



AEROSPACE INFORMATION REPORT

AIR7506™

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Impact of High Voltage on Wiring

RATIONALE

This SAE Aerospace Information Report (AIR) documents how high voltage impacts wiring insulation materials on aerospace vehicles. High voltage test methods and test methodology are documented, and laboratory results are provided on selected wire insulation systems. Basic failure mechanisms associated with high voltage impact on insulation systems and lessons learned in designing high voltage systems are reviewed. This AIR will be updated when additional data supporting the scope and purpose is available.

1. SCOPE

This SAE Aerospace Information Report (AIR) focuses on how long-term exposure of high voltage below and above wire insulation corona inception voltage (CIV) impacts round wire insulation life. This AIR will be updated when additional data is available.

1.1 Purpose

This AIR documents high voltage testing results and presentations presented at SAE AE-8D committee meetings. This document provides guidance on evaluating the impact of high voltage on aerospace wire constructions. It does not address arc propagation or arc damage.

2. APPLICABLE DOCUMENTS

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR6127	Managing Higher Voltages in Aerospace Electrical Systems
AIR6540	Fundamentals in Wire Selection and Sizing for Aerospace Applications
AS4373	Test Methods for Insulated Electric Wire
AS50881	Wiring Aerospace Vehicle

SAE Executive Standards Committee Rules provide that: "This report is published by SAE to advance the state of technical and engineering sciences. The use of this report is entirely voluntary, and its applicability and suitability for any particular use, including any patent infringement arising therefrom, is the sole responsibility of the user."

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Documents

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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 3032 Standard Test Methods for Hookup Wire Insulation

2.3 IEC Publications

Available from IEC Central Office, 3, rue de Varembe, P.O. Box 131, CH-1211 Geneva 20, Switzerland, Tel: +41 22 919 02 11, www.iec.ch.

IEC 60270 High-Voltage Test Techniques - Partial Discharge Measurements

IEC 60034-18-41 Rotating Electrical Machines - Part 18-41: Partial Discharge Free Electrical Insulation Systems (Type I) Used in Rotating Electrical Machines Fed From Voltage Converters - Qualification and Quality Control Test

2.4 ICEA Publications

Available from TechStreet Store, 3025 Boardwalk Drive, Suite 220, Ann Arbor, MI, 48108 Tel: 855-999-9870, www.techstreet.com.

ANSI/ICEA T-24-380-2013 Standard for Partial Discharge Test Procedure

2.5 IEEE Publications

Available from IEEE Operations Center, 445 and 501 Hoes Lane, Piscataway, NJ 08854-4141, Tel: 732-981-0060, www.ieee.org.

Montanari, G.C., Seri, P., and Stone, G., "Prospects for Increasing Supply Voltage and Design of Electrical Field Rotating Machine Windings Supplied from Power Electronics," IEEE Electrical Insulation Magazine, May/June 2020, Vol. 36. No. 3, pp. 31-38.

3. DEFINITIONS

3.1 HIGH VOLTAGE

Any voltage that creates a partial discharge in a wire or cable in aircraft applications. This document is based on wiring specifications having a voltage rating of 600 Vrms at sealevel. Current SAE wiring specifications state the following: "This insulation system has been used in aerospace applications using 115 V (phase to neutral), 400 Hz AC, and 28 VDC. Verification of the suitability of this product for use in other electrical system configurations is the responsibility of the user."

3.2 PARTIAL DISCHARGE (PD)

A localized electrical dielectric breakdown that only partially bridges the insulation between conductors. A detectable partial discharge is defined as an apparent charge transfer level of 5 picocoulombs or higher, where the detection system has been calibrated in accordance with the appropriate standards (refer to IEC 60270 and ANSI/ICEA T-24-380-2013). The term "corona" is sometimes used interchangeably with PD; the distinction is clarified in 3.4.

3.3 INSULATION DEFECTS

Any damage that degrades dielectric properties of wire insulation through physical, electrical, or chemical processes.

3.4 CORONA

Corona is a form of partial discharge that occurs in gaseous media around conductors which are remote from solid or liquid insulation. "Corona" should not be used as a general term for all forms of PD. Further guidance on corona prevention is given in 6.6 of AS50881, which states: "For AC operating voltages not exceeding 240 Vrms, any given thickness of flaw-free insulation is adequate to support this voltage at any pressure or temperature; thickness is dictated by mechanical requirements. For higher AC voltages, the 'equivalent insulation thickness' can be found in Figure 1."

3.5 PARTIAL DISCHARGE INCEPTION VOLTAGE (PDIV)

In AC systems, the PDIV or corona inception voltage (CIV) is the applied voltage at which repetitive partial discharges are first observed in the test object, when the voltage applied to the object is gradually increased from a lower value at which no partial discharges are observed. In DC systems, the pulse repetition rates can be very low making it difficult to measure PDIV (refer to IEC 60270, Section 11).

3.6 PARTIAL DISCHARGE EXTINCTION VOLTAGE (PDEV)

In AC systems, PDEV or corona extinction voltage (CEV) is the applied voltage at which repetitive partial discharges cease to occur in the test object, when the voltage applied to the object is gradually decreased from a higher value at which partial discharges are observed. In DC systems, the pulse repetition rates can be very low making it difficult to measure PDEV (refer to IEC 60270, Section 11).

4. GUIDANCE ON CONDUCTING CORONA INCEPTION VOLTAGE (CIV) TESTS ON WIRING

- 4.1 As written in standards, partial discharge is defined as a localized dielectric breakdown of the surrounding medium which only partially bridges the gap between two conductors. Over time, it can lead to erosion, which damages the dielectric material and can eventually cause dielectric breakdown as a result of thinning of the dielectric material. More details on partial discharges in aerospace high voltage systems can be found in AIR6127. Other aspects to consider are the internal PD between the conductor and insulation; inside the insulation, if voids are present; between the strands and external PD, which is on the outside of the wire; or surrounding atmosphere, as shown in Figure 1.

An important challenge and uncertainty when considering partial discharge phenomena is that generation of the partial discharge can differ based on the device under test (DUT) and voltage distribution between electrode configurations. Examples in Figure 1 show different scenarios in electric field distribution using the same device/material under test in different test conditions.

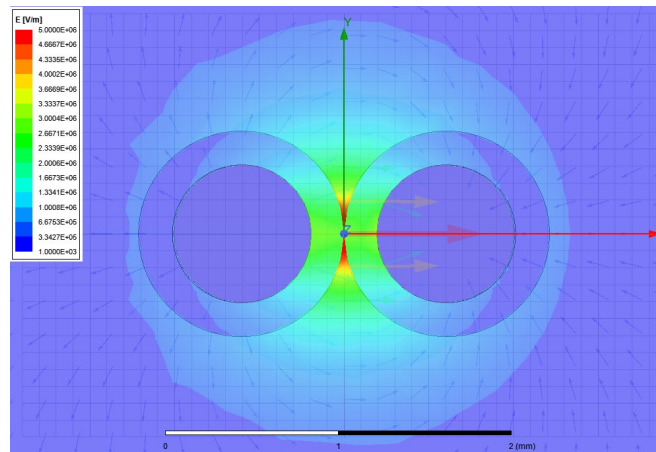


Figure 1A - Twisted pair, one wire grounded and another at $\sqrt{3} \times 600$ V peak voltage to simulate phase-to-phase voltage

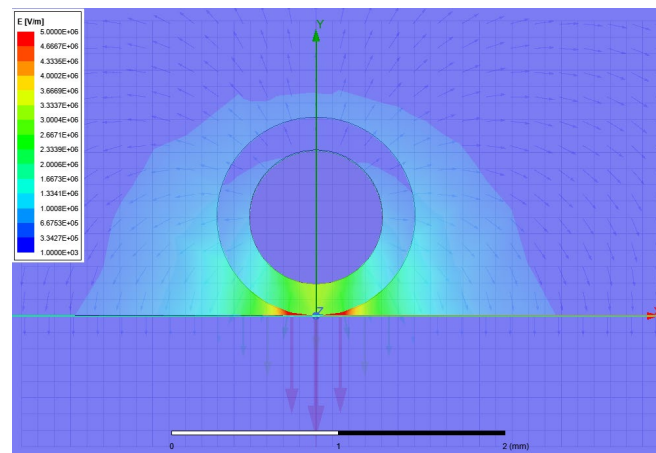


Figure 1B - Wire at 600 V peak voltage to a ground plane configuration

Figure 1 - Comparison of field distribution (vector) and electric field strength (V/m) simulated in ANSYS Q2D

From a design standpoint, more than one test configuration may be needed to generate values of PDIV and PDEV that are relevant to the application. In an AC system, we are usually interested in the phase-to-ground and phase-to-phase performance of a cabling system. A mandrel test will give a PDIV that can be expected between a single wire and grounded object; i.e., a value relevant to the phase-to-ground case. A twisted wire test will give a PDIV that exists between two insulated wires. It is not possible to determine the PDIV/PDEV wire-to-wire value from a wire-to-ground value or vice versa, but both test configurations are valuable for comparison (see Figure 1). The wire-to-ground case is similar to the mandrel test that has been utilized for voltage endurance testing (see Figure 1B). The mandrel test method is primarily focused on discharge and corona effects of the wire on the mandrel. Other possible failure modes are not evaluated. The test results are also strongly dependent on preparation of the samples, since the force applied during the winding of the cable and by the weight could result in a non-concentric insulation. Additional testing may be required for specific applications, such as shielded wiring.

In practice, for a three phase AC system, the phase-to-phase voltage requirement will determine the required insulation thickness to deliver a specific value of PDIV/PDEV, since the phase-to-phase voltage is typically 1.732 times the phase-to-ground voltage. Thus, the phase-to-phase voltage configuration would be the worst-case condition to characterize PD activity (see Figure 1A). This can be explained further by considering two wires with 0.2 mm (0.0079 inch) of ETFE insulation operating at a pressure equivalent to 9.14 km (30000 feet), as shown in Table 1. The single wire-to-ground has an expected PDIV of 707 Vrms. If used in a power system, this could be operated with a phase-to-ground voltage of 707 Vrms—equivalent to a phase-to-phase voltage of 1225 Vrms. However, the same wire when tested in a phase-to-phase configuration will see a PDIV of 978 Vrms. This is equivalent to a phase-to-ground voltage of 564 Vrms, and is therefore the limiting point in the design.

Table 1 - Example showing voltages based on phase-to-ground and phase-to-phase

	Total Insulation Thickness	Estimated PDIV at 30000 feet ETFE Insulation⁽¹⁾	Equivalent Phase-to-Ground Voltage	Equivalent Phase-to-Phase Voltage
Wire-to-Ground	0.2 mm	707 Vrms	707 Vrms	1225 Vrms
Wire-to-Wire	0.4 mm	978 Vrms	564 Vrms	978 Vrms

⁽¹⁾ Using AS50881 Figures 1 and 2.

Another challenging aspect of partial discharge testing, especially in terms of its interpretation, is that PDIV/PDEV does not take into account the amount of partial discharge occurring in the DUT/system—which means PDIV/PDEV is just a binary value, representing a threshold when partial discharge starts and partial discharge ends. These values won't tell how much activity or quantity of partial discharge is occurring, or which is essential and directly correlates to the lifetime and the degree of degradation of the material.

As an example, if there are two samples, with the difference that one sample has multiple defects/voids in parallel, the PDIV/PDEV values would be expected to be similar. However, the sample with the multiple defects and voids would most likely degrade much faster than the one with less defects.

Test systems typically measure the collective partial discharge of the system, which is the sum of all areas where partial discharge will or can occur in accordance to the applied voltage.

To get a better qualitative conclusion out of the partial discharge measurement, especially in order to identify a signal towards lifetime behavior, two different test setups are suggested.

Finally, it is important to note that a derived voltage rating based on the PDIV/PDEV measurements is not applicable to all scenarios in an aircraft environment. Moreover, it is specifically describing a voltage rating for this test configuration and allows the industry to compare different insulated wires in terms of their voltage endurance performance with reference to a specific test method. The derived voltage from a particular test method may not be applicable to a specific wiring configuration used in an aerospace system.

4.2 Recommended Test Method and Setup Procedures

AS4373 Method 502 describes the corona inception and extinction voltage measurements typically performed at 60 Hz at normal temperature and pressure (NTP). The required test equipment is defined in Section 7 of ASTM D1868. An analogue IEC Standard can be found in IEC 60270. Additional guidance on conducting PD tests is given in ANSI/ICEA T-24-380-2013.

As discussed in 4.1, the voltage (electric field) distribution of the test setup is critical. Refer to AS4373 Method 502 and 25.3.2.1 and 25.3.2.2 of ASTM D3032 for specimen selection and preparation.

In order to correlate testing with numerous specimens, preparation should follow the long-term high voltage test method for insulated wire given in Appendix A. Testing using a dielectric fluid is included in Appendix B. The specimen should be a 20 AWG insulated wire 1.5 m ± 0.025 m (60 inches ± 1 inch) in length wrapped on a stainless steel mandrel 12.7 mm ± 2.54 mm (0.5 inch ± 0.1 inch) in diameter.

More details can be found in Appendix A. The specimen and its preparation also follows the guidance in ASTM D3032, except that in the ASTM D3032, only ten turns of wiring are used.

As described in ASTM D3032, apply the voltage at a maximum rate of 50 V/s. Raise the voltage until partial discharge above 5 pC level is detected and record this voltage as PDIV (also known as CIV). Lower the voltage at the same rate until the discharges have stopped and record this voltage as the PDEV (also known as CEV).

Ramp the voltage up and down four times and measure the PDIV/PDEV values for each ramp. Exclude the values for the first ramp and take the average values of the remaining three

The waveform of the voltage source can also have a significant impact on PDIV/PDEV. Using a sinusoidal waveform is recommended for test methods in accordance with MIL-STD-704 normal operation characteristics for voltage and frequency. Specific applications may require testing using waveforms that are representative of the conditions used in an aerospace system.

4.3 High Voltage Life Testing Conducted at Below and Above Corona Inception Voltage (CIV) for Selected Wiring Constructions

When testing cables, one needs to understand an insulation system can have multiple materials involved. While an insulation system can be homogeneous, it can also have multiple layers of dielectric materials in the system. A good starting point is to measure the PDIV at room temperature (20 to 25 °C [68 to 77 °F]) and standard atmospheric pressure. PDIV can be tested in various ways. Use of a mandrel or a twisted pair configuration are accepted approaches.

To accelerate aging of a cable in a relative comparison method, testing above PDIV is recommended. Each insulation system will have a different PD curve with respect to voltage, test configuration, and environmental conditions.

5. HIGH VOLTAGE LIFE TESTING CONDUCTED AT BELOW AND ABOVE CORONA INCEPTION VOLTAGE (CIV) FOR SELECTED WIRING CONSTRUCTIONS

5.1 AE-8D Round Robin High Voltage Test Results on Aerospace Wiring

See Appendix C.

5.2 High Voltage Testing of Airframe Wire Near and Above Corona Levels

See Appendix D.

6. IMPACT OF MATERIALS AND THICKNESS OF INSULATION AND FREQUENCY, ALTITUDE, AND TEMPERATURE ON HIGH VOLTAGE LIFE

- 6.1 The thickness of the insulation, along with the voltage stress applied to the cable, will determine the voltage per mil unit thickness—typically, kV per 0.001 inch (kv/mil) used during the testing. In testing with AC voltage, the dielectric constant will be the biggest influencer on both PDIV and stress concentration. The lowest dielectric constant will typically have the highest voltage stress in the system. The dielectric constant of the insulation material typically decreases with increasing insulation temperature (from the conductor and ambient temperature). In testing with DC, surface and volume resistivity are the most important factors determining distribution of voltage stresses.
- 6.2 In AC testing, with the new solid-state oscillators, variable frequency signals are injected into a step-up transformer to create a clean sinusoidal wave output. When comparing materials to accelerate the aging, frequency can be increased to reduce the time to obtain results. Most dielectric breakdown testing equipment today uses 60 Hz power supplies and breakdown detection systems. Operating dielectric breakdown equipment at higher frequencies (such as 600 Hz) can greatly accelerate sample aging and shorten the testing times when compared with a 60 Hz system. Care must be taken since increasing the frequency too high can cause dielectric heating and rapid sample failure which may not be representative of field conditions.
- 6.3 Aircraft power systems increasingly use pulse width modulation signals to control motor speed which create voltage pulses with rise times in the 40 to 100 nanosecond range and switching frequencies of a few kHz to tens of kHz. Together with new test systems that apply short duration voltage pulses, insulation systems may need to withstand voltage waveforms with rise times of up to 20 to 30 kV/μs. The application of a pulse-width modulated voltage can further degrade insulation when compared to the application of power frequency sinusoidal waveforms or DC voltages. Insulation degradation can be accelerated because of increased voltage magnitudes (caused by travelling wave/resonance effects), the increased switching frequency, and the increased dV/dt. It is important that the life of an insulation system is evaluated using an appropriate voltage waveform representative of the stress encountered on aircraft given that the converter and system topology can significantly impact test results (refer to Montanari, G.C., Seri, P., and Stone, G).
- 6.4 Environmental conditions such as attitude, temperature, and moisture will also influence test results and reduce insulation life.

7. NOTES

7.1 Revision Indicator

A change bar (|) 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. 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 AE-8D WIRE AND CABLE COMMITTEE