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MILITARY STANDARD

LIGHTNING QUALIFICATION TEST TECHNIQUES FOR AEROSPACE VEHICLES AND HARDWARE

DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

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EMCS

DEPARTMENT OF DEFENSE
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Lightning Qualification Test Techniques for
Aerospace Vehicles and Hardware

MIL-STD-1757.

1. This Military Standard is approved for use by all Departments and Agencies of the Department of Defense.

2. Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to ASD/ENESS (Code 11), Wright-Patterson AFB, Ohio 45433, by using the self-addressed Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

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1. SCOPE

1.1 Scope. This document presents a set of standard test waveforms and techniques for lightning qualification testing of aerospace vehicles and hardware. The test waveforms presented in this document are intended to reproduce the significant effects of the natural environment and are therefore independent of vehicle type or configuration. The tests include high voltage and high current physical damage tests of fuel, structural and electrical hardware, as well as indirect effects associated with lightning strikes to externally mounted electrical hardware.

This document does not include design criteria nor does it specify which items should or should not be tested. The document is written so that test environments can be tailored for each specific program as dictated by the vehicle design, performance, and mission constraints. Acceptable levels of damage and pass-fail criteria for the tests described herein shall be established and agreed upon by the procuring agency, regulatory authority, and aerospace vehicle manufacturer.

This document does not yet include specific test techniques or procedures that deal with indirect, or induced, effects of lightning on internal electrical or electronic equipment. As these test techniques are developed and verified, they will be added to the document.

1.2 Application. The test requirements described in this document are applicable to aerospace vehicles and parts or assemblies thereof. When these requirements are in conflict with the lightning test requirements found in the specifications or standards referenced in paragraph 2, the requirements of this document govern. (Note: The term "aerospace vehicles" includes fixed/variable wing aircraft, helicopters, missiles, and spacecraft).

1.3 Method of reference. When applicable, test methods contained herein shall be referenced in the individual specification by specifying this standard and the method number.

1.4 Units. The International System of Units, designated SI, is used throughout this document.

2. APPLICABLE DOCUMENTS

2.1 Issues of documents. The following documents of the issue in effect on date of invitation for bids or request for proposals form a part of this standard to the extent specified herein.

SPECIFICATION

MILITARY

MIL-C-45662	Calibration System Requirements

(Copies of specifications, standards, drawings, and publications required by contractors in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer.)

2.2 Other publications. The following documents form a part of this standard to the extent specified herein. Unless otherwise indicated, the issue in effect on date of invitation for bids or request for proposal shall apply.

INSTITUTE OF ELECTRICAL AND ELECTRONIC ENGINEERS (IEEE)

IEEE 4-1978	Standard Techniques for Dielectric Tests

(Application for copies should be addressed to the Institute of Electrical and Electronics Engineers, 345 East 47th Street, New York, NY 10017.)

3. DEFINITIONS

3.1 Direct and indirect lightning effects. The lightning effects which aerospace vehicles experience and the effects which are reproduced through laboratory testing with simulated lightning waveforms are divided into direct effects and indirect effects. The direct effects of lightning are the burning, eroding, blasting, and structural deformation caused by lightning arc attachment, as well as the high pressure shock waves and magnetic forces produced by the associated high currents. The indirect effects are predominantly those resulting from the interaction of the electromagnetic fields accompanying lightning with electrical apparatus in the vehicle. Hazardous indirect effects, in principle, could be produced by a lightning flash that did not directly contact the vehicle and hence was not capable of producing the direct effects of burning and blasting. However, it is currently believed that most indirect effects of importance will be associated with a direct lightning flash. In some cases, both direct and indirect effects may occur to the same component of the vehicle. An example would be a lightning flash to an antenna which physically damages the antenna and also sends damaging voltages into the transmitter or receiver connected to that antenna. In this document, the physical damage to the antenna will be discussed as a direct effect and the voltages or currents coupled from the antenna into the communications equipment will be treated as an indirect effect.

3.2 Lightning attachment zones

3.2.1 Surface zones. Aerospace vehicle surfaces are divided into three zones, with each zone having different lightning attachment or transfer characteristics. These are defined as follows:

a. Zone 1: Surfaces of the vehicles for which there is a high probability of initial lightning flash attachment (entry or exit).

b. Zone 2: Surfaces of the vehicle across which there is a high probability of a lightning flash being swept by the airflow from a Zone 1 point of initial flash attachment.

c. Zone 3: Zone 3 includes all of the vehicle areas other than those covered by Zone 1 and Zone 2 regions. In Zone 3 there is a low probability of any direct attachment of the lightning flash arc. Zone 3 areas may carry substantial amounts of electric current by conduction between some pair of initial or swept stroke attachment points.

3.2.2 Division of surface zones. Zones 1 and 2 are further divided into A and B regions depending on the probability that the flash will hang on for any protracted period of time. An A type region is one in which there is low probability that the arc will remain attached and a B type region is one in which there is a high probability that the arc will remain attached. Examples of zones are as follows:

a. Zone 1A: Initial attachment point with low probability of flash hang-on, such as a leading edge.

b. Zone 1B: Initial attachment point with high probability of flash hang-on, such as a trailing edge.

c. Zone 2A: A swept stroke zone with low probability of flash hang-on, such as a wing mid-span.

d. Zone 2B: A swept stroke zone with high probability of flash hang-on, such as an outer wing trailing edge.

3.3 Waveform parameters. Definitions of the rise time, rate-of-rise, decay time, time duration and other parameters utilized in the waveform definitions that follow are consistent with section 2 of IEEE Std. 4-1978, Techniques for Dielectric Tests.

3.3.1 Average rate-of-rise of voltage. The average rate-of-rise, $\Delta v/\Delta t$, of a voltage waveform is defined as the slope of a straight line drawn between the points where the voltage is 30 percent and 90 percent of its peak value, V_{pk}, as shown in figure 1.

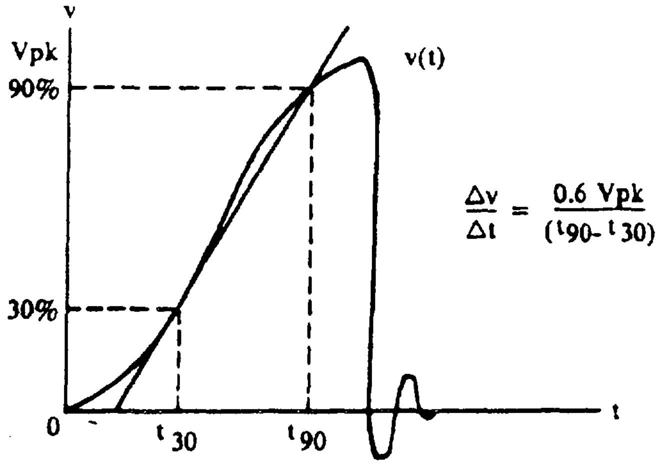


Figure 1. Average rate-of-rise of voltage.

3.3.2 Time to crest. The time to crest, T_1, of a voltage waveform is defined as 1.67 times the time interval between the instants when the voltage is 30 percent and 90 percent of its peak value as shown in figure 2.

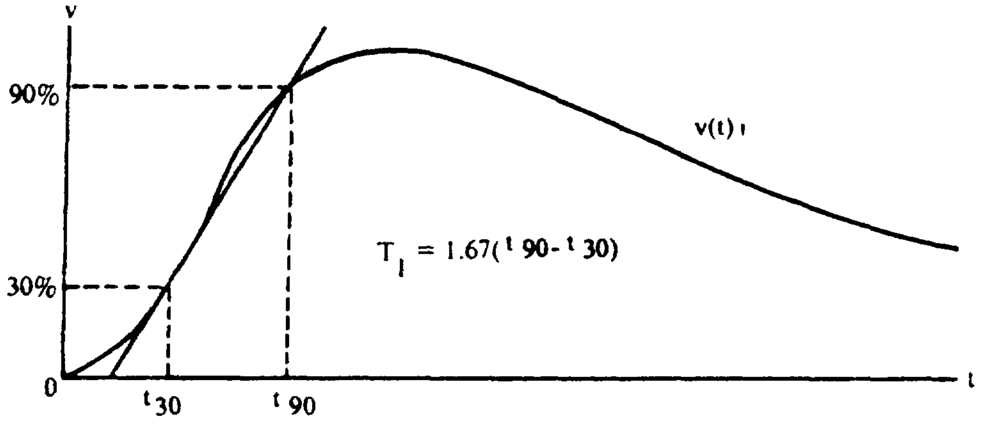


Figure 2. Time to crest of a voltage waveform.

3.3.3 Decay time. The decay time, T_2, of a voltage waveform is defined as the time interval between the intersect with the abcissa of a line drawn through the points where the voltage is 30 percent and 90 percent of its peak value during its rise, and the instant when the voltage has decayed to 50 percent of its peak value, as shown in figure 3.

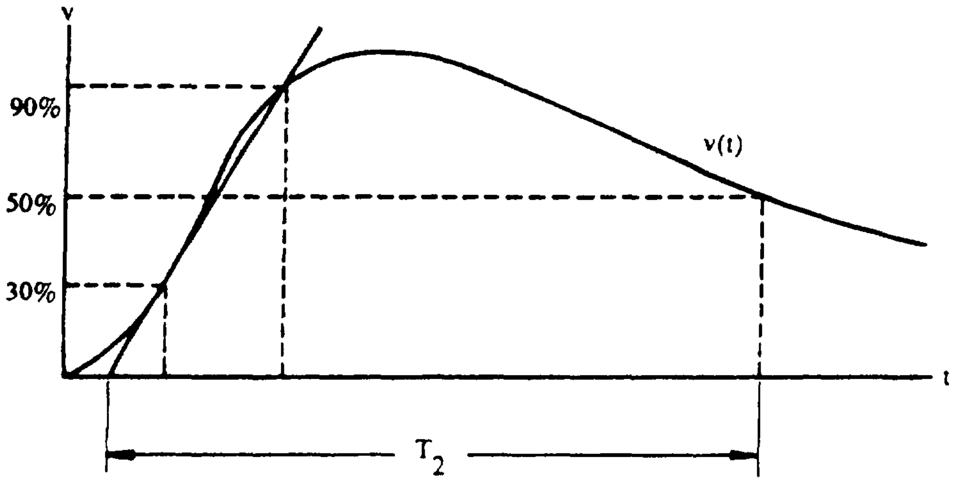
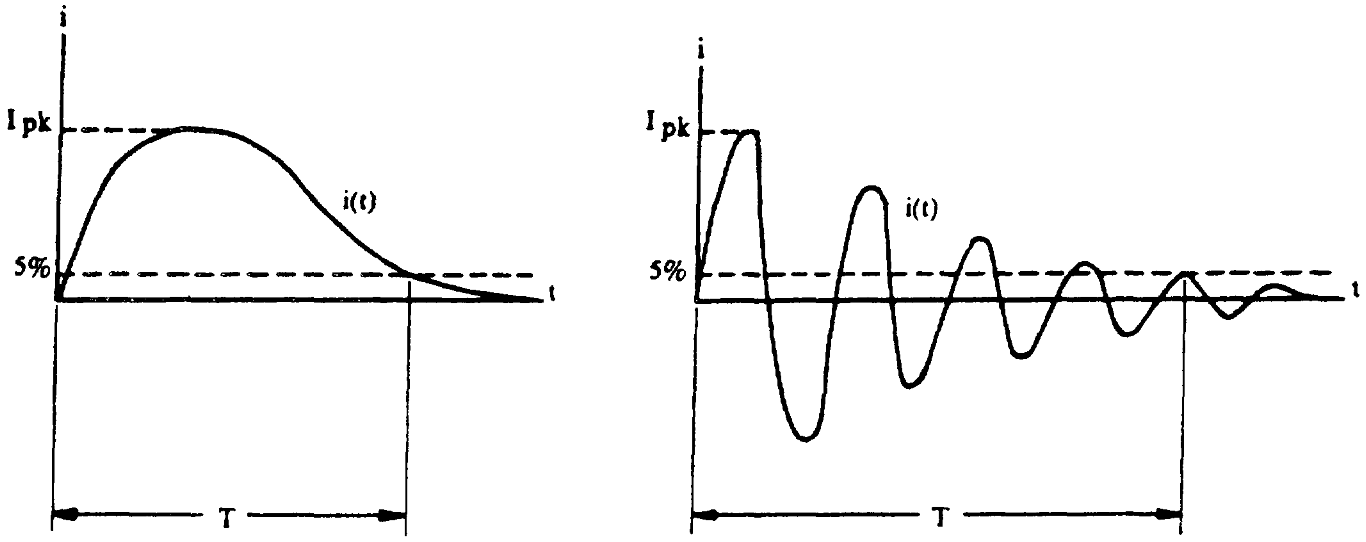


Figure 3. Decay time of a voltage waveform.

3.3.4 Time duration. The time duration, T, of a current waveform is defined as the time from initiation of current flow until the current amplitude (peak amplitude in the case of a damped sinusoid) has reduced to five percent of its initial peak value as shown in figure 4.



Unipolar current waveform

Damped sinusoid current waveform

Figure 4. Time duration of current waveform.

3.3.5 Charge transfer. The charge transfer, Q, is defined as the integral of the time-varying current over its time duration, or

$$Q = \int_0^T i(t)dt \text{ (A.s or coulombs)}$$

and is equivalent to the area beneath the current waveform as shown in figure 5.

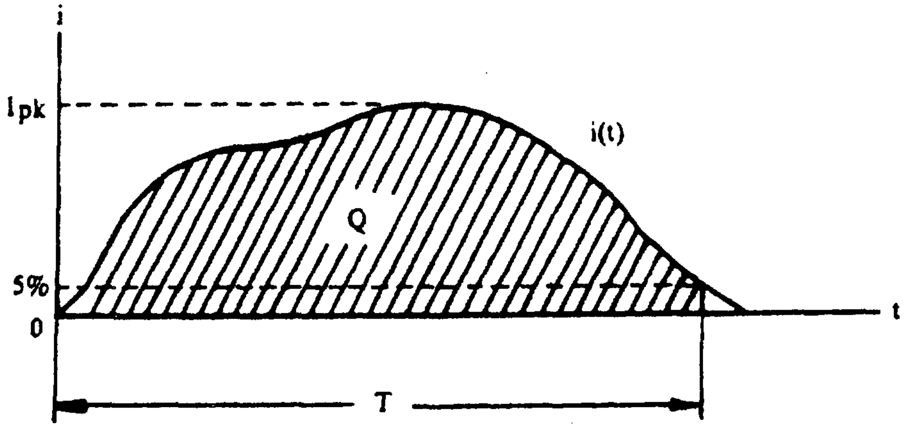


Figure 5. Charge transfer of a current waveform.

3.3.6 Action integral. The action integral of a current waveform is a measure of the ability of the current to deliver energy and is defined as the integral of the square of the time-varying current over its time duration, i.e.,

$$\int_0^T i(t)^2dt(A^2,s)$$

4. REQUIREMENTS

4.1 General requirements. General requirements pertaining to safety, test conditions and equipment calibration are included in this section.

4.1.1 Safety. Simulated lightning tests utilize high voltage and high energy electrical equipment. Tests shall be conducted with special safety measures to protect test personnel and equipment. The following procedures shall be strictly followed.

4.1.1.1 Conduct of tests. Simulated lightning tests shall be conducted by personnel experienced in high voltage testing and performed in a controlled access test area. A laboratory with adequate safety measures and controlled test procedures is required.

4.1.1.2 Equipment isolation. All high voltage equipment shall be inspected for proper isolation from electrical grounds.

4.1.1.3 Discharge circuit. The electrical discharge circuit of the lightning simulator shall be designed and maintained to avoid unnecessary arcing and other phenomena which may adversely affect personnel, equipment, and the test accuracy.

4.1.1.4 Personnel protection. All personnel shall be provided with appropriate eye and ear protection.

4.1.2 Test conditions

4.1.2.1 Test object grounding. The test object shall be installed with appropriate ground connections to simulate the actual flow of lightning current through the test object.

4.1.2.2 Test instrumentation shielding. The test instrumentation shall be adequately shielded from the electromagnetic fields produced by the simulated lightning test currents and other sources.

4.1.3 Measuring equipment calibration. Measuring equipment shall be calibrated in accordance with MIL-C-45662. Measuring and test equipment shall be calibrated by the contractor or a commercial facility utilizing reference standards whose calibration is certified as (a) traceable to the National Bureau of Standards; (b) derived from accepted values of natural physical constants; or (c) derived by the ratio type of self-calibration techniques.

4.2 Specific requirements. Waveforms of the simulated lightning currents and voltages to be used in these tests are presented in this section.

4.2.1 Test waveforms. The waveforms and components depicted in figures 6, 7, and 8 are idealized representations and need not be simulated exactly. Only the numerical parameters specified in the following paragraphs need be produced.

4.2.2 Voltage waveforms. For qualification testing, there are three voltage waveforms, A, B, and D which represent the electric fields associated with a lightning strike. Voltage waveforms A and D are used to test for possible dielectric puncture and other potential attachment points. Voltage waveform B is used to test for streamers. The tests in which these waveforms are applied are presented in table I. The objectives of each test, along with setup, measurement, and data requirements are described in the appropriate test method description. Voltage waveform C (shown in figure 7 for reference only) is used for scale model testing which is not covered by this standard.

4.2.2.1 Voltage waveform A - basic lightning waveform. Waveform A has an average rate of rise (see 3.3.1) of 1000 kV per microsecond (±50 percent) until its increase is interrupted by puncture of, or flashover across, the object under test. At that time the voltage collapses to zero. The rate of voltage collapse or the decay time of the voltage if breakdown does not occur (open circuit voltage of the lightning voltage generator) is not specified. Voltage waveform A is shown in figure 6.

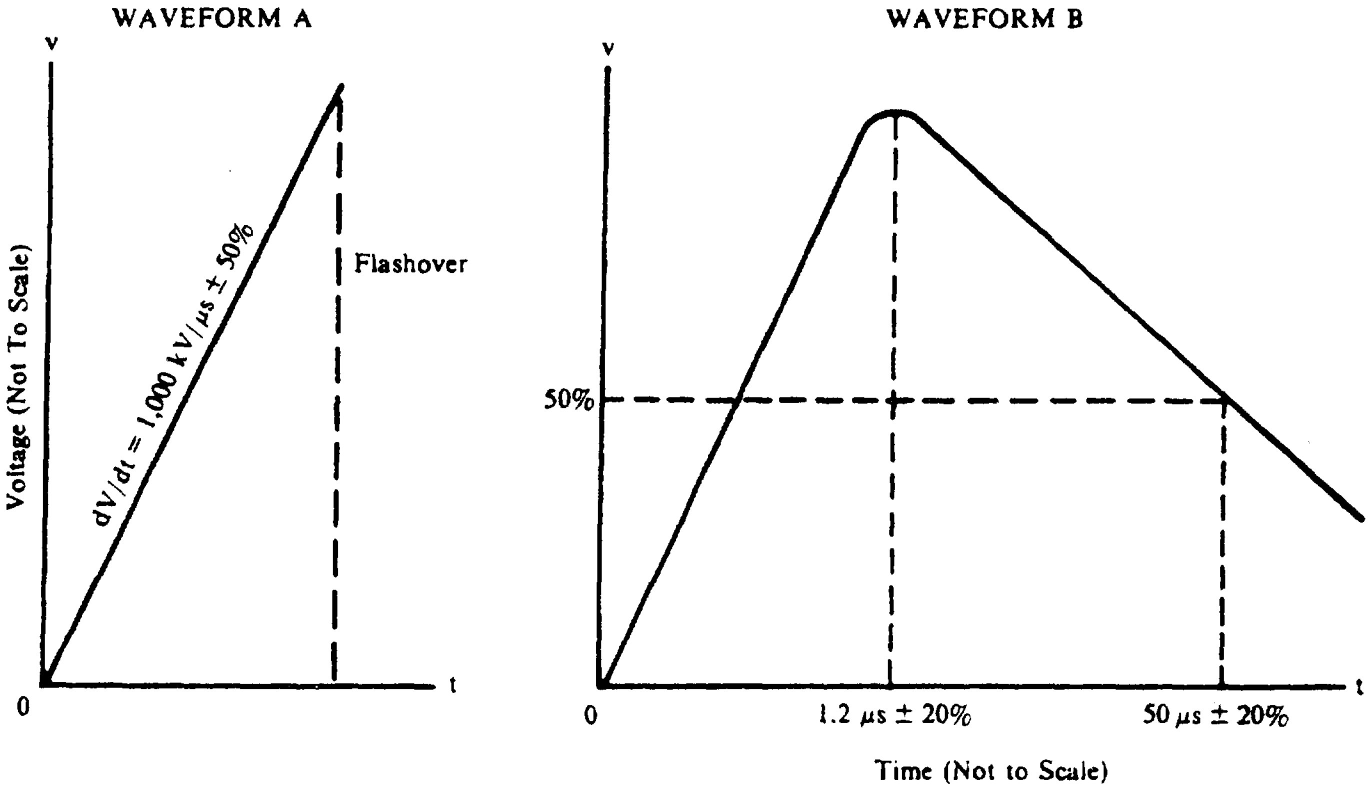


Figure 6. Voltage waveforms A and B.

4.2.2.2 Voltage waveform B - full wave. Waveform B rises to crest in 1.2 (±20 percent) microseconds. Time to crest (see 3.3.2) and decay time (see 3.3.3) refer to the open circuit voltage of the lightning voltage generator, and assume that the waveform is not limited by puncture or flashover of the object under test. This waveform is shown in figure 6.

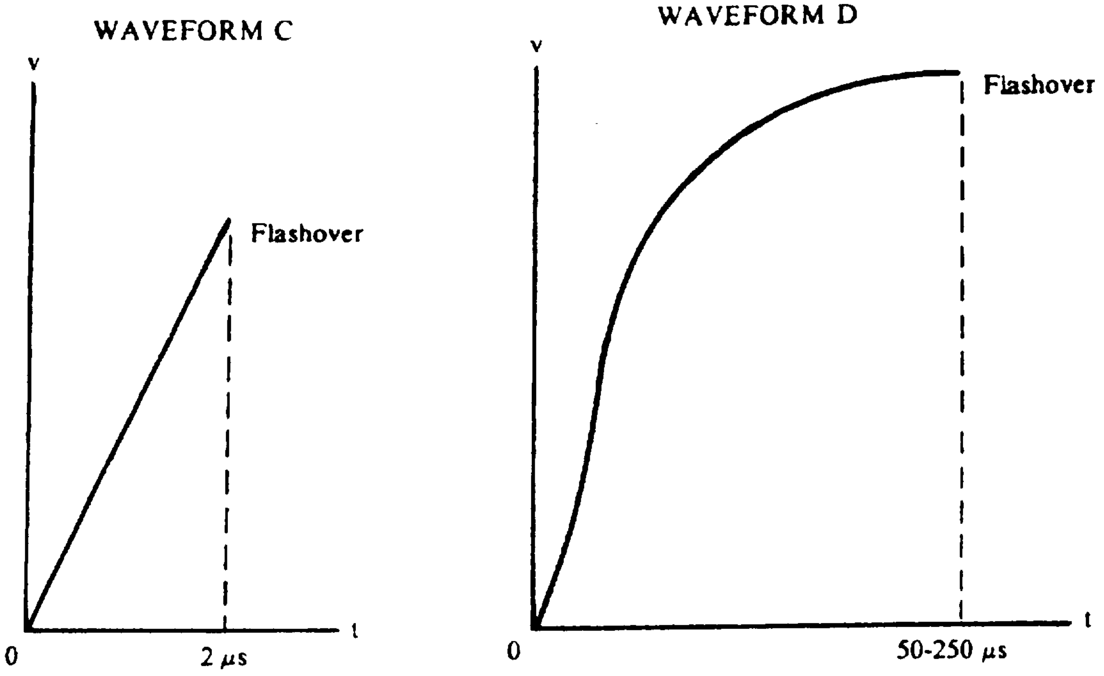


Figure 7. Voltage waveforms C and D.

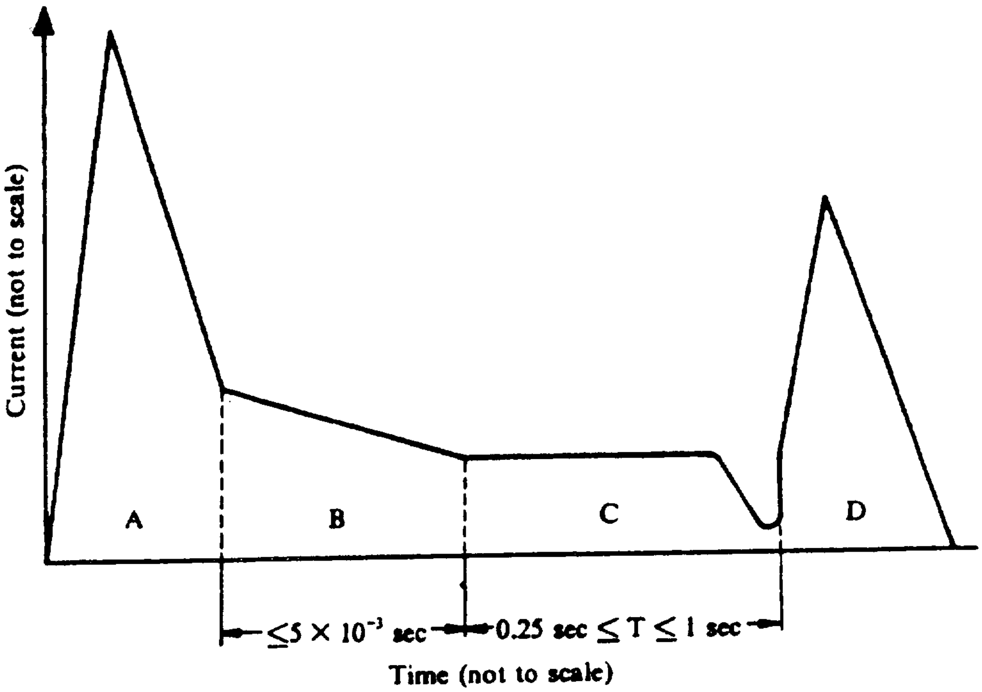
4.2.2.3 Voltage waveform D - slow front. The slow fronted waveform has a time to crest between 50 and 250 microseconds to allow time for streamers from the test object to develop. It should give a higher strike rate to the low probability regions than otherwise might have been expected. This waveform is shown in figure 7.

4.2.3 Current waveforms and components. For qualification testing, there are four current components, A, B, C and D, that are used to determine direct effects (see 3.1). Current waveform E is used to determine indirect effects (see 3.1). Components A, B, C and D each simulate a different characteristic of the current in a natural lightning flash and are shown in figure 8. They are applied individually or as a composite of two or more components together in one test. Current waveform E, also shown on figure 8, is intended to determine indirect effects. The tests in which these waveforms are applied are presented in table I. The objective of each test, along with setup, measurement, and data requirements, are described in the appropriate test method description.

4.2.3.1 Component A - initial high peak current. Component A has a peak amplitude of 200kA (±10 percent) and an action integral (see 3.3.6) of 2×10^6 $A^2.s$ (±20 percent) with a total time duration not exceeding 500 microseconds. This component may be unidirectional or oscillatory.

4.2.3.2 Component B - intermediate current. Component B has an average amplitude of 2 kA (±10 percent) flowing for a maximum duration of 5 milliseconds and a maximum charge transfer (see 3.3.5) of 10 coulombs. The waveform shall be unidirectional, e.g., rectangular, exponential or linearly decaying.

4.2.3.3 Component C - continuing current. Component C transfers a charge of 200 coulombs (±20 percent) in a time of between 0.25 and 1 second. The

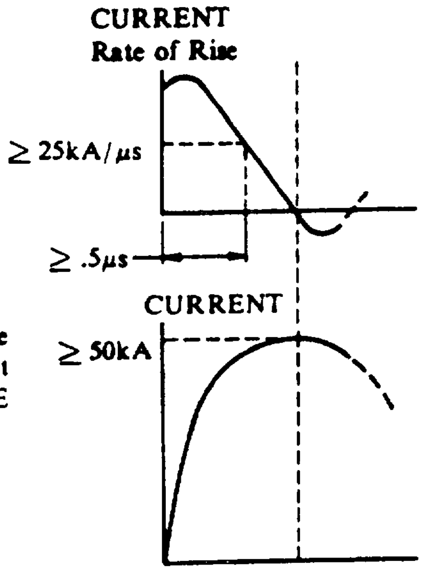


COMPONENT A (Initial Stroke)
Peak amplitude = 200kA ± 10%
Action integral = 2 x $10^6 A^2 \cdot s$ ± 20%
Time duration ≤ 500 µs

COMPONENT B (Intermediate Current)
Maximum charge transfer = 10 Coulombs
Average amplitude = 2kA ± 10%

COMPONENT C (Continuing Current)
Charge transfer = 200 Coulombs ± 20%
Amplitude = 200-800A

COMPONENT D (Restrike)
Peak amplitude = 100kA ± 10%
Action integral = 0.25 x $10^6 A^2 \cdot s$ ± 20%
Time duration ≤ 500 µs



Definition of rate
of rise requirement
of waveform E

CURRENT WAVEFORM E
Peak amplitude ≥ 50kA
Rate of rise ≥ 25kA/µs
for at least 0.5µs

Figure 8. Current waveforms.

waveform shall be unidirectional, e.g., rectangular, exponential or linearly decaying.

4.2.3.4 Component D - restrike current. Component D has a peak amplitude of 100 kA (±10 percent) and an action integral of 0.25 x 10^6 A^2.s (±20 percent). This component may be either unidirectional or oscillatory with a total time duration not exceeding 500 microseconds.

4.2.3.5 Current waveform E - fast rate of rise stroke test for full size hardware. Current waveform E has a rate of rise of at least 25 kA/ µs for at least 0.5 microsecond, as shown in figure 8. Current waveform E has a minimum amplitude of 50 kA. Alternatively, components A or D may be applied with a 25 kA/ µs rate of rise for at least 0.5 microsecond and the direct and indirect effects evaluation conducted simultaneously.

5. QUALIFICATION TESTS

5.1 Description of qualification tests. Individual test method are described in this section which are to be used for protection verification of aerospace vehicles and hardware. The test, method number, strike zone, and voltage and current waveforms applicable to each zone are summarized in table I.

5.2 Index of qualification tests. Table II is an index of qualification tests by method number and title.

Table I. Application of waveforms for qualification tests.

Test	Method Number	Attachment Zone	Voltage Waveforms			Current Waveforms/Components				
			A	B	D	A	B	C	D	E
Full Size Hardware Attachment Point	T01	1A,B	X		X^1					
Direct Effects-Structural	T02	1A				X	X			
		1B				X	X	X	X	
		2A					X^2	X^2	X	
		2B					X	X	X	
		3				X		X		
Direct Effects-Combustible Vapor Ignition	T03	1A				X	X			
		1B				X	X	X	X	
		2A					X^2	X^2	X	
		2B					X	X	X	
		3				X		X		
Direct Effects - Corona and Streamers	T04			X						
Indirect Effects - External Electrical Hardware	T05									X^3

Note 1. Voltage waveform D may be applied to identify lower probability strike points.

Note 2. Use an average current of 2KA ± 10 percent for a period equal to the dwell time up to a maximum of 5 ms; if the dwell time is more than 5 ms, apply an average current of 400A for the remaining dwell time. The dwell time shall have been determined previously through a swept-stroke attachment test or by analysis. If such determination has not been made, the dwell time shall be taken to be 50 ms.

Note 3. Indirect effects should also be measured with current components A, B, C or D as appropriate to the test zone.

TABLE II. Index of qualification test methods.

Method	Title
T01	Full Size Hardware Attachment Point - Zone 1
T02	Direct Effects - Structural
T03	Direct Effects - Combustible Vapor Ignition
T04	Direct Effects - Corona and Streamers
T05	Indirect Effects - External Electrical Hardware

Custodians:
  Army - AV
  Navy - AS
  Air Force - 11

Preparing Activity:
  Air Force - 11

(Project No. EMCS-0099)

Review Activities:
  Army - AV, ER, MI
  Navy - AS, EC
  Air Force - 10, 13, 15, 18, 19, 85, 95, 99

Certain provisions of this standard are the subject of International Standardization Agreement 3659AE. When revision or cancellation of this standard is proposed which will affect or violate the international agreement concerned, the preparing activity will take appropriate reconciliation action through international standardization channels, including departmental standardization offices if required.

TEST METHOD T01

FULL SIZE HARDWARE ATTACHMENT POINT - ZONE 1

1. PURPOSE. This test is performed on full size structures that include nonmetallic surfaces to determine the possibility of puncture and any other paths taken by the lightning current in reaching a conductive element, or to determine specific locations where initial lightning attachments may be possible.

2. APPLICABILITY. This test method is applicable to radomes, canopies, wing and empennage tips, antenna fairings, windshields and any other assemblies located in a direct strike zone and constructed of nonmetallic materials which might be vulnerable to puncture and/or damage from a lightning strike. The test method is also applicable to metallic or advanced composite structures such as wing tips or engine nacelles where initial lightning attachment may be possible.

3. APPARATUS. The test apparatus shall include the following:

a. A high voltage generator capable of producing the specified voltage waveform(s) with a peak voltage of at least 1.5 million volts.

b. High voltage measuring and recording instruments.

c. Photographic equipment for recording strike points/damage areas.

4. TEST SETUP. The test object should be a production hardware, a full-scale prototype, or an electrically representative mockup of the production configuration. All conducting objects within or on nonmetallic hardware that are normally connected to the vehicle when installed in the aircraft should be electrically connected to ground (the return side of the lightning generator). Surrounding external metallic vehicle structure should be simulated and attached to the test object. The test electrode to which test voltage is applied is positioned so that its tip is 1 meter away from the nearest surface of the test object. Dimensions of the test electrode are not critical. If model tests or field experience have indicated that lightning flashes can approach the object under test from several different directions, the tests shall be repeated with the test electrode oriented to create strokes to the object from these different directions. If the test object is so small that a 1 meter gap permits strokes to miss the test object, or if a 1 meter gap is inappropriate for other reasons, shorter or longer gaps may be used.

5. CRITERIA TO BE SPECIFIED

a. Waveforms. Test voltage waveform A should be applied between the electrode and grounded test object.

NOTE: Regulatory authorities should note that additional testing using waveform D may be advisable when the test object contains one or more flight critical components.

b. Number of discharges. Number of discharges to be fired from each electrode position.

6. TEST PROCEDURE

a. Set up the high voltage generator, test electrode and photographic equipment.

b. Inspect the high voltage equipment and area for safe operation.

c. Insert a dummy test object beneath the electrode, or place a conductive bar over the actual test object such that waveform-checkout discharges cannot damage the test object.

d. Fire a discharge to the dummy test object to check the voltage waveform and establish that the specified waveform is in fact being applied and check the operation of the photographic equipment.

e. Place the test object beneath the test electrode and begin the tests by firing one discharge at the test object. Inspect the test object to determine the point where this discharge attached.

f. Fire the specified number of discharges from each position. Inspect the test object after each discharge and record the strike attachment points. To create strokes to the object from different directions, move either the electrode or the test object. Repeat steps e and f. If a change results in the air gap between the electrode and the test object, step d must also be repeated.

g. Tests may be commenced with either positive or negative polarity. If test electrode positions are found from which the simulated lightning flashovers do not contact the test object, or do not puncture it if it is nonmetallic, the tests from these same electrode positions should be repeated using the opposite polarity.

h. Correlate photographs with strike attachment points observed on the test object.

7. DATA TO BE COLLECTED

a. Environmental data such as temperature and humidity

b. Description and photographs of the test setup

c. Date, personnel performing the tests, and location of the test

d. Test voltage waveforms

e. Photographs of discharges and attachment points and any visible indications of damage on the test object

TEST METHOD T02

DIRECT EFFECTS - STRUCTURAL

1. PURPOSE. This method is used to determine the direct effects which result from the interaction of lightning currents with aerospace vehicles and hardware.

2. APPLICABILITY. This test method is applicable to aerospace vehicle structures and components which are susceptible to lightning current attachment or transfer. This includes probes, booms, antennas, lights, landing gear and other hardware located in zones 1 or 2.

3. APPARATUS. The test apparatus shall include:

a. A high current generator(s) capable of producing the specified waveforms.

b. High current measuring and recording instruments.

c. Photographic equipment for recording strike points/damage areas.

4. TEST SETUP. The test object should be a production hardware, a full-scale prototype, or an electrically representative mockup of the production configuration. All conducting objects (within or on nonmetallic hardware) that are normally connected to the vehicle when installed in the aircraft should be electrically connected to ground (the return side of the lightning generator). Surrounding external metallic vehicle structure should be simulated and attached to the test object. The test setup shall be such that the simulated lightning currents are delivered to and conducted away from the test object in a manner representative of the aircraft being struck by lightning. Care must be taken to assure that magnetic forces, and other interactions which are unrepresentative of the natural situation, are minimized.

CAUTION

There may be interactions between the arc and the test conductors. Care must be taken to assure that these interactions do not influence the test results.

4.1 Arc-entry tests for zones 1 and 2.

a. Test electrodes - The electrode material shall be a good electrical conductor capable of resisting the erosion produced by the test currents involved.

b. Test gap - The gap spacing shall be sufficient so that arc jet and blast pressure effects do not influence the test results. This will require that the gap be at least 50 mm for Component A or D and at least 10 mm for multiple component tests. Alternatively, suitable jet-diverting techniques shall be incorporated in the design of the electrode assembly. A fine wire such as No. 30 copper wire can be used as required in the gap to assist in the current discharge of low-voltage-driven current generator(s).

c. Electrode polarity - The electrode polarity of the waveform components A and D shall be either positive or negative. The electrode polarity of the waveform components B and C shall be negative.

4.2 Conducted entry tests for zone 3. For tests of objects in zone 3, the test current is conducted directly into and out of the test object in a manner representative of the actual lightning current paths in the aircraft. This test can be combined with the zone 1 and 2 tests described in Para. 4.1.

5.0 CRITERIA TO BE SPECIFIED

a. Waveform components should be applied in one continuous discharge except as noted:

Zone 1A: Apply waveform components A and B in that order.
Zone 1B: Apply waveform components A, B, C and D in that order, but not necessarily as one continuous discharge.
Zone 2A: Apply waveform components D, B and C in that order. The total current discharge time shall be limited to 50 milliseconds or to a time period previously determined through a swept-stroke attachment test or analysis (See Table I, note 2).
Zone 2B: Apply waveform components B, C and D in that order.
Zone 3: Apply waveform components A and C in that order.

b. Number of discharges to be fired.

c. Lightning damage may be in the form of pit marks or burn-through holes on skin panels, weakened or distorted structural joints, structural deformation from blast pressures, puncture or delamination of composite structures, etc. Structural tests and/or non-destructive inspections may be required both before and after tests for damage evaluation.

6. TEST PROCEDURE

a. Set up the high current generator, discharge circuit and diagnostic equipment.

b. Inspect the equipment and area for safe operation.

c. Insert a dummy test object beneath the electrode, or place a conductive bar over the actual test object such that waveform-checkout discharges cannot damage the test object.

d. Fire a discharge to the dummy test object to check the current waveforms and establish that the specified waveform(s) are in fact being applied and check the operation of the diagnostic equipment.

e. Place the test object in the discharge circuit.

f. Fire the specified number of discharges and inspect the test object after each discharge and record the results.

g. Correlate photographs with arc entry points/damage areas observed on the test object.

7. DATA TO BE COLLECTED

a. Environmental data which may affect the test results

b. Description and photographs of the test setup

c. Date, personnel performing the tests and location of tests

d. Test object photographs both before and after lightning tests

e. Test current waveforms

8. NOTES

a. This lightning test shall be conducted by personnel experienced in high voltage testing and it shall be performed at a controlled access test area. A laboratory with adequate safety measures and controlled test procedures is required.

b. The discharge circuit of the current generator shall be designed and maintained to avoid unnecessary arcing and other phenomena which may affect personnel and equipment safety and test accuracy.

c. All personnel should be provided with appropriate eye and ear protection.

d. The test instrumentation shall be adequately shielded from electromagnetic fields associated with the lightning test currents and other sources.

e. In cases where inductive sparking may be a problem, a test with current waveform E may be advisable.

TEST METHOD T03

DIRECT EFFECTS - COMBUSTIBLE VAPOR IGNITION

1. PURPOSE. This method is used to determine the possibility of combustible vapor ignition as a result of skin or component puncture, hot spots, and sparking or arcing in or near fuel vent systems or other regions where combustible vapors may exist.

2. APPLICABILITY. This test method is applicable to integral (wet skin) fuel tanks, external tanks, or any other aerospace vehicle fuel tank located in zones 1 or 2 and any fuel tank located within a structure in zone 3 through which lightning currents may be conducted. This test is also applicable to fuel vent outlets, drain valves, dump outlets, access doors, filler caps and any other object in contact with flammable vapor and located in zones 1 or 2.

CAUTION

> These tests simulate the possible effects which may cause ignition due to a lightning strike to the aircraft. Ignition from direct strikes may also be caused by inductive voltages produced by fast rate-of-rise currents, or by lightning indirect effects such as induced voltages in fuel probe wiring, etc.
>
> Ignition sources may also arise from corona or streamering caused by intense electric fields, nearby strikes, or by direct strikes that pass near exposed fuel system components where flammable vapors may be present. A test for these effects is included in Test Method T04.
>
> In some cases, internal conductors such as fuel line couplings and bond straps must be tested individually to determine ignition sources. In these cases, a test current of at least 2500 amperes with a waveform comparable to current component B shall be conducted through the test part and the following procedures shall be used for spark detection.

3. APPARATUS. The test apparatus shall include:

a. A lightning current generator(s) capable of producing the specified waveform(s).
b. High current measuring and recording instruments.
c. Photographic equipment or other instrumentation capable of detecting electrical sparks.
d. Specialized instrumentation to detect surface temperatures, pressure rises, or flame front propagation velocities as appropriate.

4. TEST SETUP

The test object should be a production hardware, a full-scale prototype, or an electrically representative mockup of the production configuration. Fuel tanks shall be complete with filler caps, fuel quantity probes, or other appropriate hardware. If a complete fuel tank is not available or impractical for test, a sample of the tank skin or other specimen representative of the actual structural configuration (including joints, fasteners and substructures, attachment hardware, as well as internal fuel tank fixtures) should be tested in a light-tight chamber. All paints, coatings, and sealants used in the production installation should be used in the prototype.

a. Vapor ignition due to sparking or arcing. Photography is the preferred technique for detecting sparking. If photography is employed, the film speed shall be not less than ASA 3000 and the aperture opening shall be not smaller than f4.7. The fuel tank or chamber shall be verified to be light-tight and shall be fitted, if necessary, with an array of mirrors to make any sparks visible to the camera.

b. Vapor ignition due to hot spots. A number of techniques are available for detection of ignition sources due to hot spots. These include infrared detection systems, optical pyrometry, fast response thermocouples, and temperature sensitive paints.

c. Ignition detection using fuel vapors. If there are regions where a hot spot activity is not accessible to detection by any of the above means, then ignition tests may be used by placing an ignitable fuel-air mixture inside the tank. This can be a mixture of propane and air (e.g., for propane: a 1.2 stoichiometric mixture) or vaporized samples of the appropriate fuel mixed with air.

CAUTION

When making tests with combustible vapors, suitable precautions shall be taken such as the use of blow out panels to preclude explosion of the structure, the location of fire extinguishing equipment nearby, and protection for test personnel from possible flame or blast effects.

If fast development type film is used, the development time-temperature combination recommended by the manufacturer shall be followed. Outdated film shall not be used. If one or more mirrors are used, they shall have less than 30 percent total reflection loss.

Other aspects of the test setup shall be identical to those described in test method T02, paragraph 4.

5. CRITERIA TO BE SPECIFIED

a. The same current waveform components should be applied as are specified for the high current direct effects tests in method T02 and listed in table I.

b. Number of discharges to be fired.

6. TEST PROCEDURE

a. Set up the high current generator, discharge circuit and diagnostic equipment.

b. Inspect the equipment and area for safe operation.

c. Insert a dummy test object in the discharge circuit or place a conductive bar over the actual test object such that waveform-checkout discharges cannot damage the test object.

d. Fire a discharge to the dummy test object to check the current waveform, check that the specified waveform is in fact being applied, and check the operation of the diagnostic equipment.

e. Place the test object in the discharge circuit and fire the specified number of discharges. If photography is employed, verify that the camera shutter was open for the entire duration of each discharge.

f. Inspect the test object before and after the test series, and at convenient and appropriate times during the series.

g. Determine the presence of an ignition source by photography, ignition of a combustible mixture, or temperature measurement as appropriate. If photography is employed, any light indications due to internal sparking during the test shall be taken as an indication of sparking sufficient to ignite fuel. If a combustible mixture is used instead of photography, verification of the combustibility of the mixture should be obtained by ignition with a spark or corona source introduced into the test chamber immediately after each lightning test in which no ignition occurred. If the combustible mixture was not ignitable by this artificial source, the lightning test must be considered invalid and repeated with a new mixture until either the lightning test or artificial ignition source ignites the fuel.

7. DATA TO BE COLLECTED

a. Description and photographs of the test setup

b. Date, personnel performing the test, and location of test

c. Test current waveforms and magnitudes

d. Photographs of the interior of the fuel system component(s) under study during the tests, or other evidence of the absence of sparking (or of sparking, if present during the tests)

e. Photographs of discharge and attachment points and any visible indications of damage on the test object

f. Environmental data such as temperature and humidity

TEST METHOD T04

DIRECT EFFECTS - CORONA AND STREAMERS

1. PURPOSE. This method is used to determine if electrical streamers or corona can be produced at or near apertures or at other locations where corona and streamering may be of concern.

2. APPLICABILITY. This test is applicable to fuel vent and dump outlets, radomes, antennas, canopies and other components which are exposed to atmospheric electric fields.

3. APPARATUS. The test apparatus shall include:

a. A high voltage generator capable of producing voltage waveform B with a crest voltage sufficient to produce the electric field specified in paragraph 5.

b. A test electrode of a configuration that would produce a uniform electric field over the general contour of the test object.

c. High voltage measuring and recording equipment.

d. Photographic equipment capable of detecting corona and streamers, and a suitable environment for such photography.

4. TEST SETUP. The test object shall be a production hardware component, a full-scale replica, or a section of the aircraft structure, mounted in a fixture representative of the surrounding region of the airframe. The voltage may be applied either by (a) grounding the test object and locating the high voltage test electrode sufficiently close to the test object to produce the required field at the test voltage level applied or (b) connecting the test object to the high voltage output of the generator and locating the test object in proximity to a ground plane or other electrode that is connected to the ground or low side of the generator. The test object shall be at positive polarity. If all possible internal streamer sources cannot be observed by the camera or by the camera plus mirrors, the test shall be run with a combustible vapor inside the structure to determine if ignition occurs.

CAUTION

> Suitable precautions shall be taken when making electrical tests of combustible vapors to include at least the use of blow-out panels to preclude explosion of the structure, the location of fire extinguishing equipment nearby and protection of test personnel against possible flame or blast effects.

5. CRITERIA TO BE SPECIFIED

a. Waveform

Voltage waveform B of this document shall be applied for this test. The crest voltage shall be sufficient to cause streamering over the exterior of the test object but not sufficient to cause sparkover of the high voltage gap. This will usually require an average electric field of about 500 kV/m.

b. Number of discharges to be fired.

6. TEST PROCEDURE.

a. Set up the high voltage generator, discharge circuit and diagnostic equipment.

b. Inspect the equipment and area for safe operation.

c. Fire a series of test discharges to achieve the required test voltage and to check the waveform to assure that sparkover to the test object will not take place.

d. Open the shutter on the camera and fire the first test discharge. For tests of fuel system components, the same diagnostic criteria as are specified for the vapor ignition test of Method T03 are applicable.

e. Inspect for streamering data.

f. Fire additional discharges as specified in paragraph 5 and again inspect the film for streamering data.

g. Complete recording of all data.

7. DATA TO BE COLLECTED

a. Environmental data such as temperature and humidity.

b. Description and photographs of the test setup.

c. Date, personnel performing the test and location of the test.

d. Test voltage waveforms and magnitudes.

e. Photographs of corona and streamering.

TEST METHOD T05

INDIRECT EFFECTS - EXTERNAL ELECTRICAL HARDWARE

1. PURPOSE. This method is used to determine the magnitude of indirect effects when lightning strikes externally mounted electrical hardware.

2. APPLICABILITY. This test is applicable to externally mounted electrical hardware such as antennas, navigation lights, and electrically heated probes and windshields.

3. APPARATUS. The test apparatus shall include:

a. A high current generator(s) capable of producing the waveforms specified in paragraph 5.

b. High current measurement and recording instruments.

c. Induced voltage and current measurement and recording instruments.

d. Shielded instrument enclosure.

e. Photographic equipment for recording strike points and test setups.

4. TEST SETUP

a. The test object shall be mounted on or connected to a shielded instrumentation enclosure such that access to its electrical connector can be obtained in an area free from extraneous electromagnetic fields. The test object shall be mounted in a manner similar to the way it is mounted on the aircraft. Measurement/recording equipment shall be contained within the shielded instrumentation enclosure.

b. The test electrode shall be positioned so as to inject high current into the test object at the probable lightning attachment point(s). For tests run concurrently with direct effects tests on the same test object, this shall be an arc-entry (flashover from test electrode to test object); but for tests made only to determine the indirect effects, hardwired connections can be made between the generator output and the determined attachment point(s) on the test object.

c. Load impedances simulating those encountered in operational installation of the test object shall be connected across all electrical terminals of the test object.

5. CRITERIA TO BE SPECIFIED. Current waveform E should be applied for evaluation of magnetically induced effects. Also, the same current waveform components should be applied as are specified for the high current direct effects tests in method T02 and listed in table I.

6. TEST PROCEDURE

APPENDIX A

APPLICATION GUIDANCE FOR LIGHTNING QUALIFICATION TEST TECHNIQUES FOR AEROSPACE VEHICLES AND HARDWARE

10. GENERAL

10.1 Scope. This appendix provides criteria (background, rationale, and guidance) for applying test waveforms and techniques of MIL-STD-1757 to specific aerospace vehicles and hardware. It is intended to assist government and industry personnel specifying lightning qualification tests for design verification and/or for final demonstration in the procurement of aerospace vehicles, parts and assemblies.

10.2 Purpose

10.2.1 This appendix is to be used to tailor requirements in the most cost effective manner that meets established program objectives. However, it is not to be referenced, or implemented, in contractual documents.

10.2.2 The ultimate use of MIL-STD-1757 is to obtain test data that can be used in the qualification or verification of the lightning protection requirements of the equipment, subsystem, or system being procured.

10.3 Application. Since some of the test waveforms and test methods will not apply to particular procurements, the applicability of each requirement shall be determined for each specific application. Generally, a requirement and its associated verification test method should be considered jointly.

10.3.1 Verification of requirements can be accomplished by one or more of the following methods:

a. Inspection
b. Test
c. Analysis

10.3.2 Analysis may include analysis of the present design, analysis of previous test data on similar test specimens, and analysis to establish the applicability of a previous qualification of a similar equipment, subsystem, or system.

10.3.3 When lightning protection is a requirement, it is usually more cost and schedule effective to start the protection planning and design as early in the procurement as is practicable. Initial work will frequently involve development tests that may be informal and uncomplicated during the early portions of the development. The complexity and formality of development testing may increase as the equipment, subsystem, or system development nears completion.

10.3.4 Wherever appropriate and practicable, government and industry personnel should specify or use the lightning test techniques, waveform characteristics, and procedures of MIL-STD-1757 during all phases of lightning protection development. Test results and test article configuration should be well documented. By so doing, it is frequently possible to assemble test data from the development phase which is of adequate validity and applicability to be used for qualification. For some large complex systems, it may not be possible or ecomonically feasible to conduct lightning qualification tests on a production configuration. For these cases, the final qualification verification must be synthesized from the verification of the subsystems or equipment. By using the above approach, the resulting program savings in cost, schedule, and time can be substantial for more complex procurements; these savings can be significant even in low complexity procurements.

10.3.6 Administrative confidence and technical credibility are further benefits that can be derived from the discipline that permeates a program which is structured to permit development data to be used for final qualification.

20. REFERENCE DOCUMENTS

20.1 Issues of documents

SPECIFICATION

MILITARY

MIL-STD-45662	Calibration System Requirements
MIL-B-5087B	Bonding, Electrical, and Lightning Protection, for Aerospace Systems - 1964
MIL-C-38373A(ASG)	Cap, Fluid Tank Filler - 1969
DH 1-4	Electromagnetic Compatibility

20.2 Other publications

"Standard Techniques for Dielectric Tests", USA Standard C68.1/IEEE Standard No. 4, 1978.

"High Voltage Test Techniques, Part 2: Test Procedures", International Electrotechnical Commission Standard 60-2, 1973.

"Lightning Test Waveforms and Techniques for Aerospace Vehicles and Hardware", SAE Committee AE4L Report, June 20, 1978.

"Protection of Aircraft Fuel Systems Against Lightning", FAA Advisory Circular AC 20-53, 1967.

"Lightning Protection of Aircraft", by F.A. Fisher and J.A. Plumer, NASA Reference Publication 1008, 1977.

"A Ground-Lightning Environment for Engineering Usage", by N. Cianos and E.T. Pierce, Stanford Research Institute Report No. 1, 1972.

"Lightning", by M.A. Uman, New York: McGraw-Hill, 1969

"Lightning Protection", by R.H. Golde, London: Edward Arnold, 1973.

30. DEFINITIONS OF LIGHTNING STRIKE PHENOMENA

30.1 Natural lightning strike electrical characteristics

30.1.1 Lightning flashes. Lightning flashes are of two different forms, cloud-to-ground flashes and inter/intracloud flashes. Because of the difficulty of intercepting and measuring inter/intracloud flashes, the great bulk of the statistical data on the characteristics of lightning refer to cloud-to-ground flashes. Most strikes to aerospace vehicles are probably inter/intracloud flashes, although cloud-to-ground lightning flashes are also experienced, as shown in figure A-1. There is evidence that the inter/intracloud flashes lack the intensity of cloud-to-ground flashes. Therefore, the use of cloud-to-ground lightning strike characteristics as design criteria for lightning protection is conservative.

30.1.1.1 There can be discharges to ground from either a positive or a negative charge center in the cloud. A negative discharge is characterized by several recurring strokes and continuing currents as shown in figure A-2(A). A positive discharge, which occurs only a small but significant percentage of the time, is shown in figure A-2(B). It is characterized by both higher average current and longer duration in a single stroke and must be recognized because of its greater energy content. The following discussion describes the more common negative flashes.

30.1.2 Prestrike phase. The cloud-to-ground lightning flash is typically originated by a step leader which develops from the cloud toward the ground. As a lightning step leader approaches an extremity of the vehicle, high electric fields are produced at the surface of the vehicle. These electric fields give rise to other electrical streamers which propagate away from the vehicle until one of them contacts the approaching lightning step leader as shown on figure A-1. Propagation of the step leader will continue from other vehicle extremities until one of the branches of the step leader reaches the ground. The average velocity of propagation of the step leader is about 10^5 to 10^6 meters per second (m/s) and the average charge in the whole step leader channel is about 5 coulombs. Inter/intracloud discharge processes appear to be similar, although leader propagation velocities are slower and the stepping process is not as prevalent.

30.1.3 High peak current phase. The high peak current associated with lightning occurs after the step leader reaches the ground and forms what is called the return stroke of the lightning flash. This return stroke occurs when the charge in the leader channel is suddenly able to flow into the low impedance ground and neutralize the charge attracted into the region prior to the step leader's contact with the ground. Typically, the high peak current phase is called the return stroke and is in the range of 10 to 30 kiloamperes (kA). Higher currents are possible though less probable. A peak current of

200 kA represents a very severe stroke, one that is exceeded only about 0.5 percent of the time. The current in the return stroke has a fast rate of change, typically about 10 to 20 kA per microsecond, and in severe cases may exceed 100 kA per microsecond. Typically the current decays to half its peak amplitude in 20 to 40 microseconds (μs).

30.1.4 Continuing current. The total charge transported by the lightning return stroke is relatively small, a few coulombs. Most of the charge is transported in two phases of the lightning flash following the first return stroke. These are an intermediate phase in which currents of a few thousand amperes flow for times of a few milliseconds and a continuing current phase in which currents of the order of 200 - 400 amperes flow for times varying from about a tenth of a second to one second. The maximum charge transferred in the intermediate phase is about 10 coulombs and the maximum charge transported during the total continuing current phase is about 200 coulombs.

30.1.5 Restrike phase. In a typical lightning flash there will be several high current strokes following the first return stroke. These occur at intervals of several tens of milliseconds as different charge pockets in the cloud are tapped and their charge fed into the lightning channel. Typically, the peak amplitude of the restrikes is about one half that of the initial high current peak, but the time to peak is often less than that of the first return stroke. The continuing current often links these various successive return strokes, or restrikes.

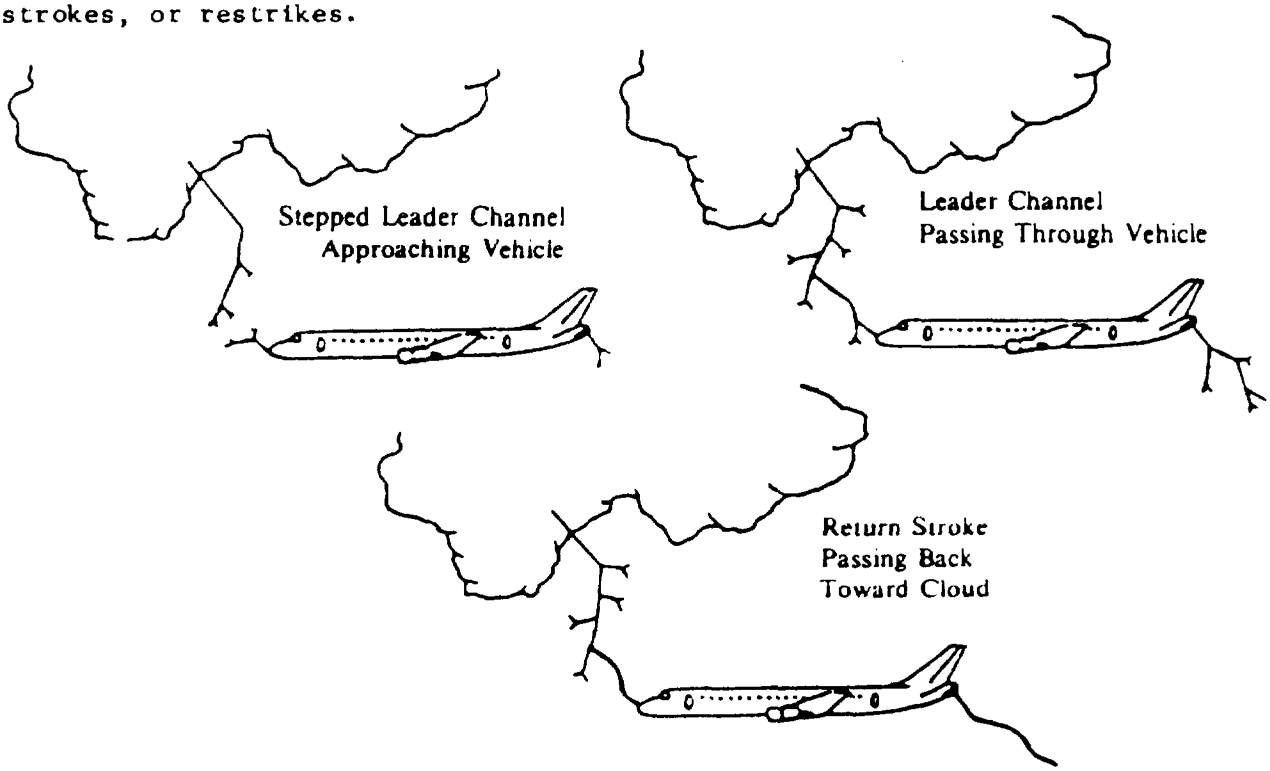


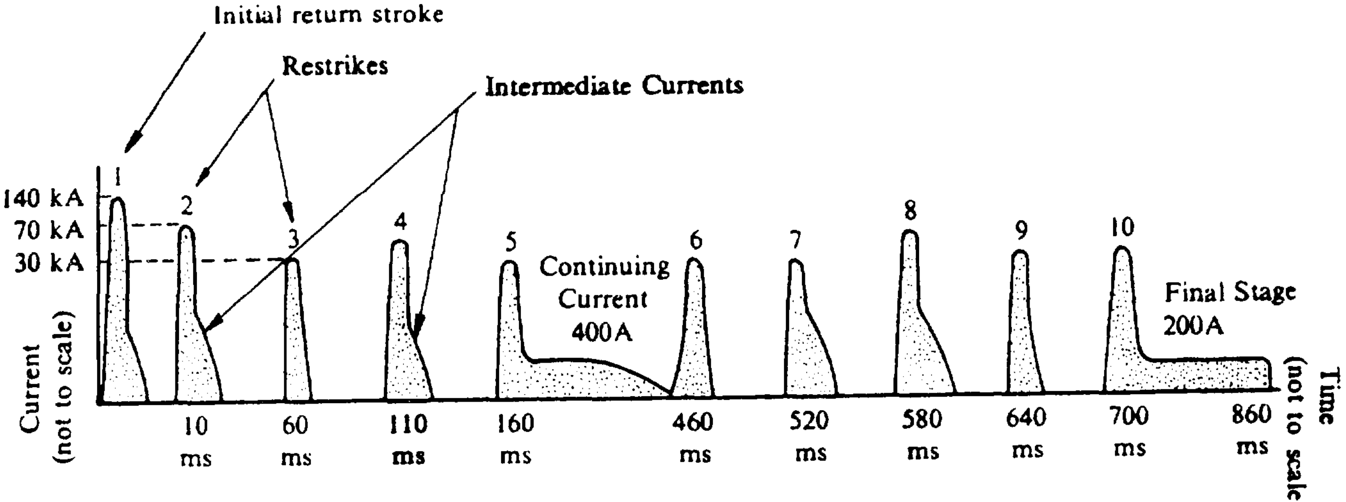
Figure A-1. Lightning flash striking an aircraft.

For each stroke:

Time to peak current = 1.2 μs
Time to half value = 50 μs

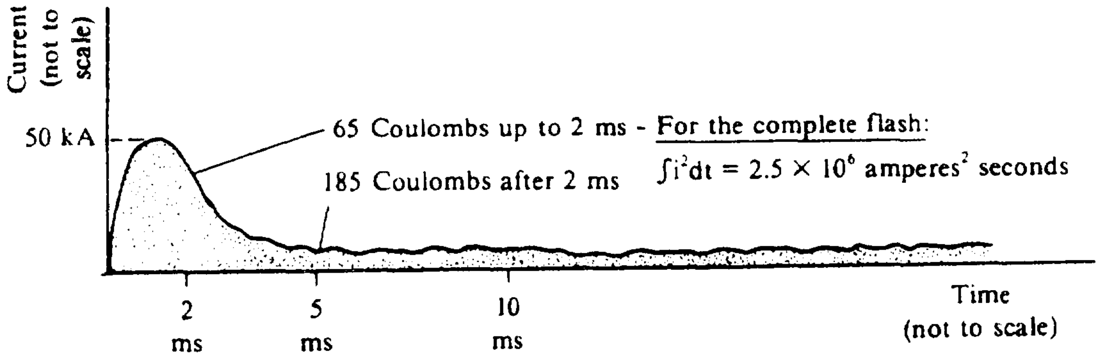
For the complete flash:

$\int i^2 dt = 1.9 \times 10^6$ amperes^2 seconds



(A) Severe negative lightning flash current waveform.

(From "A. Ground-Lightning Environment for Engineering Usage" by Cianos & Pierce)



For the complete flash:

$\int i^2 dt = 2.5 \times 10^6$ amperes^2 seconds

(B) Moderate positive lightning flash current waveform.

Figure A-2. Lightning flash current waveforms.

30.2 Aerospace vehicle lightning strike phenomena

30.2.1 Initial attachment. Initially the lightning flash will enter and exit the aircraft at two or more attachment points. There will always be at least one entrance point and one exit point. It is not possible for the vehicle to store the electrical energy of the lightning flash in the capacitive field of the vehicle and so avoid an exit point. Typically these initial attachment points are at the extremities of the vehicle. These include the nose, wing tips, elevator and stabilizer tips, protruding antennas, engine pods or propeller blades and in some cases the leading edges of swept wings and control surfaces.

30.2.2 Swept stroke phenomenon. The lightning channel is somewhat stationary in space while it is transferring electrical charge. When a vehicle is involved it becomes part of the channel. However, due to the speed of the vehicle and the length of time that the lightning channel exists, the vehicle can move relative to the lightning channel. When a forward extremity, such as a nose or wing mounted engine pod is an attachment point, the movement of the aircraft through the lightning channel causes the channel to sweep back over the surface as illustrated in figure A-3. This is known as the swept stroke phenomenon. As the sweeping action occurs, the characteristics of the surface can cause the lightning channel attach point to dwell at various surface locations for different periods of time, resulting in a skipping action which produces a series of discrete attachment points along the sweeping path.

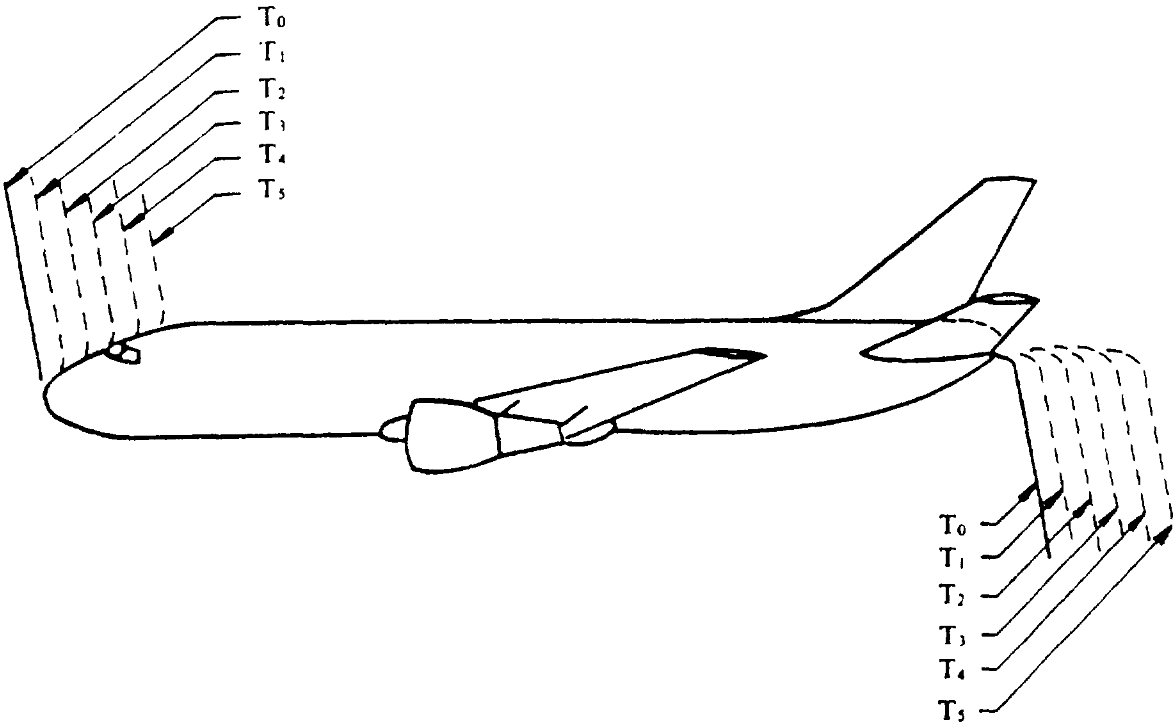


Figure A-3. Swept stroke phenomenon.

30.2.2.1 The amount of damage produced at any point on the aircraft by a swept-stroke depends upon the type of material, the arc dwell time at that point, and the lightning currents which flow during the attachment. Both high peak current restrikes with intermediate current components and continuing currents may be experienced. Restrikes typically produce reattachment of the arc at a new point.

30.2.2.2 When the lightning arc has been swept back to one of the trailing edges it may remain attached at that point for the remaining duration of the lightning flash. An initial exit point, if it occurs at a trailing edge, of course, would not be subjected to any swept stroke action. All components of the flash will enter or exit the aircraft through this point.

30.2.2.3 The significance of the swept stroke phenomenon is that portions of the vehicle that would not be targets for the initial entry and exit point of a lightning flash may be involved as the flash is swept backwards.

30.2.3 Lightning attachment zones. In advisory circular 20-53, "Protection of Aircraft Fuel Systems Against Lightning", the FAA has defined three lightning strike zones for the purpose of establishing the environment to be protected against at various locations on an aircraft. These definitions have been refined in paragraph 3.2 of the standard to remove some ambiguities that have existed and permit a more definite environment to be established for design and qualification test purposes. Neither the original nor the refined definitions prescribe the actual locations of these zones on a particular aircraft, however, nor is this the intent. The locations of each zone are dependent upon the aircraft's geometry and operational factors, and may vary from one aircraft to another.

30.2.3.1 Location of zones. Actual lightning strike zones for an aerospace vehicle can be established by a comparison with inflight experience of existing aircraft or strike attachment tests on scale models of the aircraft in question. Most experienced aerospace lightning protection engineers can establish the most probable lightning attachment points and strike zones by the former method, and flight experience on many types of airplanes confirms this approach. However, when unusual protuberances appear on a conventional geometry airframe, or where the airframe geometry is unlike conventional designs, the scale model attachment point tests may be in order. Since these model tests are not qualification tests, they are not described in this standard. Additional information on model testing can be found in SAE Committee AE4L report "Lightning Test Waveforms and Techniques for Aerospace Vehicles and Hardware", dated June 20, 1978.

30.2.3.1.1 Prior experience or model testing is especially helpful in determining the locations of probable initial attachment points. The initial attachment points that occur on trailing edges will remain at these spots, thereby placing them within zone 1B (a direct strike zone with a high probability of flash hang-on).

30.2.3.1.2 For conventional aluminum skins, the line of demarcation between zone 1A and 2A has been of little practical importance, because most aluminum skins can withstand even the first return stroke with little damage. However, if the skin or structure aft of a leading edge attachment point is made of composites, the rearward extent of zone 1A becomes more important because the intensity of the return stroke (current component A) prescribed for zone 1A is greater than that of the restrike (current component D) prescribed for zone 2A.

30.2.3.1.3 With these factors in mind, the locations of each zone on a particular aircraft may be established as follows:

a. All extremities such as the nose, wing and empennage tips, tail cone, wing-mounted nacelles and other significant projections should be considered within a direct strike zone because they are probable initial leader attachment points. Those that are forward extremities or leading edges should be considered in zone 1A, and extremities that are trailing edges should be in zone 1B.

b. Return strokes of the intensity of current component A are most probable at surfaces close to the initial leader attachment point, but there is a finite possibility of a severe return stroke occurring further aft.

c. Surfaces directly aft of zone 1A should be considered as within zone 2A. The rearward extent of zone 2A can be established by estimating the distance travelled by the aircraft during the total flash lifetime, assumed to be one second.

d. Trailing edges aft of zones 1A or 2A should be considered as in zone 1B or 2B, depending upon whether they were reached by an initial strike (zone 1B) or a swept strike (zone 2B), in accordance with the definitions of paragraph 3.2.

e. Surfaces approximately 0.5 m (18 in.) to either side of zones 1 or 2 should also be considered within the same lightning strike zone, to account for small lateral movements of the sweeping channel.

f. Surfaces and structures that are not within any of the above zones but which lie between them should be considered as within zone 3.

30.3 Direct and indirect lightning effects

30.3.1 Direct effects. Physical damage effects, produced at or near the point of direct attachment of the lightning flash, are referred to as direct effects. The nature of the particular direct effects associated with any lightning flash depends upon the structural component involved and the type and intensity of the lightning currents and voltages experienced by the structural component. The more common effects and the lightning parameters which produce the effects are discussed in this section. A discussion of the parameter definitions is included in sections 30.5 and 40.2.

30.3.1.1 Vaporization pressure. The high peak current phase of the lightning flash transfers a large amount of energy in a few tens of microseconds. This energy transfer can result in a fast thermal vaporization of material. If this occurs in a confined area, a high pressure may be created which can be of sufficient magnitude to cause structural damage. For example, the vaporization of metal and other materials and the heating of the air inside a radome can create high internal pressures that lead to structural failure. In some instances entire radomes have been blown from aircraft. The critical lightning parameters are the peak current and the action integral (see 30.5.3).

30.3.1.2 Magnetic force. During the high peak current phase of the lightning flash, the flow of current through sharp bends or corners of the aircraft structure can cause magnetic flux interaction. In certain cases, the resultant magnetic forces can twist, rip, distort, and tear structures away from rivets, screws, and other fasteners. These magnetic forces are proportional to the square of the magnetic field intensity and, thus, are proportional to the square of the lightning current. The damage produced is related both to the magnetic force and to the response time of the system.

30.3.1.3 Burning and eroding. The intermediate and continuing current phase of a lightning stroke can cause severe burning and eroding damage to vehicle structures. The most severe damage occurs when the lightning channel dwells or hangs on at one point on the vehicle for the entire period of the lightning flash. This can result in holes of up to a few centimeters in diameter on metallic aircraft skin. The critical lightning parameter is total charge transfer (see 30.5.2).

30.3.1.4 Fire and explosion. Fuel vapors and other combustibles may be ignited in several ways by a lightning flash. During the prestrike phase, high electrical stresses around the vehicle produce corona and high-voltage streamers from the aircraft extremities. The design and location of fuel vents determine their susceptibility to streamer conditions. If streamers occur from a fuel vent in which flammable fuel-air mixtures are present, ignition may occur. If this ignition is not arrested, flames can propagate into the fuel tank area and cause a major fuel explosion. The magnitude and duration of the electric field determine the amount of corona and streamering activity. The flow of lightning current through vehicle structures can cause sparking at poorly bonded structure interfaces or joints. If such sparking occurs where combustibles such as fuel vapors are located, ignition may occur. Voltage gradient, peak current, time-to-peak, charge transfer and action integral are all factors. In addition, as mentioned previously, lightning attaching to an integral tank skin may puncture or burn holes in the tank, or heat the inside surface sufficiently to ignite any flammable vapors present.

30.3.1.5 Acoustic shock. The air channel through which the lightning flash propagates is nearly instantaneously heated to a very high temperature. When the resulting shock wave impinges upon a surface, it may produce a destructive overpressure and cause mechanical damage. The critical lightning parameters are the peak current and the action integral.

30.3.2 Indirect effects. Damage or upset of electrical equipment by currents or voltages is defined as an indirect effect. In this document, such damage or upset is defined as an indirect effect even though such currents or voltages may arise as a result of a direct lightning flash attachment to a piece of external electrical hardware. An example would be a wing-tip navigation light. If lightning shatters the protective glass covering or burns through the metallic housing and contacts the filament of the bulb, current can be injected into the electrical wires running from the bulb to the power supply bus. This current may burn or vaporize the wires. The associated voltage surge may cause breakdown of insulation or damage to other electrical equipment.

30.3.2.1 Even if the lightning flash does not contact wiring directly, it will set up changing electromagnetic fields in and around the vehicle. The metallic structure of the vehicle does not provide a perfect Faraday cage electromagnetic shield, and, therefore, some electromagnetic fields can enter the vehicle, either by diffusion through metallic skins or direct penetration through apertures such as skin joints and windows or other nonmetallic sections. If the fields are changing with respect to time and link electrical circuits inside the vehicle, they will induce transient voltages and currents in these circuits. These voltages may be hazardous to avionic and electrical equipment, as well as a source of fuel ignition. The lightning parameters of most concern for this effect are the rates of change of current and voltage.

30.3.2.2 Lightning currents through the resistance of the aircraft structure can also produce voltage drops along the structure and result in voltages and currents in interior wiring. Where resistive structures such as advanced composite materials are employed, resistive voltages may exceed those produced by electromagnetic coupling. Peak current magnitude is the most critical parameter for resistive coupling.

30.4 Physiological effects

30.4.1 Flash blindness. One of the most troublesome effects on personnel is flash blindness. This often occurs to flight crew who may be looking out of the vehicle in the direction of the lightning flash. The resulting flash blindness can persist for periods of more than 30 seconds.

30.4.2 Electrical shock. Personnel inside vehicles may also be subjected to hazardous effects from lightning strikes. Serious electrical shock may be caused by currents and voltages which are conducted via control cables or wiring leading to the cockpit from control surfaces or other hardware struck by lightning. Shock can also be induced by the intense thunderstorm electromagnetic fields.

30.5 Waveform parameters

30.5.1 Waveform definitions. The waveform parameters presented in section 3.3 are defined to be consistent with the traditional waveform definitions used in the high-voltage industry and defined in section 2 of IEEE Standard 4-1978, Standard Techniques for Dielectric Tests. It is necessary to adopt a standard procedure for defining waveform parameters, because, in actual experience, the waveforms may exhibit irregularities which make them difficult to interpret.

For example, in the definition of time-to-crest, it is more practical and much simpler to identify the 30 and 90 percent points because they are in the more linear region of the waveform. Depending on the generator and test circuit, and the instrumentation system, there may be noise or delayed triggering effects near the beginning of the waveform, and the actual peak may be approached slowly as the voltage level approaches maximum. The multiplication factor of 1.67 is used since only 60 percent of the time-to-crest is actually measured (1.67 x 60% = 100%). The same rationale applies to the definition of decay time. The time duration definition is included to allow the insignificant effects of slowly decaying components (less than the five percent level) to be ignored in practical situations.

30.5.2 Charge transfer. The definition of charge transfer appears trivial, but it is included because of its importance in testing for lightning effects, and because it helps to visualize the origin of the mechanisms producing burning and erosion effects. Where oscillatory or other time varying waveforms are employed, the integral of the current record must be obtained to determine the total charge transferred.

30.5.3 Action integral. The action integral concept is difficult to visualize, but is a critical factor in the production of damage. It relates to the energy deposited or absorbed in a system. However, the actual energy deposited cannot be defined without a knowledge of the resistance of the system. For example, the instantaneous power dissipated in a resistor is by Ohm's Law, $i(t)^2R$, and is expressed in watts. For the total energy expended, the power must be integrated over time to get the total watt-seconds (or kilowatt hours). The watt-second is equivalent to the joule, which is the common unit of electrical energy used in high-voltage practice. Without a knowledge of R, we cannot specify the energy deposited. But by specifying the integral of $i(t)^2$ over the time interval involved, a useful quantity is defined for application to any resistance value of interest. In the case of lightning, therefore, this quantity is defined as the action integral and is specified as $\int i(t)^2 dt$ over the time the current flows.

40. REQUIREMENTS

40.1 General requirements

40.1.1 Safety. Relatively low voltages can be lethal under some conditions. Lightning simulation tests require high-energy electrical equipment, which may be charged to very high voltages during their operation. Normal safety measures specified for commercial electrical codes or occupational safety laws cannot be contained in grounded metal cabinets or protected by shields. Consequently, it is necessary to ensure that only personnel who are trained and experienced in the operation and maintenance of high-voltage equipment be permitted to work with the equipment.

40.1.1.1 In cases where extreme voltages, in excess of a few hundred kilovolts, are generated, unusual and sometimes unpredictable behavior may be experienced. For example, under certain conditions sparks may jump across a considerable distance to a grounded, or even an ungrounded, object. Consequently, such tests should only be conducted in an isolated area where personnel entry and access is strictly controlled. Ideally, room entry interlocks should be provided to ensure that the equipment cannot be energized unless all access doors are closed and locked. In addition, the high voltage equipment should be interlocked so that after a test, the equipment is automatically de-energized and grounded.

40.1.1.2 Energy storage capacitors should always be shorted out when personnel are in the test area. Some large capacitors may build up a substantial charge if not shorted, even though no voltage has been applied for a period of time. When automatic grounding techniques are employed, the capacitors should still be directly shorted with a shorting stick (a conducting bar attached to a long insulated rod which is held by the operator). Before the bank is worked on, the capacitors should be physically shorted by jumper wires. Always connect the jumper wire to the grounded case first, then to the capacitor terminals.

40.1.1.3 Even experienced personnel have experienced severe electrical shocks from supposedly safe equipment. Many large capacitors have grounded cases, but in some models the case is a center electrode. In the latter type, simply shorting the two output electordes together can leave charge on the case. Lasting lessons have been learned by test personnel who have touched a capacitor case with even a little residual charge on it.

40.1.1.4 Many test personnel can relate experiences where they thought an exposed element was "dead", but in following the correct procedure and shorting it with a shorting stick before touching it, were greeted by a loud explosion as the very "live" electrode discharged. Interlocks, malfunctions, momentary lapses of concentration, shortcuts, or carelessness can lead to serious injury or even loss of life. Therefore, it is essential that more than one person be invovled when performing lightning simulation tests. A necessary part of training for high-voltage test personnel should be cardio-pulmonary resuscitation (CPR).

40.1.1.5 Improper installation of diagnostic sensors can also lead to safety hazards. For example, current shunts, current transformers and other instrumentation sensors must be installed in the grounded side of the discharge circuit to prevent test voltages and currents from getting on the cables leading to the test instrumentation. Improperly installed or shielded instrumentation can result in equipment at the operation station being raised to high potentials, thus posing a hazard to both personnel and equipment.

40.1.2 Test conditions. The test object shall be properly grounded when grounding is appropraite for the test and the test instrumentaiton shall be adequately shielded.

40.1.2.1 The electrical discharge circuit of the lightning simulator and test object must be properly designed and set up, both for safety and for proper operation of the test. The test object must be mounted in such a way that the current flow through the object realistically simulates the actual flow of lightning current through the object in flight.

40.1.2.2 If any part of the generator/test object circuit is not well isolated from ground (except at the single point ground at the low end of the generator), spurious current paths will result, leading to incorrect measurements, and possible incorrect results. Stray current paths are sometimes very difficult to locate, but are usually evident in data records where RF hash may be observed, or where clearly incorrect readings are obtained.

40.1.2.3 Test instrumentation must be properly shielded from radiated RF and from the intense magnetic and electric fields produced during the discharge of the lightning simulator. These fields can induce spurious voltages and currents in the instrumentation and connecting cables which can produce significant errors in the measured results. RF interference can result in "noisy" data records that are difficult to read and interpret.

40.1.2.4 It has been shown that improper routing of current-carrying conductors in a lightning test can produce different test results, particularly where indirect effects are being measured. Care must be taken to ensure that magnetic forces, and other interactions which are not representative of the natural situation, are minimized.

40.1.3 Equipment calibration. The results of lightning simulation tests have been shown to be sensitive to the waveform parameters specified in MIL-STD-1757. In order to obtain reasonably accurate test results, some assurance is required that the test parameters are carefully controlled and measured. Equipment that is not regularly calibrated by an experienced calibration laboratory using appropriate waveforms may yield grossly misleading results. This is particularly true for equipment that is operated in a harsh EM environment such as a lightning simulation laboratory.

40.1.3.1 Some equipment used in the lightning simulation test lab is not amenable to calibration or adjustment. For some current shunts and transformers, functional checks can indicate proper operation, but calibration is based upon physical principles (number of turns, area, etc.) or the manufacturer's factory calibration. However, for most active instrumentation, such as oscilloscopes, amplifiers, recorders, etc., regular calibration is required.

40.2 Specific requirements

40.2.1 Voltage waveforms

40.2.1.1 Voltage waveform A - basic lightning waveform. Voltage waveform A is shown in figure 6 of the basic standard, and is applied in test method T01 to determine possible lightning attachment points and/or breakdown paths on full size hardware.

40.2.1.1.1 Since the purpose of the full size hardware attachment test is to evaluate initial lightning attachment points, the electric field, and its rate-of-rise just prior to leader attachment must be simulated. The importance of rate-of-rise can be explained by comparing the breakdown timelag characteristics of solids and air. All insulating materials, whether solids or gases, respond to high voltages and break down according to a timelag curve of the shape shown in figure A-4. Timelag effect means simply this: The shorter the time for which a voltage is applied across a given insulation, the higher the voltage must be to cause breakdown; and conversely, the longer the time, the lower the voltage necessary to cause breakdown. There is, of course, a voltage level below which breakdown will not occur at all, even if the voltage is applied for a long time. Most solids show a flatter timelag characteristic than do air or surface flashover paths, as illustrated in figure A-4.

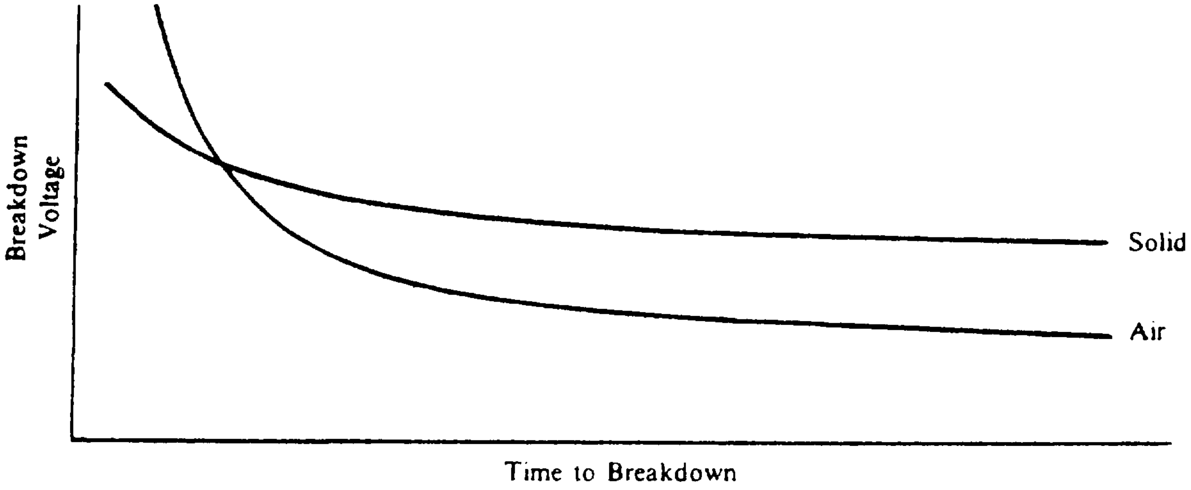


Figure A-4. Breakdown timelag curves for solids and air.

40.2.1.1.2 In general, an oncoming lightning flash has alternate paths to a metallic conductor, as illustrated for a radome in figure A-5. One is via a puncture of the nonmetallic skin to an internal metallic component, such as the radar dish. The other is via surface flashover to the nearest exposed metal. While the path via the puncture may be shorter than that along the outside surface, the added insulation provided by the solid skin often compensates to some degree for this, making both paths viable alternatives. The significance of voltage rate-of-rise now becomes evident. Because the timelag curve for the alternate paths cross each other, there are voltage waveforms that will intersect either timelag curve, as shown in figure A-5 where both a "fast" and a "slow" voltage waveform are superimposed on the breakdown timelag curves of figure A-4.

40.2.1.1.3 From figure A-5 it is evident that the faster rising voltage is the more severe in terms of increased probability of puncture. Thus, for attachment tests, a voltage with the fastest rate-of-rise expected from a natural lightning leader is desirable.

40.2.1.1.4 Few time-domain measurements have been made of the electric fields surrounding an aircraft during the lightning-strike formation process because such measurements present formidable instrumentation problems. However, it is known that leaders advance at about 10^5 to 10^6 m/s, which would result in an average of 1 to 10 μs for the leader to travel a distance of 1 m. Since about

500 kV are required to break down a 1 m air gap in 5 μs, the appropriate rate-of-voltage rise to use for attachment tests might be the following:

$$\frac{\Delta v}{\Delta t} = \frac{500\ 000\text{V}}{5\text{x}10^{-6}\text{s}} = 100\ \text{kV}/\mu\text{s} \qquad (1)$$

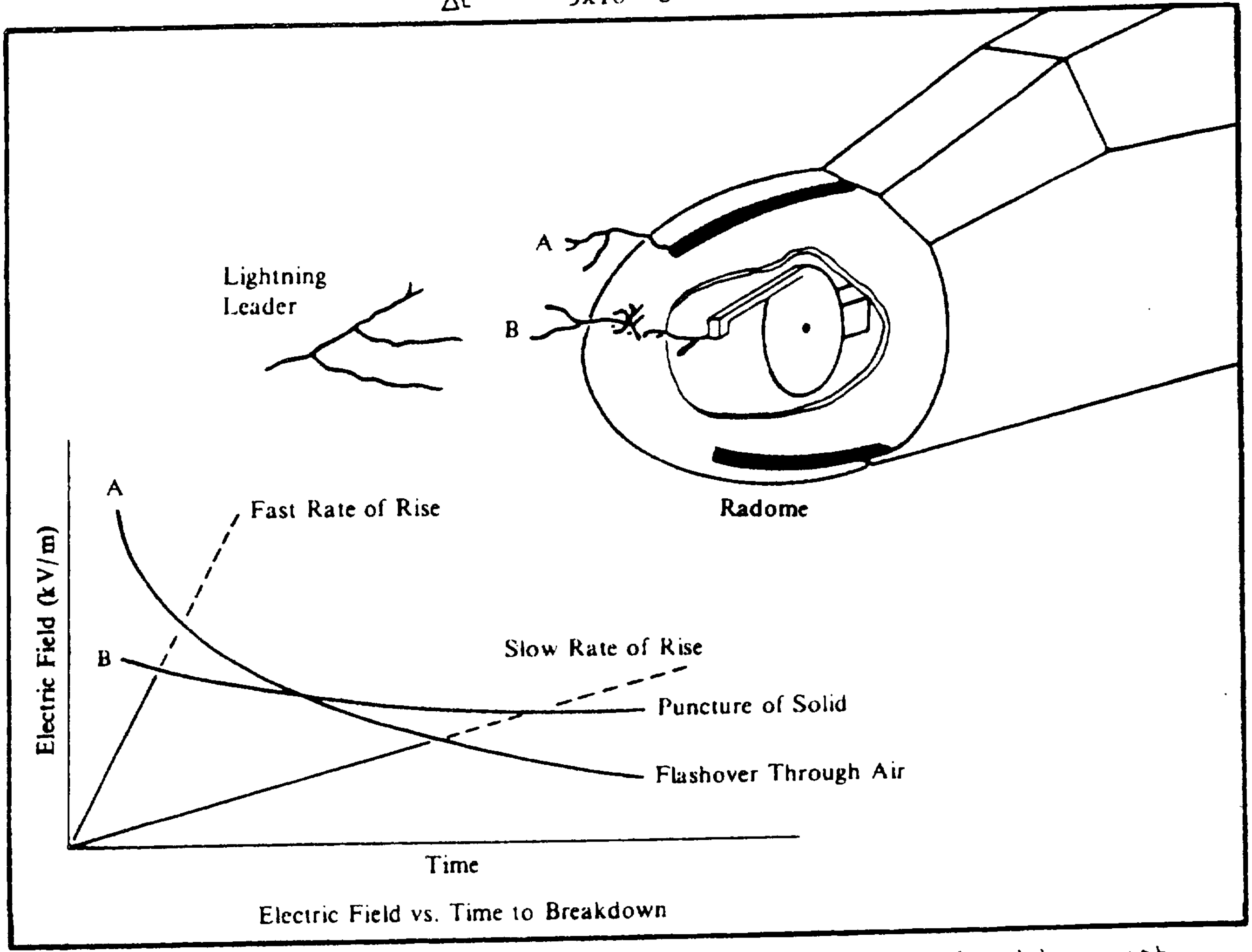


Figure A-5. How electric field rate-of-rise determines breakdown path.

40.2.1.1.5 On the other hand, if it is remembered that the actual breakdown of a single step of the leader is itself a series of smaller step breakdowns and pauses, it is likely that the rate-of-voltage rise across segments only a few meters long might be faster (or slower) than the average. Thus, to encompass the worst case, a rate-of-voltage rise 10 times as fast, or 1000 kV/μs, has been prescribed for voltage waveform A.

40.2.1.1.6 In practice, the timelag curves representing different paths through solid and air insulation are flatter and closer together than those drawn in figures A-4 and A-5 and the point where the solid and air curves cross is less clearly defined. Thus, a relatively wide difference in applied voltage rate-of-rise exists between waveshapes causing breakdowns 100% of the time along one path as compared with waveforms causing all breakdowns to occur through the other path. This fact was an additional reason for the selection of 1000 kV/μs as the rate-of-rise for voltage waveform A. This waveform should create a faster (but not excessively fast) rising electric field than most natural lightning flashes create. In cases where a comparison between the results of laboratory tests using this rate-of-rise and subsequent in-flight lightning attachments to the same piece of full size hardware have been made, the laboratory tests have accurately predicted the in-flight attachment points and breakdown paths.

40.2.1.2 Voltage waveform B - full wave. This waveform is shown in figure 6 of the basic standard and is utilized in test method T04 to evaluate the possibility of corona and streamering at critical locations on the vehicle.

40.2.1.2.1 Simulation of corona and streamering in the laboratory involves subjecting the test object to an electric field capable of producing corona and streamering, and detecting the location of these effects. Whereas corona and streamers may be produced by either DC or impulse fields of very short duration, it is often most practical to apply an impulsive field of intensity sufficient to produce corona and streamers but of insufficient duration to allow complete flashover of the electrode gap.

40.2.1.2.2 The voltage waveform (B) selected for this test is the full wave lightning impulse voltage waveform defined in "Standard Techniques for Dielectric Tests", USA Standard C68.1/IEEE Standard No. 4, 1978 and "High Voltage Test Techniques, Part 2: Test Procedures", International Electrotechnical Commission Standard 60-2, 1973. In this case, a full wave is applied at a voltage level lower than that required to flash over the gap. The voltage is normally generated by a Marx-type high voltage generator operating through a series resistance into a capacitive load. Whereas other full waveforms could as well be utilized for this test, the above-referenced waveform was selected because it is used commonly at most high voltage laboratories and equipment to produce it is generally available.

40.2.1.2.3 Whereas waveform B has been specified, the actual waveform utilized for streamer tests is not critical. Voltages with longer rise times and correspondingly longer decay times can as well be utilized with very similar results. It is only necessary that the voltage decay soon enough that complete flashover of the gap between the test electrode and the test object does not occur.

40.2.1.2.4 The amplitude of voltage waveform B has not been specified because it will be dependent upon the geometry of the test object and the spacing between it and the test electrode. In general, the peak voltage should be sufficient to cause streamering over the exterior of the test object but not sufficient to cause sparkover of the high voltage gap. This will usually require an average electric field of about 500 kV/meter.

40.2.1.3 Voltage waveform D - slow front. This waveform is shown in figure 7 of the basic standard and is applied in test method T01 to determine areas of low strike probability on full size structures.

40.2.1.3.1 During the course of a simulated lightning attachment test on a full size structural element, it is sometimes desirable (1) to encourage streamers from more distant, less probable locations, (2) to identify the boundaries of a zone over which regions where direct lightning strikes are possible, or (3) to seek out regions where strikes, though not likely, are remotely possible. For this purpose, a slower rising test voltage is desirable. If the range of electric field rates-of-rise possible from natural lightning is as broad as the range of return stroke current amplitudes (a likely possibility since both are related to charge in the leader), voltage rates two orders of magnitude lower than waveform A must also be possible.

40.2.1.3.2 Voltage waveforms with rise times of up to 250 microseconds are permitted by the definition of waveform D (50 μs to 250 μs) and the particular rise time is not critical as with voltage waveform A, when the voltage is interrupted by flashover of the gap between the test electrode and the object under test.

40.2.2 Current waveforms

40.2.2.1 Current waveforms and components. For qualification testing, the idealized current waveform (shown in the basic document, section 4.2.3, figure 8) is used to determine direct effects. Current waveform E, shown in the same figure, is used to test for indirect effects. Note that the idealized waveform shown for direct effects testing is simply a schematic representation of the four different phases of a return stroke which involve significant current flow. The four phases of the idealized waveform are designated as components A, B, C, and D. In practice, each component can be individually represented by an actual test waveform whose parameters are specified in the figure. Current waveform E, on the other hand, is a true waveform whose parameters are also noted in the figure.

40.2.2.2 Component A - initial high peak current. Component A has a peak amplitude of 200 kA (± 10 percent) and an action integral (see 30.5.3) ($\int i(t)^2 dt$ of 2×10^6 A^2.s(± 20 percent)) with a total time duration not exceeding 500 microseconds. This component may be unidirectional or oscillatory. The peak current and action integral of component A were selected to represent a stroke whose intensity is known to be exceeded in intensity only about 0.5 percent of the time. These are the parameters that have most effect on materials and structures. Current rate-of-rise is not specified because this parameter is of less importance to direct effects evaluation and is sometimes impractical to obtain when the other parameters must also be obtained in the same current pulse. This component represents the first return stroke of the lightning flash and is responsible for most of the blasting, magnetic force and acoustic shock effects on structures and components. It also causes electric sparks at joints and bonds where conductive paths are inadequate.

40.2.2.3 Component B - intermediate current. Component B has an average amplitude of 2 kA (± 10 percent) flowing for a maximum duration of 5 milliseconds and results in a maximum charge transfer of 10 coulombs. The waveform shall be unidirectional, e.g., rectangular, exponential or linearly decaying.

40.2.2.3.1 It is believed that the parameters of component B represent a severe intermediate current, but statistical data are vague regarding the possible range of such currents. The effects of intermediate currents are primarily thermal, resulting in melting of metals and burning of nonmetallic composites. Most of these effects could be duplicated by continuing current (component C), but a larger discharge time would be required. The significance of component B is that its energy is deposited in a time ($\leq$5 ms) short enough to be delivered to one lightning attachment point on a swept stroke path.

40.2.2.4 Component C - continuing current. Component C transfers a charge of 200 coulombs (± 20 percent) in a time of between 0.25 and one second. The waveform is unidirectional, e.g., rectangular, exponential or linearly decaying.

40.2.2.4.1 Component C represents the continuing current in a severe lightning flash, with only about two percent of all measured flashes delivering more charge than this. This current component also causes melting of metals and burning of composites, but the average rate of charge delivery (current amplitude) is less, so the amount of damage per unit of time is less than that produced by the intermediate current (component B). This implies that component C is more damaging to structures/components in zones 1B or 2B than elewhere, because it is only at trailing edges that sufficient dwell time exists for the full 200 coulombs of charge to enter the aircraft.

40.2.2.5 Component D - restrike current. Component D has a peak amplitude of 100 kA (± 10 percent) and an action integral of 0.25 x 10^6 $A^2 \cdot s$ (± 20 percent). This component may be either unidirectional or oscillatory with a total time duration not exceeding 500 microseconds.

40.2.2.5.1 Component D represents a severe restrike and, like the first return stroke (component A), its amplitude and action integral are known to be exceeded only about 0.5 percent of the time. Notice should be made of the fact that the action integral of this return stroke (0.25 x 10^6 $A^2.s$) is one eighth of the action integral of component A (2 x 10^6 $A^2 \cdot s$), whereas a reduction in amplitude by a factor of two would reduce the action integral by a factor of four. This implies that the time duration of component D is also one half that of component A; a logical relationship, although component D is permitted to be discharged with the same 500 μs time as for component A.

40.2.2.6 Current waveform E - fast rate-of-rise current test for fullsize hardware. Current waveform E has a rate-of-rise of at least 25 kA/μs for at least 0.5 microsecond, as shown in figure 8 of the basic standard. Current waveform E has a minimum amplitude of 50 kA. If desired, components A or D may be applied with a 25-kA/μs rate-of-rise for at least 0.5 microsecond and the direct and indirect effects evaluation conducted simultaneously. A separate test with current waveform E is then no longer required.

40.2.2.6.1 Testing for induced or indirect effects resulting from magnetic coupling is based entirely upon the time rate-of-change of current. Rather than specify rate-of-rise or time-to-peak on current component A or D, a separate rate-of-rise of 100 kA/μs has been established for indirect effects testing. This value is believed to represent a severe rate-of-rise, but the maximum possible rate is a subject of continuing investigation.

40.2.2.6.2 For testing purposes, it is recognized that rates-of-rise of 100 kA/μs are difficult to produce, even at low levels. At the peak current level of components A and D, 100 kA/μs is virtually impossible in most test articles of interest because of the electrical impedance of the test circuits and the limited driving voltages available from most high current generators. In order to overcome this difficulty, the linearity of the magnetic coupling phenomenon is employed to allow testing to be conducted at reduced peak currents and rates of current rise. Measured transients can then be extrapolated to the full 200 kA or 100 kA/μs threat. Thus, current waveform E has been defined in this standard for induced (indirect) effects qualification testing of externally mounted electrical components. The waveform and its derivative are shown in figure 8 of the basic document with the parameter values of interest. Note that this waveform is an actual waveform for test purposes. The amplitude of 50 kA was selected because it is within the capabilities of most lightning test laboratories when testing small electrical components, and it requires extrapolation by a factor of four or less.

40.2.2.6.3 Current waveform E is defined with a minimum rate-of-rise requirement of 25 kA/μs, and that minimum rate must persist for at least 0.5 μsec. Even though the fast rate-of-rise may shock excite cable resonances, the primary purpose of this paramter is to develop voltages by the classical $d\phi/dt$ (rate of change of magnetic field) mechanism. The minimum duration is specified so that instantaneous voltages thus induced are maintained at minimum levels with sufficient duration to be recorded reliably. The voltages produced by this waveform must be extrapolated to threat level by multiplying the peak induced voltage by the ratio of 100 kA/μs to the actual rate-of-rise measure on the test waveform, or by the ratio of 200 kA to the actual peak current of the test waveform, if the voltages produced are caused by structural IR voltage. Test facilities are encouraged to test with a waveform as close to the actual threat waveform as possible. However, in order to limit the range of extrapolation, the minimum values of peak current and rate-of-rise are established. See the test method T05 discussion in section 50.2.5 for more information on extrapolation procedures.

40.2.2.6.4 Some test facilities may be able to meet the minimum requirements of current waveform E with the same generator used to produce current components A and D described earlier. Therefore, provisions are made in the standard to allow induced effects to be measured during the direct effects test if the minimum rate-of-rise criterion is met.

50. QUALIFICATION TESTS

50.1 Selection of qualification tests

50.1.1 Laboratory simulation. Complete natural lightning flashes cannot be duplicated in the laboratory. Most of the voltage and current characteristics of lightning, however, can be duplicated separately by laboratory generators. These characteristics are of two broad categories: The VOLTAGES produced during the lightning flash and the CURRENTS that flow in the completed lightning channel. With a few exceptions, it is not necessary to simulate high-voltage and high-current characteristics together.

50.1.1.1 The high-voltage characteristics of lightning determine attachment points, breakdown paths, and streamer effects, whereas the current characteristics determine direct and indirect effects.

50.1.1.2 In most cases, lightning voltages are simulated by high-impedance voltage generators operating into high-impedance loads, while lightning currents are simulated by low-impedance current generators operating into low-impedance loads.

50.1.1.3 Marx surge impulse generators are normally used for high-voltage testing. Marx generators are comprised of capacitors or banks of capacitors that are charged together in parallel and then discharged together in series, so that if n capacitors are all charged to voltage V, the output voltage when they are discharged together in series is nV. A 1.5-MV generator might thus consist of 30 individual capacitors charged to 50 kV each.

50.1.1.4 Marx generators are rated according to their peak voltage (usually defined as the maximum charging voltage times the number of capacitors) and their energy storage capability (the total energy stored in all capacitors when charged to their rated level). Thus, a 50-kV generator comprised of 30 0.5 μF capacitors would have an energy rating, $W = 1/2\ CV^2$, of:

$$\begin{aligned} W &= 30\ [0.5\ CV^2] \\ &= 30\ [(0.5)(0.5 \times 10^{-6})(50 \times 10^3)^2] \\ &= 18.75 \times 10^3 \text{ joules} \\ &= 18.75 \text{ kilojoules} \end{aligned}$$

and the generator would be rated as "1.5 MV, 18.75 kilojoules."

50.1.1.5 High-current tests are typically conducted using large banks of enery storage capacitors arranged in a parallel, series-parallel, or even Marx surge configuration. Each of the basic current waveforms (i.e., A and D, B and C) requires a separate lightning generator. An example of an A or D component generator is a bank of capacitors with a total capacitance of 454 microfarads charged to 20,000 volts. Many other combinations of capacitance and charging voltage are possible.

50.1.2 Application of waveforms for qualification tests. Table 1 in section 5 of the basic standard shows which voltage and current waveforms or components are to be applied for a given test. The table is not to be used to determine what should be tested. However, once it is determined that a test is to be conducted, the table should be used to determine how it is to be tested. It should be noted that more than one test method may be required for any given test article.

50.1.2.1 For each test method included in the standard, the zonal location of the item on the aircraft should first be determined. Refer to section 30.2 for a discussion of techniques used to determine zones. Once the zonal location of the test article is determined, then the test waveforms to be applied may be found from the table by reading across on the proper zone line. Where an X occurs in a waveform column, that waveform or component is to be applied.

50.1.2.2 For example, suppose that it has been determined that an angle-of-attack probe is to be qualified by test to verify that it will not fail nor allow unacceptable voltages to find their way into the interior of the aircraft. The probe location on the aircraft is on top of the fuselage about 24 feet aft of the nose radome. It is readily seen that the nose of the aircraft is an initial attachment point and in zone 1A. Therefore, this part of the fuselage is usually in zone 2A. Since the probe has electrical leads running into the aircraft, it is a piece of external electrical hardware. Therefore, the test requirements dictate that both a direct effects damage test and an indiret effects test are required..

50.1.2.3 With this much information, it is now possible to consult table 1 and identify the tests necessary to qualify the probe. Reading down the first column headed by the title "Test", it is seen that two tests are required. The first is test T02, Direct Effects - Structural; the second is T05, Indirect Effects - External Electrical Hardware.

50.1.2.4 Reading across the test T02 line, we find the proper zone, 2A, in the next column. Reading on across on the T02, zone 2A line, we find that current waveform components B, C, and D are to be applied. Footnote 2 provides guidance on the application of components B and C. Assuming that no previous swept stroke tests or analyses have been performed, we see that the probe must withstand 2 kA for 5 ms, followed by 400 amps for 45 ms, a total of 28 coulombs. Also, a 100 kA restrike with an action integral of 0.25×10^6 $A^2.s$ must be applied. Specific details of the test conduct are described in section 5.2 of the basic standard.

50.1.2.5 It is also necessary to conduct an indirect effects test on the probe. Current waveform E is to be applied in accordance with the test technique description in 5.2. It is seen by the footnote that during the direct effects test, indirect effects should also be monitored. If the waveform parameters of waveform E are met during the indirect effects test with current component D, the waveform E test is not necessary.

50.2 Discussion of test methods

50.2.1 Test method T01 - full size hardware attachment points - zone 1

50.2.1.1 Purpose. Lightning flashes initially attach to aircraft extremities such as the nose, wing tips or vertical fin cap. If these extremities are covered with nonmetallic skins such as fiber glass radomes, wing tips, or plastic antenna fairings, the lightning flash may puncture the skin and attach to a conductor within. Conductive diverters or other means may be necessary to protect against such punctures. Whether punctures occur or not depends upon the geometry of the structure and diverter arrangement (if present), the dielectric strength of the nonmetallic skin, surface flashover characteristics, and the rate-of-rise of the electric field presented by the advancing leader. The specific purposes of the tests are thus:

a. To determine if lightning may puncture a nonmetallic component such as a fiber glass radome, wing tip or fin cap, or a polycarbonate resin component such as a windshield or canopy in zone 1A or 1B.

b. To verify the adequacy of protective diverters or other measures to prevent punctures of nonmetallic components in zone 1A or 1B.

c. To determine the detailed attachment points on conductive or nonconductive surfaces in zone 1A or 1B, for the purpose of establishing the boundaries of zones 1A or 1B, and establishing skin thickness or other protection requirements.

50.2.1.2 Applicability. Since the test is performed under stationary conditions, as described in T01, paragraph 2, of the basic standard, it cannot be used to determine the rearward extent of the initial lightning strike zone (1A), but this can be determined by analysis or other engineering tests.

50.2.1.3 Apparatus. Marx generators are commonly used for this test method. Typically tests are performed with the high-voltage electrode spaced one meter from the test object. At the 1,000 kV/μs rate of voltage rise specified for this test, approximately 1.3 MV are required to cause flashover of the one meter air gap. Since the usable output voltage of a Marx generator is diminished from the rated peak voltage by regulation inherent in the waveshaping circuit, a generator rated at 1.5 MV or greater is usually necessary. If the generator has a comparatively low-energy storage capability, an even higher peak rating may be necessary.

50.2.1.3.1 The voltage which is applied between the high-voltage electrode and the test object is usually measured with a resistance or capacitance voltage divider and recorded by an oscilloscope.

50.2.1.3.2 Still cameras with black and white film of speed ASA 200 or slower are normally used to photograph the flashovers. The camera lens opening is usually set at a high f-stop (f-16,22) and the shutter opened with the "bulb" setting prior to the discharge and closed afterwards, with total open time of about one to two seconds, depending on intensity of background lighting and the degree of background exposure desired in the photograph. Lens filters may be utilized if the light from the flashover is so intense as to mask a well-defined flashover path. If a camera with conventional film is used, an auxiliary camera with self developing film should also be used for "quick-look" data and back-up coverage.

50.2.1.4 Test setup

50.2.1.4.1 Test circuit. Figure A-6 shows a typical high-voltage test circuit employing a 5-MV, 84-kilojoule Marx generator. The figure also shows a typical oscillogram of the output voltage appearing across the air gap prior to gap flashover. In this circuit, the 150 Ω series resistance (R_S) and the 912 pF load capacitor (C_L) predominantly determine the voltage rise time. The 160 μH inductor (L_S) smooths the voltage rise towards crest, so that a more linear rise is obtained than would be possible without the additional inductance. The resistance-compensated capacitance-type voltage divider is connected directly to the high-voltage electrode so that errors due to line drops are minimized. In the example of figure A-6 the voltage reached 1300 kV when flashover occurred. This was sufficient to flash over a one meter air gap. In some cases the load capacitor can also serve as the voltage divider, or a resistance divider can be utilized.

50.2.1.4.1.1 Another test circuit employing a 5-MV impulse generator is illustrated in figure A-7. In this circuit, the stray capacitance between the high-voltage circuit and earth provides an adequate load which, together with the series resistance and lumped inductance, controls the rate of voltage rise. The added inductance enables the voltage to overshoot the value that would be obtained with an overdamped circuit, thus permitting a smaller generator to be used than would otherwise be required. In practice, the inductor regains the approximately 30% of rated voltage reduced by normal circuit losses.

50.2.1.4.1.2 The discharge currents produced by these two circuits are limited by the series resistance and inductance and usually will not exceed five kiloamperes. This is sufficient to leave an identifiable mark on the test object, but not severe enough to cause extensive damage. The degree of damage that a lightning return stroke would produce can be evaluated by subsequently directing a high-current discharge to the attachment point(s) determined by this high-voltage test, using test method T02.

50.2.1.4.1.3 In some cases, it is desirable to encourage streamers from more distant, less probable locations, to identify the boundaries of a zone over which direct lightning strikes are possible. Here a slower rising test voltage is desirable. If the range of electric field rates-of-rise possible from natural lightning is as broad as the range of return stroke current amplitudes (a likely possibility since both are related to charge in the leader), voltage rates-of-rise two orders of magnitude lower than waveform A are possible.

50.2.1.4.1.4 The voltage shown in figure A-8 rises to crest in 50 microseconds. Such a voltage has been identified as waveform D in the standard

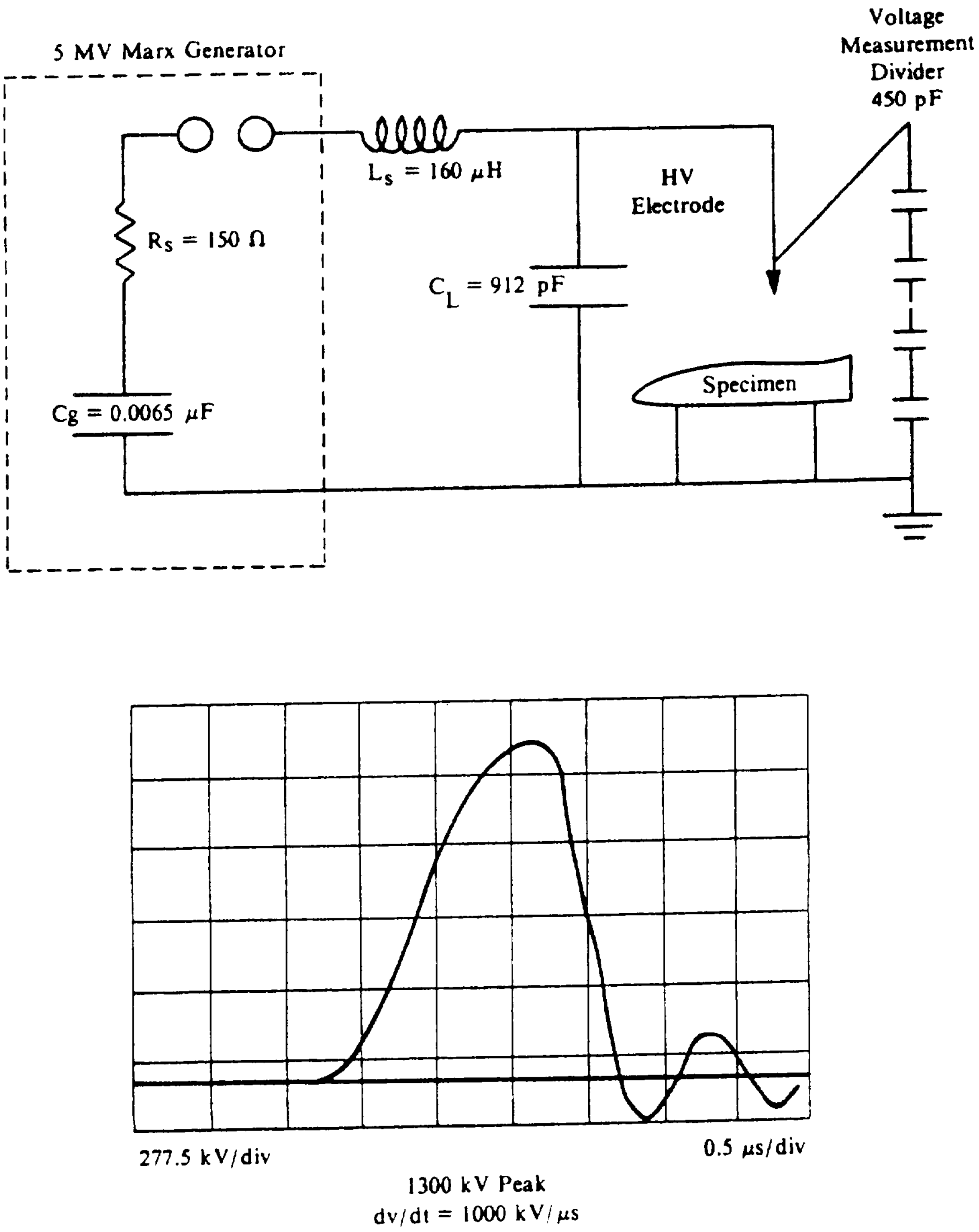
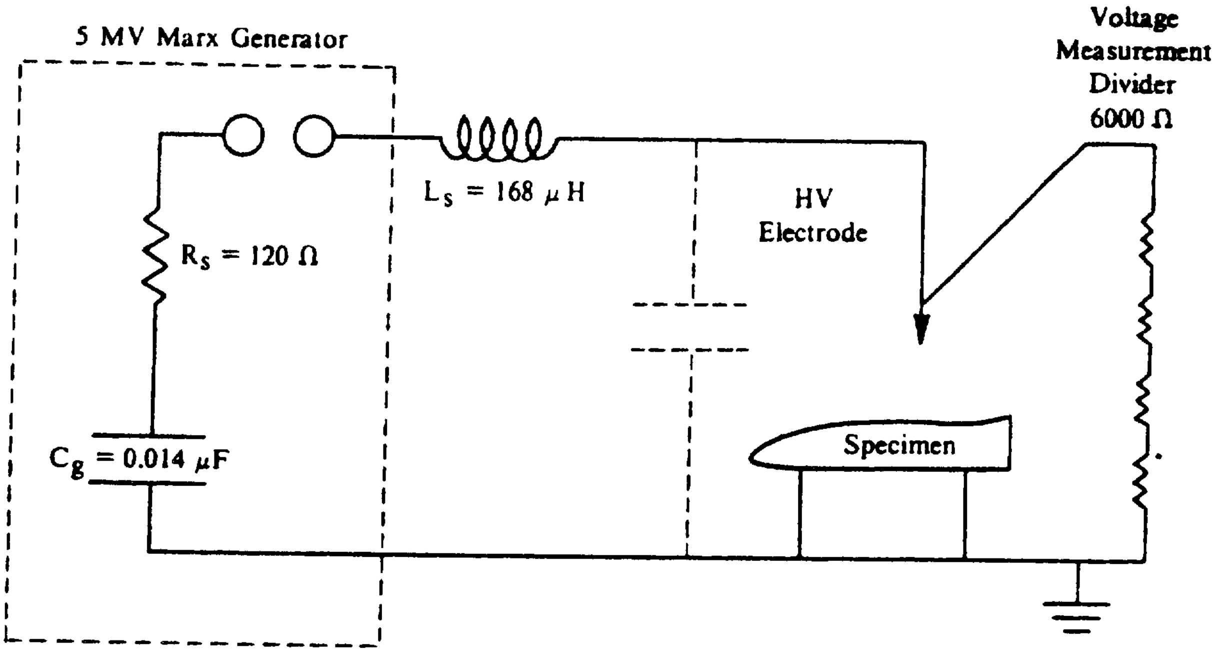
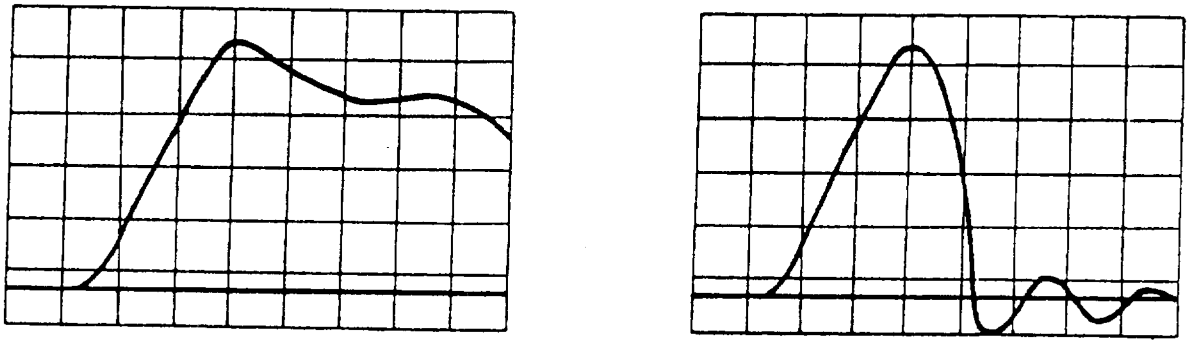


Figure A-6. Typical circuit and applied voltage waveform for simulated lightning strike attachment tests.



High Voltage Test Circuit



Crest is 1530 kV
without test object
in place

Flashover to test
object at 1115 kV
on rise

Voltage Waveforms
(Sweep is 0.5 μs/div)

Figure A-7. Typical high voltage test circuit (without load capacitor).

for use in identifying strike regions of lower probability. Waveforms with rise times of up to 250 microseconds are permitted by the definition of waveform D (50µs to 250µs), and the particular rise time is not critical. Tests with this waveform would be used, for example, to determine how far inboard zone 1 should extend on wing tips with large radii of curvature.

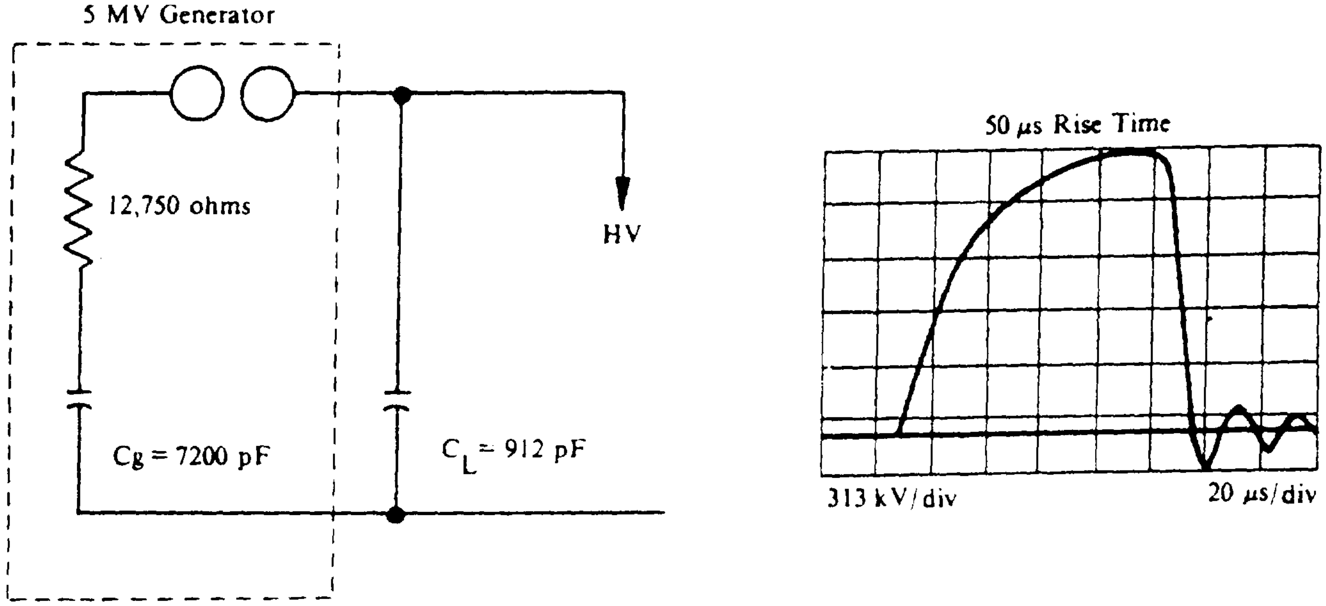


Figure A-8. Slow rate-of-rise test voltage for identification of zone boundaries.

50.2.1.4.2 Test object. For qualification tests, the complete test object (wing tip, radome, antenna, fin cap, etc.) is positioned in a manner representative of its location on the aircraft, with the test electrode positioned to direct strikes from each of the directions considered possible in flight. The test object should be a production-line component or an authentic replica thereof, constructed of the same materials. All conducting objects normally present on or inside a nonmetallic object should be present in the test setup.

50.2.1.4.2.1 It is not necessary that the conducting objects covered by test surfaces be authentic parts, but only that they be fabricated of, or at least coated with, an electrically conductive material and be properly grounded. Thus, for example, a radar reflector can be represented by a piece of wood covered with flame-sprayed metal or metal foil. This is because the streamering and attachment phenomena are dependent on the electric field intensities surrounding conductive objects, rather than the internal characteristics of the conductive parts. The external radii of internal metal parts should be representative of the actual component being simulated.

50.2.1.4.2.2 If the test object is a windshield or a flush-mounted antenna normally surrounded by a conducting aircraft skin, it should also be surrounded by a conducting skin. If, conversely, the object is itself an appendage, such as a radome, it should be set upon a pedestal representative of its location on an aircraft. Such a setup is shown in figure A-9.

50.2.1.4.3 Test electrode. The electrode to which test voltage is applied is positioned so that its tip is one meter away from the nearest surface of the test object. Electrode size and shape are not critical. If model tests or field experience have indicated that lightning flashes can approach the object under test from several different directions, the tests should be repeated with the test electrode oriented to represent strikes to the object from these different directions.

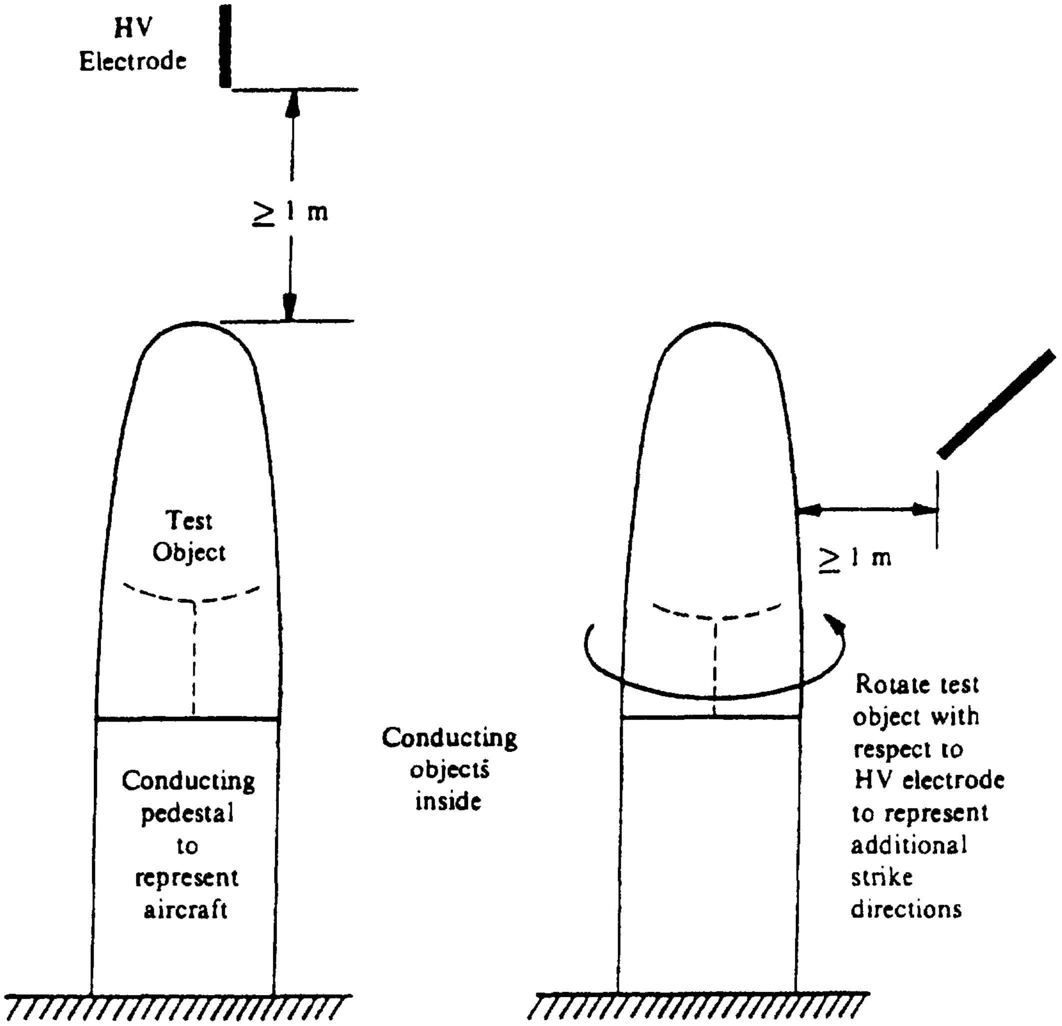


Figure A-9. Typical high voltage test setup.

50.2.1.4.3.1 Figure A-9 shows an arrangement to simulate strikes approaching from the sides as well as end-on. A one meter air gap between the high-voltage electrode and the nearest surface of the test object is usually appropriate, but when testing very large objects such as transport aircraft radomes, a larger gap may be necessary to prevent the high-voltage electrode from unduly influencing the attachment points. Similarly, a smaller gap may be appropriate if the test object is so small that the discharges miss the test object altogether. A guideline to follow is that if the largest dimension of the test object exceeds two meters, the air gap should be increased beyond one meter.

It may be increased to any length, provided that the flashovers still occur before the generator output voltage crests and the sparks do not miss the test object.

50.2.1.5 Criteria to be specified

50.2.1.6 Test procedure. In the past, it was sometimes considered appropriate to apply many discharges to the test object to cover scattering effects. It is now apparent that partial breakdowns occur within some dielectrics found on aircraft, resulting in punctures after several withstands. This effect is most pronounced in fiberglass materials, including multi-ply or filament-wound laminations and foam or honeycomb-filled sandwich configurations. Therefore, not more than three discharges should be used in the same region to insure against progressive deterioration.

50.2.1.6.1 If more than three discharges are considered necessary to evaluate scatter effects, the test object should be rotated to expose an untested surface if available; otherwise, additional test objects should be used.

50.2.1.6.2 The high-voltage test may also be used to evaluate the performance of protective devices, such as diverter strips, or to determine the maximum separation permissible without puncture. Such tests can often be performed upon samples of the dielectric wall material using the arrangement shown in figure A-10. The results of the diverter spacing tests may be plotted, to relate diverter spacing to conductor gap (g) over a range of distances. Data presented in this manner are useful in design optimization. Here again, the number of discharges fired to the same surface should be minimized to avoid progressive breakdown effects. Not more than three discharges should be used per probe position or local radome area.

50.2.1.6.3 The inside and outside surfaces of the test object should be inspected after each discharge to identify the attachment point(s) and punctures, if any. Each point should be marked with a crayon or piece of adhesive tape so that it will not be confused with attachments produced by subsequent discharges. In addition, each discharge should be photographed so that the path taken by the flashover can be identified.

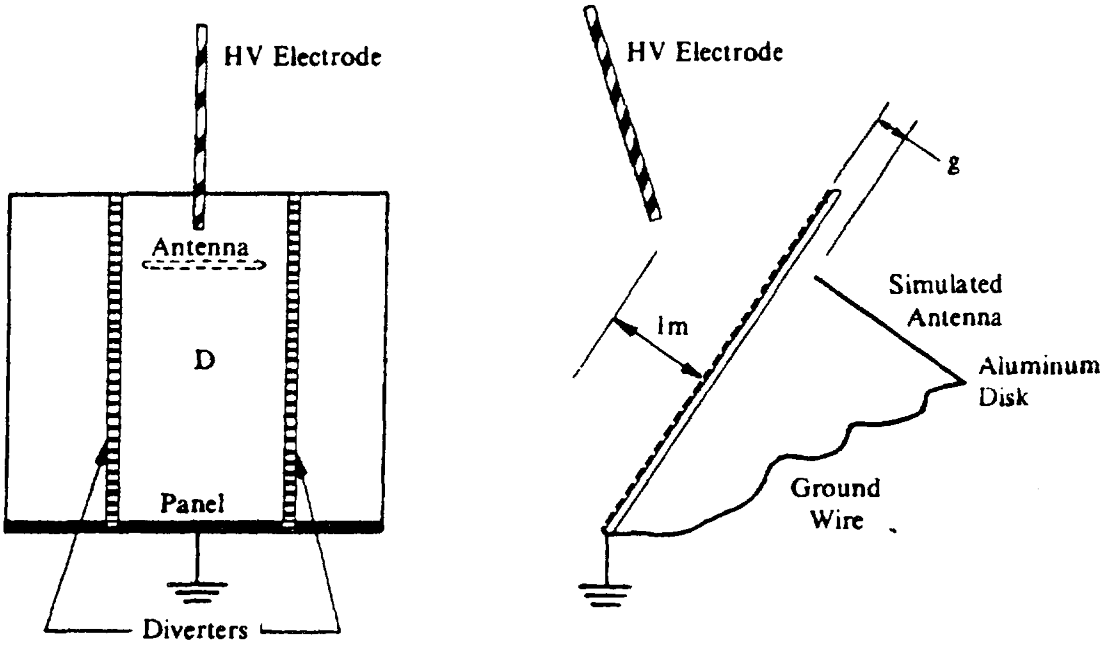


Figure A-10. Test arrangement for determining diverter spacing (D) as a function of proximity (g) to an internal conductor.

50.2.1.7 Data to be collected. Photographs of high-voltage attachment tests often show not only the main discharge path, but streamers emanating from other attachment points as well. Such streamers are indicative of other possible attachment points, and are visible if the test is done in a darkened room.

50.2.2 Test method T02 - direct effects (structural)

50.2.2.1 Purpose. The purpose of this test is to determine the direct effects which result from the interaction of lightning currents with aerospace vehicles and hardware. It is used to evaluate the extent of physical damage expected in flight for unprotected hardware, to assess the degree of inherent protection, and to assess the success of protection systems such as metallic coatings on graphite/epoxy and diverter strips on aircraft radomes.

50.2.2.2 Applicability. Test method T02 is applicable to aerospace vehicle structures and components which are susceptible to lightning current attachment or transfer. This includes probes, booms, antennas, lights, landing gear and other hardware located in zone 1 or 2. Other items frequently tested include: angle of attack probes, helicopter blades, radomes, wing tips, empennage tips, protruding antennas, elevators, rudders, ailerons, fuel tank components such as access doors, wet wing skins, drip sticks, sump drains, and filler caps.

50.2.2.2.1 If lightning damage to an item might constitute a flight hazard or compromise mission success, lightning protection testing is generally considered essential. If however, an identical part has been tested previously, retesting may not be necessary if the lightning zone, material, grounding techniques, coatings and paint are unchanged.

50.2.2.2.2 Determining what hardware to test can best be decided after the aircraft or vehicle is zoned for lightning, as discussed in section 30.2, "Lightning Attachment Zones". This will help define the extent of lightning threat the hardware must be designed to. For example, the peak currents and coulomb content are much higher in a zone 1B than in a zone 2A, and these zones are resolved after model studies.

50.2.2.2.3 Current test waveforms must comply with the requirements specified in MIL-STD-1757 for all flight or mission critical equipment. Less critical equipment may be tested to lower levels, however, as warranted by the level of protection required, cost/weight of applying protection, frequency of strike, and/or significance of damage.

50.2.2.2.4 Typical questions to ask during the lightning protection design tradeoffs are as follows:

a. How often will it get hit?

b. What is the extent and type of damage expected?

c. What are the logistics of repair and part replacement?

d. How much will a protection system cost and weigh, and what are the life-cycle considerations?

e. Will aircraft downtime be affected by either repair of unprotected hardware or maintenance of protected hardware?

50.2.2.3 Apparatus. The test apparatus generally include the following:

50.2.2.3.1 High current generators

50.2.2.3.1.1 There are four current components, A, B, C, and D, that are used to determine direct effects for qualification testing. Components A, B, C, and D each simulate a different characteristic of the current in a natural lightning flash and are shown in figure 8 of the basic standard. They are applied individually or as a composite of two or more components together in one test.

50.2.2.3.1.2 Each of the discharge waveforms (i.e., A, B, C, and D) requires a separate lightning generator. An example of an A component generator is a series parallel bank of capacitors for a total capacitance of 454 microfarads at 20,000 volts for the desired energy figure of merit (i.e., action integral). Such large capacitances are generally required on graphite/epoxy test specimens to compensate for the resistance of unprotected graphite/expoxy laminates. Tests of aluminum panels or graphite/epoxy specimens coated with a highly conductive material (e.g., aluminum) can frequently be accomplished with generator capacitances as low as 10 microfarads.

50.2.2.3.1.3 The test item and generator form a series RLC network. Therefore, standard series RLC equations apply. The capacitance is generally dominant because it provides the high energy and current for the test. R and L for the component A and D bank are generally minimized to permit as much high current as practical from a given set of capacitors. The resistance and inductance of the test item and connecting wires will influence the discharge generator parameters and must, therefore, be accounted for during calibration. This holds true for the component C and D generators, also, but to a much lesser degree.

50.2.2.3.2 High current measuring and recording instruments

50.2.2.3.2.1 Current probes or shunts are generally used to measure the discharge in the circuit. The current measuring equipment should be located near the ground or earth side of the test setup so that dangerous voltages or currents are not conducted into the instrumentation.

50.2.2.3.2.2 A wide variety of instrumentation is available to record the waveforms, including oscilloscopes and digitizing/diagnostic systems.

50.2.2.3.3 Photographic equipment for recording strike points/damage areas

50.2.2.3.3.1 Data documentation is frequently enhanced by before and after photographs of the test item. Photographs also aid in setup documentation.

50.2.2.4 Test setup. The test object should be production hardware, a full-scale prototype, or an electrically representative mockup.

50.2.2.4.1 A typical setup is illustrated in figure A-11. This shows a test using current waveform component A. Figures A-12, A-13, and A-14 show typical test setups for current waveform components B, C, and D, respectively. As shown in the figures, the currents are delivered from a test electrode positioned at the test surface of interest. The test object is connected to the return side of the generators.

50.2.2.4.2 The electromagnetic interaction of the current in the discharge circuits and test item and the blast pressure from the discharge may allow the test item to move in an unrepresentative manner during the discharge. Therefore, it is essential that the test item be held firmly in place during the test. Intense mechanical forces are created by electromagnetic interaction when test currents are forced to change direction in a manner not representative of the aircraft installation. The electromagnetic forces that would not normally be present during a natural lightning strike may also cause physical damage. Damage can be minimized by providing multiple return conductors, arranged so that the magnetic forces imposed on the test object are minimized or cancelled. An example is shown in figure A-15.

50.2.2.4.3 If a blunt electrode is used with a very small gap, the gas pressure and shock wave effects in the confined area may cause more physical damage than would otherwise be produced. The electrode should be pointed to allow relief of the pressure formed by the discharge.

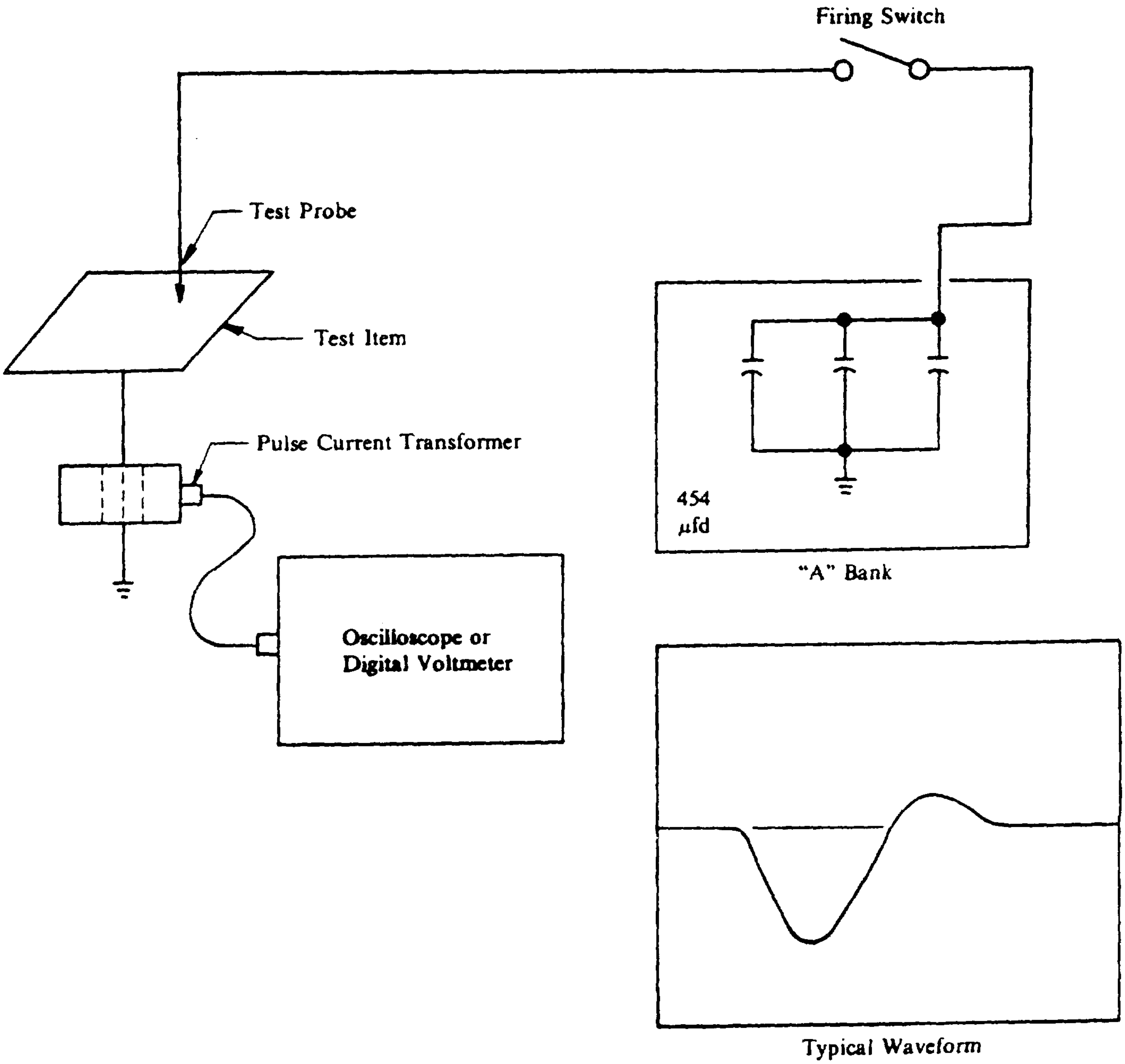


Figure A-11. Schematic of typical "A" component generator.

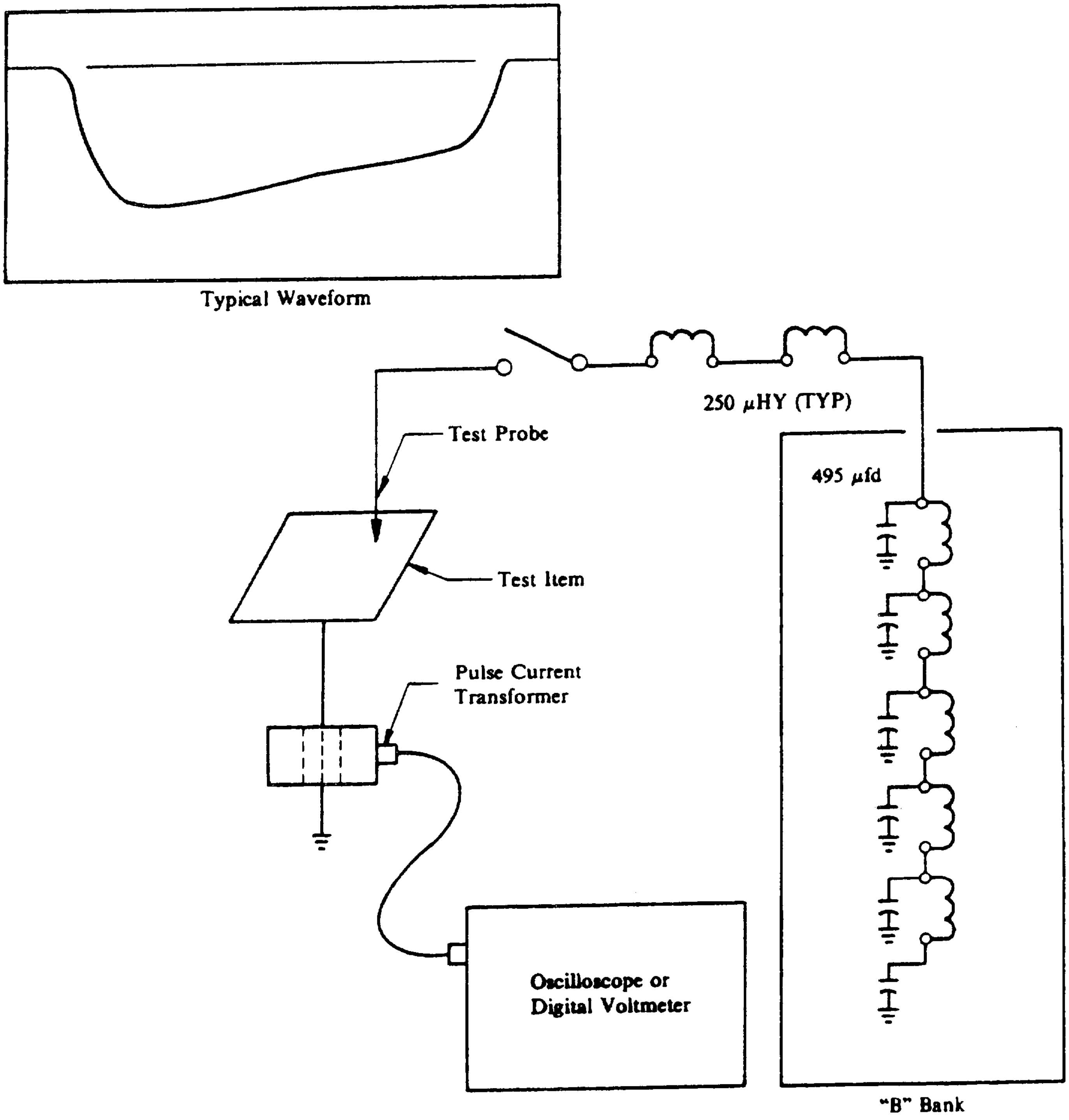


Figure A-12. Schematic of typical "B" component generator.

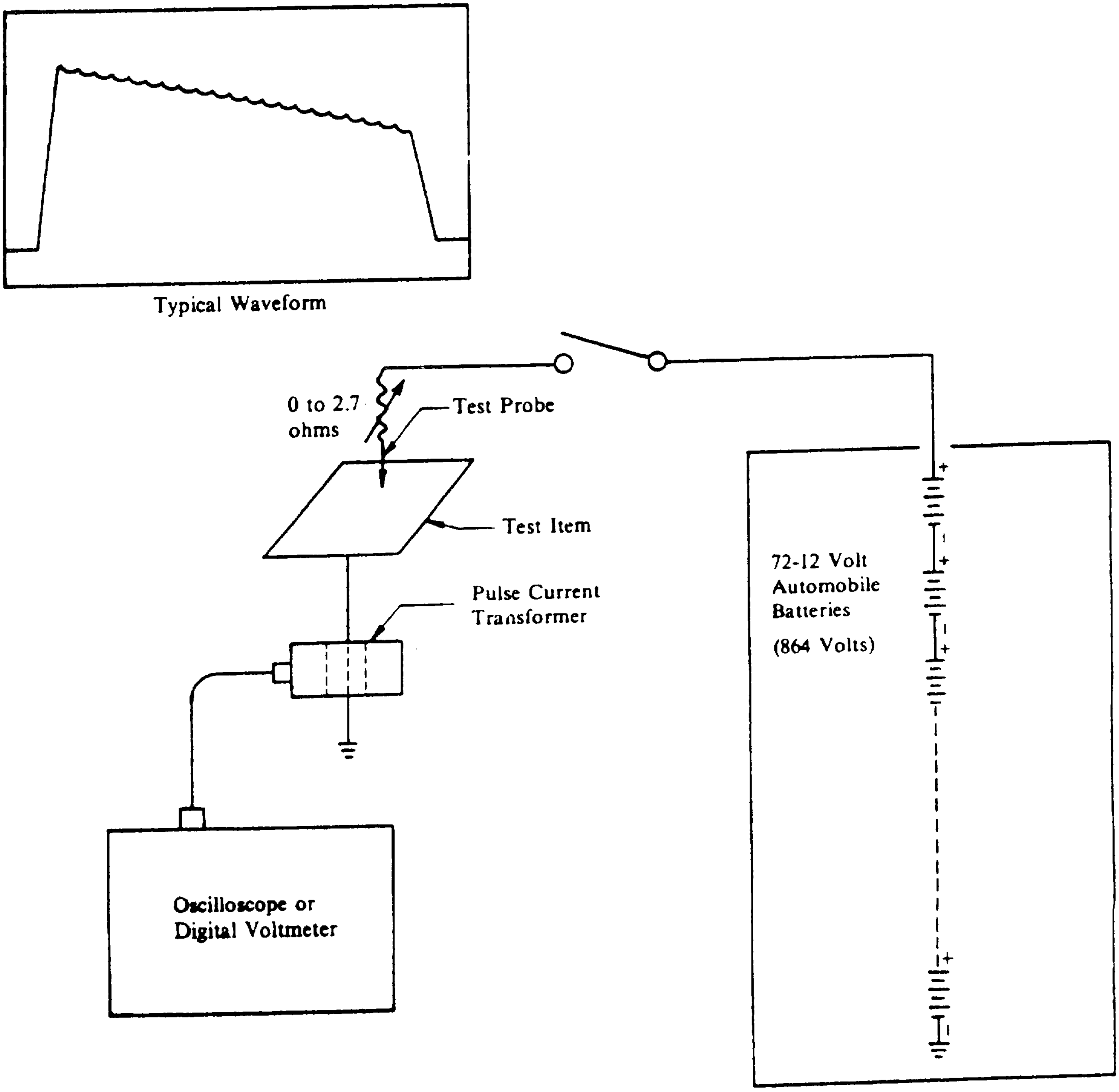


Figure A-13. Schematic of typical "C" component generator.

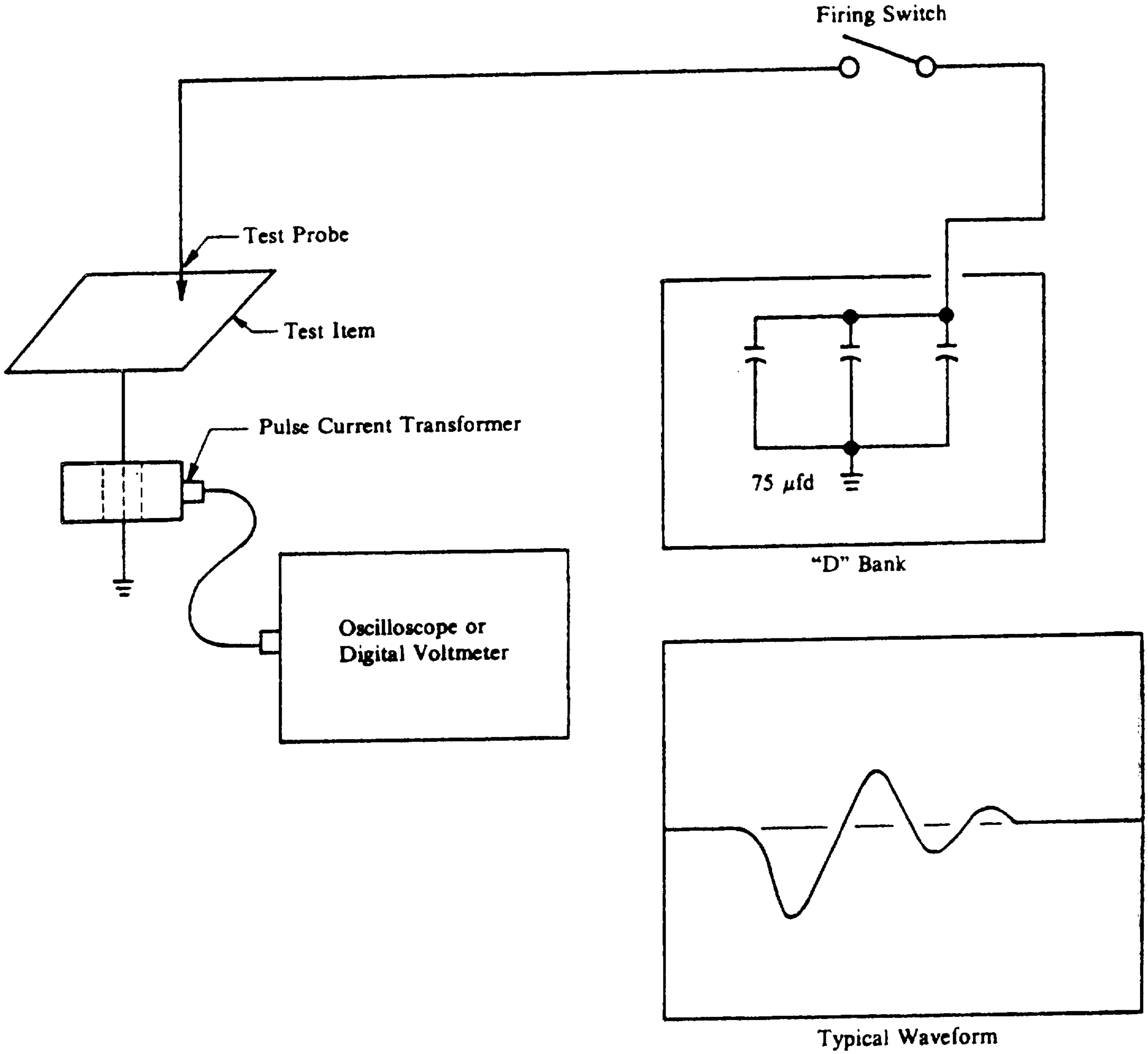
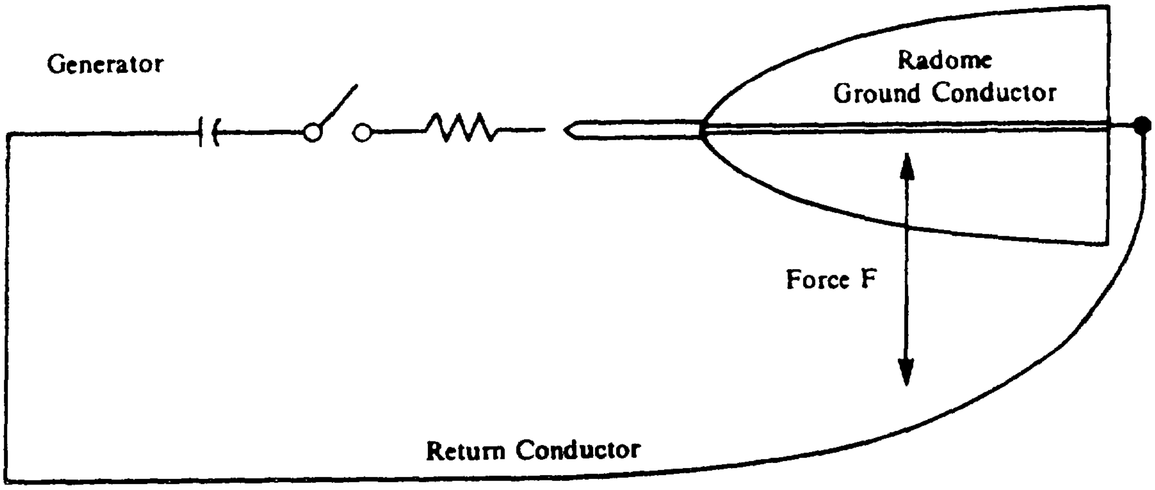
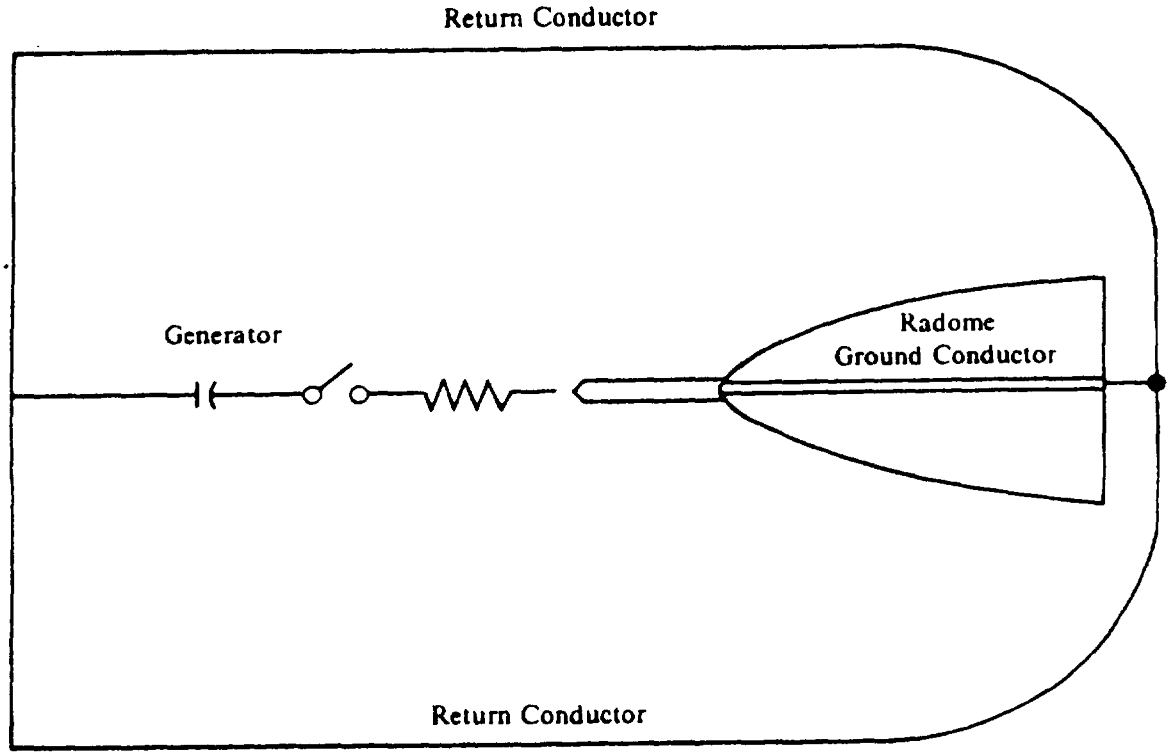


Figure A-14. Schematic of typical "D" component generator.



(a) Single return conductor produces unbalanced force (F) on ground conductor



(b) Multiple return conductors minimize force on ground conductors

Figure A-15. Method for reducing unrealistic forces on test object (A ground conductor within a radome).

50.2.2.4.4 Test for zone 1 and zone 2 structural effects require an open arc at the attachment point for complete simulation of thermal burning and eroding due to lightning.

50.2.2.4.5 To accomplish this, arc lengths of 5 cm are generally used for A component and D component discharges. This length is acceptable since the intent of the tests is to determine structural damage; tests to determine where lightning will hit have presumably been conducted. Shorter arcs are not permissible for the A and D component tests due to a pressure interaction between the probe and the test panel. This interaction creates a blast pressure that unrealistically intensifies the damage.

50.2.2.4.6 For zone 3 tests, the current is conducted directly into and out of the test object (i.e., without an open arc or gap between the test probe and test item) in a manner representative of the actual lightning current paths in the vehicle.

50.2.2.4.7 The electrode polarity of the waveform components A and D can be either positive or negative. The electrode polarity of the waveform components B and C should be negative because greater damage is generally produced when the test object is at positive polarity with respect to the test electrode.

50.2.2.5 Criteria to be specified

50.2.2.6 Test procedure. The test should be conducted in accordance with paragraph 6 of test method T02.

50.2.2.6.1 The impedance of the test object generally affects the test circuit discharge parameters. Because of this, it is advisable to have more than one test item to allow for calibration. Calibration with an actual test item (or close representation) allows adjustment of the lightning generator parameters to achieve the desired current and action integral.

50.2.2.6.2 During the open arc tests the point of the test probe will tend to erode rapidly. Since a fineness ratio of 5 to 1 is needed to reduce unrealistic blast pressure, it is advisable to sharpen the point frequently. For example, a test probe that is eroded to a blunted surface approximately 3 mm in diameter should be sharpened or replaced.

50.2.2.6.3 The test items should be visually inspected before the tests to ensure test results are not contaminated by pretest flaws.

50.2.2.7 Data to be collected. In addition to the data to be collected, sufficient details of the test setup and test hardware must be recorded as a normal laboratory procedure. As a general rule, details should be sufficiently clear that another qualified test engineer could repeat the test from the details documented. Therefore, in addition to the above, the peak current, action integral and discharge duration should also be recorded. The description should include all interconnecting cables/wires, power supplies, sensors, oscilloscopes, etc.

50.2.2.7.1 Environmental data, such as temperature, humidity and pressure may be recorded but usually are not critical to the test results.

50.2.2.8 Notes. Refer to paragraph 8 of test method T02 for general information.

50.2.3 Test Method T03 - direct effects - combustible vapor ignition

50.2.3.1 Purpose. This test method is used to determine the possibility of combustible vapor ignition as a result of skin or component puncture, hot spots, and sparking or arcing in or near fuel vent systems or other regions where combustible vapors may exist.

50.2.3.1.1 Lightning strikes to fuel tank skins or other components can cause electrical sparking to occur and ignite fuel vapors if they are flammable. Internal sparking may be of two varieties: high-voltage air breakdown which develops into arcs with temperatures of 10^4°K or incandescent gases and particles (spark showers) with temperatures of a few thousand degrees. Heating can also occur from external arc contact with external skin which can cause ignition of flammable vapors if the interior surface temperature is sufficiently high. The specific purposes of the test method thus include:

a. To determine if arcing or spark showers can occur in the fuel tank interior from lightning strike contact with the exterior of a fuel tank skin or a component such as a fuel filler cap, access door or quantity probe.

b. To determine if hot spot ignition can occur from heating of the component interior surfaces to ignition temperature.

50.2.3.2 Applicability. Test method T03 is applicable to integral (wet skin) fuel tanks, external tanks, or any other aerospace vehicle fuel tank located in zones 1 or 2 and any fuel tank located within a structure in zone 3 through which lightning currents may be conducted. This method is also applicable to fuel vent outlets, drain valves, dump outlets, access doors, filler caps and any other object in contact with flammable vapor and located in zones 1 or 2.

50.2.3.3 Apparatus. The same generators used in test method T02 may be used for this method. In addition to the apparatus specified in paragraph 3 of test method T03, equipment is necessary for supplying the fuel/air mixture for ignition tests if that approach is used. If small components are tested a shielded chamber with a replaceable mounting panel is needed.

50.2.3.3.1 The high-current generators are banks of capacitors connected in series/parallel combinations to provide the required output current and waveform for the high-current components A and D. For current test waveform B, a capacitor bank or high-current DC power supply is used which needs to be capable of providing an average of 2,000 amperes for five milliseconds. A high-voltage battery tank or DC supply of 400 volts or more is used to provide the DC current component C. These components may be applied individually or sequentially as a multiple component discharge, as discussed in paragraph 4.2.3.

50.2.3.3.2 Mixing circuits are required for applying the multiple component waveform in one discharge. This is usually done with air gaps and inductors. Component D is usually applied with a time delay system at the end of the low-current DC continuing components for zone 1B or 2B tests. In zone 2A tests, component D initiates the discharge waveform.

50.2.3.4 Test setup. Test setup requirements are essentially the same as those described for structural damage tests, with the following additional considerations. For regions where possible sparking activity cannot be made visible to the camera, ignition tests may be used by placing an ignitable fuel-air mixture inside the tank. Verification of the combustibility of the mixture should be obtained by ignition with a spark or corona ignition source introduced into the test chamber immediately after each test in which no ignition occurred. If the combustible mixture was not ignitable by this artificial source, the test must be considered invalid and repeated with a new mixture until either the test or artificial ignition source ignites the fuel.

50.2.3.4.1 Photographic techniques. If a shielded chamber is used for component tests using photographic techniques, it should be light-tight and have good electrical conductivity. Discharges into the component, when mounted on the chamber, must not cause sparking in other parts of the chamber which might obscure photographs of the area of interest. Similarly, if photographic equipment is installed inside actual fuel tanks, care must be taken to ensure that the equipment installation and placement do not cause extraneous sparking.

50.2.3.4.1.1 Polaroid cameras are typically used because of the availability of ASA 3000 film. A lens opening of f4.7 is used. Other camera systems such as 35-mm can be used if film speeds of ASA 3000 or faster can be obtained.

50.2.3.4.1.2 A small hole may be drilled in the test panel away from the test area to allow a spot of light to be recorded on the camera film, thus indicating that the shutter was actually open during the tests. A flaw on the film can give a false indication of sparking. Repeated tests or use of an optional observer in the test cabinet can be used to confirm the test results. The use of a four-lens camera with different aperture settings is an effective approach to clarifying sparking activity. It eliminates the problem of flaws on the film, and at the same time helps show the location and intensity of sparking. The sparking may be sufficiently bright to completely overexpose the film used with the lens having the maximum opening. However, optimum exposure would be obtained with one of the reduced aperture settings of the four lens camera permitting good definition of the problem area.

50.2.3.4.1.3 The distance from the component being tested for sparking to camera is also critical. This distance shall not be greater than ten feet.

50.2.3.4.1.4 Another problem which occurs is that of ensuring that all sparking areas are visible to the camera. A single camera may be used with a combination of spherical and plane mirrors, or multiple cameras may be used. As noted in the test standard, the overall light loss in the complete mirror system must be less than one camera stop to assure that all sparking is observed.

50.2.3.4.1.5 In addition, the following guidance is offered. When using photographic monitoring, it is desirable to photograph the internal test arrangement without moving the camera. This helps to locate the source of any sparking which may have occurred by superposition of the sparking and a separate photograph of the test area.

50.2.3.4.1.6 The rationale for photographic recording of incendiary sparks is that the sparks which occur across fuel tank joints have relatively large currents and a long time duration matching the lightning waveform duration. This is in contrast to static sparks with low energy and short time durations which may or may not be photographically recorded by a camera with an f4.7 aperture and ASA 3000 film.

50.2.3.4.1.7 Spark showers of molten metal particles are highly visible. Laboratories that use observers along with photographic recordings confirm that spark showers are quite bright and the eye is much more sensitive than the camera with an f4.7 aperture and ASA 3000 film. This provides further confidence that the tests are conservative.

50.2.3.4.1.8 It may be noted that not all spark showers are incendiary. If the particle velocity is sufficient, the hot particle does not remain at any one position long enough to cause ignition. If spark showers are observed or photographed, an ignition source should be assumed or tests with flammable fuel vapors should be run.

50.2.3.4.1.9 It is important in using the photographic techniques to maintain consistency in the film and the development technique. This requires fresh film and adherence to the manufacturers time temperature development specification.

50.2.3.4.2 Hot spot testing. For hot spot testing, the temperature inside the test article can be measured most easily using temperature sensitive paints. Thermocouples and infrared systems with millisecond response can also be used. Paints may be applied in a closely spaced pattern of spots. A paint with a 450°F temperature sensitivity should be used, since 450°F is the minimum spontaneous ignition temperature of aircraft fuels. If the paint does not change, the test is considered successful because it is assured that the temperature did not exceed this safe level. If the paint does change, then additional tests using fuel ignition or other diagnostics must be utilize to prove a safe condition. No well-accepted success criteria have been developed for other temperature measuring devices above the 450°F range.

50.2.3.4.2.1 Figure A-16 shows a typical test arrangement. The circuit as shown in the figure is for illustration purposes only, and is not a requirement. Any circuit providing the proper waveforms may be used.

50.2.3.4.3 Test electrodes. The test electrode shape and spacing is important to the results of the test. Pointed electrodes should be used which permit departure of the shock wave without pressure effects on the test object. Such effects can occur from blunt test electrodes. The fineness ratio of the test electrode should be more than 5 to 1. Spacing of the test electrode to the test object should be not less than ten millimeters. Fifty millimeters or more is desirable if the intermediate and low current generators can maintain the current through this arc length.

50.2.3.4.4 Mounting of test object. The mounting of test component is particularly important in fuel system tests. The mounting should be the same as in the actual aircraft in terms of skin thickness, shapes and interface materials, surface finishes, and sealants. The test is as much a test of the mounting arrangement as of the component itself, since sparking from either source constitutes a hazard to the vehicle in which it is to be installed.

50.2.3.5 Criteria to be specified. A single test discharge is freqently used in these tests because the damage which occurs from each test prohibits multiple tests of the same hardware component. In product development phases it is often difficult to obtain multiple test samples. The use of a single test object is allowed on the basis of the severe test waveform parameters. Two or three test components are desirable and should be used whenever possible.

50.2.3.6 Test procedure. Tests should be conducted in accordance with paragraph 6 of test method T03.

50.2.3.6.1 If flammable fuel vapors need to be used because all fuel vapor spaces in the test article cannot be photographed, the additional procedure is as follows:

a. Enclose the potential sparking surfaces or test component (such as boost pump) with the thin clear plastic, as shown in figure A-17, to provide a gas seal. Install a spark plug and in-flow and out-flow gas connections in the enclosed area.

b. Adjust fuel air mixture in a separate container such as a plastic bag outside the fuel tank or test chamber (flow meters may be used for this purpose). Ignite the mixture in the test region in the separate plastic bag with a spark plug to verify that the mixture is flammable. Mixture should be about 1.2 times richer than stoichiometric for propane/air mixture.

c. Fire test discharge and record whether or not fuel vapor exploded.

50.2.3.7 Data to be collected. The data to be collected should be in accordance with paragraph 7 of test method T03.

50.2.4 Test method T04 - direct effects - corona and streamers

50.2.4.1 Purpose. The purpose of this method is to determine if electrical streamers or corona can be produced at or near apertures or at other locations where corona and streamering may be of concern.

50.2.4.1.1 When an aircraft becomes subjected to an electric field of sufficient intensity, corona and streamering may occur at locations where the electric field exceeds the corona inception level. Simply defined, corona is the ionization of a volume of air surrounding a sharp conducter under high electric field conditions. The term "streamer" as used in this test method refers to the luminous filaments or leaders extending from corona regions as fields intensify. Streamers resulting from the instantaneous discharge of concentrations of electrical charge built up on dielectric surfaces are not included in this discussion.

50.2.4.1.2 Often corona discharges occur at extremities where the radii of curvature are small and fields are high, such as probe tips, antennas, and tips of wings, empennage or propellers. They may also appear at discontinuities such as windshields or fuel vent outlets, or beneath dielectric covers. Since these discharges may have sufficient energy to ignite fuel vapors, it is sometimes necessary to determine if they may occur within non-metallic fuel tanks and other unshielded enclosures that may contain such vapors.

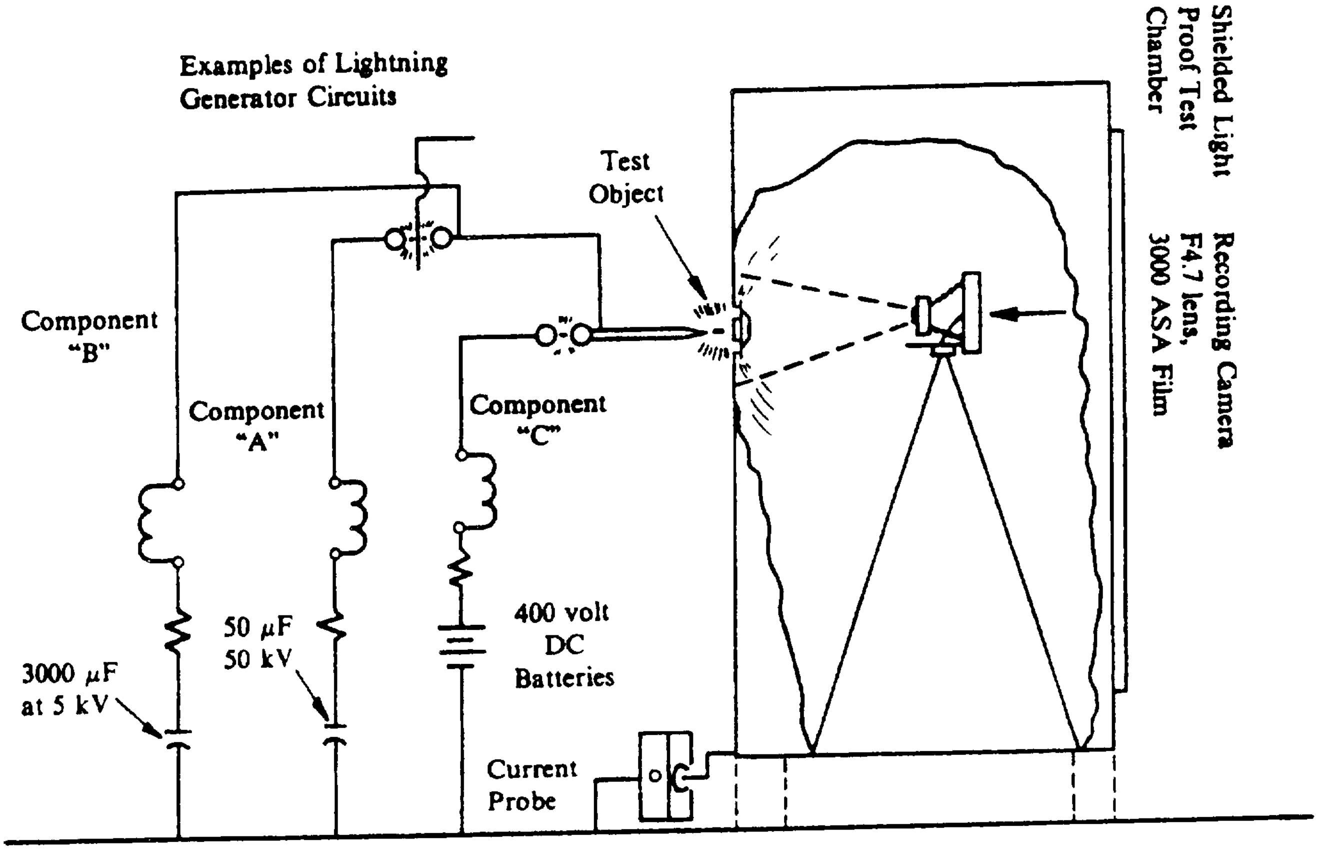


Figure A-16. Test arrangement for sparking tests using cameras.

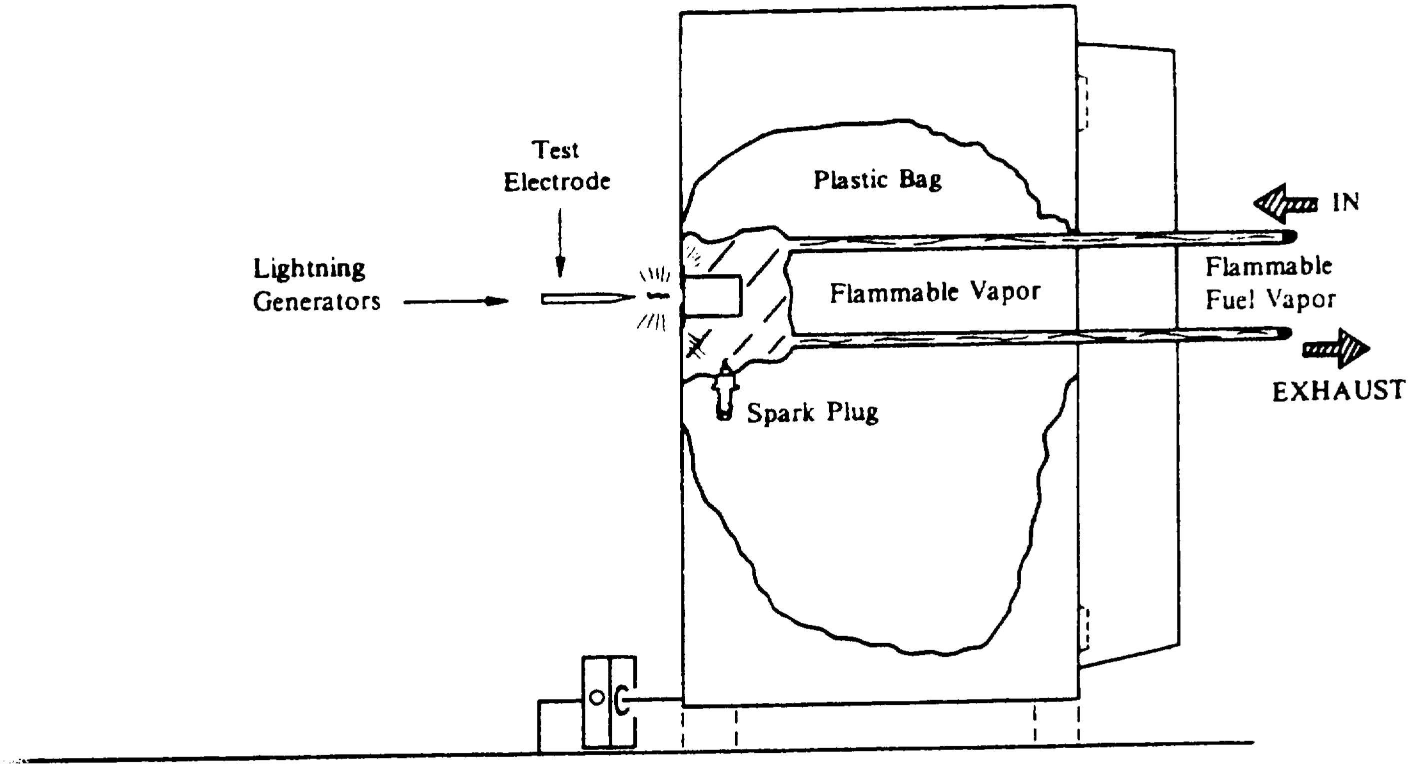


Figure A-17. Test arrangement for sparking tests using flammable vapors.

50.2.4.2 Applicability. This test is applicable to fuel vent and dump outlets, radomes, antenna, canopies and other components which are exposed to atmospheric electric fields.

50.2.4.2.1 In addition to thunderstorm electric fields (sometimes called cross-fields) triboelectric charging during flight through areas of precipitation or other particulate matter can lead to corona at the aircraft extremities. Extensive streamering can also be experienced during a direct strike to the aircraft.

50.2.4.2.2 During triboelectric charging, the aircraft may reach a potential of 500 kV or more with respect to its surroundings, creating an intense electric field about the aircraft. This field is sufficient to produce the violet-colored luminous corona around wing tips, propeller blades, trailing edges and other sharp appendages. This corona is often referred to as St. Elmo's fire. Corona occurs at a conductor when the electric field surrounding it reaches the ionization potential of air, which is about 30 kilovolts per centimeter at sea level and somewhat less at flight altitudes. These fields may be either impulsive, as in the lightning-strike case, or constant (DC) as in a cross-field or precipitation charging situation. In either case, the voltage level of the aircraft with respect to its surroundings when corona begins is called the corona inception level. This depends on the geometry of the aircraft. In the laboratory, it also depends upon the proximity of an oppositely charged electrode, and is typically about 100 kilovolts.

50.2.4.2.3 Objects with sharp radii of curvature intensify the surrounding electric fields and produce corona at lower inception voltages than rounder, smoother surfaces. Corona is accompanied by a liberation of heat, and can liberate sufficient energy to cause ignition of a flammable vapor. Corona is also accompanied by broadband electromagnetic radiation which can produce interference in susceptible aircraft avionics and communication systems.

50.2.4.2.4 Some common locations where corona and streamers may be of concern include windshields (puncture, and induced surge voltages), fuel vent and dump outlets and refuelling probes (ignition of fuel vapors), radomes and tips of wings and empennage (puncture of nonmetallic skins, and voltage surges in enclosed wiring), canopies (streamers from the pilot's head, producing electrical shock). This test method may be utilized to evaluate each of these and other situations in which corona and/or streamers may be a hazard to flight safety or mission reliability.

50.2.4.3 Apparatus. Simulation of corona streamering in the laboratory is a relatively simple affair; it involves subjecting the test object to an electric field capable of producing corona and streaming, and detecting the location of these effects. Whereas corona and streamers may be produced by either DC or impulse fields of very short duration, it is often most practical to apply an impulsive field of intensity sufficient to produce corona and streamers but of insufficient duration to allow complete flashover of the electrode gap. This may be done with the same Marx-type generator that is utilized for the strike attachment test described in paragraph 50.2.1. The generator must have a sufficient crest voltage to produce an electric field of about 500 kV/m, using voltage waveform B.

50.2.4.3.1 The instrumentation utilized in the streamering test should be capable of detecting the location of corona and streamers, as well as any other effects of consequence, such as induced voltage transients. Still photography techniques of paragraph 50.2.3 are usually adequate to detect the presence of corona and streamers.

50.2.4.4 Test setup. There are two basic methods of applying an electric field to the test object. In the first method the test object is connected to the high voltage output of the test circuit and suspended in proximity to a ground plane or a grounded electrode. In the second method, the test object is at ground potential and a high voltage electrode is used to apply the electric field. In either case the test object should be at positive polarity with respect to ground or the electrode, as this polarity produces the highest degree of streamering at the test object. Either method will provide adequate streamers. The average intensity, E_{ave}, of the electric field about the test object is given by:

$$E_{ave} = V/h \qquad (1)$$

where V is the voltage to which the test object is raised and h is the distance between the test object and the ground plane. Considerations pertinent to each method are as follows:

50.2.4.4.1 Test object at HV potential. In this case, the test object must be suspended above (or otherwise in proximity to) a grounded electrode representing an equipotential plane as shown in figure A-18. The ground plane must be large enough so that field concentrations about its edges do not influence the field at the test object. Its size, therefore, is dependent on the size of the test object and the distance, h, between itself and the test object. The following relationships have been found to provide a satisfactory test:

$$\ell \geq 5d \qquad (2)$$

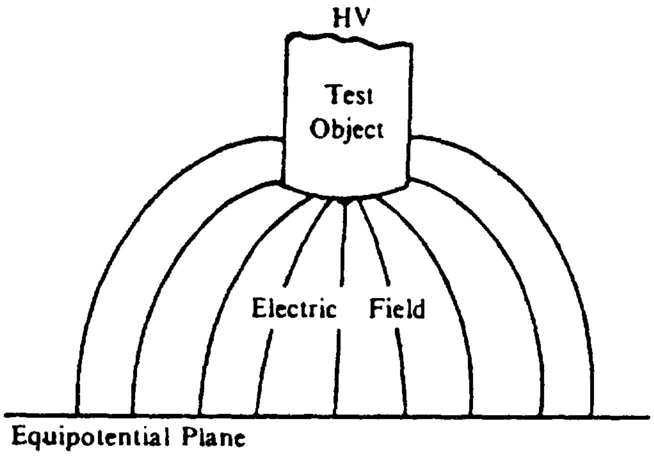
$$h \geq 2d \qquad (3)$$

which implies that:

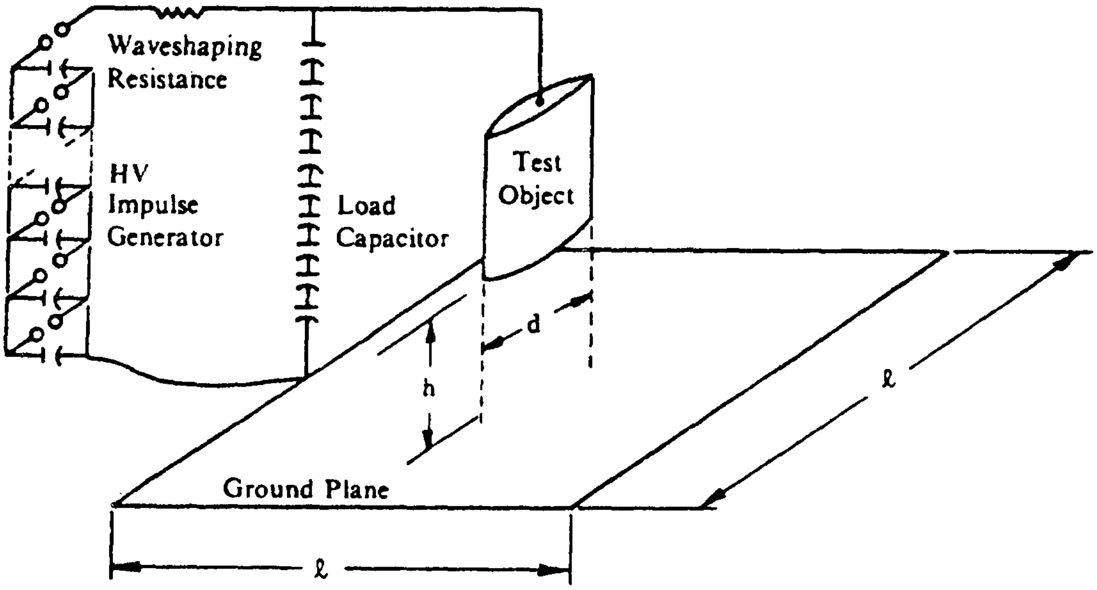
$$h \gtrsim 0.4\,\ell \qquad (4)$$

For example, for a wing tip fuel tank of chord d = 1 meter, the gap, h, should be at least 2 meters, requiring a crest voltage of about 1,200 kV to produce corona and streamering.

50.2.4.4.2 Test object at ground potential. In this setup, the test object is usually set upon a pedestal and high voltage is applied to a large electrode suspended above the test object. This produces an electric field about the test object as shown in figure A-19.



a. Situation represented

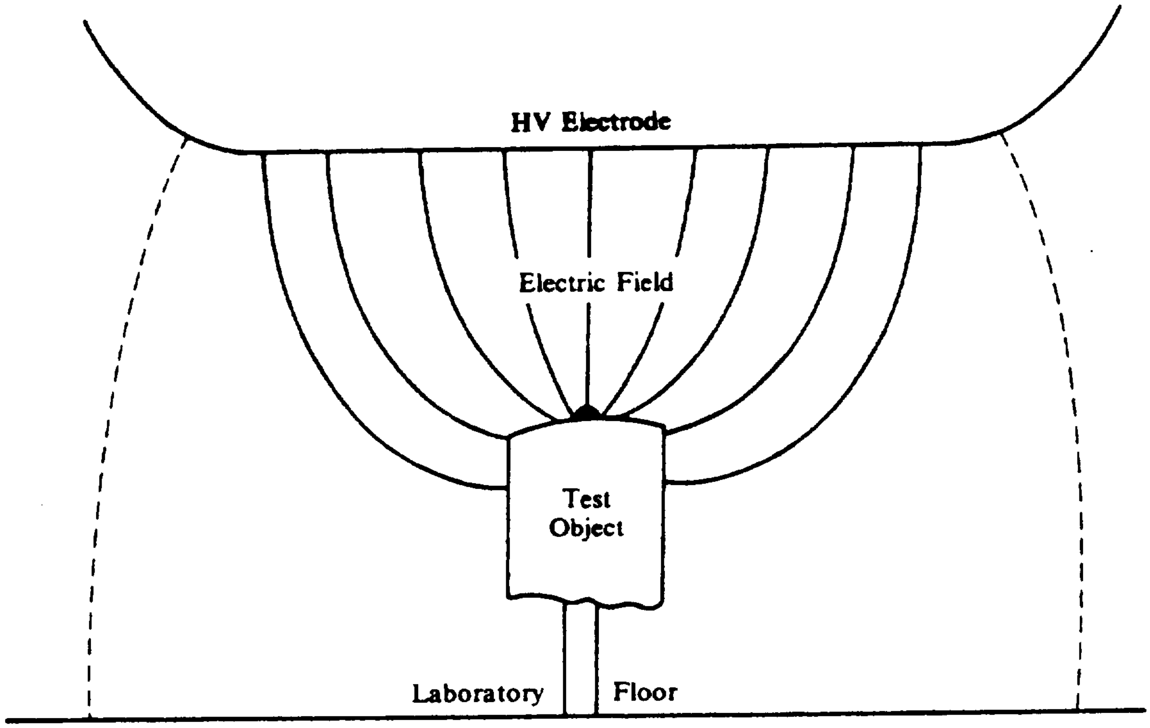


b. Test Setup

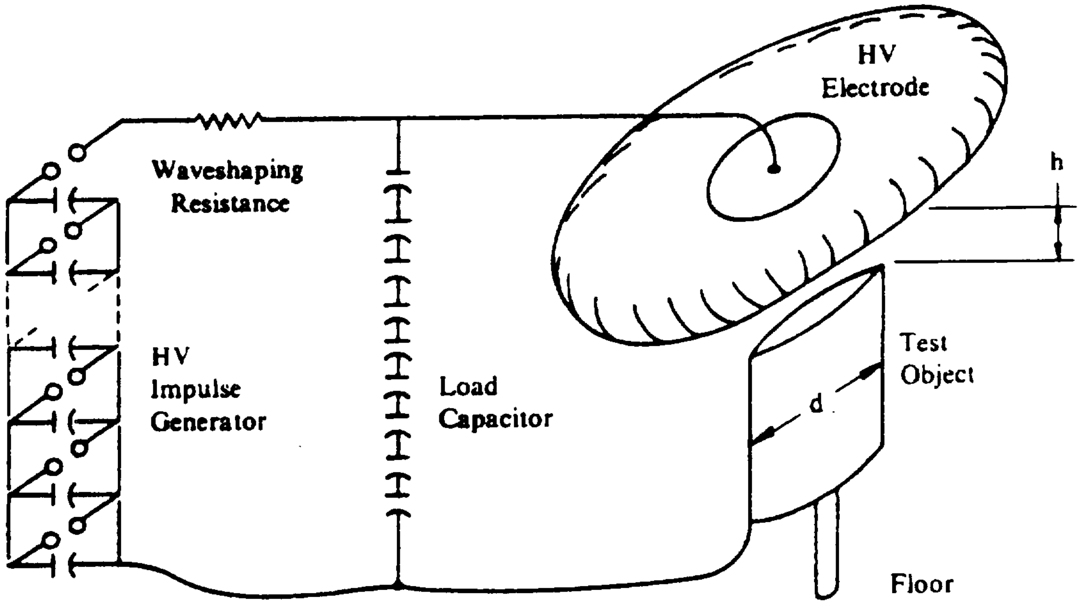
Figure A-18. Streamering test with test object at high voltage.

50.2.4.4.2.1 For the setup of figure A-19, the HV electrode should have sufficiently large radii of curvature in all dimensions to prevent corona and streamers from occuring at its surfaces. The air gap should normally bear the same relation to test object size as described previously for the setup with the test object at HV potential. A large automotive inner tube may suffice for the electrode, provided it has sufficient electrical conductivity to distribute charge over its surface. Otherwise, a smooth metal object with rounded edges may be utilized.

50.2.4.4.2.2 There are advantages and disadvantages of each of the above setups. If instrumentation such as induced voltage measurement cables or remotely controlled cameras are to be installed with the test object, it may be best to have the test object grounded as in figure A-19. On the other hand,



a. Situation being represented.



b. Test Setup

Figure A-19. Streamering test with test object at ground potential.

this requires that a relatively large HV electrode be provided. The arrangement of figure A-18 utilizes the test object itself as the high voltage electrode and requires only that a flat conductive sheet or wire screen be laid upon the floor to serve as the ground electrode.

50.2.4.4.3 Other setups. Each of the test arrangements just described requires that one end or side of the test object be in a region where the electric field is not intense. This is the apropriate condition for most simulations, but there may be situations in which it is desirable to have streamers develop from both sides of the test object at once. Such a case might arise when a non-metallic wing tip or empennage section is exposed to a thunderstorm cross-field or to a nearby lightning flash. To simulate these cases the test object may be positioned between a high voltage electrode and a ground plane as shown in figure A-20. During the test, the test object will acquire a potential between that of the HV electrode and ground, and streamers will develop on both sides.

50.2.4.4.3.1 Selection of the test voltage level as well as the electrode and gap dimensions necessary to produce corona and streamers may require some adjustment, but dimensions similar to those for setups of figures A-19 and A-20 are suggested as a beginning.

50.2.4.5 Criteria to be specified. It is important that more than one discharge be applied with the electrode and test object in the same positions, because of the random nature of streamering phenomena. The occurrence of a streamer at one place, for example, may preclude initiation of streamers at adjacent locations, due to the field cancellation effect of the first streamer. On a subsequent test, streamering may occur first at one of the other locations. To be sure that all possible corona and/or streamer locations are identified, at least 5 discharges should be applied in each location.

50.2.4.6 Test procedure. In photographing corona activity, the camera should be focused upon suspected corona initiation points on the external surface and/or within the test object. The shutter should be opened just prior to the generator discharge and closed immediately afterwards to assure that background light does not overcome the light emanated by streamers. In some cases the light produced by the streamers may be very faint. Therefore, it is usually necessary to perform the test in a darkened room and it may not be possible to show the test object background on the same film. A subsequent background photograph under lighted conditions should be taken to assist in identifying the location of streamers visible in the darkened photographs.

50.2.4.6.1 When investigating fuel containing structures, if all possible internal streamer sources cannot be observed by the camera or by the camera plus mirrors, the test should be run with a combustible vapor inside the structure to determine if ignition occurs, per test method T03.

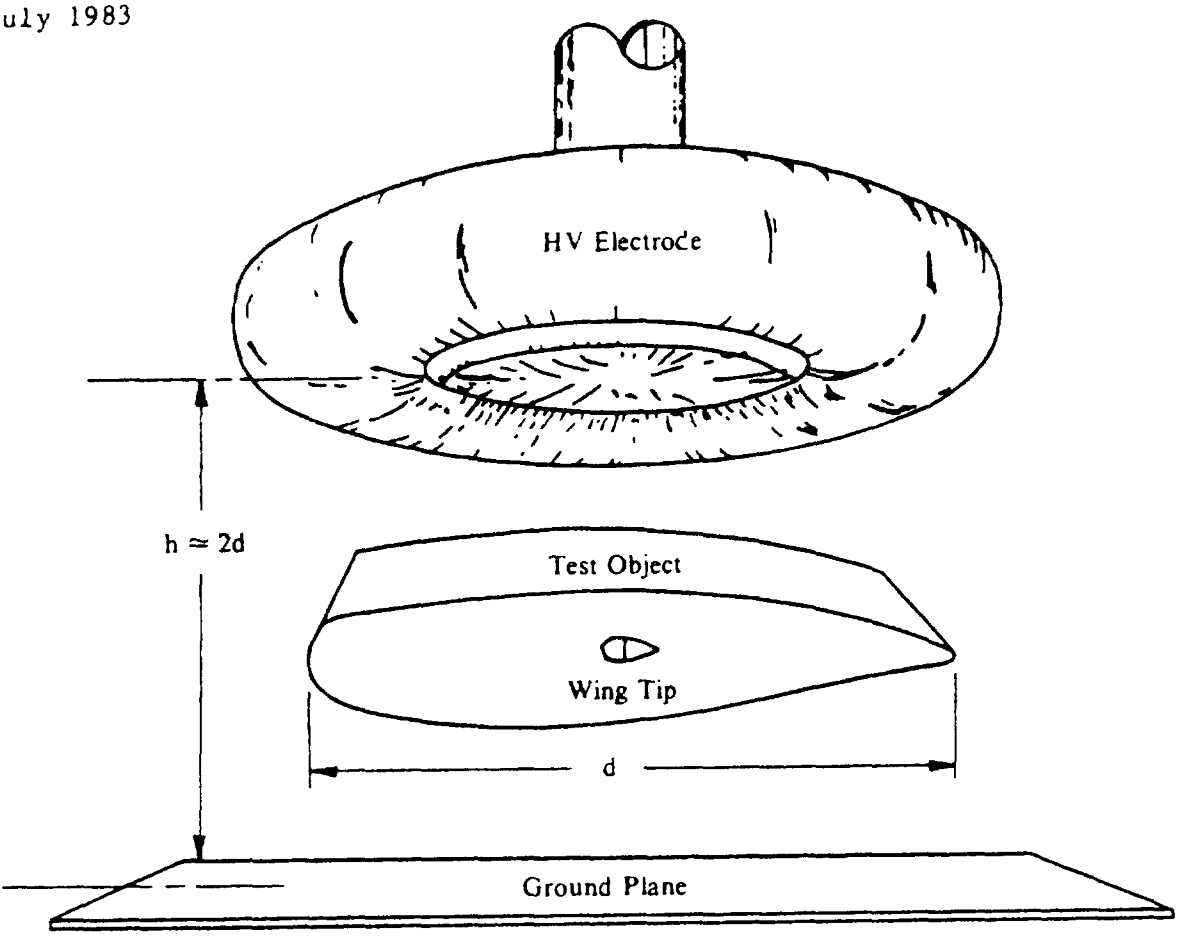


Figure A-20. Test setup with test object suspended between HV and ground electrodes.

50.2.5 Test method T05 - indirect effects - external electrical hardware

50.2.5.1 Purpose. This method is used to determine the magnitude of indirect effects when lightning strikes externally-mounted electrical hardware. It is used to qualify externally-mounted equipment by evaluating protective design measures (both inherent and added) and by ensuring that hazardous voltages and currents are not produced inside the aircraft.

50.2.5.1.1 Lightning strikes to electrical equipment mounted on the external surface of an aircraft may produce undesirable currents and surge voltages on internal wiring, either by direct contact of the lightning arc to the electrical circuit or by electromagnetic coupling due to the intense fields produced by the lightning strikes. These undesired transients may not only threaten the operation of avionics equipment connected directly to the external components, but may even couple electromagnetically into other unrelated circuits and equipment within the airframe.

50.2.5.2 Applicability. Test method T05 is applicable to externally-mounted electrical hardware such as antennas, navigation lights, and electrically-heated probes and windshields.

50.2.5.2.1 All aircraft are equipped with numerous electrical devices mounted on the external surfaces of the vehicle. Modern military aircraft are typically equipped with a wide array of lights, probes, antennas, and various other electronic devices for defensive and offensive military purposes. Each such device is typically connected by electrical wiring to associated avionics equipment located inside the aircraft. The electrical wiring to and from these components is often bundled together with other wiring into cable runs which may be routed throughout the aircraft.

50.2.5.2.2 The most serious lightning incidents on aircraft relate to strike damage involving fuel and electrical systems. The greatest threat to the electrical systems is from lightning attachments to externally-mounted electrical components or equipment. These external components provide opportunities for lightning currents and voltages to gain entrance into the interior regions of the aircraft where serious electrical damage may be produced. For example, a lightning attachment to a wing tip navigation light might shatter the protective glass covering or burn through the metallic housing and contact the filament or electrical power leads. The current can then melt or explosively vaporize the wires, and the associated voltage surge may cause widespread breakdown of insulation and damage to electronic equipment.

50.2.5.2.3 In some instances, undesired currents and surge voltages may be produced even though the lightning arc does not directly contact the system wiring. The intense electromagnetic fields produced by the lightning flash may induce transient voltages and currents into the electrical circuits. In such cases, no observable physical damage may be produced, but sensitive electronics may be damaged or temporarily disabled. In either case (direct attachment or induced), transients may be coupled or transferred to nearby wiring so that other unrelated electrical equipment may be affected.

50.2.5.2.4 Of the various indirect effects mentioned, test method T05 is specifically intended to evaluate voltage penetrations to internal wiring at the locations on the vehicle where external hardware has been mounted. The method is confined to the external hardware and the particular wiring associated with it. This method is not intended to assess the overall induced effects at the systems level. It is not designed to test for induced effects which can occur in wiring adjacent to external hardware wiring (cross-talk) or which could occur at other locations in the vehicle.

50.2.5.3 Apparatus. The rationale for selection of the indirect effects test apparatus and guidance for its use are included in the following sections on test setups and procedures.

50.2.5.4 Test setup. The test object is mounted on the test chamber exactly as it is mounted on the aircraft, since normal bonding impedances can contribute to the voltages induced in the electrical circuit. Inside the shielded enclosure, connectors and wiring representative of the flight installation may be used to connect the test object to either the actual equipment or to a simulated load impedance. Usually a dummy load is used since the test is designed primarily to measure the levels of voltage and current appearing on the wires. The measuring instruments may also be located in the same shielded enclosure or in a separate shielded room connected by a suitably shielded instrument cable.

50.2.5.4.1 An aperture in the shielded enclosure can be fitted with an adapter or mounting plate, which is machined with apertures and fastener hole patterns representative of the aircraft skin where the component is mounted. Mounting of the component to the adapter plate is then exactly as it is on the aircraft, including any paint, primers, coatings or sealants. The adapter plate is then fastened carefully to the shielded enclosure to ensure a good EMI seal and good high-current transfer across the interface. All connecting wiring and terminating impedance elements are then located inside the shielded enclosure, which is grounded to the return side of the lightning high-current generator. A typical installation is shown in figure A-21.

50.2.5.4.2 A laboratory generator, capable of producing the prescribed lightning waveform, is used to inject simulated lightning currents into the test object at the various points where lightning can attach. The test object is grounded via the shielded enclosure so that current flows through the test object in a manner representative of the aircraft installation. The conducted and induced transients produced in the related electrical circuit are measured at the terminals of the circuits with suitable measuring equipment.

50.2.5.4.3 The configuration of the return conductors is important because they can influence current flow patterns in the vicinity of the test object and, therefore, the amount of induced coupling. The return conductors should be distributed around the test article and spaced a few test article widths away, to ensure minimum impact on the test.

50.2.5.4.4 The test object should be an actual production item or a representative prototype of the item to be installed on the aircraft mold line; that is, an actual light, probe, antenna or other component and its mounting flange or structure. The associated avionics need not be included, so the hardware expense is mainly that of the external component. Although the associated avionics may be included in the test, if they are not, it is important to simulate the effective impedances across the terminals of the components. The circuit impedance will generally affect the magnitude of induced transients.

50.2.5.4.5 Care must be taken in the arrangement of the diagnostic equipment used for induced coupling measurements. The physical circuit must be arranged to ensure that the diagnostic equipment is not influencing the system response. The discharge of laboratory generators produces intense electromagnetic fields over a wide range of frequencies. High-frequency RF energy from spark gap switches and rapidly changing electric fields accompany the magnetic fields produced by the high-peak current surges. This intense EM field environment will induce currents in any exposed electrical conductors, including exposed signal leads, building power lines, and measuring instruments. These spurious signals can easily mask the desired signal if care is not taken in the design and installation of the instrumentation system.

50.2.5.4.6 In addition to the problem of shielding the instrumentation system, the frequency response of the total measurement must be fast enough to detect the very sharp high-frequency transients which often occur at the instant the generator is triggered. For small component-sized test articles, system resonances and coupling modes other than magnetic or resistive are not under study. Therefore, the upper frequency limit requirement will be determined by the test waveform. For example, direct effects tests on external hardware may employ fairly slow current waveforms (10 to 20 μs to peak). On the other hand, indirect effects tests using current waveform E will need to be able to see induced transients rising to peak in a tenth of a microsecond. Therefore, equipment with a bandwidth of at least 10 MHz should be used in those tests.

50.2.5.4.7 For some tests, as mentioned earlier, the instrumentation may be installed in the same shielded enclosure on which the test object is mounted (see figure A-22). Such installation requires adequate volume in the enclosure as well as good ventilation for cooling and quick access for data retrieval. The advantages of this arrangement are that the measurement leads are short, and a minimum additional effort is required in shielding of the instruments.

50.2.5.4.8 In other instances, the instrumentation may be housed in a separate shielded room, as shown in figure A-23. The measured transient signals must then be transmitted to the shielded room via signal leads of some type. In this case, precautions must be taken to ensure that spurious signals are not induced in the signal leads. One way to eliminate interference is to use balanced twin cables in solid copper tubes. Each copper tube must be kept directly against and in electrical contact with the ground plane from the position of the test chamber to the shielded screen room. Care must be taken, however, to ensure that long-shielded cable runs do not load down the signal, whether in frequency or magnitude. Care must also be taken in the design of impedance matching devices and other interface circuitry to ensure that the signal is not distorted or masked. If such an arrangement is used, a known calibration waveform should be transmitted through the system to ensure good fidelity. Other low-noise signal transmission techniques include the following:

a. Double-shielded duplex cable and differential readout instrumentation to eliminate common mode voltages.

b. Completely floating battery-powered instrumentation (elimination of ground loops and power line filtering).

c. Optical data links to isolate the readout instrumentation from both the electrical circuit under test and the transient generator.

d. Optical couplers or data links and very short instrumentation cables to minimize loading effects on the test circuit.

e. Isolation resistors at the voltage pick-off point to minimize the loading effects on the circuit under test.

50.2.5.4.9 Even after all these precautions have been taken, the elimination of noise in the measurement instrumentation system should be verified. This can be accomplished by delivering the test current to the shielded enclosure while monitoring the readout instrumentation with the leads disconnected from the electrical circuit under test. This should be done with the disconnected measurement leads open circuited, and with the disconnected leads shorted.

50.2.5.4.10 When the direct effects test is conducted, measurements should be made of transients appearing on internal wiring. Even if the waveform used does not have the fast rate-of-rise required to meet the induced coupling requirement, voltage may be produced by other mechanisms. The arc may attach directly to the wiring, as discussed earlier, or the high-peak current may produce resistive voltage drops which can appear across the wiring. When a direct effects test is conducted, the high-current electrode is placed a small distance from the desired arc attachment point on the test object, leaving an air gap of a few centimeters. If a separate waveform E test is conducted, the output of the generator may be clamped directly to a point on the test object, especially when it is desirable to minimize damage to the test article.

50.2.5.4.11 The points of attachment are determined from separate high-voltage, long-spark attachment tests to the full-scale components. Numerous current flow patterns may be indicated by these tests, possibly leading to a requirement for several induced coupling tests to determine the worst case attachment point. The point or points thus determined can then be used in the direct effects test. In a direct effects test, the open arc is essential to the accurate simulation of the natural condition. The open arc contributes to the surface damage at the point of attachment. This effect is pronounced in advanced composite materials. In an indirect effects test, the open arc is not thought to contribute significantly to the induced transients. Since an open arc does produce surface damage, even at low current levels, it is desirable to use a direct connection to minimize damage. In this way, a number of indirect effects tests can be conducted on the same test article.

50.2.5.4.12 When indirect effects tests are conducted on an electrical component, it is important for load impedances simulating those of the equipment normally attached to the test object to be connected across all electrical terminals of the test object. The simulated load impedances should be chosen to make the effective load presented to the test object wiring as representative as possible over a broad frequency range. Where possible, actual circuit components should be used, or replicas thereof, so that low, medium, and high frequency impedance is duplicated. It is not sufficient to load a 50-ohm antenna cable with a 50-ohm resistor. The radio receiver/transmitter unit will normally only match the cable with a 50-ohm resistor over a small frequency range. During the test, the circuit might act like a very low impedance to low frequencies if the receiver includes a shunt choke to ground, or be very high impedance if there is only a small series capacitor. Therefore, some knowledge of the real circuitry into which the feeder operates is required so that meaningful measurements might be made.

50.2.5.5 Criteria to be specified. It can be seen from table 1 of the basic standard and from the zone definitions that electrical hardware located in either zone 1 or 2 will receive either current component A or component D, or both. Each of these current pulses in nature may exhibit very fast rates-of-rise, although the rate-of-rise is not specified in the waveform parameters for these components. Rate-of-change of current is an important parameter, since magnetic coupling effects are directly influenced.

50.2.5.5.1 Since the model waveform does not specify rates-of-rise of current, a specialized current waveform designated as current waveform E, (see figure 8 of the basic document) has been defined for use in tests for induced coupling effects. Current waveform E is not intended to resemble a particular lightning strike component in terms of energy content, and is not used, therefore, in damage effects testing. It is intended to simulate the early-time initial wavefront of the return stroke current pulse (either initial strike or restrike), where di/dt's (rate-of-change of current) can reach 100 kA/μs or higher.

50.2.5.5.2 As discussed earlier, undesired voltages and current surges can be produced in aircraft wiring by either arc attachment to the wiring or by induced coupling. Therefore, a complete evaluation of zone 1 or zone 2 externally-mounted electrical hardware should include tests with the proper waveform components from table I, plus a fast rate of rise test with current waveform component E. If the component A or D waveform actually used in the direct effects test has a fast rate of rise conforming to the requirements for waveform E, the separate fast rate of rise test is not required. However, current waveform E is often used separately for induced coupling measurements because it is a low-energy waveform and can be applied repeatedly with no damage to the test article.

50.2.5.6 Test procedure. The test procedure of test method T05 is straightforward and routine for any high voltage, high energy discharge laboratory. In order to verify the required current waveform before beginning the test, a dummy test article or an electrically similar circuit setup may be utilized. During the waveform setup, it is necessary to verify the interference free operation of the measurement systems. The background noise measurement should be conducted at the beginning and at the end of a test series to ensure that nothing unexpected has occurred. Background shots should be conducted with leads short-circuited to ensure that no low impedance loop (magnetic) coupling is being introduced into the signal leads. The open lead check ensures that no high impedance E field coupling is being introduced. The ground connection is maintained to preserve the true grounding configuration, thereby ensuring no ground loop problems. It is important to follow the background check procedure. Many times experimenters have been deluded by the appearance of realistic transients in their data, only to find later that the transients were getting into the measurement system through spurious means.

50.2.5.7 Data to be collected. In addition to the normal descriptive photographs and narrative records, test currents and amplitudes should be recorded on the actual test shot rather than relying on calibration data or past performance. The actual transients measured should be relatable to the driving current waveform to ensure that any shot-to-shot anomalies are accounted for. For this reason, it is desirable to utilize a dual trace oscilloscope or to take both the driving current and the transient data on the same time base. If baseline (background) noise levels are very low, they can be recorded on the same trace as the zero line.

50.2.5.8 Notes. Although not required by specification, it is desirable to conduct the induced coupling test at a number of different peak current levels (maintaining the same waveshape) leading up to, or beyond, the 50 kA level. The measured voltages at each driving current level can then be plotted to verify that a linear relationship exists. This linearity is important, because it is necessary to extrapolate the measured transients to correspond to a full threat level waveform.

50.2.5.8.1 Further interpretation of the measured transients and the rationale for extrapolation are summarized below, and illustrated in figures A-24 and A-25.

50.2.5.8.1.1 Resistive/diffusion flux induced voltages. When the construction of the test object is such that the simulated lightning current produces voltages arising from resistive voltage drops in the test object or its mounting system, then the voltage so generated will be related to the current amplitude and waveshape. Extrapolation should therefore be up to 200 kA. That is, voltages and currents measured with a test pulse of 50 kA peak should be scaled up four times to give the equivalent value at 200 kA. The important characteristics of these voltages are as follows:

a. There is no instantaneous jump in voltage at t = 0+; the waveform starts at zero and may then (1) commence to rise at finite slope similar to the current waveshape (especially in very resistive materials like graphite/epoxy or thin wires), or (2) show a dead time (i.e., zero slope) for a short period before rising (as would be observed in high conductivity materials like aluminum).

b. Peak voltage does not occur at t = 0+, but will normally occur at or near peak current, often somewhat early when measured within carbon fiber/metal structures; and in high conductivity materials may occur late, owing to the time delay introduced by the diffusion process.

50.2.5.8.1.2 Fast flux (aperture) coupling. When the magnetic flux surrounding conductors carrying the simulated lightning pulse couples with loops (e.g., in unshielded pitot heater wires, etc.), then the induced voltages will be proportional to $d\phi/dt$ in that loop. The flux external to a conductor, or flux within apertures having insulating covers, is instantaneously proportional to the current, and hence the induced voltage is proportional to $d\phi/dt$ and di/dt. Therefore, the voltage waveform will normally bear a strong resemblance to the first derivative, di/dt, of the current waveform, and extrapolation will be up to 100 kA/μs. This is, an induced voltage of di/dt type caused by a current pulse whose peak di/dt is say 40 kA/μs should be multiplied by 2.5 to give the 100 kA/μs value. The important characteristics of these waveforms are as follows:

a. A fast step in the waveform amplitude occurs at t = 0+, at the commencement of the current pulse. The waveform is often accompanied by high-frequency oscillatory components, and the first zero crossing will be at peak current, where di/dt = 0.

b. The peak voltage attained will normally occur at the initial transient at t = 0+. (If peak voltage occurs at or near peak current, the mechanism cannot be aperture coupling).

50.2.5.8.1.3 In practice, the measured voltage may be a combination of resistive voltage, magnetically induced dϕ/dt voltage, and superimposed HF oscillations. However, since dϕ/dt voltages peak at the instant of starting of the current pulse, the amplitude here is unaffected by IR effects and extrapolation is easy. At peak current of the test pulse, dϕ/dt = 0, therefore, the observed voltage must be resistive, and scaling can be based on the amplitude of the voltage at peak current. HF oscillations can usually be ignored in component tests because they will often be facility effects. However, in some cases, they may be important, and their relevance should be closely examined.

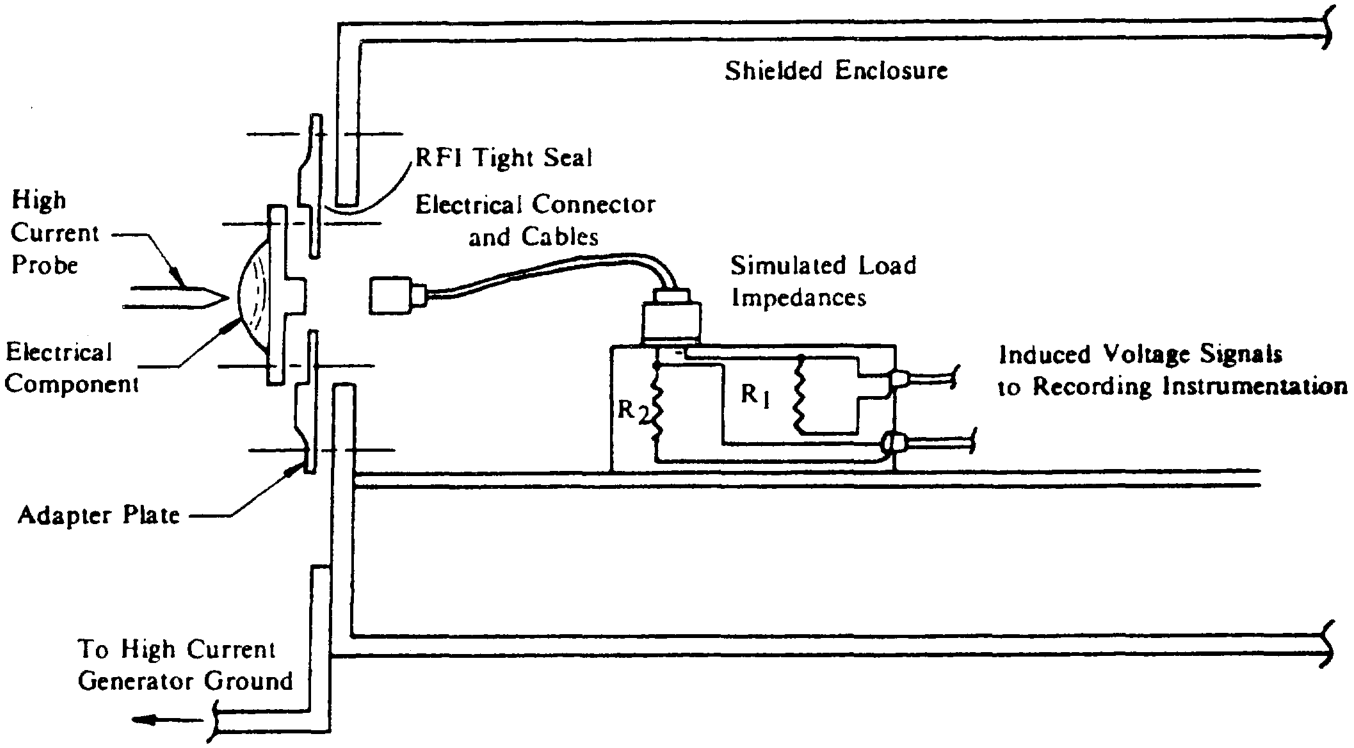


Figure A-21. Installation of electrical component on shielded enclosure.

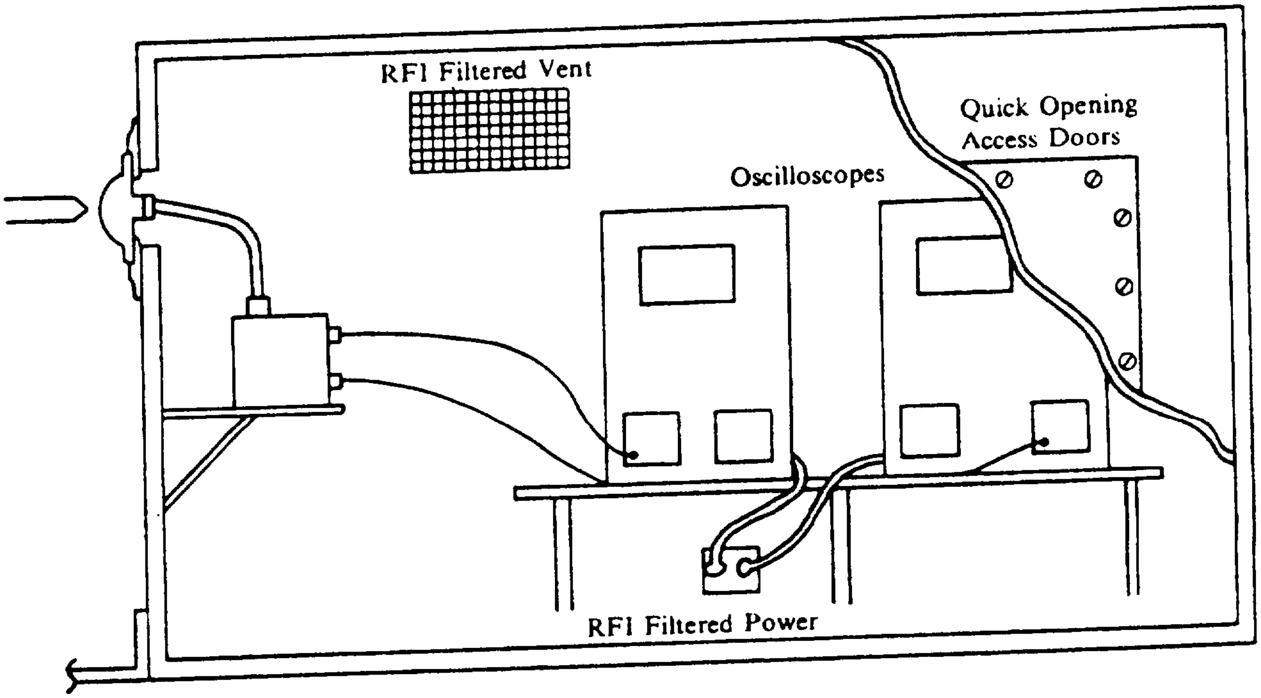


Figure A-22. Self contained instrumentation test chamber.

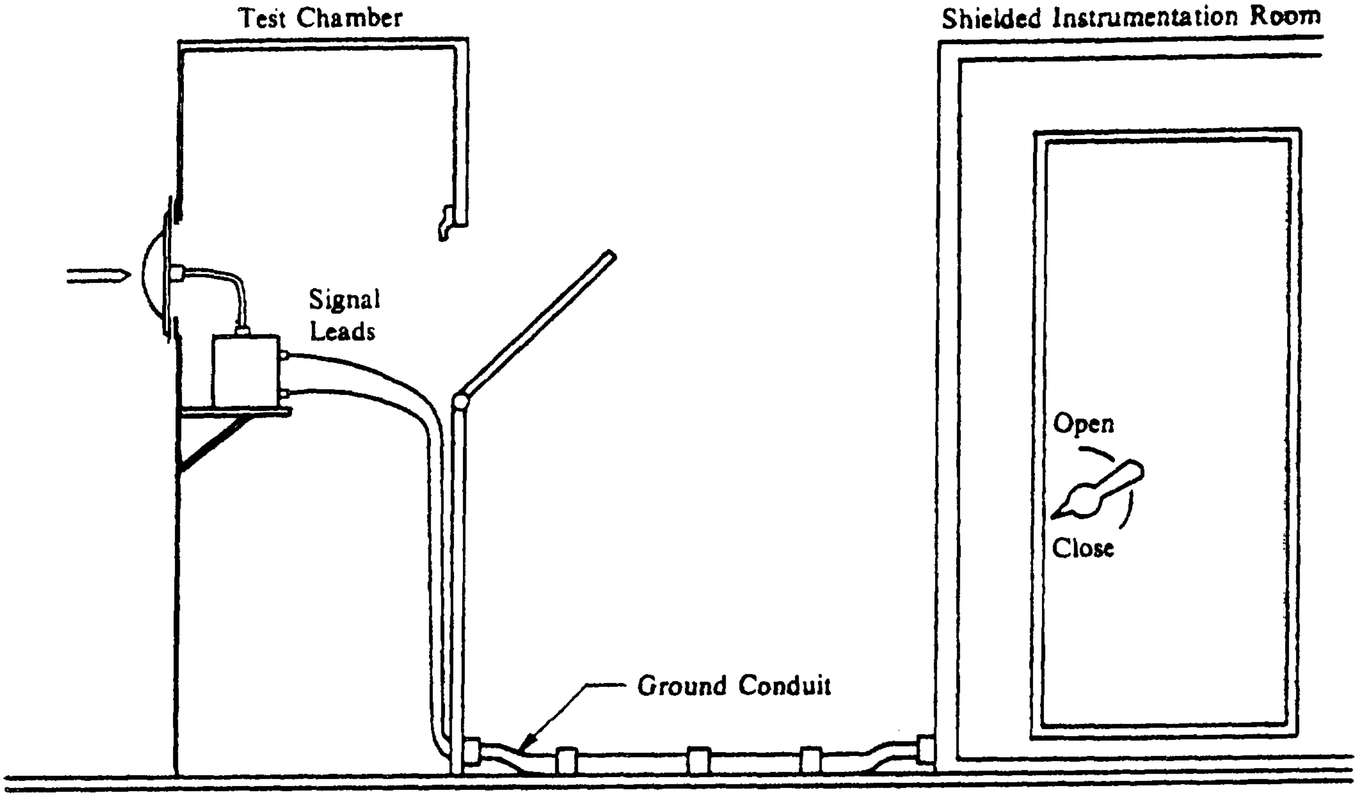
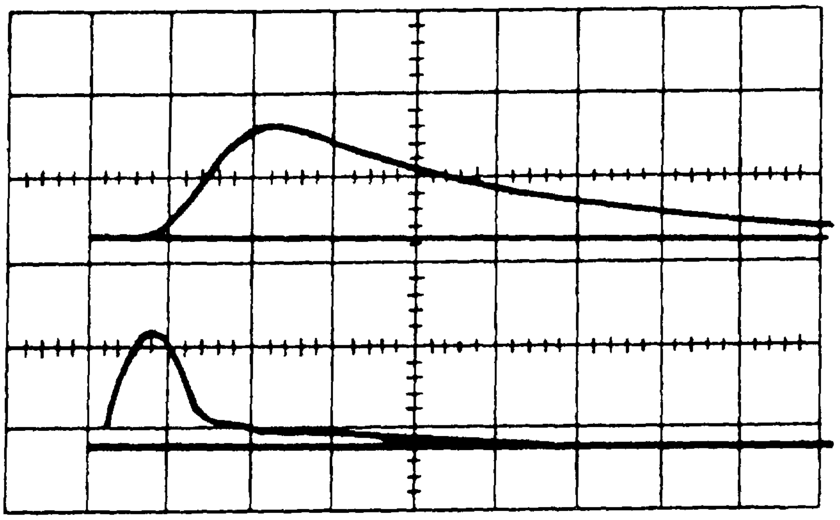


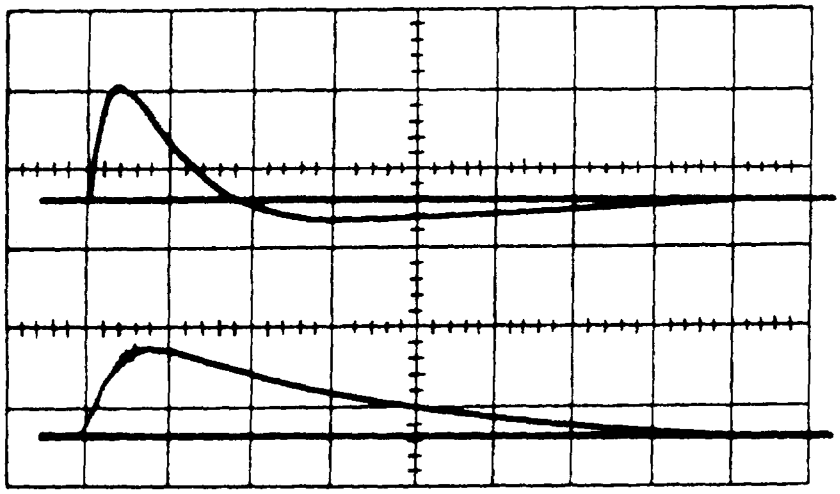
Figure A-23. Separate test enclosure and shielded instrumentation room.



Induced voltage waveform.
Vertical sensitivity = 4 V/Division.

Test current waveform.

(a) 1 inch O.D. copper tube (high conductivity material).
Note 1. The voltage waveform "dead time".
Note 2. That voltage peak occurs much later than current peak.

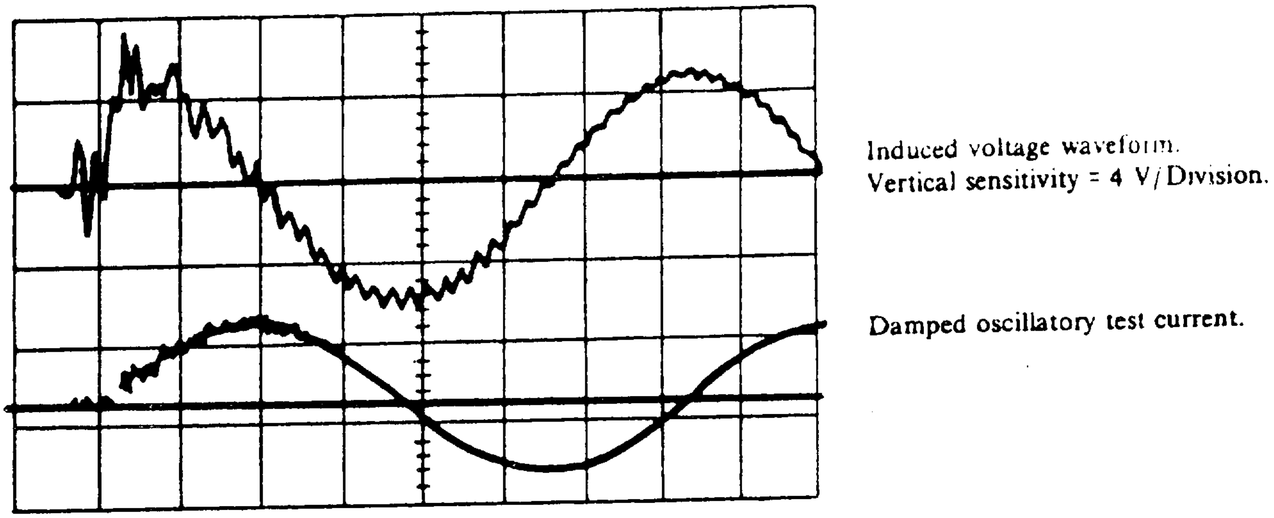


Induced voltage waveform.
Vertical sensitivity = 51 V/Division.

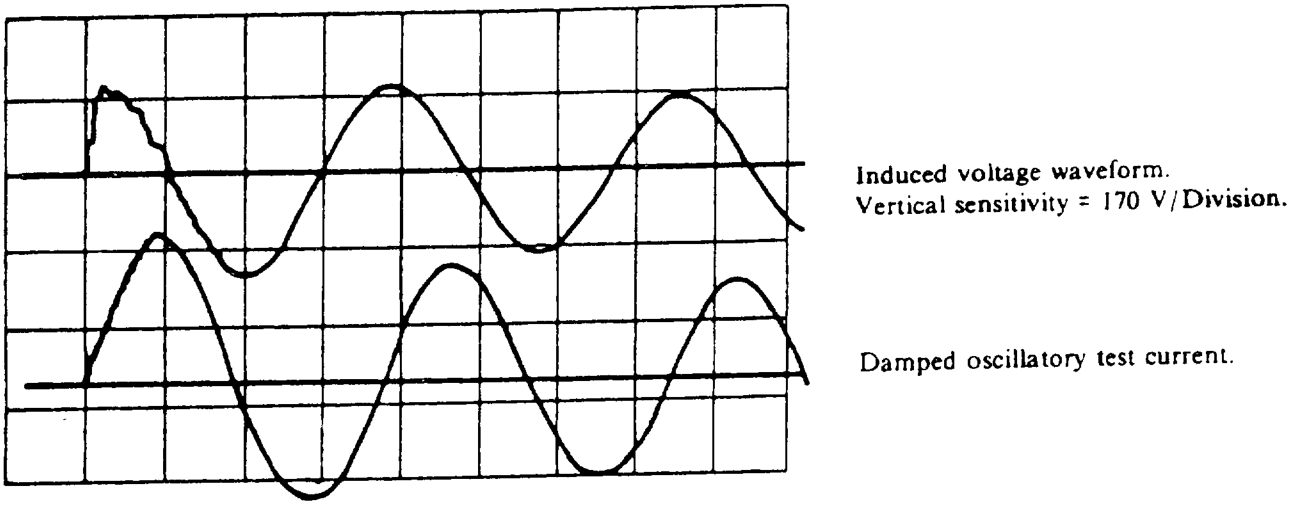
Test current waveform.

(b) Composite structure (carbon fiber/aluminum).
Note 1. The voltage waveform exhibits no discernable dead time but slope of rise is finite (closely follows current waveform rise).
Note 2. The voltage peak occurs slightly earlier than the current peak.

Figure A-24. Examples of resistive/diffusion flux induced voltage waveforms.



$\frac{dB}{dt}$ measurement - current distribution around aircraft fuselage.



Voltage on internal fuselage wire located behind aperture covered by insulated carbon fiber panel. Note that carbon fiber panel does not carry main structure current and so the low frequency voltage is still of the $\frac{dB}{dt}$ type; the high frequency transient, however, is severely attenuated.

Figure A-25. Examples of magnetically induced voltage waveforms.

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