleum and Coal Science and Technology, Hamburg, Germany, February 1996

Report on the Risk of Static Ignition During Vehicle Refueling: A Study of Available Research—Institute of Petroleum, London, May 2001

SAE 1999-02-0797—Electrostatics of Fuel System for the Automobile; Hironori Ueda, Takashi Nagai, Genjiro Tada, Shoichi Yamamoto and Takayuki Kato

American Institute for Chemical Engineers—Center for Chemical Process Safety—Electrostatic Ignitions of Fires and Explosions; Thomas H. Pratt, PhD, PE

American Institute for Chemical Engineers—Center for Chemical Process Safety—Avoiding Static Ignition Hazards in Chemical Operations, Laurence G. Britton

Electrostatic Ignition Hazards in Motor Cars—Occurrence, Detection and Prevention—Proceedings ESA/IEEE Joint Meeting on Electrostatics, June 24-27, 2003, University of Arkansas, Little Rock, 78-89, U. von Pidoll

## 3. DEFINITIONS

In addition to this section, refer also to the Electrostatic Discharge Association publication: Glossary of Terms (ESDA Adv. 1.0).

### 3.1 ACCUMULATION

An increase in the amount of electrostatic charge present on a fuel system component resulting from a rate of charge dissipation that is slower than the rate at which charge is delivered.

### 3.2 ASSEMBLY

A group of parts or components that form a self-contained unit designed to perform two or more specific functions. Examples are fuel pump/sender assembly, fuel tank assembly, fuel rail assembly, and fuel line assembly.

### 3.3 BONDING

An intentional electrical connection made between components for equalizing electrical potential between the components.

### 3.4 BREAKDOWN FIELD STRENGTH

The critical electric field strength that causes dielectric breakdown.

See also *dielectric breakdown, field strength*

### 3.5 BREAKDOWN VOLTAGE

The potential difference between two objects that causes breakdown of the dielectric material between the objects. It is the potential difference that causes the electric field strength to exceed the breakdown field strength over a sufficient part of the gap.

## 3.6 CAPACITANCE

A measure of the amount of electric charge stored for a given electric potential. The capacitance is defined as the total electric charge (measured in coulombs) placed on an object divided by the potential of the object (measured in volts):

$$C = Q / V \qquad \text{(Eq. 1)}$$

Where:

C is the capacitance of the body (F)
V is the difference in electrical potential between the body and ground (V).
Q is the amount of charge (in coulomb C)

The unit of measure is the farad (F).

## 3.7 CHARGE (or ELECTRIC CHARGE)

Quantity of unbalanced electricity on (or in) a body; i.e., an excess or deficiency of electrons, giving the body negative or positive electrification, respectively.

The unit of measure is the coulomb (C).

$$Q = CV \qquad \text{(Eq. 2)}$$

Where:

C is the capacitance of the body (F)
V is the difference in electrical potential between the body and ground (V).
Q is the amount of charge (in coulomb C)

## 3.8 CHARGE DENSITY

The net electric charge per unit volume (volume charge density) or electric charge per unit area (surface charge density).

The unit of measure is coulombs per cubic meter ($C/m^3$) or coulombs per square meter ($C/m^2$).

## 3.9 CHARGED PLATE MONITOR

An electrical measuring system that employs a high voltage source, an isolated test surface, timing circuitry and an electrostatic field meter to provide quantitative measurements of the rate of decay of static charges on a component or assembly.

## 3.10 COMPONENT

A part or product that performs a single function in its smallest assembled state. Examples are fuel pump, float rod, inline fuel filter, and fuel tank shell.

## 3.11 CONDUCTANCE

A property of component or sub-system indicating how easily it allows the flow of electric current through it – as measured between two electrodes placed in specified positions. Reciprocal of resistance ($1/\Omega$).

The unit of measure is the siemens (S).

See also *conductivity*.

## 3.12 CONDUCTION

Flow of electricity in a medium that does not involve movement of the medium itself. An example of this is the flow of electrons or ions in a material.

## 3.13 CONDUCTIVE MATERIALS

Materials exhibiting resistance low enough to prevent any meaningful electrostatic charge to accumulate by allowing those charges to be rapidly conducted to system or earth ground.

## 3.14 CONDUCTIVITY

A property of a material indicating how easily the flow of electric current passes through it – denoted by $\sigma$. The reciprocal of volume resistivity.

The unit of measure is siemens per meter (S/m).

See also *conductance*.

## 3.15 CORONA DISCHARGE

Luminous discharge due to ionization of the air surrounding a conductive material, around which the electric field strength exceeds the breakdown field strength over a limited distance only.

## 3.16 COULOMB

The unit of electric charge. The coulomb is the quantity of electric charge that passes a cross-section of a conductor in one second when the current is maintained at one ampere.

## 3.17 DIELECTRIC (or DIELECTRIC MATERIAL)

A material with very few free charges throughout its volume. Electrons are closely bound to atomic nuclei and cannot drift or diffuse about the material as in a conductor or semiconductor. A perfect dielectric (an insulator) has no free charge and therefore, zero conductivity.

## 3.18 DIELECTRIC BREAKDOWN

Condition arising when a dielectric material is subjected to an electric field that exceeds the breakdown field strength. Electrons are pulled out of molecular bonds and accelerated until they collide with other parts of the molecular lattice, causing chemical changes or physical damage to the material. After breakdown occurs, a dielectric material may become irreversibly more conductive.

## 3.19 DISCHARGE

A rapid reduction in the amount of electrostatic charge accumulated in a particular region caused by the flow of electric current following a dielectric breakdown.

## 3.20 DISSIPATION

A gradual decay, over time, of the amount of a physical quantity such as electrostatic charge or heat in a particular region. In this Recommended Practice the term is used exclusively for the loss of electrostatic charge (charge dissipation).

## 3.21 DISSIPATIVE (MATERIALS)

Materials that prevent the accumulation of electrostatic charges to hazardous levels by allowing charge dissipation to either system or earth ground. In the context of this Recommended Practice these materials are characterized by level of volume resistivity.

### 3.22 ELECTROMETER

A refined DC voltmeter exhibiting very high input resistance and negligible leakage current or an equivalent ammeter with a low voltage burden.

### 3.23 ELECTROSTATIC CHARGE

An accumulation of essentially stationary electric charges on the surface or in the volume of a material. (Volume charges can only exist in a dielectric material, not in a conductor). Associated with the charge distribution is its surrounding electrostatic field.

### 3.24 ELECTROSTATIC (or ELECTRIC) FIELD

The (vector) electric force exerted on a charge divided by the amount of charge. See also 3.30 Field Strength.

The unit of measure is the volt per meter (V/m).

### 3.25 ELECTROSTATIC POTENTIAL

The electrostatic potential (voltage) at a point is the energy required to move a charge from a specified reference location to that point, divided by the amount of charge moved. The reference location is usually called ground or zero potential.

The unit of measure is the volt (V).

### 3.26 ENERGY OF SPARK DISCHARGE

The energy (W) of a spark discharge to ground is described by the following equations:

$$W = \tfrac{1}{2} CV^2,\ \ W = \tfrac{1}{2} QV,\ \ W = \tfrac{1}{2} Q^2 / C \qquad \text{(Eq. 3)}$$

Where:

C is the capacitance of the discharging body (F)
V is the difference in electrical potential between the discharging body and ground (V)
Q is the amount of charge (in coulomb C)
W is the energy (in joules J)

### 3.27 EROSION, ELECTRICAL

The progressive deterioration of a dielectric material by the action of electrical discharges through the material.

### 3.28 FARADAY CUP or CAGE

An apparatus for measuring electric charge that consists of two conducting enclosures: an inner conductor and an outer conductor, which are insulated from each other. The grounded outer enclosure shields the inner one from external electric fields; the charge object to be characterized is placed within the inner enclosure.

### 3.29 FIELD STRENGTH METER

A non-contact measuring instrument for detecting and quantifying the presence of electrostatic fields and potentials on items and surfaces. Electrostatic field meters can be calibrated to provide accurate potential measurements when used at a fixed distance from a surface. Key factors affecting the measurement are object size and the proximity of other objects or ground surfaces.

### 3.30 FIELD STRENGTH

The magnitude of the electric field vector. See electric field (3.24 above).

The unit of measure is volts per meter (V/m).

### 3.31 FUEL CONTAINMENT BOUNDARY

That portion of the fuel system that is in direct contact with liquid fuel or the vapor space directly above liquid fuel. Vapor management systems that are connected to the fuel tank interior via liquid/vapor discriminating valves are not considered part of the liquid containment boundary although the valves are.

### 3.32 GROUNDING

The intentional electrical connection of a component or vehicle to a ground plane, the earth, or a large conductor taken as the zero potential reference thus eliminating the electrical potential difference between the component and the ground plane, earth, or reference conductor.

### 3.33 HALF LIFE

For the purposes of this Recommended Practice, it refers to the time required for the charge level on or in a body of material to decay to ½ of its original value (rather than 1/e, as in 3.39).

### 3.34 INSULATIVE (of Materials)

Allowing the accumulation of electrostatic charges to values above a defined acceptable limit by preventing adequate dissipation of those charges to either system or earth ground. (In the context of this Recommended Practice, this is characterized either by volume resistivity or rate of static decay).

### 3.35 PERMITTIVITY OF FREE SPACE ($\varepsilon_0$)

A universal constant such that in a vacuum, the product of $\varepsilon_0$ and the electric field, E, is equal to the electric flux density.

$D = \varepsilon_0 E$. The numerical value for $\varepsilon_0$ is $8.854 \times 10^{-12}$.

The unit of measure is farad per meter (F/m).

### 3.36 PRO-STATIC AGENT

A substance that increases the charge density generated on a fuel in a particular operation without increasing its conductivity.

### 3.37 QUENCHING DISTANCE

The minimum gap through which a flame can propagate between parallel plates. The quenching distance for typical hydrocarbon gasoline components in air at atmospheric pressure is approximately 2 mm.

### 3.38 RELATIVE PERMITTIVITY ($\varepsilon_R$)

The permittivity of a medium, $\varepsilon$, divided by the permittivity of free space, $\varepsilon_0$. See 3.35.

$$\varepsilon_R = \varepsilon / \varepsilon_0 \qquad \text{(Eq. 4)}$$

Relative permittivity is dimensionless.

### 3.39 RELAXATION

The return of a system to electrical charge equilibrium. It may follow an exponential form, a hyperbolic form or a combination of the two. Exponential relaxation is the most common. It is characterized by a time constant "$\tau$." For a system with a capacitance C and a resistance R the time constant is:

$$\tau = RC \qquad \text{(Eq. 5)}$$

If the dissipation results from current flow within a dielectric material

$$\tau = (\varepsilon_R \cdot \varepsilon_0)/\sigma \qquad \text{(Eq. 6)}$$

Where:

$\varepsilon_R$ = relative permittivity of the dielectric material
$\varepsilon_0$ = free space permittivity, and
$\sigma$ = conductivity of the dielectric material

In Equation 6, $\tau$ is also called the material's dielectric relaxation time. See 3.40: Relaxation Time

The unit of measure is the second (s).

### 3.40 RELAXATION TIME

The time required for the charge in a system to drop to 1/e of its original value (e = base of the natural log system and is equal to 2.718). For an exponential decay, this is $\tau$, the relaxation time constant. See also *Half Life* and *Relaxation*.

### 3.41 RESISTANCE

A property of component or sub-system indicating how strongly it opposes the flow of electric current through it as measured between two electrodes placed in specified positions.

The unit of measure is the ohm ($\Omega$)

See also *volume resistivity*, *surface resistivity* and *surface resistance*.

### 3.42 SHEAR RATE

The gradient of flow velocity in a gas or liquid perpendicular to the flow direction

The unit of measure is $s^{-1}$.

### 3.43 STREAMING CURRENT

The current carried by an electrically charged fluid as a result of its movement or flow. The streaming current, $I_s$, is given by:

$$I_s = \rho_c F \qquad \text{(Eq. 7)}$$

Where:

$\rho_c$ is the charge density of the fluid (in $C/m^3$) and

F is the volumetric flow rate (in $m^3/s$)

The unit of measure is the ampere (A).

### 3.44 SURFACE RESISTIVITY

A property of a material indicating how strongly it opposes the flow of electric current across its surface – defined as the ratio of DC voltage drop per unit length to the surface current per unit width. Denoted by $\rho_s$.

The unit of measure is the ohm (Ω).

NOTE: To differentiate from surface resistance, the unit ohms/square (Ω/sq) is often used. This arises from the units of length and width in the above definition. For every square surface area, i.e., an area in which the length equals the width, the surface resistance numerically equals the surface resistivity.

See also *volume resistivity*, *volume resistance* and *surface resistance*.

### 3.45 SURFACE RESISTANCE

A property of a component or sub-system indicating how strongly it opposes the flow of electric current across its surface – as measured between two electrodes placed in specified positions. For example, the resistance R of a component consisting of a flat, rectangular surface with width d and length l (d and l at right angles) and surface resistivity $\rho_s$ is:

$$R = \rho_s \, l/d \quad \text{(Eq. 8)}$$

In measuring this resistance it is assumed that current flows along the direction of length "l" in response to a voltage applied to the edge of width "d". For a more arbitrarily-shaped component the current flow is more complicated, but the resultant total resistance between the two points of measurement is still the relevant quantity.

NOTE: There is a standard surface resistance test with a 10:1 ratio of d and l. When using the term surface resistance it is necessary to be clear whether a general value or this specific test value is intended. The general meaning is used throughout this Recommended Practice.

The unit of measure is the ohm (Ω).

See also *volume resistivity*, *volume resistance* and *surface resistivity*.

### 3.46 SYSTEM

A combination of components and assemblies that accomplishes the full function of the subject system, including interfacing with features outside of the system that may be required to accomplish a vehicle function level. (Examples are fuel [liquid] system and powertrain system.)

### 3.47 VEHICLE GROUND

Basic metallic structure of the vehicle that includes such major elements as chassis, engine and body that are electrically bonded to each other and to the negative terminal of the battery. (Sometimes, "chassis ground" is used; that is synonymous with vehicle ground.)

### 3.48 VIRTUAL CHARGE (Also Called MIRROR CHARGE, INDUCED CHARGE or CHARGE BY INFLUENCE)

Conductive bodies near a charged object tend to acquire a charge of opposite sign (virtual charge) under the influence of the electric field created by the charged object. Under some circumstances discharges can occur from the object with the virtual charge. For example, a plastic fuel tank can contain a large charge during refueling with no adverse effects inside the tank. However, an ungrounded metal object near the tank exterior can acquire a virtual charge and discharge, possibly igniting vapors resulting from the refueling event.

### 3.49 VOLUME RESISTIVITY

A property of a material indicating how strongly it opposes the flow of electric current through it – denoted by $\rho_v$, the reciprocal of conductivity.

$$\rho_v = R\ (A / L) \qquad \text{(Eq. 9)}$$

Where:

R = resistance
A = minimum cross sectional area through which the current flows
L = mean length of part in the direction of current flow

The unit of measure is the ohm-meter (Ω-m).

See also *resistance*, *surface resistance, volume resistivity* and *surface resistivity*.

## 4. RECOMMENDED PRACTICES FOR MINIMIZING ELECTROSTATIC CHARGE ACCUMULATION

Uncontrolled electrostatic charging in liquid fuel systems can have damaging effects on vehicle systems including:

i. EMI (electromagnetic interference) effects on electronic components and computers up to and including component damage.

ii. Electrical erosion of fuel system components resulting in pinhole leaks.

iii. Unintended ignition of combustible air-fuel mixtures that might occur under certain conditions.

This document recommends the use of materials, components and fuel system designs that can help prevent the above-mentioned damaging effects as follows:

a. Reducing charge separation.

b. Reducing charge accumulation.

c. Recombining separated charges.

d. Preventing discharge.

NOTE: Fuel is a highly significant variable that controls whether harmful electrostatic charges develop or not. Marketplace fuels are constantly being revised to address issues relating to emissions, economics, global warming, etc., for example Ultra-Low Sulfur Diesel and Biodiesel. The effect of changes to marketplace fuel should be continuously monitored for their effects on any given fuel system design particularly those that are not fully compliant with section 4.1 below.

### 4.1 Specifications for Materials, Components and Subsystems to be Used in Conjunction with Resistance and Resistivity Tests

NOTE: Each of the following recommendations apply unless they individually can be shown to be unnecessary as described in Section 4.2.

### 4.1.1 Recommendations for Flow Channels

For all flow channels within the fuel system that are specifically designed to transport fuel from one component to another, the electrical resistance measured between points A and B and between points A and C should not exceed $1X10^8\Omega$ ($100M\Omega$) when measured by procedure 5.2. Definitions of point A, B and C are as follows:

Point A.Any point on any surface that is in contact with flowing liquid fuel and is part of a grounding strategy for the fuel system (refer to 3.32 of glossary).

Point B.Vehicle ground (refer to 3.46 of glossary).

Point C.Any metallic component with a capacitance greater than 3pF located within 25mm of any ungrounded or non-conductive component in the fuel system that could develop a virtual charge from within the fuel system. See APPENDIX A, Section A.2.1.3.

NOTE: The above should be verified as installed in a representative vehicle environment.

### 4.1.2 Recommendations for Filler Nozzle Grounding

The electrical resistance measured between a typical marketplace nozzle inserted into the filler pipe (point A above) and the vehicle ground (point B above) should not exceed $1 \times 10^6\Omega$ when measured by procedure 5.2.

The electrical resistance measured between a typical marketplace nozzle inserted into the filler pipe (point A above) and a metallic plate on which each tire sits in succession should not exceed $5 \times 10^8\Omega$ measured with up to 1000V applied and with all other tires sitting on an insulating surface.

### 4.1.3 Recommendations for Conductive Components Inside the Fuel Containment Boundary

The resistance between installed conductive components and vehicle ground (with all relevant ground connections in place) should not exceed $1 \times 10^8\Omega$ when measured by relevant procedure of Section 5.2.

### 4.1.4 Durability Recommendations

The recommendations of Sections 4.1.1, 4.1.2 and 4.1.3 should be met for the vehicle life under expected conditions of vehicle usage, representative of the marketplaces in which the vehicle is intended for sale and at the time of initial retail sale. The fuels and exposure conditions to be considered to meet this recommendation should be agreed upon between the end user and the producer of a particular component or subsystem (refer to Section 5.4).

### 4.1.5 Component Recommendations

The off-vehicle (i.e. bench test) performance of individual components and sub-assemblies that contribute to compliance with Sections 4.1.1, 4.1.2 and 4.1.3 should be separately verified by means of a specified test procedure. Such specification should include details of simulated or actual mating component(s) where these form part of the required electrical path. Except where otherwise determined by expert testing and/or expert judgment, one of the following acceptance criteria should be applied:

a. The resistance between any location on the component and a ground connection point for the component (e.g. inlet and outlet, if these are mounted on metal brackets or vehicle ground connection point if separately provided) should not exceed $1x10^6\Omega$ as measured by procedure 5.2.3.

b. The static dissipation time of the component as measured by the procedure specified in Section 5.3 (the decay time required for the charge level to reach 10% of an initial value of the applied voltage) should not exceed 0.5 seconds.

NOTE: The resistance criterion is considerably more conservative than the dissipation time criterion because, in order to allow simplified measurement procedures, the resistance limits are reduced by a factor 10 below those that are strictly necessary (see B.1.4 for details).

### 4.1.6 Material Recommendation

The relevant electrical properties (i.e. surface resistance and/or volume resistivity) for each individual material that contributes to compliance with sections 4.1.1, 4.1.2 and 4.1.3 should be separately verified by means of the test procedures specified in 5.2.2 and (for fuel-exposed testing) 5.4. Except where otherwise determined by expert testing and/or judgment and except where susceptibility to prolonged fuel immersion is found, the following should be applied to virgin material that is representative of the intended production process:-

a. Volume resistivity should not exceed $1 \times 10^4 \Omega$-m. See Definition 3.49.

b. Surface resistivity should not exceed an empirically derived value consistent with the recommendations of section 4.1.5. See Definition 3.4.5.

Examples of appropriate test methods are given in section 5.2.2.

The effect of prolonged immersion in fuels should be evaluated by physical testing as described in 5.4. Where it is found that such immersion adversely affects the material such that the recommendations of sections 4.1.1, 4.1.2 or 4.1.3 cannot reliably be met, the recommendations of section 4.2 should be invoked.

Materials and combinations of materials should be specified such that the recommendations of section s 4.1.1 to 4.1.5 can be met.

## 4.2 Specifications for the Limits on Electrical Charge Accumulation and Transfer

Designs that do not conform to the recommendations of 4.1 might, nevertheless, be judged acceptable on the basis of the criteria and testing presented in this section (4.2). Verification testing to demonstrate compliance with this section and engineering judgments made on the basis of such testing require specialist personnel with the appropriate knowledge, experience, test equipment and testing environment. See APPENDIX C and APPENDIX D for further details.

Examples of designs or circumstances that meet the criteria stated in 4.2 and therefore, do not have to meet the recommendations of 4.1 are presented in APPENDIX E.

### 4.2.1 Vehicle grounding during refuelling

If the tire or nozzle contact resistance does not meet the requirements in 4.1.2 it is necessary to verify, by flow testing, as referenced in 5.5 and described in APPENDIX D, that the stored energy on the vehicle could not exceed 0.2 mJ or that the potential on the vehicle could not exceed 1 kV.

### 4.2.2 Conductive components that do not meet the recommendations of section 4.1

All of the following should be demonstrated by means of suitable testing involving expert practitioners:-

a. Charge accumulation on such components cannot result in a spark discharge having an energy exceeding 0.2mJ in a zone that could contain a flammable atmosphere.

b. Discharges that would cause significant cumulative damage to materials over the intended operational life cannot occur from the component. Here, “significant cumulative damage” is that which could cause unspecified migration of fuel – unless such migration has no reasonable safety implication.

c. Discharges that would cause damage to electronic systems over the intended operational life cannot occur.

Items b. and c. apply regardless of the presence of a flammable atmosphere, NOTE:

For components or assemblies that are inaccessible to people while the engine is running or during re-fuelling, it may be possible to meet the criterion in item a. even if the stored energy exceeds 0.2mJ. For example, the objects may have large radii of curvature and/or be separated by large gaps so the voltages and electric fields are too low for breakdown.

For components that are accessible to people (e.g., those around the filler opening), the discharge geometry cannot be predicted in advance (e.g. people may introduce metal tools). In these areas of unknown geometry the only way to ensure that discharge energies cannot exceed 0.2mJ is to ensure that the stored energy on every ungrounded metal component or sub-assembly is less than 0.2mJ (here ungrounded sub-assemblies that are bonded together should be considered as a single item and the total energy on the whole bonded item should be used in the assessment)."

### 4.2.3 Non-conductive components

Both of the following should be demonstrated by means of suitable testing involving expert practitioners:-

a. Brush discharges with charge transfers that exceed 60nC in any one event cannot occur with any foreseeable fuel in any zone that could contain a flammable atmosphere.

b. Regardless of the presence of a flammable atmosphere, discharges cannot occur that would cause cumulative damage to materials over the intended operational life, which could cause unspecified migration of fuel, unless such migration has no reasonable safety implication.

## 5. TESTING PROCEDURES

### 5.1 General Comments for Resistance and Static Dissipation Testing

### 5.1.1 Instrumentation

Instrumentation details can be found by consulting the various test procedures referred to throughout the text. Whatever instrumentation is utilized, the user should refer to the manufacturer's instructions and follow them carefully.

### 5.1.2 Sequence of Testing

The suggested sequence of testing for components is as follows

a. Measure resistance first. If the resistance meets the acceptance criterion, then no further testing is necessary.

b. If the resistance does not meet the acceptance criterion, then perform a static dissipation test.

If the requirements of either the dissipation test or the resistance test are met, then the component or material is considered acceptable. This order of testing is implied in Sections 5.2 and 5.3 and specifically mentioned in Section 5.4. If the OEM/end user and the supplier agree, then the sequence can be changed to include only the static dissipation test or only the resistance test.

### 5.1.3 Sequence of Voltage Level Utilized

Whenever a test procedure includes more than one level of voltage, the lowest should be utilized first. Subsequent voltage levels should then be increased stepwise up to the highest indicated level.

## 5.2 Resistance and Resistivity Test Procedures

### 5.2.1 Factors that influence measured resistance values

Measured resistance values can be influenced by a number of factors including:

a. Sample preparation

b. Relative humidity (see C.2.2.1.1, in particular)

c. Temperature

d. Test voltage

e. Electrode configuration

Consequently, the steps of a specific procedure should be followed carefully. All the considerations and guidelines of APPENDIX C should be followed to assure the accuracy and repeatability of the measurements taken.

When results are obtained, the conditions of the test and other pertinent factors should also be recorded (refer to Section 5.6).

### 5.2.2 Test Procedures For Materials

#### 5.2.2.1 Surface Resistivity/Resistance

To measure the surface resistance of the material, follow the procedure described in ESD STM 11.11. The following modifications to the standard procedures should be used for conductive or dissipative materials:

#### 5.2.2.1.1 Instrumentation:

The instrumentation must be capable of making measurements from less than $1 \times 10^3 \Omega$ to greater than $5 \times 10^8 \Omega$. A humidity/temperature meter is recommended to record the test conditions.

#### 5.2.2.1.2 System Verification Fixtures:

This fixture need only conform to the Lower Resistance Range Fixture specified in Section 6.4.1 of ESD STM 11.11.

#### 5.2.2.1.3 Testing specimens:

Procedures are performed on flat plaques that are molded without use of mold release using recommended molding conditions for the material being tested. The dimension of the plaques are 70 mm to 80 mm wide, 120 mm to 130 mm long, and 3 mm thick.

#### 5.2.2.1.4 Testing steps:

Measure and record the resistance after 5s using a voltage that is as low as practical (at no time should this voltage exceed 100V). If the instrumentation cannot measure resistance below $1 \times 10^6 \Omega$ using 100V, report only lower voltage measurement. If the resistance is very low and no resistance value can be measured then report the results as < (lowest meter reading) $\Omega$.

See Section 4.1.6 for guidelines on acceptance criteria for measured resistivity values.

#### 5.2.2.1.5 Volume Resistivity

The test procedure to be followed is ASTM D-4496. The following modifications to the standard procedures should be used for conductive or dissipative materials.

#### 5.2.2.1.6 Relating to sample preparation

a. Accepted methods for reading the volume resistivity of a material include breaking the surface, painting silver paint for contact, and/or puncturing surface electrodes such as are described in ASTM D-4496.

b. In order to account for surface effects caused by moisture, dirt, oil, and skinning effects caused by molding conditions, the volume resistivity should be measured through the volume by some means of breaking the surface. Sample preparation is outlined in Annex A1 of ASTM D-4496; further information is found in Section C.2.2.1.1.

c. ISO or ASTM tensile bars are molded on a standard injection-molding machine without mold release. A total of ten bars are molded for each resistivity test. The bars are then placed into a jig, cut with a razor knife, and the two ends are removed. This leaves the middle 60 mm of the tensile bars.

d. The broken ends are painted with conductive paint, along with 4 mm wide stripes across the face of the bar, 3 mm from each end. The paint is allowed to dry for a minimum of one hour.

#### 5.2.2.1.7 Relating to the test procedure

a. With the test apparatus set at the lowest voltage range resulting in a measurable current, the current in milliamps (mA) through the volume of the part and across the surface of the part is determined.

b. Tester should specify voltage used when testing, which should not be less than 9 V, and not more than 510 V.

See Section 4.1.6 for guidelines on acceptance criteria for measured resistivity values.

### 5.2.3 Resistance Tests for Components (Not Installed In The Vehicle)

The following test procedures shall be followed for measuring the resistance of components where they have not been exposed to fuel. When fuel exposure has occurred, follow the test sequence of Section 5.4.

#### 5.2.3.1 Test Procedure

Refer to APPENDIX C.2.2.1.2 for recommendations concerning clamps and contacts.

Place the component being measured on a surface having a resistance at least two orders of magnitude higher than the upper resistance limit (greater than $1x10^{11}$ ohm is suggested).

Verify the test set up by clamping the electrodes to a 100MΩ, 1% resistor and measuring its resistance at a low level of voltage (10V is recommended, if available), 100V and 1000V.

Connect the positive electrode to the designated point where a measurement is to be taken. The electrode should have a contact surface of 18 $mm^2 \pm 0.5$ $mm^2$. Connect the meter lead to its banana jack. For most tests, more than one ground connection may be required to match the links that will exist when the component is mounted in the vehicle. The contacts for these links should be provided in a realistic way and should be brought to a common point to which the negative electrode should be connected.

In all cases, make sure that the contact electrodes sit as flat as possible and make maximum surface contact with the part.

If the part has a metal ground strap, take measurements at the point on the plastic part where the ground strap is attached and at the point on the strap where the strap is connected to the vehicle.

If the resistance meter being used designates Source and Sense inputs, connect the Voltage Source to the “positive” electrode and the Sense input to the “negative” electrode.

If the resistance meter being used allows manual selection of the test voltage, select the lowest level of voltage (identified in 5.2.3.1). Apply the voltage for 5s, then take and record the reading. If the reading is unstable and the values drift outside the acceptable range, record the reading as “unstable”. If the reading is stable or unstable but all values are less than or equal to the acceptance criterion, the test is passed and no further measurements are needed. If the reading is unstable with values outside of the acceptable requirement or stable but greater than the acceptance criterion, repeat the test at successively higher voltage levels at the settings available on the megohm meter being used (e.g., 100V, 250V, 500V then 1000V).

If the reading at any voltage up to 1000V is stable and less than or equal to the acceptance criterion, the test is passed. The test is failed if all readings are above the acceptance criterion or are unstable for any reason other than those given in the Note below. The recorded resistance value is that obtained at the highest voltage that gives a stable reading.

For acceptance criteria, see Section 4.1.

NOTE: Parts that exhibit unstable resistance values during measurement are considered acceptable for use if any of the following are true:

- A measured resistance may be unstable at lower voltage levels, but stable and within the specified limit at 100V or 1000V.
- The resistance may be below the measurement capability of the instrument (e.g., less than $1x10^3\Omega$) at the lower voltage level or at 100V. If so record this fact in the data.

### 5.2.4 Resistance Test for Installed Components, Assemblies and Systems

### 5.2.4.1 Test Procedure and Voltage

The procedure is the same as Section 5.2.3 with the following exceptions:

The test item should be installed in the vehicle rather than lying on an insulating surface.

Complete assemblies with several interfaces may have higher resistance than individual components. Consequently, it is more likely that voltages of 1000V will have to be used. The maximum current when measuring at 1000V should not exceed 1 mA. Extreme care should be exercised when testing at this voltage. DO NOT touch the electrodes while the measurement is being taken.

### 5.2.4.2 Test Setup:

5.2.4.2.1 The aim of testing is to measure the highest resistance to vehicle ground from any point on the installed assembly/system. Therefore the setup should include the ground path connections that would occur on the vehicle. Make sure all ground connections are secure during the test.

5.2.4.2.2 If serviceable fluid couplings are part of the system/assembly being tested, then those couplings should be set up in a way that simulates how they would be configured during vehicle operation. For example, a pressurized system will extend metal tubing slightly within a connector. For this reason, it would be acceptable to pull the metal tube so it “bottoms out” within the connector. It is also acceptable to apply up to a 2N side load to the barbed end of a fitting to create the type of internal contact that would be present in the coupling as-installed on a vehicle.

Care must be taken for environmental conditions of testing to be controlled adequately. (Refer to Section C.2.2.1.1.)

### 5.3 Static Charge Dissipation Test Procedure for Components

### 5.3.1 Sample Preparation

Prepare the samples to be tested in the same manner as described in Section 5.2.2.2.1.

### 5.3.2 Calibration / Verification

Verify the test set up by measuring the dissipation time for a 10MΩ, 1% resistor. Connect the positive electrode to the Charge Plate Monitor (CPM) detector plate and the resistor. Connect the negative electrode to ground such as the ground connection at the wall outlet. If a battery powered CPM is used, make sure it is also connected to ground. Leave the clamp unconnected.

Set the measurement parameters for voltage level up to 5000V. Using that 5000V as an example, the actual charging voltage is approximately 5300V to 5600V or more, but the decay time measurement starts when the voltage on the plate reaches 5000V. Set the stops at the 10% cut off (500V in our example). Apply the charging voltage for approximately 2s. Release the "arm" button and quickly connect the grounded negative electrode to the resistor. Record the dissipation time. Repeat the measurement 3 times. Dissipation time must be less than 0.5s. If a grounding module is used, charge the system as above then depress the “reset” pushbutton and record the reading.

NOTE: Do not use the grounding function of the CPM to perform this test. This function only grounds the detector plate.

### 5.3.3 Test Procedure

Connect the electrodes to the assembly in the same manner as was done in Section 5.2.3.1 (including the reference to C.2.2.1.2 for clamp and contact details). Place the assembly on a highly insulative surface having a surface resistivity greater than $10^{12}\Omega$, such as acrylic, PTFE, polycarbonate etc. to ensure there is no secondary leakage path for the applied charge to bleed off.

Apply the charging voltage for approximately 2s. Immediately ground the assembly by clamping the negative electrode to the desired point. Repeat the measurement 3 times and record the results.

If the grounding module is utilized follow the same procedure described for system verification.

### 5.3.4 Acceptance Criteria:

Refer to Section 4.1.5.

## 5.4 Test Procedures for Fuel Exposed Components

When testing parts or materials that have been exposed to fuel, a maximum relative humidity should be specified by the OEM/end user because the effects of fuel exposure can significantly affect material properties. (Refer to Appendices C and D).

### 5.4.1 Types of Fuel

The test fluid used in exposure testing should be a non-alcohol containing fuel such as test fluid C, US EPA Certification Gasoline, or similar grades per SAE J1681. Alcohol fuels can be used in exposure testing, but care must be taken because results can be misleading. (Refer to APPENDIX Section A.5.1). If exposure to alcohol fuels is required by the end user, the specific sequence of testing described in Sections 5.4.4 and 5.4.5 should be followed. (Specific fuels to be used should be decided between the OEM/end user and the producer.) Whenever handling fuel in any situation, the appropriate safety measures should be taken.

### 5.4.2 Fuel Soak Preconditioning

The time and temperature used to pre-condition in the fuel are to be decided between the OEM/end user and the producers. The time and temperature chosen should be sufficient to allow the fuel to fully equilibrate with the materials prior to testing.

### 5.4.3 Time After Fuel Exposure

The time between completion of fuel exposure and the start of the test procedures should be as short as practical and consistent with safe laboratory practice. Minimizing the time between removal from fuel soak and electrical testing will minimize the changes that can occur due to fuel evaporating out of the material. The time should not exceed 2 hours.

### 5.4.4 Recommended Test Sequence

When exposure to fuel is required, resistance can increase, for example, due to swelling of a material. If capacitance decreases at the same time, then the rate of electrostatic charge dissipation can improve even though resistance may have increased to a level that might be considered unacceptable when tested under unexposed conditions. For these reasons, the sequence of tests identified in 5.4.5 is recommended for fuel-exposed components.

### 5.4.5 Components/Assemblies Tests (after fuel exposure)

a. Measure the resistance first as in Section 5.2. If acceptable values are obtained, then no further testing is needed (the component is acceptable).

b. If the resistances do not meet the acceptance criteria, then conduct the appropriate static decay test as in Section 5.3. If the results of static decay tests are acceptable, the component performance is considered acceptable.

### 5.5 Flow test procedures

Flow test procedures for the approach outlined in Section 4.2 are not sufficiently well-defined to be described as standard test methods. Therefore, detailed procedures are not given in the main body of this standard. However there are basic minimum requirements that must be met by any successful flow test procedure and these are given APPENDIX C and APPENDIX D.

### 5.6 Recording and Reporting Results

For any procedure that is performed, the specific results should be recorded and retained for future consideration. In addition, there are a number of other factors that should be recorded so they could be included when results are reported to an interested party. The level of data required for processing is a function of end user requirements. The following list is recommended (key parameters are discussed in APPENDIX C.).

a. The specific procedure performed

b. Date, time, and location

c. The specific instrumentation used

d. Electrode configuration or any other pertinent details about the nature of the contacts made

e. Environmental conditions of the test (temperature and relative humidity at a minimum). (Refer to Sections A.5.2 and C.2.2.1.1)

f. Specific test voltages and the sequence in which they were used

g. Specific resistance meter range if selected manually

h. Description of the test sample used and how it was prepared for the procedure. If components or assemblies were used, adequate description of those should be included.

i. For any procedures involving fuel or test fluid, describe the type of fuel or test fluid and the nature of the exposure (time, temperature, etc.). Also, record the length of time between fuel or test fluid exposure and conducting the test procedure.

j. For flowing fuel/fluid tests:
   i. The conductivity of the fuel or test fluid
   ii. The level of streaming current that was generated and the means of generating it
   iii. Details of any pass/fail criteria employed

## 6. NOTES

### 6.1 Marginal Indicia

A change bar (l) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. However, this revision is so extensive that changes bars have not been used. An (R) symbol to the left of the document title indicates a complete revision of the document, including technical revisions. Change bars and (R) are not used in original publications nor in documents that contain editorial changes only.

PREPARED BY THE SAE J1645 TASK FORCE OF THE SAE FUEL SYSTEMS TECHNICAL STANDARDS COMMITTEE

# APPENDIX A: BACKGROUND INFORMATION

## A.1 GENERAL COMMENTS

### A.1.1 Liquid Fuel Phenomenon

Electrostatic charge separation can be generated when sufficiently non-conductive materials move past each other in a shear mode. The effect can occur both at solid-solid interfaces and at solid-liquid interfaces such as those between fuel system components and liquid hydrocarbon fuels including biofuel blends. Charge generation does not occur to any significant degree in gases that flow at rates encountered in fuel vapor management systems, therefore, fuel vapor systems are not affected.

### A.1.2 Development of Electrostatic Charge

There are two primary functional areas of fuel systems where an electrostatic charge might develop:

a. The vehicle liquid fuel delivery system

b. The refueling system.

During refueling, electrostatic charges can be produced by:

a. Charges introduced into the fuel as it is pumped through fuel dispensing equipment.

b. Charges introduced into the incoming fuel as it flows through the fuel filler neck into the fuel tank.

### A.1.3 Background Literature

Five documents that offer extensive background information on the electrostatic charge phenomenon are:

a. NFPA 77—National Fire Protection Association—Recommended Practice on Static Electricity 2000 Edition.

b. American Petroleum Institute—Recommended API RP 2003, 7th ed., Jan 2008—"Protection Against Ignitions Arising Out of Static, Lightning, and Stray Currents.

c. Electrostatic Ignitions of Fires and Explosions American Institute for Chemical Engineers—Center for Chemical Process Safety; Thomas H. Pratt, PhD, PE

d. Avoiding Ignition Hazards in Chemical Operations. American Institute for Chemical Engineers—Center for Chemical Process Safety, Laurence G. Britton

e. CLC/TR 50404 Electrostatics—Code of Practice for the Avoidance of Hazards Due to Static Electricity

While these publications do not specifically address automotive applications, they contain thorough discussions of the physics of the electrostatic charge phenomenon as well as recommendations for preventing or mitigating the formation of significant electrostatic charge accumulation. For additional background, the references cited in Section 2 can be consulted.

## A.2 HOW FUEL SYSTEM COMPONENTS CONTRIBUTE TO THE ELECTROSTATIC CHARGE PHENOMENON

### A.2.1 The Four Processes

Electrostatic charges can be generated in a fuel system by fuel flowing against and through fuel system components. Due to subtle chemical, electrical, fluid, and thermal forces, a charge separation occurs between the liquid and the surfaces the liquid touches. Local velocity conditions can further enhance the separation of charges contributing to an electrically unbalanced condition. Each component of a fuel system can participate in these phenomena in one or more of the following four processes.

### A.2.1.1 Charge Separation

The interactions between flowing fuels and the solid surfaces of fuel delivery system or vehicle fuel system components can lead to the separation of (initially-balanced) charges of opposite polarity at contact surfaces. This allows both the fuel and the fuel system components to acquire electrostatic charges. Significant electrostatic charging is associated mainly with the action of flowing, low-conductive fuels (range between $5 \times 10^{-11}$ siemens per meter and $2.5 \times 10^{-10}$ siemens per meter (50pS/m and 250pS/m)).

### A.2.1.2 Charge Transport

Separated charges move from one part of the system to another, within the flowing, low-conductive fuel, and conductive or semi-conductive system components.

### A.2.1.3 Charge Accumulation

Separated charges can accumulate in areas with a poorly conductive path to the chassis ground. These accumulations grow until the rate of dissipation (determined by the resistance of the conductive path to the chassis ground) equals the rate of accumulation or until some limiting mechanism (such as an electrical discharge) causes a sudden reduction in the accumulated charge.

For example, a plastic fuel tank could become charged by fuel entering it during refueling and that charge could remain in place until it is dissipated through the fuel to the (grounded) sender unit.

NOTE: The exterior surface of the tank will exhibit a virtual charge (due to dielectric polarization) that is of similar magnitude, and of the same polarity as the interior charge. Nearby ungrounded metal components will become polarized by the charge in the interior of the tank and discharges may occur from the ungrounded metal component either to the surface of the tank or to other nearby grounded metal components.

### A.2.1.4 Charge Dissipation

Dissipation is the gradual loss of electrostatic charge to regions where it can recombine with charge of the opposite sign or give rise to only a low voltage (e.g. by arriving at a location where the capacitance to ground is high). Mechanisms of dissipation are discussed in A.3.

### A.1.1 Contributions of Various Components

Tables A1 and A2 present the relative contribution of fuel system components to the processes described in A.2.1.

Table A1 shows the relative contribution of the various components of an operating fuel delivery system to electrostatic charge processes. The information in Table A1 is independent of the information in Table A2.

Table A2 shows the relative contribution of the various components of a vehicle's fuel system to electrostatic charging processes during refueling. The information in Table A2 is independent of the information contained in Table A1.

## TABLE A1 - RELATIVE CONTRIBUTION OF FUEL SYSTEM COMPONENTS TO ELECTROSTATIC CHARGE PROCESSES DURING OPERATION OF THE FUEL DELIVERY SYSTEM

| DEGREE OF CONTRIBUTION OF VARIOUS FUEL SYSTEM COMPONENTS | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Charge Process | Tank (Containing Liquid Fuel) | Fuel Pump | Fuel Lines & Connectors Conductive (and Properly Bonded) | Fuel Lines & Connectors Dissipative (and Properly Bonded) | Fuel Lines & Connectors Insulative | Fuel Filter Conductive (and Properly Bonded) | Fuel Filter Dissipative (and Properly Bonded) | Fuel Filter Insulative | Fuel Rail(1) | Pressure Regulator |
| Separation | --- | Large | Small To Medium(2) | Small To Medium(2) | Small To Medium | Very Large | Very Large | Very Large | --- | Medium |
| Transport | --- | Medium | Large | Large | Large | Medium | Medium | Medium | Small(2) | Medium |
| Accumulation | Medium | Small | --- | Small | Medium | Small | Medium | Very Large | Small | Small |
| Decay Or Dissipation | Large | Small | Medium | Medium To Small | Small | Medium | Medium To Small | Small | Medium | --- |

1. Contribution depends on type of material.
2. Degree of grounding to the engine block depends on configuration.

## TABLE A2 - RELATIVE CONTRIBUTION OF FUEL SYSTEM COMPONENTS TO ELECTROSTATIC CHARGE PROCESSES DURING THE REFUELING PROCESS

| DEGREE OF CONTRIBUTION OF VARIOUS FUEL SYSTEM COMPONENTS | | | | | |
|---|---|---|---|---|---|
| Charge Process | Filler Neck Conductive (and Properly Bonded) | Filler Neck Dissipative (and Properly Bonded) | Filler Neck Insulative | Fuel Tank (Containing Liquid Fuel) | Fuel SendingUnit |
| Separation | Small | Medium | Large | Small | --- |
| Transport | Medium | Medium | Medium | --- | --- |
| Accumulation | --- | Small | Medium To Large | Large | Small |
| Decay Or Dissipation | Large | Small | --- | Medium | Large |

Tables A1 and A2 describe components as "insulative", "dissipative" or "conductive." These terms are given in Definitions 3.34, 3.21 and 3.13 respectively. Material properties are usually measured on samples that have not been exposed to fuel and properties may be altered by fuel exposure. Experience has shown that fuel system materials do not need to exhibit the high levels of conductivity associated with "conductive" such as metals in order to avoid the adverse effects of electrostatic charging. It is sufficient for them to have the intermediate, "dissipative" level of conductivity.

## A.3 MECHANISMS OF CHARGE DISSIPATION

If charge builds up in a fuel system there are at least four separate mechanisms that can dissipate the charge (i.e., reduce it slowly):

a. Conduction through bonded components to ground.

b. Dissipation through the fuel to bonded conductive components and hence to ground.

c. Surface dissipation along bonded plastic components or along the interface between the liquid and components to ground.

d. Ionization of air (corona discharge). This is usually an external effect. It is not a direct dissipation route for charged fuel, except inside the fuel tank.

Fuel system design needs to promote these slow dissipative processes that generally occur with no destructive effects.

NOTE: Corona discharges tend to occur from sharply radiused protrusions. Although they still arise from the dielectric breakdown of the local gas (air or air-fuel mixture), they are slower than sparks or brush discharges and typically have few destructive consequences (e.g. non-incendive to ordinary automotive fuel vapors in air). They generally produce charge dissipation.

## A.4 DESTRUCTIVE MECHANISMS OF CHARGE REDUCTION (SPARKS OR BRUSH DISCHARGES)

Sparks or Brush Discharges are potentially damaging or hazardous mechanisms of charge reduction. They should be avoided because they can result in one or more of the following:

a. Ignition of combustible air/fuel mixtures.

b. Creation of microscopic holes through arcing or erosion of fuel system components.

c. Interference with the operation of electrical or electronic devices on the vehicle that are outside of the fuel system. (NOTE: See NFPA 77 referenced in Section 2.1.7)

### A.4.1 Spark or Brush Discharge Mechanisms

Spark or brush discharges occur when the electric field generated by an electrostatic charge exceeds the dielectric breakdown strength of the material where the charge is located. Spark discharges with potentially destructive energy occur between two metallic or conductive materials at different voltages (with at least one ungrounded). Brush discharges usually occur from charged dielectric surfaces to metal surfaces.

Both types of discharge generally occur through a dielectric medium such as air either:

a. Directly from a charged component to ground or to another component at a sufficiently different potential

b. From one part of a component to another if there is sufficient potential difference between the two parts

### A.4.2 Breakdown Strength of Air

Under standard conditions (e.g., using electrodes of a specified size and shape), dry air breaks down when the local electric field exceeds a value of 3kV/mm.

### A.4.3 Reductions in Dielectric Strength

Spark or brush discharges become more likely if the dielectric strength of the material is reduced by mechanisms such as:

a. Extended periods of exposure to electric fields or high but sub-critical levels of electrostatic charge

b. Environmental factors (such as lower temperatures and higher relative humidity)

c. Aging: Degradation of the dielectric strength due to chemical (fuel) exposure, thermal exposure, thermal cycling, mechanical fatigue, etc.

### A.4.4 Ignition of Fuel/Air Mixtures

Sparks or brush discharges can ignite fuel/air mixtures if:

a. A flammable fuel/air mixture exists in the discharge gap and

b. The electric field in the gap exceeds the breakdown strength of air and

c. The discharge has sufficient energy, voltage and charge transfer. The threshold charge transfer levels are similar for both types of discharge (~60 nC for the most easily ignited gasoline/air mixtures) but more energy and higher voltage is needed for brush discharges than for sparks.

d. The discharge gap exceeds twice the quench distance (See 3.37) for that fuel and air/fuel ratio

NOTE: Ignition can still occur with smaller gaps but significantly increased energies are needed to overcome heat losses to the adjacent solid surfaces.

#### A.4.4.1 Flammable Air/Fuel Mixtures

Flammable mixtures may exist at the following locations of a vehicle:

a. Around the filler neck during refueling

b. Near atmospheric vent outlets for the vapor management system

c. Near redundant overpressure relief valves

d. In the vapor space inside the fuel system under the conditions listed below

For different fuels, the conditions mentioned in connection with location d. are:

| FUEL TYPE | UPPER COMBUSTIBLE TEMPERATURE LIMIT |
|---|---|
| Diesel fuel; | above its flash point; typically 40º to 58º C |
| ULSD | above its flash point; typically 52º-82ºC |
| M100 (methanol) | below 42°C |
| E100 (ethanol) | below 42°C |
| M85 (methanol/gasoline) | below 3°C |
| E85 (ethanol/gasoline) | below 9°C |
| gasoline; 15 RVP (103 kPa) | below -34°C |
| gasoline; 13 RVP (90 kPa) | below -29°C |
| gasoline; 10 RVP (69 kPa) | below -22°C |
| gasoline; 7 RVP (48 kPa) | below -14°C |

#### A.4.4.2 Ignition Energy

Spark discharges can ignite flammable air/fuel mixtures if the discharge has sufficient energy. The energy (W) of a spark discharge to ground is described by the following equations:

$$W = \frac{1}{2} CV^2 \text{ or } W = \frac{1}{2} QV \text{ or } W = \frac{1}{2}Q^2/ C; \text{ where } Q = CV \qquad \text{(Eq. A1)}$$

Where:

C is the capacitance of the discharging body (F)
V is the difference in electrical potential between the discharging body and ground (V).
Q is the amount of charge on the body(C)
W is the energy (J)

For most automotive fuels the minimum ignition energy for a flammable mixture of air and saturated hydrocarbon vapor is greater than 0.20mJ.

Brush discharges need much higher energies than spark in order to cause ignition but brush discharge energies are hard to calculate as the voltage may not be constant over the charged surface and the fraction of the charge on the insulator that participates in the discharge is difficult to calculate. Also, for brush discharges, the total discharge energy is less relevant as only a fraction of the total discharge energy is dissipated in the hot channel that causes ignition. It is probably better to use charge transfer rather than energy to indicate the possible incendivity of brush discharges. The theoretical maximum effective energy for a Brush Discharge is 4mJ.

### A.4.5 Pinhole from Inside

Localized dielectric breakdown can occur through polymeric materials. The energy released in the discharge can melt, degrade, or burn the material in the discharge path and over time can produce a pinhole through the wall of an insulator. Residue from burned polymeric material has high carbon content and the path produced by such discharges is sometimes referred to as a carbon track. Once dielectric breakdown occurs, the insulating properties of materials are weakened and subsequent breakdowns will generally occur at a lower electrical field strength. Any subsequent discharge or current flow will tend to occur along the more conductive path of the carbon track (enlarging the hole). In fuel systems where the charge is generated in flowing fuel, the hole in the non-conductive component grows from the inside out.

### A.4.6 Pinhole from Outside

Discharge can also occur in the air between the surfaces of a non-conductive component to some other nearby conductive object that is at a different electric potential. This can cause the surface to decompose. This kind of discharge will occur between components having potential differences such that the electric field intensity in the air space between the components exceeds the dielectric breakdown strength of air (≈ 3kV/mm). Many successive discharges from the outside to the same location of the non-conductive component can lead to erosion of the surface material. Eventually a pinhole could result from the outside in.

## A.5 UNCONTROLLABLE FACTORS AFFECTING HAZARDS

### A.5.1 Fuel

Fuel has a major effect on the formation of electrostatic charges because its conductivity varies from less than $10^{-12}$ to over $10^{-9}$ siemens per meter (<1 pS/m to >1000pS/m) and it contains a wide range of components, additives and impurities. There are many sources and refining techniques for automotive fuels and an extremely wide array of compositions is encountered. Very small amounts (parts per billion) of impurities, additives and even moisture can have a large effect on charge density (see Definition 3.8). No controls on automotive fuel for reducing its propensity for generating electrostatic charges are considered practical. Recent introduction of biofuel blends and biodiesel blends in particular have added a new dimension to the fuel composition equation.

The following characteristics and circumstances can significantly influence the ability of a fuel to develop electrostatic charge:

a. Temperature: The rate of electrostatic charging often depends on fuel temperature but can exhibit a wide range of dependency and has been seen to both increase and decrease as the temperature is reduced. Accumulation tends to increases as the temperature falls due to reduced conductivity.

b. Composition, including the presence or absence of alcohol,

NOTE: Alcohols are pro-static agents (i.e., materials that increase fuel charge density more rapidly than conductivity). The effect of alcohols as pro-static agents is most pronounced at low concentrations. As the concentration increases, a point is reached where the conductivity increases rapidly and the fuel ceases to develop electrostatic charge. This can occur with an alcohol concentration of between 0.1% and 10%.

a. Conductivity: For gasoline, diesel including low sulfur diesel and biodiesel, this can vary from less that 1 pS/m to over 1000pS/m. For E10 fuel it can range from 3000pS/m to ~20,000pS/m. Note that although charge density is not a predictable function of conductivity, the highest charge densities tend to occur when the conductivity is in the region of 50pS/m to 250pS/m. At higher conductivity levels, the rate of charge generation starts to be overtaken by the rate of charge dissipation from the fuel and conductivities above 10,000pS/m are not generally associated with high charge density. The relaxation time (see Definition 3.40) is a characteristic of materials, including fuels, that indicates how quickly charges dissipate. Highly conductive fuels have very low relaxation times (charges dissipate very quickly)

b. Viscosity: See E.3.2.2 discussion of Reynolds Number. Turbulent flow fosters charge separation and the propensity for turbulent flow is directly related to viscosity. Fuel constituents (such as alcohol) have unique viscosity properties and their presence in higher concentrations can affect viscosity of the mixture. Also, viscosity increases as temperature decreases which can lead to turbulent flow.

c. Additives which can be pro-static, (See b above)

d. Impurities and contaminants can act as pro-static agents (see Definition 3.38). Some trace materials in fuel are ionic and these affect both charge density and relaxation time.

e. Moisture content, especially if the level is high enough to form a second phase. Emulsions are classed as 2-phase flow. The surfaces on very small droplets in emulsions provide locations where charges could form or accumulate.

Static-dissipator additives are available to improve a fuel's ability to dissipate charge by raising the electrical conductivity of the fuel. The use of these static-dissipator additives has proven unreliable as a "solution" for preventing electrostatic charge concerns in automotive fuel systems because:

a. The large number of fuel producers and fuel outlets that exist make it difficult to guarantee the addition of a specific ingredient in every case

b. These additives tend to plate out on surfaces of pipes, tanks and tubing so their effect changes over time.

c. Moisture content of the fuel can affect the performance of the additives.

### A.5.2 Environment

The environmental factors that have the most significant effects on the electrostatic behavior of a vehicle's fuel system are temperature and humidity. As a fuel system is exposed to moisture, environmental conditions, and dirt that can accumulate on a vehicle, the fuel system will tend to perform better from the standpoint of electrostatic charging (less likely to accumulate charge; what charging does occur is to a lower level, and dissipates faster).

High humidity can create a conductive path that permits charge dissipation over fuel system surfaces, thus preventing charge accumulation and discharge. A low absolute humidity environment, such as experienced at temperatures below freezing, is more likely to permit dielectric breakdowns by allowing a higher degree of charge accumulation. While environmental humidity primarily affects the exterior of the fuel system, it can also affect the moisture content of the fuel. A change in moisture content can cause fuel to change its conductivity. (Refer also to Section C.2.2.1.1.)

As temperature goes down, fuel conductivity decreases, fuel chemistry can change, and fuel viscosity increases. For each fuel, the combination of changes of these factors can contribute to a reduced amount of charge dissipation. Usually charge separation reaches a peak at a certain temperature.

### A.5.3 Factors External to the Vehicle

#### A.5.3.1 Fuel Dispensing Equipment

Local regulations and codes usually require that fuel dispensing equipment be conductive (or sufficiently conductive) and require a connection from the dispenser nozzle to earth ground (per NFPA 77, see section 2.1.7). If the electrical connection from nozzle to earth is interrupted and the vehicle is on insulating tires or standing on an insulating surface, a net charge can develop on the vehicle during refueling. Also, the use of pump mechanisms that greatly agitate fuel or cause air bubbles to form in the fuel can generate increased charge density levels.

#### A.5.3.2 People-Induced Charges

The actions of vehicle operators can cause them to develop a charge (e.g., sliding across a vehicle's seat). In addition, artificial materials used in some modern shoe soles tend to keep charges on a person rather than allowing them to pass to earth ground. As a result, a discharge is possible to whatever part of the vehicle or fuel dispensing equipment that a person touches. No fuel system or fuel dispenser equipment design practice can adequately deal with this circumstance. However, the following points/recommendations should be noted:

a. Vehicle and fuel dispenser operators might be advised to either remain in contact with the dispenser throughout the refueling operation or to ground themselves to the vehicle at a point away from combustible air/fuel vapor mixtures before contacting the fuel dispenser nozzle.

b. Vehicle designs that include a filler door that covers the fuel filler inlet can provide a charge dissipation point at the beginning of the refueling process if the filler door is not completely opened by a remote release mechanism.

## APPENDIX B: THEORY FOR ACCEPTANCE CRITERIA

This appendix provides justifications for the resistance, volume resistivity and decay time limits that are used in Section 4.1.

### B.1 JUSTIFICATION OF RESISTANCE AND VOLUME RESISTIVITY LIMITS

The limits are derived in four stages:

1. A fundamental resistance limit for assembled systems is derived that is designed to ensure safe voltages. It is based on the requirement that there should be a “sufficiently” low resistance path from every point of each component in contact with the fuel to some common point in the system, which is taken as the vehicle or chassis ground.
2. The fundamental resistance limit for assemblies is modified (reduced so that safety margins are increased) to provide a practical assembly resistance limit that is easily measured with widely available instruments and non-specialized procedures. This reduction step could be waived with expert advice on measurement procedures.
3. Limits for the individual components that contribute to the practical assembly resistance are derived. These are designed to ensure that the practical assembly limit can be met by an assembly of such components.
4. The volume resistivity needed for materials to enable components to meet the practical resistance requirements obtained in the third step is estimated.

### B.1.1 The fundamental resistance limit for assemblies

The fundamental requirement is that the voltages on plastic surfaces should not reach levels that could generate incendive discharges. The highest voltages arising from liquid flow occur on the surfaces that are in contact with the liquid (i.e. the inner surfaces of the fuel containment system). Therefore, in resistance terms, the fundamental requirement is that plastic surfaces that are in contact with the main liquid flow (i.e. the inner surfaces of the fuel containment system) must, in the fully assembled condition in the vehicle, have a resistance, $R$, to vehicle ground that everywhere meets the criterion:

$$R<R_{Max}$$

where $R_{Max}= V_{Haz}/I_{Max}$. Here, $V_{Haz}$ is the voltage at which hazardous discharges become possible and $I_{Max}$ is the maximum current that could be delivered to the assembly from the liquid by the flow of fuel through the assembly. This fundamental requirement is designed to insure that charges carried by the fuel cannot accumulate on the components to a hazardous degree.

To illustrate the use of the total resistance limit consider the illustration in Figure B1, which shows a vehicle being refueled. The streaming current carried by the flowing fuel is $I_S$ at the exit of the filler nozzle and $I_{IN}$ at the entry into the fuel tank. Current flows must be continuous so a total current of $I_S$ must flow back to the pump by a number of different electrically conducting paths such as the tires and pavement, the fuel hose, and through the electrical conductivity of the fuel itself. Also, a current $\Delta I_S=I_S-I_N$ must flow to the vehicle body via the filler neck and the hoses connecting the fuel filler tube to the fuel tank and the inlet housing, etc.

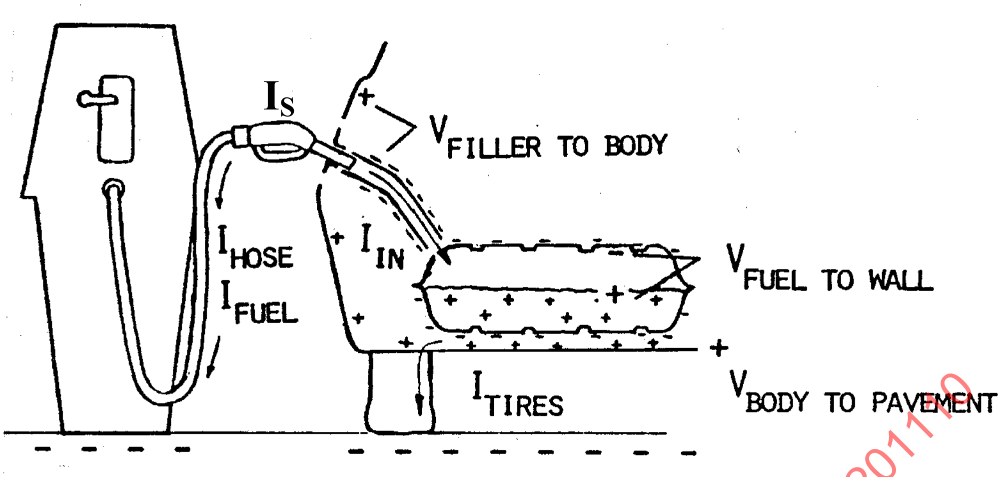


FIGURE B1 - REPRESENTATION OF CHARGING CONDITIONS AS VEHICLE IS REFUELED

To some degree of approximation, the equivalent electric circuit that represents this electrostatic flow of charge in Figure B1 is shown in Figure B2 which represents the system as a number of capacitors, upon which charges can be stored, and resistors that provide conducting paths in parallel and series with these capacitors.

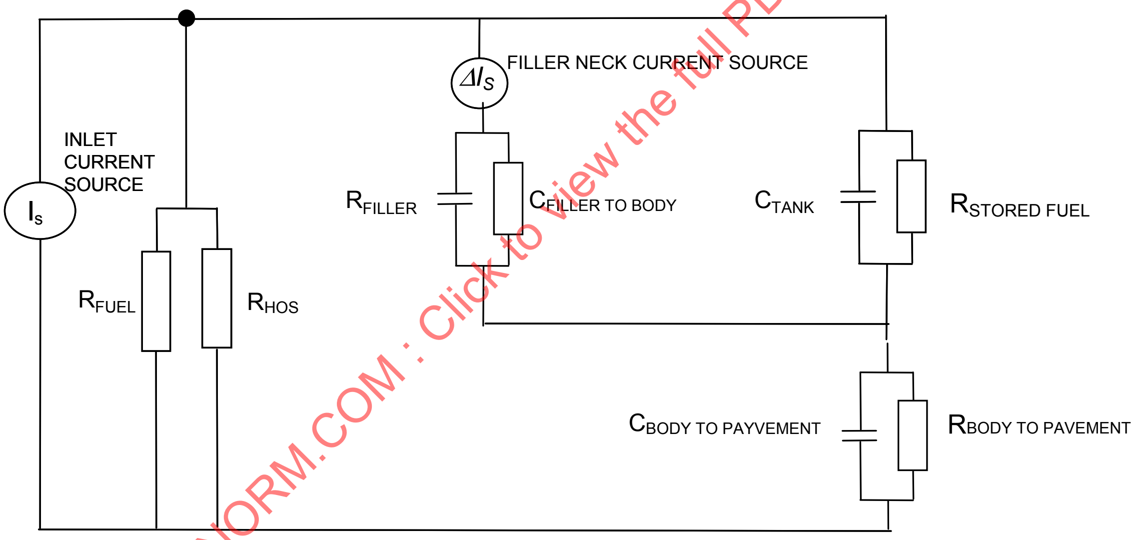


FIGURE B2 - EQUIVALENT CIRCUIT FOR FIGURE B1 (STREAMING CURRENT INTO TANK = $I_{IN}=I_S-\Delta I_S$)

NOTE: The filler neck is grounded at each end so the maximum resistance to ground, RFILLER, is formed from the parallel combination of the resistances upstream and downstream of the mid-point.

The streaming currents vary from segment to segment depending on the fuel/surface interactions. The various RC time constants found in the system are generally found to be short compared to operational timescales. Consequently, the voltages have time to develop fully and approach steady-state values. These steady values depend only on the resistances and currents and not on the system capacitances. The details depend upon geometry and material properties but, in order to derive a general resistance limit, they are avoided by requiring that the highest resistance to vehicle ground that occurs anywhere on an assembly must be low enough to keep the voltage to a safe value when dissipating the maximum possible current that could flow to the walls of any fuel system assembly. This is equal to the maximum possible change in streaming current that could occur as fuel flows through the assembly.

In the given example, consider the filler neck, for which the maximum resistance to vehicle ground is, $R_{FILLER}$. From experience, the highest streaming current change is known to be of order $5x10^{-7}$A. If there are no ungrounded metal parts with a capacitance of more than 3pF, then $V_{Haz}$ = 25kV (the threshold voltage for incendive brush discharges). If there are ungrounded metal components with a capacitance of more than 3pF, then we should take $V_{Haz}$ = 1kV (a practical threshold voltage for incendive spark discharges[1]). With the maximum current, these voltage thresholds lead respectively to $R_{Max}$= $5x10^{10}\Omega$ if there are no ungrounded conductors or $R_{Max}$ = $2x10^{9}\Omega$ if there are ungrounded conductors. For a round number limit we therefore take $R_{Max}$ = $10^{9}\Omega$ as the worst-case value. This is regarded as the fundamental resistance limit for assemblies.

NOTE: Here the 1kV threshold is used purely to derive generic safe resistance limits for isolated conductors. Ungrounded conductive parts with voltages in excess of 1kV may still be considered safe if they are not in a flammable atmosphere, if the voltage is too low for breakdown with the given geometry or if the stored energy is less than 0.2mJ.

### B.1.2 Examples of safety margins with specific assemblies

The fundamental resistance limit derived in the previous section is based on full dissipation of the highest known streaming currents, the presence of an ungrounded conductor and the assumption that the effective dissipation resistance is equal to the maximum measurable resistance to ground. These worst-case assumptions were adopted because we cannot, in general, be certain of the distribution of resistance along an insulative component and because our knowledge of streaming currents is incomplete. In practical assemblies, these worst-case assumptions can often provide a considerable safety margin. This is illustrated now for some specific cases.

In the hypothetical case of a metal filler neck insulated from vehicle ground at either end by two short insulative tubes, the highest possible streaming current could occur, all the streaming current change ($\Delta I_S$) could be delivered to the wall of the filler neck in a region where the resistance to ground is at its highest and there would be an ungrounded metal conductor in the system. This case fits all the worst-case assumptions and there would be no additional safety margin.

In contrast, for an all-plastic filler neck grounded at each end and with a uniform resistance per unit length, the actual local resistance to ground is high in the centre and small at the ends. The streaming current delivers charge to the surface of the neck in a distributed fashion. Thus, some current is delivered near the ends where the resistance to ground is low. When this is taken into account, theory indicates that the effective resistance to ground for the wall current is only 1/2.35 of the maximum measurable resistance to ground, $R_{FILLER}$. Because the system is all plastic there are no ungrounded conductors and the voltage threshold is 25kV. Thus the maximum tolerable resistance to ground is 25x2.35x1 = 59G$\Omega$ rather than 1G$\Omega$ and the worst-case assumptions are now seen to provide a considerable safety margin.

A similar circuit to that in Figure B2 could be developed for the fuel flows that arise from the vehicle's fuel pump although this circuit would be confined to the interior of the vehicle. The maximum streaming current expected in this case is around 1/3 of that expected in the filler system so a resistance of up to ~3G$\Omega$ could be tolerated even in the presence of ungrounded conductors. Again application of the worst-case assumptions would provide a margin.

### B.1.3 The practical resistance limit for assemblies

The most widely available forms of resistance tester are capable of measuring resistances only up to $10^{8}\Omega$ (100M$\Omega$). To simplify measurement procedures this is recommended as a practical acceptance criterion for installed resistance rather than the fundamental $10^{9}\Omega$ limit derived in B.1.1. It is expected to keep in-service electrostatic voltages below 100V and hence provides an additional safety margin beyond that provided by the fundamental limit.

NOTE: With suitable measuring equipment and expert advice on measurement procedures, the fundamental limit given in B.1.1 could be used in place of the practical resistance limit.

---

[1] At 1kV, the breakdown gap is much smaller than the quenching distances associated with hydrocarbon fuels so, to compensate for quenching, the discharge energy would need to greatly exceed the minimum ignition energy (MIE) before ignition could occur. The capacitance would need to exceed 400 pF, which is a high value for an isolated fuel system component, before even the MIE was exceeded. Therefore ignitions at voltages below 1kV are considered practically unlikely even though they may be possible under laboratory conditions with very high capacitance and stored energy.

### B.1.4 Resistance requirements for individual components

A system would be safe if the fundamental requirements given for the whole assembly in Section B.1.1 were met irrespective of any individual component requirements. Furthermore, moderately high resistance components could be tolerated in an assembly provided their resistance was compensated for by low-resistance components elsewhere in the assembly. Consequently, the basic component resistance requirement is the same as the assembly resistance requirement, that is:

$$R<R_{Max} \qquad \text{(Eq. B1)}$$

Where $R_{Max}$ is the reduced practical resistance limit defined in B.1.4 and $R$ is the maximum resistance to ground with the inlet and outlet and all grounding points connected to ground.

This condition is sufficient to ensure that excessive voltages will not occur on the component itself if both ends are grounded. However, the possibility remains that a high voltage could occur if a chain of components that individually satisfied (Eq. B1) were connected in series without grounding the junctions and without specific additional grounding points on any component in the chain. For such a chain of it is necessary that the sum of the R values is less than $R_{Max}$. That is:

$$\sum_{n=1}^{n=N} R_n < R_{Max} \qquad \text{(Eq. B2)}$$

where $R_n$ is the R value of the nth component in the chain. This requirement is not included explicitly in the main text as N can, in principle, vary from design to design and it may not be needed. (Eq. B2) will be satisfied if the assembly resistance test is passed so this omission does not allow a possible unsafe condition.

### B.1.5 Requirements for materials: the volume resistivity limit

The final limit is a material specification that sets the maximum volume resistivity ($\rho$) at $10^4 \Omega$m. This is chosen in anticipation of the material ultimately being used to form components in an assembly that satisfies the practical limit on assembly resistance to vehicle ground (section B.1.4). If the fundamental resistance limit given in B.1.1 were to be used in place of the practical resistance limit, the volume resistivity limit would be correspondingly increased to $1 \times 10^5 \Omega$m. The relationship between resistivity and resistance is geometry dependent, but an order of magnitude rule of thumb estimate is:

$$R = \rho\, L / A \qquad \text{(Eq. B3)}$$

where $\rho$ is the volume resistivity, L is the mean length of the part in the direction of current flow and A is the minimum cross-sectional area across which the current flows. A component that has a large resistance is one that is long and thin. Consider a 1.22m (4 foot) length of 0.01m (3/8 inch) diameter fuel line with a wall thickness of $1.59 \times 10^{-3}$m (1/16 inch) and resistivity of $1 \times 10^4 \Omega$m. Substitution into the formula estimates the maximum resistance to ground when earthed at both ends to be 30M$\Omega$, which is on the order of magnitude of the 100M$\Omega$ limit.

## B.2 JUSTIFICATION OF STATIC DECAY TIME

The highest steady-state voltage that can occur on the wall of an insulating pipe that is grounded at both ends is given by:

$$V=G_{max} I_s R_{eff} \qquad \text{(Eq. B4)}$$

Where $R_{eff}$ is the effective end-to-end resistance of the pipe including the conductance of the liquid and $G_{max}$ is the highest possible value of a geometric factor, G that depends on the fuel conductivity, component length and flow velocity. For exponential changes of streaming current with pipe length it can be shown that $G_{max}$ = 0.106. For fuels with low conductivity and pipes that meet the resistance or dissipation times recommended in this document, the liquid contribution to the effective resistance is negligible and $R_{eff}$ = R where R is the end-to-end resistance of the pipe wall alone.

For components that pass a dissipation time test it can be shown that:

$$R(C_p+\alpha C_{test})\ln(10) \le t_{diss} \qquad \text{(Eq. B5)}$$

where $C_p$ is the plate capacitance, $C_{test}$ is the capacitance of the test object to ground under the test condition, $\alpha$ is a calibration factor that depends on the test object resistance and is generally ~0.35 and $t_{diss}$ (=0.5s) is the acceptance limit for the dissipation time.

Combining equations (B4) and (B5) gives the maximum attainable voltage as:

$$V=G_{max}I_s t_{diss}/[(C_p + \alpha C_{test})\ln(10)] \qquad \text{(Eq. B6)}$$

If we require that $V \le 1000V$, $C_p$=20pF, $G_{max}$= 0.106 and $I_s=5x10^{-7}$A, equation (B6) with the worst-case of $C_{test}$ =0 gives $t_{diss} \le 0.43s$. This may be rounded down to 0.5s. A 0.5s limit would be expected to keep voltages below 1000V and hence should provide for safe operation. The safety margin associated with the 0.5s limit is comparable to that associated with the fundamental resistance limit given in B.1.1 and is about a factor of 10 lower than that associated with the practical resistance limit that is defined in B.1.4 and used in the main body of these Guidelines.

The suggested initial test voltage for dissipation time tests is 3000V. This level is chosen because the endpoint of the decay process would then be a voltage of 300V. These two voltages are the round-number levels that come closest to symmetrically bracketing the 1000V hazard threshold and so give the decay time that is likely to be of most relevance to this voltage.

# APPENDIX C: TESTING AND MEASUREMENTS - BASIC GUIDELINES AND CONSIDERATIONS

## C.1 GENERAL COMMENTS

The approach to static control outlined in Section 4.1 requires testing for the electrostatic dissipative properties (resistivities, resistances and dissipation times) of materials, components and assemblies used in automotive fuel systems. The relevant test procedures are given in Sections 5.2 and 5.3. Section C.2 gives the basic guidelines and cautions associated with these procedures and APPENDIX B gives the theoretical background to the acceptance criteria used in Section 4.1.

The approach to static control outlined in Section 4.2 allows designs that do not meet the requirements of 4.1 by demonstrating that the design prevents all harmful consequences of electrostatic charges by testing for charge accumulation or the occurrence of incendive discharges. Guidelines for these procedures are given in Sections C.3 thru C.6 and APPENDIX D.

## C.2 MEASUREMENT OF RESISTANCE AND DISSIPATION PARAMETERS

### C.2.1 General approach for materials, components and assemblies

The most important ESD characteristic of a fuel system assembly is its ability to dissipate electrostatic charge in a controlled manner to prevent charge accumulation reaching a level at which damaging discharges could occur. This is accomplished by controlling either the maximum resistance to ground or the charge dissipation time.

The evaluation of the resistance or dissipation characteristics of materials, components and assemblies should be accomplished in four separate steps.

- The basic material used to make the components should have the correct electrostatic characteristics. Guidelines are provided as a starting point (Section 4.1.6).
- The components should be tested to confirm that the manufacturing process does not significantly alter the basic material electrostatic properties and that the geometric shape of the object does not compromise the dissipation performance.
- The complete assembly should be tested to ensure that satisfactory bonding occurs between all components.
- The bonding of the installed assembly to vehicle chassis ground should be tested.

The properties used for characterizing materials are not directly applicable to components and assemblies because geometric factors, which are standardized for materials testing, play a critical role in defining the properties of manufactured objects. Thus, for example, the resistance through a thin sheet of insulating material separating two metal plates is many orders of magnitude lower than the end-to-end resistance of a thin-walled tube made of the same material simply because of the geometric differences even though the material properties are the same in both cases. Thus, materials are generally characterized in terms of volume resistivity and surface resistivity whereas objects are usually categorized in terms of maximum resistance to ground, resistance between specified points or dissipation time.

More specifically, the key requirement for a fuel system assembly is to dissipate charge from the inside surface where the flowing fuel contacts the part. Hence, all resistance measurements on an assembly should be made between specified points on this inside surface and the vehicle ground (chassis). If the part used on a vehicle involves mating parts that are inserted into a component with a conductive interior, measurements can be made from the inserted component.

If the resistance from any chargeable point on an assembly exceeds the specified upper limit (see 4.1) the dissipation time of a static charge from points of the assembly should also be measured. An assembly that exceeds the specified resistance limit will still be able to bleed off a static charge in a timely manner if the dissipation time is within the specified limit. A system is considered acceptable if it passes either test.

To ensure repeatable measurement results between different test laboratories of the same material or parts, it is necessary to specify all parameters that may have an effect on the measurement. ASTM D-4496 and ESD STM 11.11 and 11.12 are excellent references for defining these parameters (for tests on fuel-exposed components refer also to Section 5.4).

### C.2.2 Test Procedures

The steps adopted during the test procedure can have an important influence on the results. How the sample is prepared, test electrode requirements, how the instrumentation is connected, test voltages used and how the measurement is taken all affect the accuracy of the data and should be reported with the results.

### C.2.2.1 Resistance Measurements

For thermoplastic resins containing conductive fillers/reinforcements, the test instrumentation, electrodes and system verification are all critical in obtaining multi-lab correlation and must be specified.

### C.2.2.1.1 Sample Preparation (refer also to Section A.5.2)

When measuring dissipation properties (dissipation time, resistance or resistivity), it is best to use controlled environmental conditions. Since lower humidity can affect the material resistance properties all certification tests should be prepared and performed at 12 ± 3% RH and 23°C as specified in ESD STM 11.11 and 11.12.

Testing can be conducted at 50% relative humidity if the data collected is considered "useful". (The 50% level of RH conforms to generally accepted test conditions for testing material properties). This additional information will allow comparison to existing data. It must be kept in mind, however, that the humidity level recommended for compliance to the requirements of Section 4.1 is 12 ± 3% RH.

Testing components and assemblies in a controlled environment may not be practical. Under these conditions the humidity and temperature should be recorded at the time of testing. It is recommended that relative humidity should be between 9% and 65%. Humidity levels outside of that range will cause measurement results that are less accurate and consistent.

### C.2.2.1.2 Contact Probes

When measuring resistance, a point contact can give a different result from a surface contact. Thus, it is highly recommended that the measurement of resistance for certifying material/material plaques and for verifying components and assemblies should be done with the electrode configurations as outlined below. However, it should be noted that the use of the recommended probes is not always possible or practical when performing testing on components, assemblies, and when conducting vehicle level testing. Therefore DMM clips or probes may be used in these instances; however, the issues associated with DMM clips and standard probes and the recommended contacts are as follows:

1. Point contact could break through corroded, contaminated, or coated surfaces of a component.
2. Thermoplastic resins containing conductive fillers/reinforcements may be heterogeneous mixtures that could create inconsistent contact with point probes. For this reason, contacts such as needle point probes or alligator clips should be avoided, if possible.
3. Resistance measurements should be made using methods that do not disturb the surface and that average the effects of surface variability; these include:
    a. Use of compliant contacts made of a conductive elastomer (with a surface resistance lower than the material being measured) with a hardness not to exceed 65D shore hardness and an applied force of 2N to 4N. A clamp having 0.25" x 0.25" (6mm x 6mm) outer and x 0.125" (6mm x 3mm) inner electrodes is recommended.
    b. Use highly conductive materials for contact or connections.

NOTE: ASTM D257-99 is a test procedure for insulative materials. It is not a procedure to be used as part of this document; however, it does provide important support to the measurement procedures in Section 5.2. It identifies fixtures that can be used in the resistance measurement process and recommends that measurements be taken using a contact method that mimics the way a particular component or subsystem is attached to the larger system.

### C.2.2.1.3 Instrumentation

Using STM 11.11 and/or 11.12 will meet the requirements of certifying the thermoplastic material used in fuel systems. These standards can be adapted in whole or modified to meet the specific requirements for fuel systems.

Prior to use, the system performance should be checked by measuring the resistance of a 100MΩ, 1% resistor using all relevant test voltages (see Sections 5.2.2.1 , 5.2.3.1 and 5.2.4.1).

The resistances of the materials being measured are generally time and voltage dependent. When using test voltages of 100V or more, the maximum current allowed is 5mA. However, many instruments limit the maximum current to 2mA to 3mA, especially when testing at 500V. If testing is performed using 1000V or more, the maximum current should be limited to 1mA or the level designed into the measuring instrument. When testing at 500V or more extreme care must be taken to avoid electrical shock. The minimum resistance that can be measured at different test voltages with current limited to 5mA and 1mA for 1000V are as shown in the following list:

| Applied Test Voltage (V) | Minimum Measurable Resistance (Ω) |
|---|---|
| 1000 | $1\times10^6$ @ 1mA |
| 100 | $2\times10^4$ @ 5mA |
| 10 | $2\times10^3$ @ 5mA |

Resistance values for materials used in fuel systems are typically in the less than $10^3\Omega$ to less than $10^{10}\Omega$ range. ESD STM 11.11, 11.12 and 11.13 utilize 10V and 100V to measure over the range of less than $10^3\Omega$ to $10^{11}\Omega$. These test voltages have been found to be satisfactory for measuring ESD materials over the above range. A number of manufacturers now offer resistance meters that utilize these test voltages. In addition, some meters automatically switch from 10V to 100V when the measured resistance is greater than or equal to $1\times10^6\Omega$. ESD TR 02-99 details the voltage characteristics of these instruments.

### C.2.2.1.4 A Defined Electrification Period (Measuring Time).

When measuring very high resistance, the RC time constant of the sample and the instrumentation may be so long that a significant amount of time is required for the test voltage to completely develop across the sample. The electrification time may be different for different instruments. Measuring a known resistor at the upper limit will help the user to determine a lower limit to the time it takes to measure the correct value but longer times may be needed if the test object adds significant extra capacitance to the system.

High resistance values are time-dependent. In general, therefore, measurement times should ideally be comparable to the timescales for the operation concerned (e.g., for re-fuelling issues, timescales of the order of minutes (~60s) would be most appropriate). However, the upper resistance limits recommended for fuel system components in this standard are not extremely high and in this case, measurement values tend to stabilize fairly quickly. In these circumstances, a measurement taken at a relatively short time may be used. A measurement time of 5s is recommended.

If, however, the resistance value continues to change substantially over the measurement period, consideration should be given to increasing the measurement time either until the resistance stabilizes or until the measurement time matches the timescale of the operation concerned. Otherwise, the measured resistance may be too low to be representative. If a non-standard measurement time is used it should be clearly recorded.

### C.2.2.2 Static Dissipation

When measuring static dissipation (static decay) the test method must be specified since several different test methods are available. Unfortunately, there is no direct correlation between methods. For fuel system analysis it will be necessary to use two different test methods.

The first, based on Mil Std 3010, Method 4046.1 and following the proposed test procedure in 5.3, would be used for certifying material plaques.

The second, using a charged plate monitor (CPM) and following the proposed test procedure in 5.3, would be used for testing assemblies. The same sample preparation used for resistance measurements would also be used for dissipation testing.

The electrostatic decay/dissipation time measuring equipment needs to meet the following requirements:

a. The time resolution of the equipment shall not exceed 0.1 sec.

b. The equipment would preferably display a 1 volt resolution.

c. All probes used along with this equipment shall comply with SAE J1645 document.

d. The equipment shall meet ESD STM 3.1-2000 and other relevant specifications

### C.2.3 Cautions.

#### C.2.3.1 Misinterpretation of Measurement

It often appears deceptively simple to make a measurement of parameters related to electrostatic charge dissipation. However, it can be difficult to measure a specific parameter accurately or to obtain a relevant value that properly describes the effect of that parameter on the overall system behavior because factors that contribute to the measured result can depend on features specific to individual component or system design and these may differ between the measurement test setup and the finished system. Also, there are many sources of variability that can cause errors in obtaining or interpreting test results.

#### C.2.3.2 Small Variations

Small, seemingly inconsequential variations in test methods as well as component conditioning and testing circumstances can cause wide differences in results. This can be especially important when attempting to compare the performance of different designs. Therefore, all aspects of such measurements should be controlled, or at least noted. These include:

a. Temperature

b. Humidity

c. Surface conditions (paint, roughness, etc.)

d. Aging due to such factors as fuel and chemical exposure, thermal exposure, mechanical fatigue, etc.

e. Corrosion/wear

f. Manufacturing variations

g. Accumulation of dirt and foreign substances

h. Characteristics of fuel (conductivity, viscosity, additives, etc.) if in contact with the assembly during measurement

#### C.2.3.3 Effects Of Measurement Procedures

The procedure used to make measurements of electrostatic related parameters can affect the results. Standardizing factors such as the following will reduce variations in the measurements taken.

#### C.2.3.3.1 Field Strength Measurements

a. Distance to Point or Component Being Tested.—Field strength varies as a function of the distance from the charge that is causing the field. Therefore, the distance from the charge to the measurement device should be carefully controlled to obtain an accurate measurement from test to test.

b. The Measurement Instrument Itself.—Placing a measurement device into an electrostatic field to measure the field strength disturbs the field and changes the result. For consistent results it is therefore necessary to use the same type of instrument for each measurement or at least instruments with the same geometry of measurement head.

#### C.2.3.3.2 Resistance Measurements

a. Motion During Measurement—Movement of the probe, sensor or contact device can affect the measured value obtained. There should be either no movement or the movement should be identical during each measurement.

b. Surface Condition At Point Of Contact—If surface conditions vary from measurement to measurement (humidity, dirt, roughness, etc.) the results obtained can vary widely. Differences should be minimized.

## C.3 TESTS USING FLOWING LIQUID

### C.3.1 General

When safety is based on the requirements of section 4.2, it becomes necessary to base the testing on flow charging tests. These involve flowing a fuel or test fluid through a fuel system or portion of a fuel system in a manner simulating the worst-case conditions that could occur in vehicle operation and measuring the electrostatic effects created by flow in that specific design condition.

In contrast to the tests that are required when safety is based on the resistance or dissipation time requirements, flow charging tests cannot be conducted solely on a routine basis with standard tools by technicians with normal training. Instead, they must be designed and applied on the basis of specialized and expert knowledge of the field of electrostatics. This section establishes the minimum conditions that must be observed if these tests are to be adequate for assessing the potential for harmful electrostatic charge effects.

It is not possible or appropriate to formulate standardized test procedures and the flow-test method descriptions are not included in the recommendations portion of this document for that reason.

Although a standard method is not available, the guidance in the present section provides a set of minimum requirements for successful flow test measurement.

### C.3.2 Categories of flow testing

The quantities that can be measured during flow testing fall into two categories:

- Discharge charge-transfer data
- Accumulation data.

The key feature of discharge charge-transfer data is that readings cannot be scaled with Ohm's law. As a consequence, it is necessary to carry out these tests with the worst-case (highest possible) streaming current. In contrast, accumulation data (measured charge, voltage or electric field) can be scaled using Ohm's law so measurements can be made with a convenient level of streaming current and then Ohm's law can be used to scale the results to represent the worst-case.

NOTE: Accumulation data includes the stored energy, which can be derived, for example, by measuring both charge and voltage or by measuring one of these plus the capacitance of the object.

### C.3.3 Significance and Measurement of Capacitance

C.3.3.1 Great care and expertise is required in measuring capacitance due to the following:

a. The act of measuring capacitance and the instrumentation involved can affect the result. This is especially true when measuring small capacitances (less than 10 pF).

b. A capacitance measurement may only be valid when the component concerned is in a fully representative vehicle environment.

In some references, maximum "safe" capacitances are quoted. Great care should be taken with these statements because even the smallest capacitance can produce an incendive discharge if the applied voltage is sufficiently high.

C.3.3.2 Fixing object capacitance during testing

The environment in which an object is located (in particular the location and shape of nearby conductors) has a notable impact on its capacitance, and hence on accumulated charge, stored energy and charge transfer.

NOTE: Because in-service conditions usually approach the steady state, the capacitance is normally expected to have a much smaller influence on voltage and electric field.

Where testing is not possible in the intended application environment, it is important, particularly for accumulated-charge, capacitance, stored-energy and discharge charge-transfer determinations, that the test setup should simulate the capacitance in the application environment as closely as possible by the provision of suitable arrangement of earthed conductors around the test object.

### C.3.4 Temperature and Humidity

Tests should be conducted at low temperature and low relative humidity representative of the worst case (the case that gives the least effective charge dissipation) for the intended market. Tests should be conducted over the temperature range from 23°C down to the lowest temperature anticipated for the product in its intended marketplaces. A minimum temperature of –40°C is recommended where uncertainty exists. The relative humidity should preferably be 12% ± 3% and should not exceed 30%.

When using the test fluid recommended in C.3.7 the following conditions apply:

- Temperature: +4.5ºC ±1.5ºC (+40ºF ±3ºF)
- Relative humidity < 30%.

These conditions represent the worst case environment for charging experiments to be executable in a climate chamber. Lower temperatures are not favorable because at temperatures below 0°C less charging can occur due to the building of ice on the surface of the tested parts has been observed. To ensure safe operation at even lower temperatures a safety factor of 1.2 has to be applied on all measured values under the specified conditions.

### C.3.5 Streaming currents and conductivities for charge accumulation tests

Charge accumulation data (measured charge, voltage or electric field) can be scaled approximately linearly with streaming current so it is possible to test with a reasonably representative streaming current, $I_{sTest}$, at the inlet of the component or assembly under test and then scale the measured charge, voltage or electric field to estimate the value that would occur with a current, $I_{sScal}$, that is estimated to represent the maximum possible in-service streaming current plus any required safety margin. No specific polarity of fuel charge is required when measuring charge accumulation data.

Thus, if $I_{sMax}$ is the maximum streaming current that has been observed in practice, then:

$$Standard\_Result = Test\_Value*I_{sScal}/I_{sTest} \geq Test\_Value*I_{sMax}/I_{sTest}$$

Where:

Standard_Result is the reportable value for the quantity being measured,

Test_Value is the actual measured value,

$I_{sMax}$ is the maximum streaming current that could occur at the inlet of the component or assembly being investigated

$I_{sScal}$ is the scaling current derived from $I_{sMax}$ and

$I_{sTest}$ is the streaming current actually obtained during the tests.

For reliable results, the scaling factor, $I_{sScal}/I_{sTest}$, should not be too large. Consequently, a minimum $I_{sTest}$ value of 25nA is suggested. Additional charge generating elements such as filters or corona chargers may be required in order to ensure that the current does not fall too far below the guideline value of 25nA.

If the highest possible current, $I_{sMax}$, is not known, then the measured values may be scaled to a level of $I_{sScal}$ = 100nA (0.1µA) for filler system components/assemblies and $I_{sScal}$ = 25nA (0.025µA) for fuel delivery system components/assemblies. These standard scaling currents are based on our knowledge of fuel behavior in years 2008/2009 and may change with the introduction of new and possibly pro-charging fuel components e.g., as a result of biofuel initiatives or as a result of new measurement data on fuel charging.

The degree of charge accumulation usually goes through a maximum as the conductivity is varied. Theory suggests that the worst-case occurs when the contact time (length/flow velocity) between the fuel and the component is approximately three times the relaxation time of the fuel (see 3.40). However, the theory is only approximate and the maximum potential will need to be found by experiment. Therefore, data should be obtained for a range of conductivities to ensure that the conductivity that gives maximum accumulation is covered.

NOTE: Typically the peak occurs at between 50pS/m and 250pS/m.

The inlet streaming current (or charge density), fuel conductivity, fuel temperature, ambient relative humidity, volumetric flow rate and mean flow velocity (or inlet pipe diameter) should all be measured and recorded during flow discharge measurements.

### C.3.6 Streaming Currents And Conductivities For Discharge Tests

Discharges have onset thresholds. Consequently, their occurrence with high streaming currents cannot be estimated by scaling the data obtained with lower streaming currents. Discharge testing must therefore be done using the highest level of streaming current that is known to occur for the operation concerned plus a suitable safety margin.

To provide this margin, the test current at the inlet of the component or assembly under test should be at least a factor of 2 higher than the maximum that has been observed in practice (i.e. $I_{sTest} \geq 2.0xI_{sMax}$) i.e. a 100% safety margin in streaming current should be allowed. If the highest streaming current that could occur at the component inlet is not known, a test current of $I_{sTest}$ = 100nA (0.1µA) may be used for filler system components/assemblies and $I_{sTest}$ = 25nA (0.025µA) for fuel delivery system components/ assemblies. These standard test currents are based on fuel properties known in 2008/2009 and may change with the introduction of new and possibly pro-charging components e.g., as a result of biofuel initiatives or as a result of new measurement data on fuel charging. Additional charge generating elements such as filters or corona chargers will usually be required in order to achieve the necessary streaming current.

Discharge charge transfers from insulating surfaces are sensitive to the polarity of charging. Negatively charged surfaces produce the largest charge transfers and are more likely to cause ignition. Therefore, for flow tests done to establish the maximum charge transfer from insulating components, there should be a net loss of negative charge from the fuel as it passes through the component. This will normally require that the fuel at the inlet is negatively charged. Charging of either polarity may be used for characterizing spark discharges between metal objects.

The fuel conductivity and flow velocity should together be adjusted within the expected operating ranges to maximize the potential produced on the test object and thereby maximize the likelihood of generating an incendive discharge. Theory suggests that the worst-case occurs when the contact time (length/flow velocity) between the fuel and the component is approximately three times the relaxation time of the fuel. However, the theory is only approximate and the maximum potential will need to be found by experiment.

The inlet streaming current (or charge density), fuel conductivity, fuel temperature, ambient relative humidity, volumetric flow rate and mean flow velocity (or inlet pipe diameter) should all be measured and recorded during flow discharge measurements.

### C.3.7 Test Fluids For Flow Testing

It has been found that certain common industrial solvents with relatively high flash points can exhibit chargeability representative of worst-case fuels. This avoids the safety issues associated with gasoline and makes it easier to obtain consistent and reproducible results. Since 1952 the fluid MIL-F-7024A Type II has been proved of value as a test fluid for electrostatic tests (C. B. Shepherd jr, Standard calibration fuels, WADC Technical Report 52-331, Wright Air Development Center, Ohio (1952)). Therefore these fluids are recommended for use in the tests described in the Appendices of this document

These types of relatively safe fluids have the following characteristics:

- Known commercially as de-aromatized white spirits they are mixtures of paraffinic and naphthenic hydrocarbons with very low aromatic content.

- They should have a boiling range of 145ºC/200ºC so that the flash point temperature is above 35ºC

NOTE: Although the above solvents are suitable for discharge testing still higher flash points may be preferred because incendive discharges may occur during testing at temperatures above 35 °C

- The electrical conductivity, at 23ºC ±1.5ºC should be capable of being varied over the range 25 pS/m to 250 pS/m per ASTM D 2624-02, Standard Test Method for Electric Conductivity of Aviation and Distillate Fuels.

NOTE: In order to allow testing over this range of conductivities a base fuel with conductivity at or below the bottom end of this range is needed. The base fuel conductivity can then be increased using small amounts (typically <ppm) of a static dissipator additive (e.g. Stadis 450) or with larger amounts of any other conductivity-increasing additive.

Test Fuel 145/200 is recommended as a suitable test fluid and is available in small quantities as follows:

1. In Germany "Testbenzin 145-200"

2. In USA and Canada "Stoddard solvent 145-200"

   Stoddard solvent is available as follows:

   Mallinckrodt Baker Inc

   222 Red School Lane

   Phillipsburg, New Jersey 08865

3. In rest of the world, also e.g. Austria, "white spirit (145-200)"

It may be possible to use such solvents directly for charge accumulation testing but the level of charging necessary for discharge testing will not usually be obtainable directly from the flow of test fluid through the usual components of the equipment under test (by definition the test current is intended to be at least double the maximum that has been seen in practice) and it will often/usually be necessary to augment the natural charging by including a high-charging element in the test system upstream of the item under test. The high-charging element may consist of a fine filter with a bypass system to tune the streaming current to the required value or a high voltage corona-charging device with variable voltage to tune the streaming current. With a filter system a pro-charging additive may also be needed.

### C.3.8 Specific Features Of New Types Of Fuel

The new bio fuels EXX (gasoline with an amount of 5% ethanol (E5) up to 100% ethanol (E100)) and BXX (diesel fuel with an amount of 5% FAME (B5) up to 100 % FAME (B100)) have different characteristics than fuel made from petroleum fuel. FAME is not so critical at high (outlet flow) temperatures due to its higher flash point (flash point > 130°C) than standard diesel fuel (flashpoint around 60°C). However, blended fuels such as B5 or B20 should be treated like pure petroleum diesel because the diesel characteristics will predominate.

Unlike FAME fuels, E85 up to E100 can develop an ignitable mixture inside the fuel tank under higher temperature conditions than standard gasoline. With standard gasoline the mixture inside the fuel tank is too rich to ignite over wide range of ambient temperature conditions but not at sufficiently low temperatures.

If an ignitable mixture can exists inside the fuel tank under reasonable conditions, the fuel tank has to be free from sources of ignition and be designed against hazards caused by charging of persons during refueling.

### C.3.9 Test Fluid Qualification

If a supplementary charging device is not to be used, the test fluid should be tested to verify its capability to generate the required level of electrostatic charge by measuring the streaming current it carries at the inlet to the component under test. For charge accumulation tests (electric field, voltage or charge measurements) a streaming current of at least 100 nA should be achieved. For discharge testing either the required test current for the operation or one of the standard test current levels identified in Section C.3.5 should be achieved. The method selected for streaming current measurement must be appropriate for the type of system testing that is being utilized as described in the two following paragraphs (C.3.9.1 and C.3.9.2).

### C.3.9.1 Fuel Dispenser Measurement Method

At room temperature, fuel or test fluid is flowed through a grounded conventional fuel dispensing nozzle with a new fuel dispenser filter (or, if necessary, a high charge generating device) attached directly to the nozzle inlet. Flowing fuel is dispensed into an isolated metal container at 45 L/min.

Acceptance Criterion: Current flow from the isolated container to ground must exceed the required test current as defined in C.3.5.

### C.3.9.2 Fuel Delivery Measurement Method

At room temperature, fuel or test fluid is flowed through a new, grounded, worst-case in-line fuel filter (or, if necessary, a high charge-generating device) into an isolated metal container at 120 L/hr.

Acceptance Criterion: Current flow from the isolated container to ground must exceed the required test current as defined in C.3.5.

### C.3.9.3 Alternative fuel

If different fuel is chosen the following pre-test procedure has to be done to verify the chargeability of test fuel. This test may be performed at room temperature (< 50 % rel. humidity). Streaming currents specified in C.3.6 must be achieved in the tests described in C.3.9.1 and C.3.9.2.

PTB developed specific test procedures as follows:

### C.3.9.3.1 Refueling Test

Do not necessarily use an in-hose filter during the specific tank system test, but at least show, that >100nA is generated when using a filter and having a flow rate of 45 l/min.

- Nozzle positions: 6 o-clock, hands off
- Nozzle types:
    - EU-Gasoline nozzle: ZVA 1.0 R
    - US-Gasoline nozzle: OPW 11
    - Diesel Nozzle: ZVA 1.0

### C.3.9.3.1.1 Test Procedure:

- Run the setup with Hydrosol per C.3.7
- Find the tube position with the maximum potential using the field meter app. 30s after the flow started
- The measured surface potential is the reference.
- Repeat the procedure with the medium planned for the tests
- Applicable fuels should generate at least 2 times the reference value

### C.3.9.3.2 Fuel Delivery Test

### C.3.9.3.2.1 Test equipment:

- Electrostatic fuel pump (standard production type – in tank or inline)
- PTFE tube: I.D.=6mm, O.D.=8mm, l=2000mm
- Petroleum p.a. (Merck 1.09718.6025)
- Field meter

### C.3.9.3.2.2 FDM Test

The complete Fuel delivery system shall be used.

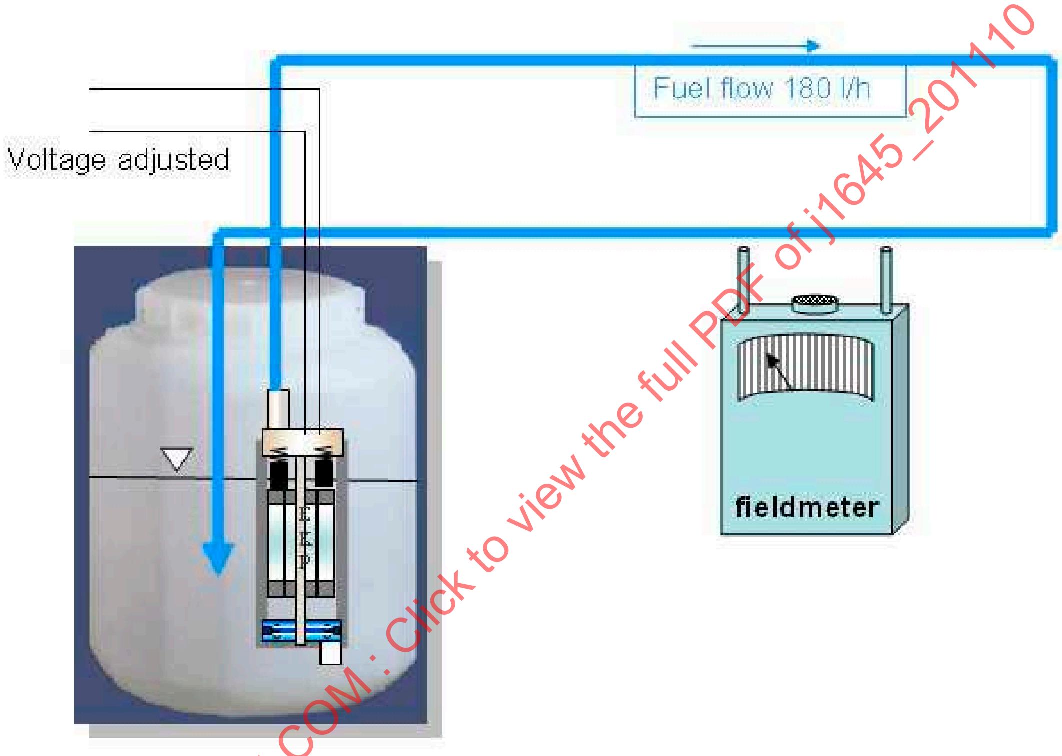
Highest applicable flow (There may be different operating conditions that create highest charging for specific parts), e.g.:

- Test at highest engine consumption
    - Test at the highest relevant flow is reached for the engine consumption set to a pressure 10% below system pressure.
- Test at zero engine consumption.
    - If the max. voltage is given by the OEM, 110% of this should be used. Otherwise a voltage of 16 V should be applied.
- Time: Run system until values are stable or start to drop
- Fuel Temperature: + 4.5°C ±1.5°C (+40ºF ±3ºF)

### C.3.9.3.2.3 Test Procedure:

- Run the setup with Hydrosol per C.3.7
- Find the tube position with the maximum potential using the field meter app. 30s after the flow started
- The measured surface potential is the reference.
- Repeat the procedure with the medium planned for the tests
- Applicable fuels should generate at least 2 times the reference value

This setup is to be used for testing.



### C.3.10 Justification Of Environmental Conditions And Flow Test Fluid Used

C.3.10.1 Environment: 4.5°C (40ºF), 30% rel. humidity.

Electrostatic charging increases with decreasing temperature and humidity. For this reason, the stated combination of temperature and humidity - the worst climate conditions that can be achieved with common climate chambers - represents the worst conditions to be found in the world on common usable roads. Only in some special parts of the world (the Poles, Gobi desert) even worse conditions are to be found. As the absolute amount of water in the air (which has the main effect on the ability of loosing charges through the air) is already very low at the stated climate it won't get much lower at colder and less humid conditions and a safety factor of 1.2 is, therefore, sufficient. This is especially true because at temperatures less than the freezing point parts will usually become coated with ice which drastically reduces charging.

### C.3.10.2 Flow Test Fluid

Testbenzin 145/200 is a fluid which is known to consistently produce very high charging and is similar to regular fuel. It is standardized and commercially available.

According to the boiling characteristics, Testbenzin 145/200 has already a higher viscosity than regular fuel. Therefore its viscosity at the recommended test temperature is comparable to that of petrol at temperatures far below freezing point.

## C.4 GENERIC FEATURES OF TEST METHODS

### C.4.1 Tests to Measure Charges Generated During Refueling Operations

Tests of the system should be conducted with typical marketplace nozzles and flow rates. The test rig should include the entire vehicle refueling system including the vent system. The test rig should also include all significant isolated capacitances near the fuel filler system and fuel tank as well as all significant nearby ground planes.

### C.4.2 Tests to Measure Charges Generated During Operation of the Fuel Delivery System

Tests should be conducted with the fuel delivery system operated at its typical pressure and at its maximum flow rate. The test rig should include the complete portion of the fuel delivery system being evaluated. The test rig should also include all significant isolated capacitances near that portion of the fuel delivery system as well as all significant nearby ground planes.

## C.5 SPECIFIC TESTS FOR ASSEMBLIES OR COMPONENTS THAT DO NOT MEET THE REQUIREMENTS OF SECTION 4.1

### C.5.1 Tests for Conductive Components

Recommendation (a) of section 4.2.2 can be verified by vapor composition measurements and flow testing in either of the following ways:-

a. Verify by measurement that a stored energy of 0.20 mJ cannot be achieved on any component located where a flammable atmosphere might occur. The energy is determined by measuring both charge and voltage on the object or by measuring one of these plus the capacitance of the object. The energy then follows from equation (Eq. A1). The charge and/or voltage measurements should be carried out according to the requirements specified in D.3.2 and D.3.3.

b. Verify that, even if 0.20 mJ of stored energy can be achieved, the voltage on any component located where a flammable atmosphere might occur is too low for ignition (<1000V).

c. Verify that a spark discharge is not possible (the electric field strength at the surface of the component and at the surface of all nearby conductors is too low for breakdown) at any location where a flammable atmosphere might occur.

### C.5.2 Tests for Non-conductive Components

Compliance with recommendation a. of section 4.2.3 can be verified by means of flow testing and either:

a. Measurement of local electric fields to ensure they are too low for breakdown to occur or of local voltages to ensure that they are too low to generate incendive discharges. With this approach, relatively low levels of streaming current can be used in testing (100 nA is a recommended minimum) but the measured voltages or fields must then be scaled linearly to the maximum streaming current level that could occur in practice at the location of the component. In the absence of information on the maximum streaming current associated with the specific component location, the scaling should be done using the appropriate standard test current level given in D.3.3 and D.3.4. With this approach great care is needed to ensure that:

   i. the configuration of surrounding conductors during the test is the same as on the vehicle

   ii. the duration of charging and flow during the test matches the maximum that could occur in practice

   iii. if voltage measurements are used, the maximum voltage occurring anywhere on the component is located and observed without being disturbed by the measurement system

   iv. If electric field measurements are used, the maximum electric field occurring at the surface of the component or at the worst case protuberance from adjacent earthed metalwork is located and observed without being disturbed by the measurement system.

b. Alternatively, it may be shown directly that the component or assembly, when mounted in the vehicle (or in a rig that closely simulates the vehicle with respect to bonding of the component and to the disposition of adjacent components - particularly conductive ones) is incapable of generating brush discharges that transfer more than 60nC either to chassis ground, to other vehicle components or between parts of the assembly. This type of charge transfer test is related to the method given in IEC 60079-0 section 26.14 (see Section 2.1.4) but differs considerably in practice because of the need to incorporate continuous charging by liquid flow rather than intermittent tribo-charging (charging by rubbing), the need to replicate surrounding conductors and in the constraints on the range of objects to which possible discharges may be considered to occur.

Compliance with recommendation (b) of section 4.2.3 involves making an engineering judgment regarding the ability of a component and its constituent materials to safely withstand the measured (normally cyclic) electrostatic stress for the vehicle's expected working life. Such a judgment should involve comparison of this quantity with a measurement of the dielectric strength under representative temperature, humidity and ageing conditions. An example of a test method is given by IEC 60243-2 (see section 2.1.4).

## C.6 MEASUREMENT OF THE CHARGE THAT IS TRANSFERRED TO CONDUCTIVE PARTS

While tests D.3.2.3.4, D.3.2.4.8 and D.3.3.2.5.3 simulate the discharge to a conductive and grounded part with a large radius (the coulombmeter), in reality counter electrodes could be conductive, ungrounded and of small capacitance or with sharp edges.

The conductive part can be brought into proximity of the charged nonconductive part until it is in its designated position, then:

- The transferred charge is measured with the part in direct contact to the coulombmeter
- Its voltage measured by field meter
- Its voltage measured by field meter and high voltage measurement head

Difficulties

- Cable connections to the conductive parts can reduce the maximum voltage on a part if a corona discharge starts from thin wire or electrostatic connections. Therefore, insulation between cable and atmosphere can be necessary.

- The part might collect more charges than in reality because the designated position can contain charges of opposite sign to reality.

- The real discharges, which will have lower transferred charge, can be calculated from a recording of the voltage. Voltage jumps and capacitance can be re-calculated to energy. Take into account the influence of the added capacitance of the instruments and cables.

- Discharges depend also on areas that are sometimes covered with fuel (discharge is prevented) and sometimes exposed in vapor (free to discharge).

# APPENDIX D: MODEL TEST PROTOCOL TO EVALUATE FUEL SYSTEM DESIGNS FOR COMPLIANCE WITH THIS RECOMMENDED PRACTICE

## D.1 CRITERIA TO BE EVALUATED

- Is a conductive part grounded to the level specified?
- Can an ungrounded conductive material charge up so that incendive discharges can occur?
- Can a nonconductive material charge up so that incendive discharges can occur?
- Does an object made from a nonconductive material have a sufficiently high breakdown voltage to prevent damage due to pinholing?
- Is an ignitable atmosphere possible in the area of a part?
- Can electronics be damaged or disturbed by the electrostatic effects?

## D.2 TEST LOGIC

Testing to demonstrate compliance with this recommended practice must show that the design being evaluated can prevent all of the following as stated in section 4.0:

- EMI (electromagnetic interference) effects on electronic components and computers up to and including component damage.
- Electrical erosion of fuel system components resulting in pinhole leaks.
- Unintended ignition of combustible air-fuel mixtures that might occur under certain conditions

The decision trees presented below in Figure D1 and Figure D2 show the logic path and criteria that must be met.

NOTE: As stated in paragraph 4.1 the simplest way to meet the requirements of this recommended practice is to be sure that all components in contact with flowing fuel are conductive (< 106 ohms) and bonded to vehicle ground (< 108 ohms). Only test D.3.1 is required for this verification. Table D1 below presents the criteria in another format that might prove useful

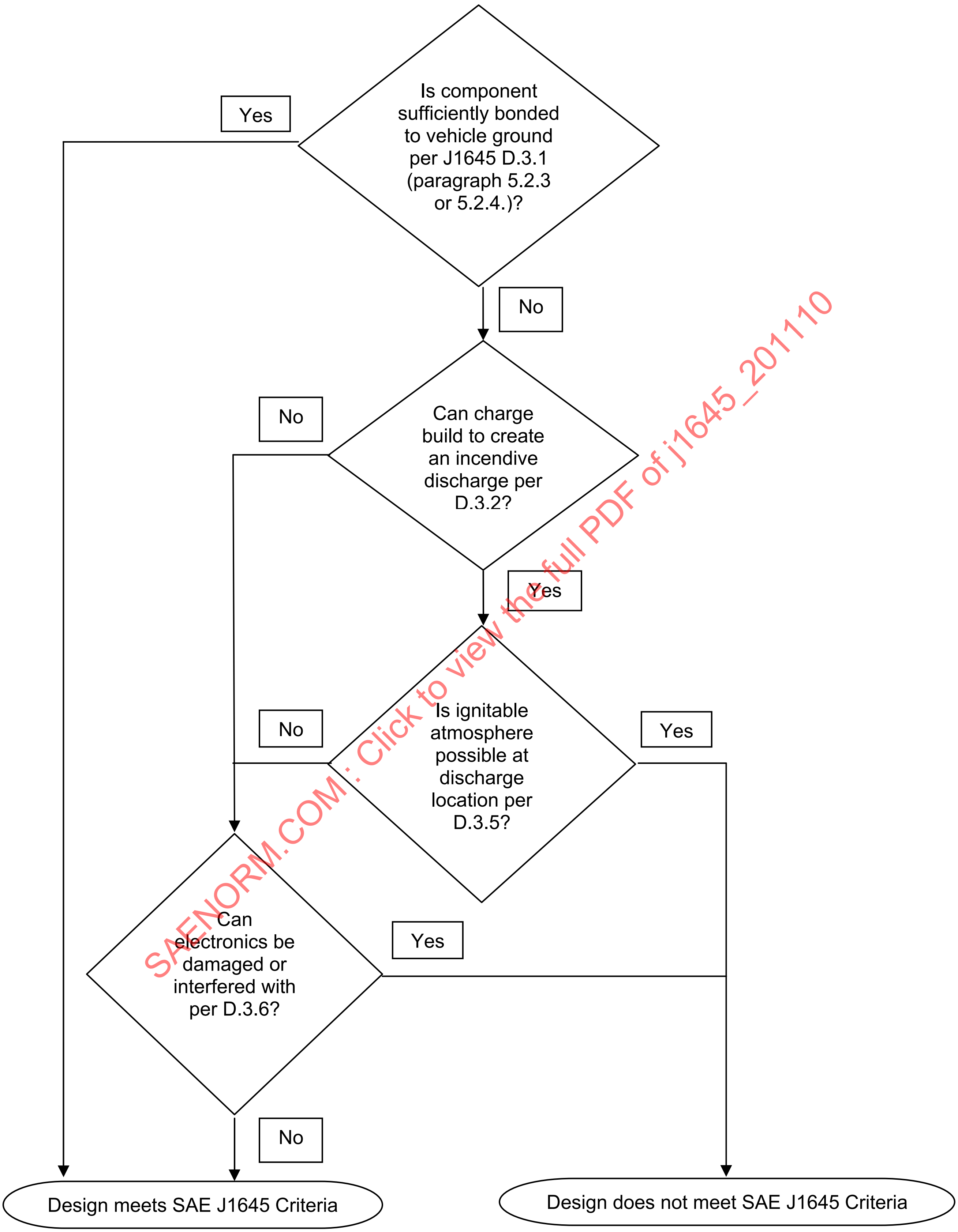


FIGURE D1 - J1645 DESIGN QUALIFICATION DECISION TREE FOR CONDUCTIVE COMPONENTS (< $10^6$ OHMS)

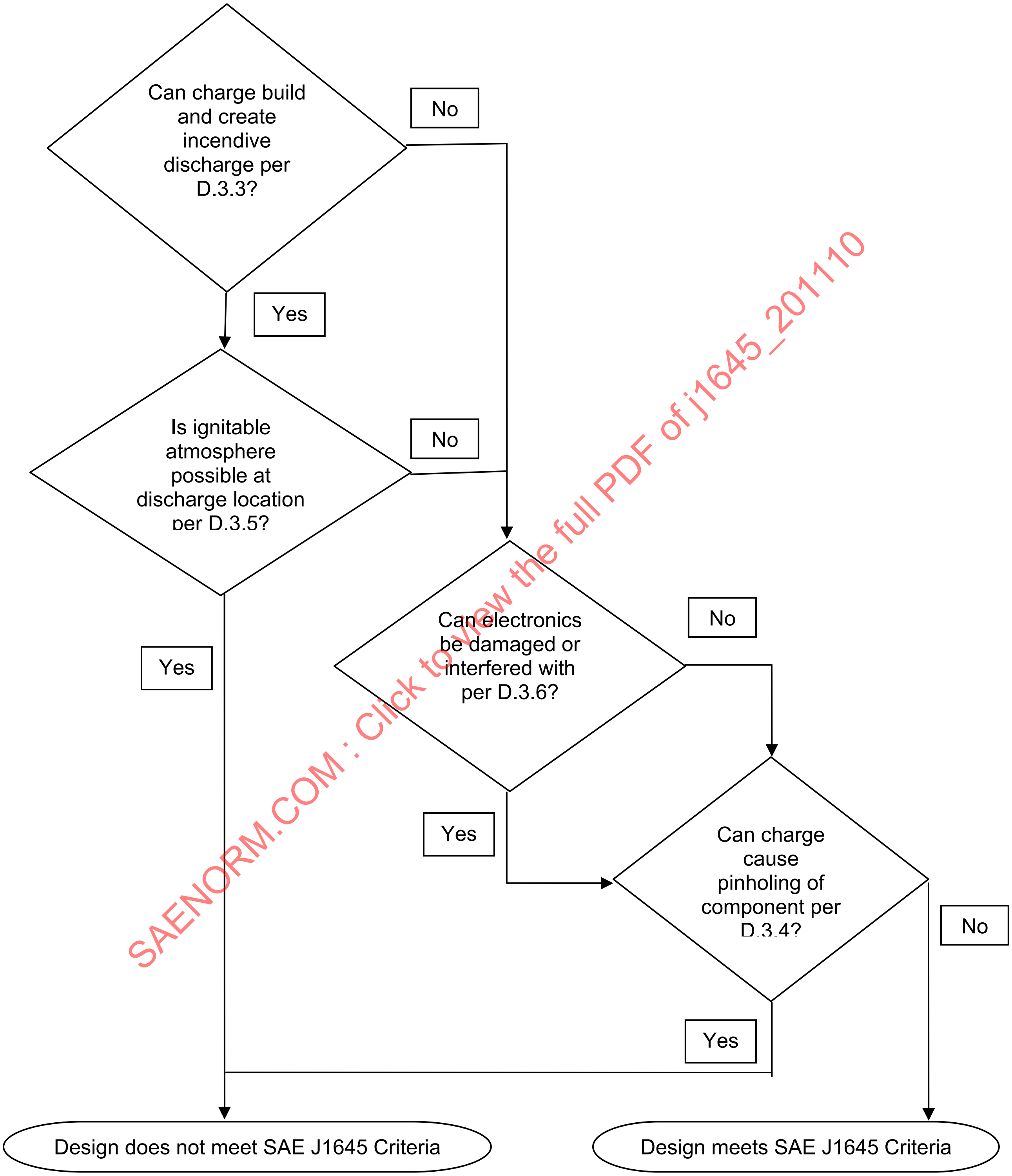


FIGURE D2 - J1645 DESIGN QUALIFICATION DECISION TREE FOR NON-CONDUCTIVE COMPONENTS (> $10^8$ OHMS OR UNBOUNDED AND > $10^6$ OHMS)

TABLE D1: CRITERIA ACCORDING TO THE CONDUCTIVITY OF A PART

| | Requirement For Parts, Grouped According To Their Intended Conductivity And Bonding To Vehicle Ground | | |
|---|---|---|---|
| | Conductive & Grounded | Conductive & Insulated | Not Conductive |
| Measuring Task | Prove conductivity and grounding | Proof that no incorrect charging occurs, no incendive spark discharge can happen | Proof that no incorrect charging occurs, no incendive brush discharge or propagating brush discharge can happen |
| Measuring Method | Resistance measurement with 1000V (lower Voltages at lower resistances) | Run system in a climate chamber at 5°C and max. 30% relative humidity with a suitable test fuel/fluid. Measure voltage with a field meter or charges with a coulomb meter or capacities with a LCR meter.<br>Voltages and charges have to be multiplied with 1.2 to extrapolate "worst case" conditions (-20°C / 30% relative humidity) and then to be rated.<br>To simplify the testing, a spraying of electrons to create at min. -50kV can be done. In this case the original environment (metal body) as active ground is very important. Otherwise sheet metal parts of the environment can be simulated by grounded aluminum foil. | |
| Limits (for gasoline and diesel fuels) | In the area of the filler neck:<br>Limit 1 MΩ<br>Beyond the area of the filler neck:<br>Limit 100 MΩ | There are no high energetic (spark-) discharges<br>Or<br>Sparks appear only outside ignitable areas and don't disturb electric / electronic / mechanic devices<br>Or<br>For voltages (extrapolated) higher than 3kV: amount of discharge must be less than 0.23mJ respectively less than 60nC in ignitable areas<br>For voltages less than 3kV the single case has to be considered.<br>At 4kV at least 120nC are necessary for ignition at less than 0.3kV no ignition is possible | There is no high charging (less than 6kV extrapolated with the factor 1.2 to worse case conditions)<br>Or<br>Discharges in non-ignitable areas don't disturb electric / electronic / mechanic devices<br>And<br>According to sufficient break through resistivity and considering nearby parts, there is despite charging no danger, for example of fuel leakage<br>And<br>The amount of discharge in ignitable areas is less than 0.23mJ respectively less than 60nC |

## D.3 TEST METHODS

The test protocol and procedures presented in this section are an abridged version of requirements set forth in sections 4 and 5 of the main document. They are presented to provide an example of a simplified, structured approach that might be used to conduct a thorough evaluation of a fuel system design. Other approaches may be used by the testing activity or they might rely on the direction of the automotive OEM. Regardless, the requirements of 4 and 5 of this document must be adhered to unless specifically directed otherwise by the automotive OEM.

### D.3.1 TEST WHETHER A CONDUCTIVE PART IS SUFFICIENTLY GROUNDED (PER REQUIREMENTS OF SECTION 4)

### D.3.1.1 Method A: Measuring the resistance (See 4.1 and 5.2 for requirements)

D.3.1.1.1 Limit values: (see 4.1)

Nozzle to ground (via contact on vehicle):≤ 1 MΩ, (test voltage ≤ 1000V, test current ≤ 1 mA)

Single part resistance:≤ 1 MΩ, (test voltage ≤ 1000V, <= 5mA, or ≤ 1 mA)

Assembly to ground:≤ 100MΩ, (test voltage ≤ 1000V, test current ≤ 1 mA)

D.3.1.1.2 Measurement instrument:

Resistance meter capable of measuring with 1000V, 100V and less.

Range:> 100MΩ
Resolution: 100kΩ
or
DC voltage source and ampere meter to create those measurement conditions. The resistance is calculated as
R[Ω] = V [V] / I[A]

Current shall be limited to avoid overheating of the sample. That makes a minimum measurable resistance of

1 MΩ at 1000V/ 1mA
20kΩ at 100 V/ 5mA
2kΩ at 10 V/ 5mA

D.3.1.1.3 Calibration

Instrument might be calibrated / tested by measuring a 1 MΩ resistor with 1% tolerance.

D.3.1.1.4 Measurement

D.3.1.1.4.1 Contacting

Contacts should not damage the surface of the parts: the following may be used:

Conductive rubber
Silver paint
Metal film with conductive adhesive
Solid metal with smooth and rounded surface

Section 5.2.3.1 recommends a contact clamp with contact surface of 18mm² but less contact surface delivers results on the safe side and is therefore acceptable.

Some parts might need to be earthed only to safeguard themselves, others also to provide an earthing path for further parts. Therefore measure resistances over the longest distances of the part or assembly and between all connections, including welds that form part of an earthing path.

D.3.1.1.4.2 Test conditions

Test shall be performed at normal room conditions (rel. humidity < 50%). In case of values close to the limits (> 80%) the measurements shall be repeated according to the climatic conditions of C.2.2.1.1

Fuel soaked parts shall be tested under soaked conditions (still filled with fuel or vapor) within 5 minutes after being taken from the climate chamber (time sensitive).

D.3.1.1.4.3 Preconditioning of parts:

Parts shall be preconditioned to simulated use conditions by

- soaking in Liquid fuel / Fuel vapor depending on real use condition of the fuel type CARB Phase II or CEC RF02-03 or EPA §86.113-94 (Emission test fuels, alcohol free) (Resistance rises due to swelling but falls due to conductivity of the fuel. Fuel conductivity might especially have influence on dissipation time measurement at very high resistances)
- at a temperature of 40°C
- for the time of 4 weeks minimum

For short time tests alternatively soak the parts for 96h @ 60°C

NOTE: Parts may be tested new / unconditioned for quality check, correlation with preconditioned parts etc.

D.3.1.1.4.4 Measure resistance between contacts **A** and either **B1** or **B2** per FIGURE D3 (below)

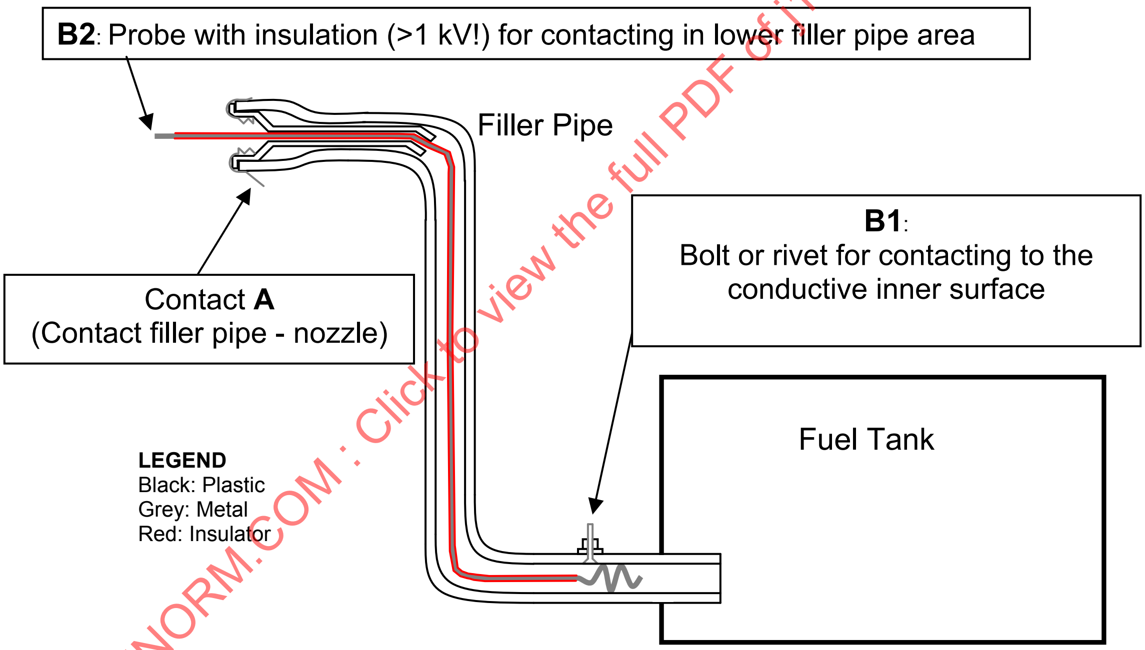


FIGURE D3 - CONTACTING PROPOSALS FOR MEASURING RESISTANCE OF THE CONDUCTIVE INNER SURFACE OF PLASTIC FILLER PIPES UNDER SOAKING CONDITIONS

D.3.1.2 Method B: Measuring the static dissipation time. (Alternative test if parts failed resistance measurement test) (See section 5.3 for testing requirements)

D.3.1.2.1 Limit value:

Dissipation time<= 0.5s for dissipation to 10% of starting applied voltage. (e.g., from 3000V to 300V)

### D.3.1.2.2 Measurement Instruments

Charge Plate Monitor (CPM), an instrument designed for automatically measuring the static dissipation time. The CPM has a metallic plate with defined capacity, which is charged and then discharged via the sample part that is tested. The plate capacity does not exist on the fuel system, so measurement result is “to the safe side”.

If a CPM with the desired voltage range is not available, a setup with other equipment can be used:

- High voltage DC source, range ≥ 3kV
- Electrostatic field meter, depending on distance to the sample the range shall be sufficient to measure at least 3kV and its signal output must be fast enough to follow the voltage dissipation.
- Device to measure and record the time between the points where the limit voltages are reached, resolution and uncertainty <0.1sec.

### D.3.1.2.3 Calibration

- The Electrostatic field meter may be calibrated for uneven sample surfaces by covering the surface with metal foil and applying a known voltage.
- The surface voltage can be calculated from the field meter reading of [V/m] by multiplication with the measuring distance [m]. Some field meters have an option to display that voltage directly.
- The ratio between voltage obtained from measurement and the applied voltage shall be used for correction of the measurements

Alternative to avoid that calibration: To avoid measurement on uneven surfaces, an even metal plate may be connected to the sample part, at the end opposite to the designated grounding point. This plate is an additional capacity (like the plate at a CPM device). Therefore dissipation time will increase, but results will be “on the safe side”

### D.3.1.2.4 Measurement

- Setup part or assembly on highly insulating surface (resistance parts to ground > 1 TΩ or surface resistance >1 TΩ/square)
- Set electrostatic field meter probe at the correct distance to the sample, according to its manual and calibration.
- Start data recording device
- Apply slightly over 3kV to the sample for approximately 2s. Contact point should be the end opposite to the designated grounding point for the part or assembly
- Remove the electrification contact and immediately contact ground to the designated grounding point for the part or assembly.
- Read the dissipation time between the defined voltage levels
- If using the specially designed device, follow its manual.

### D.3.1.2.5 Test conditions

Test shall be performed according to the climatic conditions of C.2.2.1.1

Fuel soaked parts shall be tested under soaked conditions (still filled with fuel or vapor) within 5 minutes after taken from the climate chamber (time sensitive).

#### D.3.1.2.6 Preconditioning of parts:

Parts shall be preconditioned by soaking as follows:

- Liquid fuel / Fuel vapor depending on real use conditions
- Fuel type CARB Phase II or CEC RF02-03 or EPA §86.113-94 (Emission test fuels, alcohol free) (Resistance rises due to swelling but falls due to conductivity of the fuel. Fuel conductivity might especially have influence on dissipation time measurement at very high resistances.)
- At a temperature of 40°C
- For the time of 4 weeks minimum (For short time tests alternatively soak the parts for 96h @ 60°C).

Unconditioned parts as manufactured may be tested for quality assurance reasons or to provide a correlation with preconditioned parts.

## D.3.2 TEST FOR INCENDIVE DISCHARGES FROM UNGROUNDED CONDUCTIVE PARTS

### D.3.2.1 Method A: Measuring The Electrostatic Capacitance And The Stored Energy On The Part

For small capacities method B (D.3.2.2) is recommended

(NOTE: Refer to section C.3.3 for cautions regarding the use of capacitance measurements. Caution and discretion must be taken when conducting & interpreting the capacitance results with respect to their accuracy and meaning. Given these facts, it is recommended that the preferred method of measuring the voltages & charges generated on the part be performed instead.)

#### D.3.2.1.1 Limit Values

Capacitance ≤ 3 pF Object does not need to be grounded, no further measurement needed.

Capacitance > 3 pFStored energy, W ≤ 0.2 mJ

$W = 0.5\ C\ V^2$

V = Voltage

C = Capacitance

#### D.3.2.1.2 Measurement instruments

Capacitance meter

- Range100pF
- Resolution0.1pF
- Measure at least with 2 different frequencies; if results differ significantly this method should not be used (this effect does not occur with metallic parts)

Electrostatic field meter

- Depending on distance to the sample the range shall be sufficient to measure at least 50KV on the sample

  or

- Electrostatic field meter plus high voltage measurement head.

#### D.3.2.1.3 Calibration

Capacitance meter might be calibrated / tested by measuring known capacitors in the desired range.

To eliminate the effect of the capacitance of the measurement cables, the instrument shall be set to zero with the cables in place but not connected to the sample. See manual.

Field meter: calibrate as in D.3.1.2.3

Field meter with high voltage head might be calibrated with a standard voltage source

#### D.3.2.1.4 Measurement

##### D.3.2.1.4.1 Capacitance

- Have surrounding conductive parts grounded / not grounded as designed
- Use setup that represents real vehicle surrounding
- Find the highest Capacitance by measuring between the sample and the surrounding conductive parts.
- Connect instrument “+” to the sample and “-“ to the surrounding part.

##### D.3.2.1.4.2 Voltage

- Electrostatic field meter:
  - Calibrate to zero.
  - Measure at the distance specified in the instruments manual or for which the calibration was performed
  - Calculate voltage from : V[V] = E [V/m] x distance[m]
- Electrostatic field meter + high voltage head:
  - Connect to sample via cable
  - Measure field strength
  - Calculate voltage according to manual

For time critical measurements on samples with an electrostatic capacitance that is not much higher than the capacitance of the high voltage head, it may be necessary to take into consideration that the additional capacitance of the head slows down the rising of the voltage.

#### D.3.2.2 Method B: Measuring The Electrostatic Capacitance By Artificial Charging And Measuring Transferred Charge

(NOTE: Refer to section C.3.3 for cautions regarding the use of capacitance measurements. Caution and discretion must be taken when conducting & interpreting the capacitance results with respect to their accuracy and meaning. Given these facts, it is recommended that the preferred method of measuring the voltages & charges generated on the part be performed instead.)

D.3.2.2.1 Limit values:

≤ 3 pF do not need to be grounded, no further measurement needed

D.3.2.2.2 Measurement instruments

High voltage source adjustable up to -10 kV

Electrostatic field meter: Depending on distance to the sample the range shall be sufficient to measure at least 10 KV on the sample

Coulombmeter range up to 200 nC

D.3.2.2.3 Calibration

Refer to manuals

D.3.2.2.4 Measurement

D.3.2.2.4.1 Capacitance:

- Have surrounding conductive parts grounded / not grounded as designed
- Use setup that represents real surrounding (For example car body, ground surface)
- Connect part to high voltage source and apply a voltage and disconnect again while voltage is on.
- Measure voltage with fieldmeter.
- Ensure, that voltage does not drop significantly (1%) by bleed currents during the voltage measurements
- Measure transferred charge to coulombmeter by the first single spark discharge while approaching the instrument immediately after the voltage source had been disconnected.
- Measure residual voltage on part.
- Calculate capacitance from C = Q / delta U

D.3.2.3 Method C: Measuring The Charge Transferred In A Discharge Under Worst Case Conditions

D.3.2.3.1 Limit values:

transferred charge ≤ 60nC

D.3.2.3.2 Measurement instruments:

Coulombmeter

- Rangeat least 100nC
- Resolutionpreferably 1nC.
- Preferably with the ability to measure the highest single discharge, usually the first one.

D.3.2.3.3 Calibration

See manual

D.3.2.3.4 Measurement

Transferred charge: See manual

- Example for "Schnier HMG 11/02" Coulombmeter, second "red" series:
  - Hold instrument away from sample
  - Switch on instrument, reset to zero.
  - Approach the sample with the probe at the area
    - where the highest charge is expected

    or

    - where a discharge occurs

Remark: While these tests simulate the discharge to a conductive part with big radius and big capacity (The coulombmeter – a worst case counter-electrode concerning incendivity of sparks), in reality counter electrodes could be conductive and ungrounded or of small capacitance or with sharp edges. Those sharp edges or small radii can have the effect that no incendive spark will occur. There might be a non incendive corona discharge instead.

The Coulombmeter might be used with electrodes of similar shape, to get closer to the actual discharge type. (Refer to C.6 for details)

D.3.2.4 Method D: Measuring the Maximum Voltage Created By Vehicle Operating Conditions and the Maximum and Minimum Discharge Voltage.

The maximum voltage on a conductive part is limited not only by the charge generation process, but also by:

- The voltage at which discharges to surrounding parts occur
- The voltage at which a non-incendive corona discharge into the atmosphere will occur
- The voltage at which the resistance to vehicle ground is sufficient to dissipate the incoming charges (equilibrium at high voltage, though resistance does not meet the criterion $R < 10^8 \Omega$.)

(Maximum voltage observed, ~max. energy available)

The maximum real voltage may be too low for an incendive discharge to a part in the surrounding, because the gap is too wide.

D.3.2.4.1 Limit Values

Stored energy, $W \leq 0.2mJ$

$W = 0.5\, CV^2$

V=Maximum Voltage,

C=Capacitance

or

If the part is insulated so that it cannot spark discharge then minimum discharge voltage > maximum observed voltage

D.3.2.4.2 Measurement Instruments:

Adjustable High voltage DC source, capable of delivering up to -60kV and a current of > 1μA

Voltage and Current meters integrated (or use field meter)

D.3.2.4.3 Calibration

See manual

D.3.2.4.4 Measurement

- Connect high voltage device output (negative to ground) to the sample and “ground“ to the surrounding part.
- Raise voltage slowly and watch current meter and the sample. Stop, if any of the following occur:
  - Current or sparks indicate a non continuous discharge.
  - Current reaches a steady value of ≥ 1μA
  - Voltage reaches 60kV
- Report voltage, current and observed effects (For example: 35kV, 0.1μA between sparks, sparks to vehicle ground)

D.3.2.4.5 Charge Generation And Test Conditions

There are at least three ways to create the charge imbalance:

- By refueling
- By running the pump
- By contacting to a high voltage DC source

The test engineer must decide which of these methods best simulates the situation being investigated.

D.3.2.4.6 Fuel/Test Fluid:

“Hydrosol” fuel per C.3.7 is recommended

If test fluid other than Hydrosol is used, qualify the test fluid per C.3.9. If necessary, augment flow circuit with a suitable filter to force charge generation to a level sufficient to meet acceptance criteria.

D.3.2.4.7 Environment:

- Test shall be done in dry atmosphere:
    - Temperature + 4.5°C ±1.5°C (+ 40ºF ±3ºF)
    - Relative Humidity: ≤ 30%
- Measuring results have to be multiplied by the factor 1.2 according to the international agreed multiplication factor in the case of the electrostatic break through voltage.
- New samples conditioned in this environment for >24h

Experience and experimental results validate the proposed test fuel in combination with the described conditions creates the highest charging that is likely to occur during normal operation. As the test conditions (e.g. pump voltage, pump rate) include expected malfunction, therefore, the results in combination with a safety factor of 1.2 provide sufficient assessment of the system concerning hazards due to electrostatic charging.

D.3.2.4.8 Test setup:

- Fuel system in test rig; grounded.
- For some tests the car body may be needed, if it has an influence on capacitance etc. or to test for real sparks. (Refer to C.6 for details)
- Measure on all conductive, ungrounded parts
- Take into consideration the intended design situation in the vehicle
- Test with the lowest and the highest distances that are to be expected, because:
    - Max. voltage is found with max. distance to other conductive parts to which the discharge can go.
    - Max. voltage is found with low humidity
    - Min. discharge voltage is found with the shortest distance to other conductive parts to which the discharge can go.
    - Min. discharge voltage is found with high humidity.
- When calculating possible energies there is no need to combine minimum distance (possibility of discharge) and max distance (max. energy of discharge), because this cannot happen in a single situation.

D.3.2.4.9 Direct Charging Test (Artificial Charging)

Highest applicable voltage has to be evaluated.

D.3.2.4.9.1 Method To Impose The Highest Voltage A Part Can Hold:

- Connect to a high voltage, current limited to 10 microamperes.
- Watch field strength/voltage by contactless method. (Take care to avoid measuring the cable connection)
- Raise voltage until 1 microampere is reached or obvious discharge occurs.
- If voltage drops, after still electrified connection is removed, the remaining voltage is the maximum voltage.

### D.3.3 TEST FOR INCENDIVE DISCHARGES FROM NONCONDUCTIVE SURFACE

### D.3.3.1 Method A: Measure The Surface Voltage

### D.3.3.1.1 Limit value

It is recommended that a limit of 6kV max be used to account for events experienced in some automotive applications.

### D.3.3.1.2 Measurement Instrument

Electrostatic field meter

Depending on distance to the sample the range shall be sufficient to measure at least 10kV. (For example 200kV/m at distance of 50mm)

### D.3.3.1.3 Calibration:

For non-flat surfaces calibrate with a metal foil on the surface with known voltage (e.g. 1 kV) make sure, you measure the voltage on the surface. It may be necessary to use some grounded shields to eliminate influences from other charges in the vicinity (backside, fuel etc.)

### D.3.3.1.4 Measurement

- Electrostatic field meter: Calibrate to zero.
- Measure in the distance according to the instruments manual.
- Value should be measured for t > 30s.
- Calculate Voltage from: V [V] = E [V/m] x distance[m]

### D.3.3.2 Method B: Measure The Transferred Charges

### D.3.3.2.1 Limit Value

Charge transfer < 60nC

### D.3.3.2.2 Measurement Instrument

Coulombmeter:

- Range at least 100nC
- Resolution; preferably 1nC.
- Preferably with the ability to measure the highest single discharge.

### D.3.3.2.3 Calibration

- For example, by using a battery cell with known voltage.
- Calculate Q from Q = C x U.
- C = Capacitance of the Coulombmeter.

D.3.3.2.4 Measurement

See manual

Example for “Schnier HMG 11/02” Coulombmeter, second “red” series:

- Hold instrument away from sample
- Switch on instrument, reset to zero.
- Approach the sample with the probe at the area -where the highest charge is expected or -where a discharge occurs

D.3.3.2.5 Charge Generation And Test Conditions

D.3.3.2.5.1 Environment

- Test shall be performed in dry atmosphere
  - Relative Humidity: ≤30%
  - Temperature + 4.5°C ±1.5°C (+ 40 F ±3 F)
- Measuring results have to be multiplied by the factor 1.2 according to the international agreed multiplication factor in the case of the Electrostatic breakthrough voltage.
- New samples conditioned in this environment for ≥ 24h
- Fuel soaked parts shall be tested within 10min (time sensitive)
  - Exceptions: fluorinated fillers shall not be pre-conditioned.

D.3.3.2.5.2 Preconditioning In Liquid Fuel / Fuel Vapor Depending On Real Use Condition

- Fuel type: CARB Phase II or CEC RF02-03 or EPA §86.113-94 (Emission test fuels, alcohol free).
- Test Temperature of 40°C
- Test duration: 4 weeks minimum
- For short time tests alternatively soak the parts for 96h @ 60°C.

D.3.3.2.5.3 Test setup:

Fuel system in test rig; grounded.

For some tests the car body may be needed if it has an influence on capacitance etc. or to test for real sparks. This must be determined for each individual system. (Refer to section C.6 for details)

There are at least three ways to create the charges

- By refueling
- By running the pump
- By artificial corona charging with a high voltage DC source

D.3.3.2.5.4 Fuel

"Hydrosol" fuel per C.3.7 is recommended

If test fluid other than Hydrosol is used, qualify the test fluid per C.3.9. If necessary, augment flow circuit with a suitable filter to force charge generation to a level sufficient to meet acceptance criteria.

D.3.3.2.5.5 Refueling Test

Perform the refueling with: Test fuel 145/200

OEM should specify the highest applicable flow rate for each project If no values are given following flow rates should be used:

- Diesel and European gasoline: 60 l/min
- US-ORVR Systems: 45 l/min

For specific nozzles these values may not be reached. In this case use the highest value achievable volume should be used.

- Temperature: +4.5ºC ±1.5ºC (+40ºF ±3ºF) Relative humidity < 30%.
- Nozzle positions: 6 o-clock, hands off
- Nozzle types: Use nozzles appropriate for the fuel being dispensed that conform to SAE J285 and SAE J398. The following examples may be used:
    - EU-Gasoline nozzle:ZVA 1.0 R
    - US-Gasoline nozzle:OPW 11
    - US-Diesel nozzle:OPW 11AL
    - Diesel Nozzle:ZVA 1.0

D.3.3.2.5.6 Fuel Delivery Module Test

- The complete Fuel delivery system shall be used.
- Use highest applicable flow (There may be different operating conditions that create highest charging for specific parts), e.g.:
    - Test at highest engine consumption
    - Test at the highest relevant flow achieved for the engine consumption set to a pressure 10% below system pressure.
    - Test at zero engine consumption
- If the max. Voltage is given by the OEM, 110% of this should be used. Otherwise a voltage of 16V should be applied.
- Time: Run system until values are stable or start to drop.
- Fuel temperature: +4.5ºC±1.5ºC (+40ºF±3ºF)

### D.3.3.2.5.7 High Voltage DC Charging

- Use a DC Voltage source with at least -30kV (negative Polarity in relation to ground) and a suitable tip or fakir electrode.

- Use a sufficiently grounded working surface (e. g. wooden table).

- Spray at the surface to be charged

- Remove electrode while voltage is applied

    - Fakir electrode: direct contact to surface

    - Tip electrode: Keep distance to surface of 10mm to 50mm

    - Remove the object from the working surface (distance more than 100mm).

- Discharge the object to a Coulombmeter

- Number of tests ≥ 3

Alternative:

- Charge up the part in its original position in the car/tank.

- Make sure you get the max. charge on the surface, for example by use of removable grounded background material.

### D.3.3.2.5.8 Rubbing With A Cloth

- Use a sufficiently grounded working surface (e. g. wooden table).

- Rub the surface to be charged.

- Remove the cloth with a strong last strike.

- Remove the object from the working surface (distance more than 10 cm).

- Discharge the object to a Coulombmeter

- Number of tests ≥ 10

## D.3.4 RESISTANCE AGAINST DIELECTRIC BREAKDOWN OR OCCURRENCE OF PINHOLES

Because of the process of electrostatic erosion (See A.5.5) the voltage limits for preventing pinholes is based on a fraction of the measured breakdown voltage for a non-conductive component

### D.3.4.1 Method A: Compare Resistance Against Dielectric Breakdown To Maximum Voltage Achieved With Specific Design

### D.3.4.1.1 Acceptable Limit Values

a. Breakdown voltage for preconditioned parts should be > 5 times the maximum voltage found in the charging test (D.3.4.1.4.2.1.)

b. The current is > 1μA at V =10kV.

### D.3.4.1.2 Measurement Instruments

- High voltage DC source with voltmeter, range ≥ 60kV
- Applicable Ampere Meter
- Electrostatic field meter and high voltage head

### D.3.4.1.3 Calibration

The Electrostatic field meter may be calibrated for uneven sample surfaces by covering the surface with metal foil and applying a known voltage. The ratio between voltage obtained from calculating the field strength and distance into voltage and the applied voltage shall be used for correction of the measurements.

### D.3.4.1.4 Measurement

### D.3.4.1.4.1 Measuring Resistance Against Dielectric Breakdown

- A metal rod is fitted tight inside and a metallic foil with a conductive adhesive (width 25mm) is glued at the outer side around.
- Alternatively the outer side can be painted with conductive paint e.g. silver paint for rear window heating repair.
- Connect electrodes to the high voltage source
- Apply DC voltage on both electrodes and slowly increase the voltage from 1 kV to at least 50kV.
- Stop the measuring either when a breakthrough occurs or when the upper voltage limit is reached or when due to a small conductivity the current increases above 10μA.
- See EN 60243-1. This is a worst case measurement, because on both sides metallic electrodes in direct contact with the sample part are used.
- Test shall be performed at normal room conditions (rel. humidity < 50%).
- Electrification for dielectric breakdown strength according to EN60243-1&2 shall be:
  - Voltage continuously increased from Zero to breakthrough - OR
  - Significant current increase with 10kV/min ±5 kV/min.
  - Speed of increase has to be reduced (inside tolerance) close to breakthrough

D.3.4.1.4.2 Measuring The Actual Voltage On The Charged Side Of The Part:

Either:

- Insert a metallic probe, that has contact to the inner wall and should not disturb the flow (e.g. thin metal sleeve) in the sample and connect it to the high voltage measurement head.
- Record voltage over time until stable values are found.
- Use the highest reading

or

- Measure contactless by field meter and calculate voltage from field strength and distance:

$$V\ [kV] = E\ [kV/m] * d\ [m]$$

D.3.4.1.4.2.1 Charge Generation, Dielectric Break Down And Test Conditions

D.3.4.1.4.2.2 Charge Generation And Test Conditions

D.3.4.1.4.2.3 Environment

Test shall be conducted in dry atmosphere

- Temperature +4.5°C ±1.5°C (+40ºF ±3ºF)
- Relative Humidity: ≤30%

Measuring results have to be multiplied by the factor 1.2 according to the international agreed multiplication factor in the case of the Electrostatic break through voltage.

New samples conditioned in this environment for > 24 h

Fuel soaked parts shall be tested within 10min (time sensitive)

D.3.4.1.4.2.4 Test Fluid:

D.3.4.1.4.2.5 “Hydrosol” fuel per C.3.7 is recommended. Highest applicable flow

There may be different operating conditions that create highest charging for specific parts therefore, test at highest engine consumption and at zero engine consumption. The highest relevant flow is reached for the engine consumption set to a pressure 10% below system pressure. This setup is to be used for testing.

If the maximum fuel pump operating voltage is given by the OEM, 110% of this should be used. Otherwise a voltage of 16 V should be applied.

The complete Fuel delivery system should be represented by the setup.

Prevent corona discharge from the measurement cables/harness by good insulation, also on connections.

Electrode at the outside as described above, except for cases, where there are specific insulations at the concrete application.