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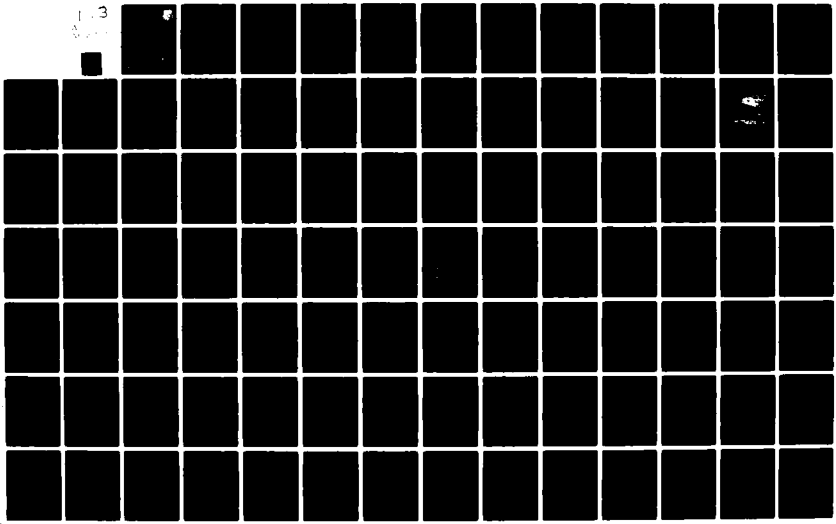

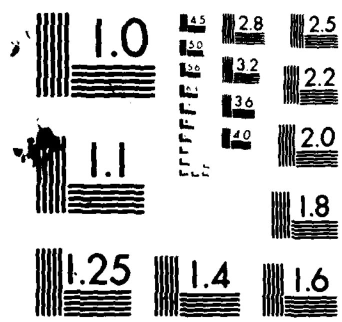

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PROTECTION OF ELECTRICAL SYSTEMS FROM EM HAZARDS - DESIGN GUIDE

D.L. SOMMER

BOEING MILITARY AIRPLANE COMPANY
SEATTLE, WASHINGTON 98124

DECEMBER 1981

INTERIM REPORT FOR PERIOD JUNE 1979 TO OCTOBER 1981

AERO PROPULSION LABORATORY
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AIR FORCE SYSTEMS COMMAND
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report contains results of a two-phase study program investigating the effects of lightning strikes on aircraft and the resulting transients coupled on to the electrical systems. The design guide contains the historical background and the lightning threat assessment in the sections 1 and 2.

Section 3 of the design guide contains the techniques for inherent hardening against the lightning strike electromagnetic energy. Section 4 of the (cont'd)

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design guide provides two methods for evaluating electrical systems to determine the levels of transients that can be induced. The first method allows an electrical systems designer to make a preliminary assessment of the lightning strike threats. The second method allows a more detailed evaluation using a computer program called PRESTO. Section 5 identifies and examines the various military specifications covering the transients that existing electrical equipment has to withstand. Using this information, add-on protection hardware and hardening techniques were evaluated in Sections 6 and 7. Section 8 provides examples for selecting hardening techniques for advanced electrical systems. Sections 9, 10, and 11 discuss the reliability/maintainability, system safety and Design to Cost considerations in selection of the appropriate hardening techniques.

PREFACE

This Design Guide presents the results of work performed by the Boeing Military Airplane Company, Seattle, Washington, under Air Force Contract F33615-79-C-2006, during the period June 15, 1979 to October 15, 1981. The work was sponsored by the Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio, under Project 3145, Task 31459, Work Unit 3142958, with Mr. Duane Fox, AFWAL/POOS-2, as the project engineer.

This document fulfills the requirement of CDRL item numbers 8, Technical Report - Design Handbook and CDRL item number 10, Drawings, Engineering and Associated Lists.

The technical work was done by Mr. David L. Sommer, Mr. D. K. Heier, and Dr. W. P. Geren, and the report was prepared by Mr. Sommer under the direction of Mr. I. S. Mehdi, Boeing Program Manager.

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LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

SYMBOL	DEFINTION
A	Amperes
BL MOD	Beacon Light Moderate Threat
BL SEV	Beacon Light Severe Threat
CCTC	Common Mode Wire Self Capacitance
CCTR	Common Mode Wire Mutual Capacitance
IBUSLOAD	Current at the Bus Input Terminals
ICON	Current at the Converter Output Terminals
IGEN	Current at the Generator Output Terminals
IGENNEU	Current at the Generator Neutral Terminals
ILOAD	Current at the Load Input Terminals
ISC	Short Circuit Current
Kv	Kilovolts
LSELF	Wire Self Inductance
mS	Milliseconds
Mutual	Wire Bundle Mutual Inductance
RCNDAC	Wire AC Resistance
RCNDDC	Wire DC Resistance
S.E.	Shielding Effectiveness
TEM	Transverse Electromagnetic
T1,T2	Test Points 1 and 2
V	Voltage
VBUSLOAD	Voltage at the Bus Load
VCON	Voltage at the Converter Output Terminals
V_d	Reverse Biased Device Voltage
VGEN	Voltage at the Generator Output Terminals

ABBREVIATIONS (Cont.)

VGENNEU	Voltage at the Generator Neutral Terminals
VLOAD	Voltage at the Load Input Terminals
VOC	Voltage Open Circuit
V_r	Reverse Stand Off Voltage
VSCF	Variable Speed Constant Frequency
S	Microseconds
WH MOD	Window Heater Moderate Threat
WH SEV	Window Heater Severe Threat
6MF	Six Meter Wire Behind Fiberglass
12GE35	Twelve Meter Wire 2 Feet Behind 35 Plies of Graphite/Epoxy
12GE45	Twelve Meter Wire 2 Feet Behind 45 Plies of Graphite/Epoxy
12GE50	Twelve Meter Wire 2 Feet Behind 50 Plies of Graphite/Epoxy
12GE51	Twelve Meter Wire 1 Foot Behind 50 Plies of Graphite/Epoxy
12GE52	Twelve Meter Wire 0.5 Foot behind 50 Plies of Graphite/Epoxy
12MF	Twelve Meter Wire Behind Fiberglass
12M3MF	Twelve Meter Wire Behind Three Mil Foil on Fiberglass
18MF	Eighteen Meter Wire Behind Fiberglass

SUMMARY

This design guide contains results of the work conducted under the program titled "Protection of Advanced Electrical Power System from Atmospheric Electromagnetic Hazards." The program was conducted in three tasks in Phase I and a fourth task in Phase II. The objective of this program is to define the electromagnetic threat imposed on advanced aircraft electrical system in metallic and non-metallic aircraft due to lightning strikes and to develop cost effective techniques for protection of the electrical systems from these threats.

The approach to assess the threats due to lightning strikes consisted of utilizing computer programs and analysis methods to calculate the threat levels for typical aircraft electrical system circuits. Several circuits were evaluated for three types of aircraft; cargo, fighter and fighter-bomber. For each type of aircraft an engineering survey was performed to obtain geometrical data. The survey included visual examination of various aircraft in the Air Force inventory to determine the important electromagnetic energy coupling paths. Open circuit voltages, short circuit currents, and energy coupled on to nine of the circuits were determined.

After the threats for the various circuits were determined, several key circuits were selected for further evaluation in Task 2. In this task the circuits were terminated in the appropriate impedances that would normally be expected and again the voltages and currents at key points in the circuits were determined. This data was used to examine some of the equipment that would be exposed to these transients and their impact on the equipment was evaluated. In addition, the various specificaitons and standards were also examined to determine the level of hardness that present day equipment are required to meet. The impact of wire routing to reduce the electromagnetic flux coupling onto conductors was also examined.

In the third task, the circuits selected in the previous task were reevaluated to determine the impact of added protection such as linear filters and non-linear protective devices along with various methods of shielding. An

alternative to signal transmission via the use of fiber optics was also examined.

In phase II, the definition of lightning hardness criteria was developed, and the evaluation of various hardening methods to meet these criteria was accomplished. A trade-off of the alternatives was conducted on the basis of cost, weight, reliability and maintainability. Based on this analysis, data for selection of optimum protection has been developed and included in this design guide.

The results of the study did indicate that lightning strike would impose transients on the electrical systems of aircraft with metal or composite structures. These transients will be higher than the equipment inherent hardness. Present specifications do not cover the level of the threats expected due to lightning strikes. However, there are various alternatives available to provide protection from these transients or harden the equipment. The design guide contains all the alternatives that were examined and sufficient data to allow the electrical systems designer to make an appropriate selection for his application. Examples of how to use the design guide are included.

SECTION I

INTRODUCTION

1. BACKGROUND

The interaction of lightning with an aircraft, either by direct strike or near-miss, induces electrical transients into the aircraft circuitry. The next generation of military aircraft may contain large amounts of poorly conducting composite material in skin and structure. In addition, the advanced electrical power systems used in these aircraft will contain solid state components. The combination of the two; i.e., reduced inherent shielding effectiveness of nonmetallic materials coupled with circuit components that have lower tolerance to electrical transients, presents a serious problem for aircraft designers. To trade-off the penalties/benefits of advanced structure and electrical power systems against conventional structures and systems, an in-depth analysis of the lightning problem is required, as is an evaluation of the effectiveness of various protection methods.

Lightning-induced transients present a hazard to electrical power systems which must be met by the provision of an adeqauate protection system (i.e., the occurrence of several direct strikes to a given aircraft during the service life of the aircraft is a certainty). For a direct strike to an electrical circuit; e.g., a power feeder, considerable physical damage is done to the wiring, as well as circuit components attached to the wires. When the typical twenty-kiloamp lightning current is injected into wires, magnetic forces and resistive heating will break or vaporize even heavy-gauge wiring. At the very least, dielectric breakdown of wire insulation will occur, which may disable the circuit. If the circuit is not struck directly, it will still have potentially damaging transient levels induced by magnetic coupling to the lightning currents flowing through aircraft structure. These indirectly induced transients will have sufficient energy to damage or upset solid state components. Therefore, lightning protection of aircraft electrical systems is a design requirement.

The mechanism whereby lightning currents induce voltages in aircraft electrical circuits is as follows. As lightning current flows through an aircraft, strong magnetic fields which surround the conducting aircraft and change rapidly in accordance with the fast-changing lightning-stroke currents are produced. Some of this magnetic flux may leak inside the aircraft through apertures such as windows, radomes, canopies, seams, and joints. Other fields may arise inside the aircraft when lightning current diffuses to the inside surfaces of skins. In either case these internal fields pass through aircraft electrical circuits and induce voltages in them proportional to the rate of change of the magnetic field. These magnetically induced voltages may appear between both wires of a two-wire circuit, or between either wire and the airframe. The former are often referred to as line-to-line voltages and the latter as common-mode voltages.

In addition to these induced voltages, there may be resistive voltage drops along the airframe as lightning current flows through it. If any part of an aircraft circuit is connnected anywhere to the airframe, these voltage drops may appear between circuit wires and the airframe. For metallic aircraft made of highly conductive aluminum, these voltages are seldom significant except when the lightning current must flow through resistive joints or hinges. However, the resistance of titanium is 10 times that of aluminum, and that of composite materials many hundred times that of aluminum, so the resistive voltages in future aircraft employing these materials may be much higher.

Upset or damage of electrical equipment by these induced voltages is defined as an indirect effect. It is apparent that indirect effects must be considered along with direct effects in assessing the vulnerability of aircraft electrical and electronics systems. Most aircraft electrical systems are well protected against direct effects but not so well against indirect effects.

Until the advent of solid state electronics in aircraft, indirect effects from external environments, such as lightning and precipitation static, were not much of a problem and received relatively little attention. No airworthiness criteria are available for this environment. There is increasing evidence, however, of troublesome indirect effects. Incidents of upset or damage to avionic or electrical systems, for example, without evidence of any direct attachment of the lightning flash to an electrical component are showing up in lightning-strike reports.

While the indirect effects are not presently a major safety hazard, there are trends in aircraft design and operations which could increase the potential problem. These include the following:

- Increasing use of plastic or composite skin
- Further miniaturization of solid state electronics
- Greater dependence on electronics to perform flight-critical functions

Design of protective measures against indirect effects is treated in this design guide.

A major difficulty in aircraft design is to provide the designer with sufficient information about design options and trade-offs to make intelligent choices for the aircraft under consideration. For lightning protection, which is a relatively new and rapidly-changing technology, this is particularly true. The additon of lightning protection hardware to an aircraft carries with it various cost/weight/volume penalties, and, in some cases, will compromise the performance of the protected systems (e.g., surge arrestors may degrade with age and fail, shorting out the system they were intended to protect). This can result in an over-designed protection system that may be almost as bad as one that is inadequate. An accurate assessment of the lightning threat is required as is an accurate evaluation of the effectiveness of protection hardware.

SECTION II

LIGHTNING THREAT ASSESSMENT

1. Lightning Threat Definition

The cloud-to-ground lightning strike begins with the leader process, i.e., the formation of a plasma channel of ionized air. This is followed by a current surge, the return stroke. During the leader process, the average currents are on the order of 100 amps. Return stroke currents have peak values of tens of kiloamps. A positive strike consists of a single return stroke; a negative strike will have from 3 or 4 to as many as 26 consecutive return strokes and has a duration on the order of tenths of a second.

There are two types of lightning threat - direct attachment to the aircraft and a nearby strike. Previous work on a navy contract (Reference 1) indicates that the direct attachment case is much more severe than the nearby strike. Hence protection requirements will be determined by the direct attachment threat, and the threat assessment is accordingly limited to the direct attachment case. For the directly attached case, there are two separate processes: initial leader attachment and return stroke (or strokes). The latter has much larger associated surface currents and is considered to be the dominant threat of the two.

The starting point in threat definition is the lightning current waveform at the aircraft altitude. The most important lightning current parameters for induced effects analysis are peak amplitude, peak rate-of-rise, and total charge transfer for a single stroke.

The lightning current waveform was represented as a double exponential, with rise time, fall time, and peak determined by the antitipated threat parameters (i.e., peak amplitude, peak rate-of-rise, and total change transfer). The transients were based on two double exponential waveforms, which corresponded to the following threat parameters:

Severe:

Peak current = 200 kA

Peak rate-of-rise = 2.1×10^{11} A/sec

Total Charge = 41 Coulombs

Moderate:

Peak current = 20 kA

Peak rate-of-rise = 5.4×10^{10} A/sec

Total Charge = 1.6 Coulombs

These two threats are composites based on statistics for cloud-to-ground positive strokes, negative first strokes and negative subsequent strokes. Since all three categories of strokes are possible, the statistical data was treated independently.

The double exponential is intended to simulate only the so-called "current peak" of the stroke. The current peak has a duration of a few hundred microseconds and is followed by a slowly-varying continuing current (also referred to as intermediate current) which lasts for several milliseconds. This low-frequency continuing current does not excite appreciable induced transients. However, this low frequency continuing current could add an additional voltage of up to 20 volts to equipment that use the metallic airframe structure for circuit return. Present practices require that all equipment sensitive to a voltage change in the return path will have a dedicated wire for circuit return. Equipment insensitive to a quartersecond variation in voltage which use the structure for the return path will most likely not be affected by the additional voltage developed by the low frequency continuing current as is the case with present day metallic aircraft. The dominant threat is the current peak component which does induce transients on the wiring.

The severe stroke parameters chosen above fall in the upper 1% to 10% of the statistical distribution; the moderate stroke parameters are around the median. For example, the severe and moderate peak rate-of-rise values correspond to the upper 1% and upper 30%, respectively, for negative subsequent strokes (Reference 2).

a. Lightning Characteristics

All aircraft flying inside or in the vicinity of a thundercloud or cloud cover are potential victims of a lightning strike. When struck, the aircraft becomes a part of the discharge circuit of the lightning. The source of lightning strikes which may hit the aircraft are categorized into three types: the cloud-to-ground strokes, the intra-cloud discharges, and the cloud-to-cloud discharges.

According to Pierce, et. al., (Reference 3) the outstanding differences between the intra-cloud discharges the cloud-to-cloud discharges, and the cloud-to-ground strokes are as follows:

1. Global lightning strike statistics compiled the ratio between the freqeuncy of occurrence of intra-cloud discharges and the cloud-to-ground strokes as well as that between the cloud-to-cloud discharges and cloud-to-ground to be approximately 3:1.

2. The return stroke phenomena are often observed in the case of the cloud-to-ground, however, none has been noted through observation concerning the intra-cloud discharges or cloud-to-cloud discharges. The peak value and the rise rate of the lightning current caused by the intra-cloud discharges or cloud-to-cloud discharges are both smaller than those caused by the cloud-to-ground strokes. The effects of the intra-cloud discharges or the cloud-to-cloud discharges on aircraft are generally less serious than the effects of the cloud-to-ground strokes.

3. The danger of receiving the cloud-to-ground strokes is always present within a range of altitude from 0 to about 3,000 meters; however, the danger suddenly diminishes from 3,000 meters upwards.

4. The danger of the intra-cloud discharges strikes is present from an altitude of about 1,000 meters upwards and the danger increases along with the altitude. At an altitude of 3,000 meters and higher, the danger of the intra-cloud discharges and the cloud-to-ground strokes strikes are about equal. The upper limit of the intra-cloud discharges is normally 6,000 meters.

5. Approximately 95% of all the strikes take place within an altitude range from 0 to 16,000 feet. Over the 20,000 foot altitude, the incidence of strokes is about 1%.

6. Lightning strikes occur most frequently at about 0°C. About 65% of all the strikes take place within a temperature range from -5°C to +5°C. About 90% occurs between -10°C and +10°C. These facts indicate that strikes to aircraft take place most frequently in a relatively low layer of a thundercloud.

b. Lightning Stroke Zones for Aircraft

Generally, aircraft are zoned according to the probable magnitude of lightning strike. The zones help the designer and lightning test engineer to determine the extent and type of protection required for any specific aircraft component. Test techniques that make use of these zones are discussed in References 3 and 4.

Lightning strike zones are illustrated in Figure 1 and are defined below. The zones are shown to illustrate the concept. Zones are normally developed for specific aircraft by long arc tests on scale-model aircraft or by comparison to zones established for an aircraft similar in size and configuration.

Zone 1--Direct-Stroke Attachment Zone. As the name implies, this zone is subject to initial attachment by a lightning strike. It is possible for lightning to attach to this area and remain attached for the entire duration of a stroke. Discharge times can approach, and in rare instances exceed, 1 sec. This zone includes--

- o All surfaces of the wingtips located within 18 inches of the tip, measured parallel to the lateral axis of the aircraft, and surfaces within 18 inches of the leading-edge on wings having leading-edge sweep angles of more than 45 deg.

- o Projections such as engine nacelles, external fuel tanks, propeller disks, and fuselage nose.

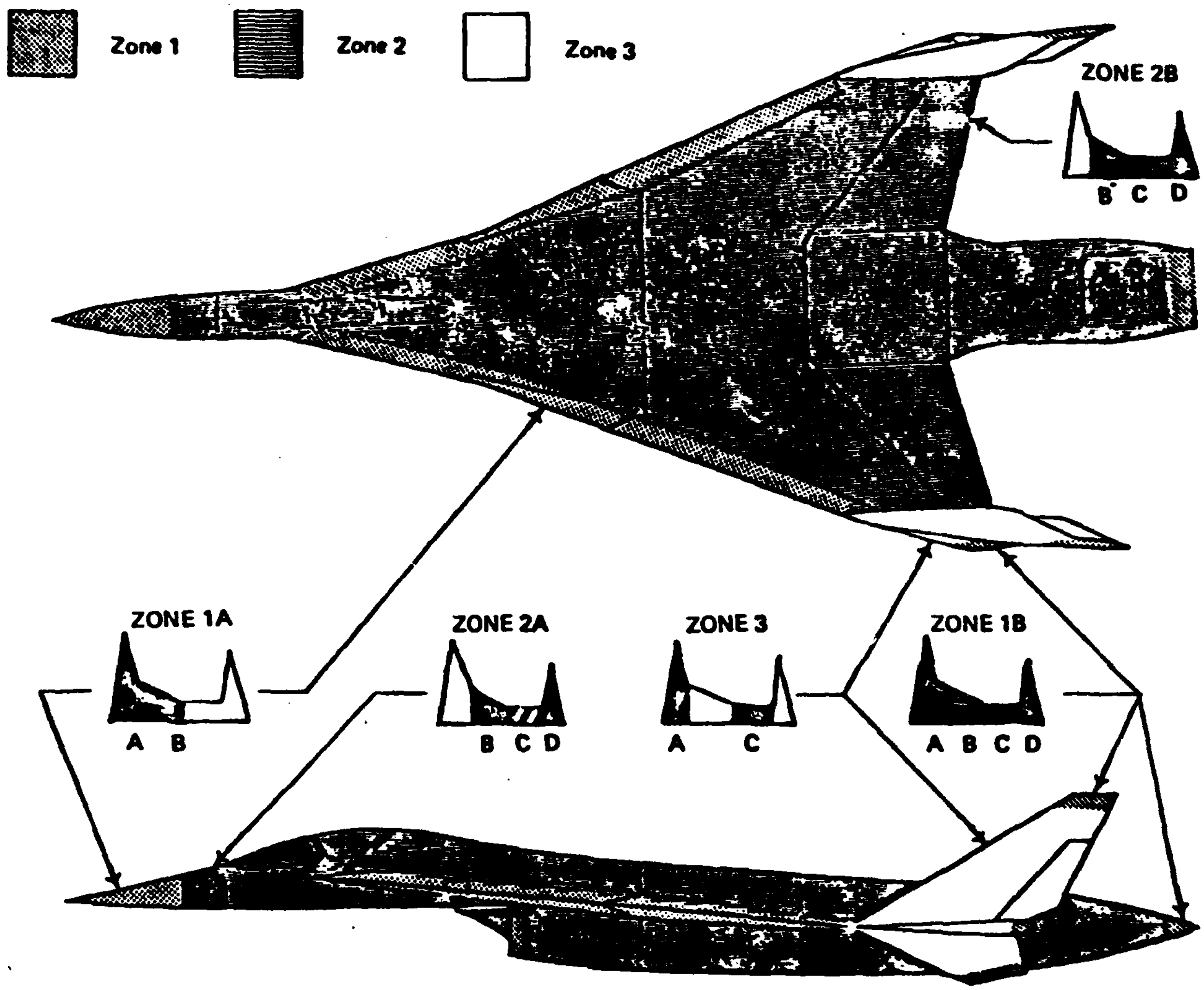


FIGURE 1 AIRCRAFT LIGHTNING STRIKE ZONES

- Tail group within 18 inches of the tips of the horizontal and vertical stabilizers, trailing edge of the horizontal stabilizer, tail cone, and any other protuberances.

- Any other projecting part that might consitute a point of direct strike attachment.

Zone 2--Swept-Stroke Attachment Zone. Swept-stroke surfaces are surfaces for which there is a possibility of strikes being swept rearward from a zone 1 point of direct strike attachment. This zone includes--

- Surfaces that extend 18 inches laterally to each side of fore and aft lines passing through the zone 1 forward projection points of strike attachment.

- All fuselage and nacelle surfaces, including 18 inches of adjacent surfaces, not defined as zone 1.

Zone 3. Zone 3 includes all of the vehicle areas other than those covered by zones 1 and 2. In zone 3, there is a low probability of any attachment of the direct lightning flash arc.

Zone 3 areas may carry substantial amounts of electrical current, but only by direct connection between some pair of direct of swept-stroke attachment points.

Zones 1 and 2 can be 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-region is one in which there is low probability that the arc will remain attached and a B-region is one in which there is high probability that the arc will remain attached. Some examples of zone subdivisions follow.

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

- Zone 1B: Initial attachment point with high probability of flash hang-on, such as a tail cone

- Zone 2A: A swept-stroke zone with low probability of flash hang-on, such as a wing midspan
- Zone 2B: A swept-stroke zone with high probability of flash hang-on, such as a wing trailing edge

2. Lightning Coupling Mechanisms

Four basic coupling mechanisms are listed below:

- EXPOSED CONDUCTORS - conductors directly exposed to the lightning fields (e.g., windshield heater, front and rear spar wiring).
- APERTURES - non-conductive portions of airplane exterior. Some examples are the cockpit canopy, windows, and fiberglass access doors.
- JOINTS - electrical discontinuities in aircraft exterior; e.g., the narrow gap between a metallic access door and underlaying airframe or the interface between two graphite epoxy panels.
- DIFFUSION - low-frequency penetration of fields into the interior of metallic or graphite-epoxy fuselage, wings; etc.

a. Coupling Analysis Methods

The analysis methods employed for the various coupling mechanisms are as follows:

1. Exposed wires - using the method described in section II.3.a, one obtains the fields directly. For more complicated structure, such as landing gear, it is necessary to do further analysis to obtain the fields on structural members protruding from the basic airframe.

2. Apertures - when a conducting surface is interrupted by openings (e.g., cockpit canopy), the exterior surface fields penetrate into the

interior. At low frequencies, this coupling mechanism may be decomposed into magnetic and electric coupling or, equivalently, stray inductance and capacitance between conductors in the interior of the body and the exterior surface. The magnetically and electrically-coupled interior fields are proportional to the surface current and change density which would appear on a shorted aperture. With certain restrictions, the interior fields due to magnetic coupling may be modeled as those due to a magentic dipole. With similar restrictions, the electrically-coupled fields may be approximated as those of an electric dipole. In the general case, one may solve for the interior fields by calculating the fields in the aperture and using the equivalent sources, distributed over the aperture, to solve the interior problem. The process is simplified by the fact that, for the lightning frequency spectrum, the apertures of interest are electrically small, reducing the problem to a quasistatic one.

An aperture of particular interest is the narrow slot. On equipment bay doors, for example, the hinge and latch side make good electrical contact with structure, while the two other sides form narrow slot apertures. The fields of the gap may be modeled as those of a magnetic dipole. For wires lying across the gap, however, the voltage induced in the wire is simply the gap voltage at the wire location.

3. Joints - Well-formed joints (those of uniform construction without cracks or large openings) can be described in terms of a distributed admittance/unit length. The joints are similar to the narrow slot, except that the voltage along the joint is approximately constant. For either joint or slot, the interior fields may be obtained by using the fields in the opening to obtain the equivalent sources for solving the interior problem.

4. Diffusion - In the low frequency limit, this mechanism is equivalent to what has been referred to in lightning studies as the so-called "IR drop". For all-aluminum aircraft, this mechanism is important only for the low frequency continuing current and is a threat only to circuits using structural return. For a graphite epoxy aircraft, however, the electromagnetic fields associated with the high frequency peak current can diffuse entirely through the structure, inducing considerable voltage in interior wiring.

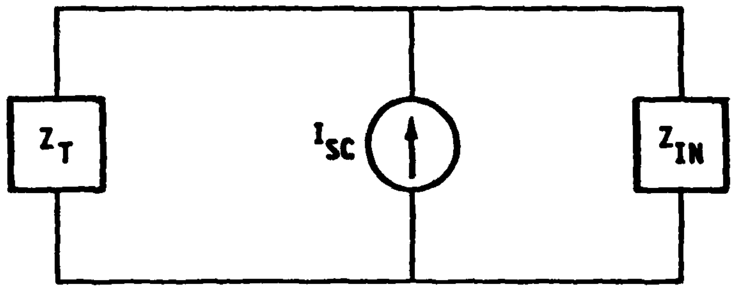
b. Equations for Threat Estimation

For simplicity, the threat waveforms are categorized according to four types of coupling, i.e., exposed wire, inductive slot, resistive joint, and diffusion. For each type of coupling, the open circuit voltage and short circuit current are computed for two cases, $Z_T = 0$ (the terminating common mode load at the far end is small compared to the common mode characteristic impedance of the wire bundle) and $Z_T = 00$ (the terminating load is large compared to the common mode characteristic impedance).

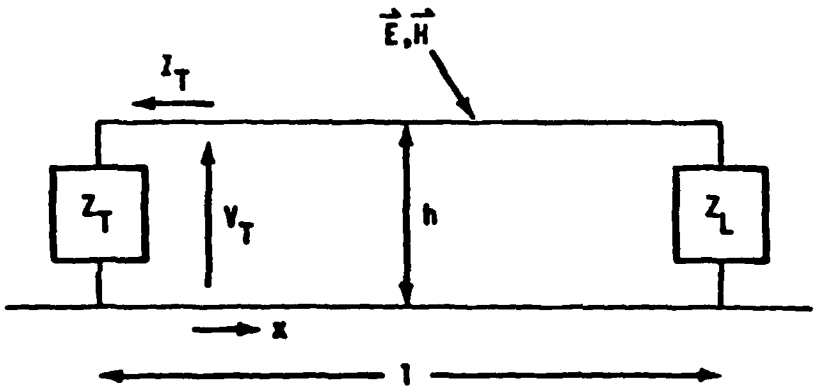
Figure 2 depicts the electromagnetic problem, i.e., a wire bundle of length l and height h above the ground plane, with exposure to lightning-induced electromagnetic fields. The Norton equivalent circuit is also shown in Figure 2. The transient current or voltage waveforms are seen at the terminating load, Z_T. In obtaining the equations shown in Tables 1 to 4, it was assumed that airframe resonances may be neglected for the direct strike case. Analysis of airframe resonances using the transmision line model of Section II.3.a, together with limited in-flight data show that this is the case.

The rationale for limiting the threat definition to a common mode transient is as follows. For a common mode excitation (i.e., the incident electromagnetic field is the same at all wires in the bundle), the differential mode transients are determined by the terminating loads. If the computed common mode threat is injected into the interconnecting wire bundle with the terminating equipment loads attached, then the differential mode transients (as well as common mode) obtained in the test will be an adequate simulation of the true threat. For determination of survivability by analysis, the application of the common mode threat is more complicated. A worst case approximation to the threat may be obtained on a case-by-case basis, by identifying the circuit component most likely to suffer voltage breakdown, and assuming that it draws the full short circuit current taking into account the circuit loads at the far end of the cable.

The complex circuit models may not be appropriate for preliminary lightning protection design requirements. A more cost-effective approach is to estimate the common mode threat seen on the circuit and determine circuit survivability by analysis or a threat simulation test. The threat simulation test is described in the following paragraphs.



NORTON EQUIVALENT CIRCUIT



EXPOSED CONDUCTOR CIRCUIT

Figure 2 Lightning Induced Electromagnetic Fields

TABLE 1 EQUATIONS FOR THREAT ESTIMATION FOR EXPOSED WIRE

	Low Frequency Component	Damped Cosine Amplitude	Damped Sine Amplitude	Resonance
V_{OC} $(Z_T=0)$	$F(\dot{I}_L)$	$(4F)\,\dot{I}_{PK}/\pi$	$\frac{(4F\dot{I}_{PK})}{\pi}(Z_L/\beta Z_A)$	$\lambda/4$
I_{SC} $(Z_T=0)$	$\frac{F}{L_W}(I_L)$	$(2F\dot{I}_{PK}/\pi Z_C)(Z_L/\beta Z_A)$	$(2F)\,\dot{I}_{PK}/\pi Z_C$	$\lambda/2$
I_{SC} $(Z_T=\infty)$	$\frac{F}{Z_C}(\dot{I}_L)$	$(4F\,\dot{I}_{PK}/\pi Z_C)(Z_L/\beta Z_A)$	$(4F)\,\dot{I}_{PK}/\pi Z_C$	$\lambda/4$
V_{OC} $(Z_T=\infty)$	$\frac{Z_C F}{L_W}(I_L)$	$(2F)\,\dot{I}_{PK}/\pi$	$(2F\,\dot{I}_{PK}/\pi)(Z_L/\beta Z_A)$	$\lambda/2$

$F = \mu \int_{\text{exposure}} h\,dx/C(x)$ $\mu = 4\pi \times 10^{-7}$ henries/meter

h = height of wire above ground plane

$C(x)$ = effective circumference of airframe

Z_C = common mode characteristic impedance of wire bundle

Z_L = characteristic impedance of lightning channel

Z_A = characteristic impedance of airframe

β = common mode relative velocity of wire bundle

I_L = lightning current waveform

$\dot{I}_{PK}$ = peak rate-of-rise of lightning current

L_W = common mode total inductance of wire bundle

TABLE 2 EQUATIONS FOR THREAT ESTIMATION FOR INDUCTIVE SLOT

	Low Frequency Component	Damped Cosine Amplitude	Damped Sine Amplitude	Resonance
V_{OC} $(Z_T=0)$	$K\ L_S\ \dot{I}_L$	$4\ K\ L_S\ \dot{I}_{PK}/\pi$	0	$\lambda/4$
I_{SC} $(Z_T=0)$	$K\ L_S\ I_L/L_W$	0	$2KL_S\ \dot{I}_{PK}/\pi Z_C$	$\lambda/2$
I_{SC} $(Z_T=\infty)$	$*K\ L_S\ C_W\ (1-X/l)\ddot{I}_L$	0	$4\ KL_S\ \dot{I}_{PK}/\pi Z_C$	$\lambda/4$
V_{OC} $(Z_T=\infty)$	$K\ L_S(1-X/l)\ \dot{I}_L$	$2\ KL_S\ \dot{I}_{PK}/\pi$	0	$\lambda/2$

K, L_S defined in Appendix C; $(V_{wire} = K\ V_{slot})$

X = distance from end of wire bundle to slot

l = length of wire bundle

All other parameters described under Table 2-1

* There is insufficient data to determine $\ddot{I}_L$.

TABLE 3 EQUATIONS FOR THREAT ESTIMATION FOR RESISTIVE JOINT

	Low Frequency Component	Damped Cosine Amplitude	Damped Sine Amplitude	Resonance
V_{OC} $(Z_T=0)$	$KR_J\ I_L$	0	$4\ KR_J\ \dot{I}_{PK}/\pi W_0$	$\lambda/4$
I_{SC} $(Z_T=0)$	$\frac{KR_J}{L_W}\ Q_L$	$2\ KR_J\ \dot{I}_{PK}/\pi W_0 Z_C$	0	$\lambda/2$
I_{SC} $(Z_T=\infty)$	$KR_J C_W(1-X/l)\dot{I}_L$	$4\ KR_J\ \dot{I}_{PK}/\pi W_0 Z_C$	0	$\lambda/4$
V_{OC} $(Z_T=\infty)$	$KR_J(1-X/l)\ I_L$	0	$2\ KR_J\ \dot{I}_{PK}/\pi W_0$	$\lambda/2$

K defined in Appendix C; $(V_{wire}=K\ V_{slot})$

$R_J = 1/(Y_J C)$

Y_J = joint admittance/length

C = effective circumference of airframe at joint

C_W = total common mode capacitance of wire bundle

$W_0 = 2\pi f_0$, fo = resonant frequency

$Q_L(t) = \int^t I_L(\bar{t})d\bar{t}$

TABLE 4 EQUATIONS FOR THREAT ESTIMATION FOR DIFFUSION

	Low Frequency Component	Damped Cosine Amplitude	Damped Sine Amplitude	Resonance
$V_{OC}(Z_T=0)$	$Z_M(0)\ K\ I_L$	$4K\ B(W_0)\dot{I}_{PK}/\pi W_0$	$4\ K_A(W_0)\dot{I}_{PK}/\pi W_0$	$\lambda/4$
$I_{SC}(Z_T=0)$	$\frac{Z_M(0)\ K\ Q_L}{L_W}$	$2K\ A(W_0)\dot{I}_{PK}/\pi W_0 Z_C$	$2\ KB(W_0)\dot{I}_{PK}/\pi W_0 Z_C$	$\lambda/2$
$I_{SC}(Z_T=\infty)$	$Z_M(0)K_1 C_W \dot{I}_L$	$4K\ A(W_0)\dot{I}_{PK}/\pi W_0 Z_C$	$4\ KB(W_0)\dot{I}_{PK}/\pi W_0 Z_C$	$\lambda/4$
$V_{OC}(Z_T=\infty)$	$Z_M(0)K_1\ I_L$	$2K\ B(W_0)\dot{I}_{PK}/\pi W_0$	$2\ KA(W_0)\dot{I}_{PK}/\pi W_0$	$\lambda/2$

$$K = \int_{\text{exposure}} dx/C(x)$$

$C(x)$ = effective circumference of airplane at x

$Z_M(W)$ = transfer impedance for diffusive surface

$Z_M(W) = A\ (W) + jB(W)$

$Z_M(0) = 1/(\sigma t)$

σ = conductivity of material

t = thickness of material

$$K_1 = \int_{\text{exposure}} (1-X/l)\ dx/C(x)$$

$W_0 = 2\pi f_0$, f_0 = resonant frequency

l = length of wire bundle

c. Threat Simulation for Equipment Tests

In order to define a test which adequately simulates an induced transient threat, the following is required:

1. An accurate representation of the threat waveform seen at the circuits, i.e., the spectral content and energy.
2. An accurate source impedance for the pulser.
3. Representative hardware, which includes:
   a. Terminating loads
   b. Interconnecting wire bundles
4. A well-defined pass-fail criterion

A detailed test procedure is beyond the scope of this section. It is intended, instead, to give an overview of test methods. A forthcoming document being drafted by the SAE committee AF4L (Reference 5) will give general guidelines for test definition.

There are three test methods for simulating an induced transient threat:

1. Direct injection into interface circuits.
2. Transformer coupling to interconnecting wiring.
3. Exposure of equipment and interconnecting wiring to transverse electromagnetic (TEM) fields in a parallel-plate simulator.

In the following discussion, only a common-mode threat simulator will be considered.

Direct Injection Method

In order to illustrate this method, consider a pair of LRU's connected by an unbranched wire bundle which is exposed to lightning-induced fields. Designate the LRU to be tested as "Box A" and the other as "Box B". Given the common mode termination of the wire bundle at Box B, one can compare this to the characteristic impedance of the wire bundle and determine whether to use $Z_T = 0$ or $Z_T = \infty$ in Tables 1 through 4. The appropriate source impedances are shown in Table 5.

TABLE 5 SOURCE IMPEDANCES FOR DIRECT LOW FREQUENCY INJECTION TESTS

	Low Frequency Component	Damped Sine or Cosine
$Z_T = 0$	jwL_W	$2\ Z_c$
$Z_T = 00$	$1/jwC_W$	$Z_c/2$

The parameters of Table 5 are defined in Tables 1 through 4. For a pulser with the appropriate source impedance, the threat waveform may be established by comparing the pulser output to the desired V_{OC} or I_{SC}.

Transformer Coupling to Interconnecting Wiring

Again consider a pair of LRU's connected by a wire bundle. The test will consist of coupling an induced transient on the interconnecting wire bundle with Box A at one end and Box B, or a simulation thereof, at the other. If the test bundle is the same length as that which will be used in the aircraft, the simulator need only produce the low frequency component, as the resonances will be produced by the wire bundle. If the test bundle is appreciably shorter than the actual installation, then both the low frequency and resonant waveforms must be simulated.

Parallel-Plate Simulator

For a system consisting of several LRUs, it may be appropriate to excite the interconnecting wiring simultaneously. For this test, the wiring and equipment for the entire system should be representative of that to be used on the aircraft. The threat waveform for the TEM fields produced in the simulator should approximate the lightning current waveform. The lay of the wire bundles, which determines the characteristic impedance, should be the same as the aircraft installation.

Ideally, the simulator should be sufficiently large to enable one to lay out the wiring in straight runs between equipment boxes. The termination of the parallel plates enables one to test for TEM (matched), H-field only, (short circuit), or E-field only (open circuit).

3. Lightning Math Model

To assess the lightning threat, computer models of selected circuits were developed to calculate lightning-induced transients for the moderate and severe threats. In developing the circuit models, it became apparent that certain design modifications can significantly reduce the lightning induced transients. These modifications are noted in the text describing the circuit models. Also, data are derived from these models to aid the design engineer in the overall protection of his electrical system design.

The direct attachment of the lightning column to aircraft wiring was not analyzed. Rather, it was decided to protect against this threat by controlling the wire routing and adding protective coatings to non-conductive structure to prevent this occurrence as suggested in References 6 and 7. This protection will be more reliable and cost-effective than incorporating protective devices in the wiring and circuitry adequate for the full lightning current. (See Sections VI and VII)

a. Lightning-Airframe Interaction Model

The lightning channel-airframe interaction was modeled as a mismatched transmission line. The lightning channel impedance was chosen to be 500 ohms. The airframe impedance was obtained by approximating the fuselage wing as an ellipsoid of revolution.

The simple model gives the total current and charge in the airframe at any point along the current path. The surface current and charge were then obtained by calculating the effective circumference at the point of interest. The current density on the leading edge of a wing of rectangular cross section, for example, is given by the equation:

$$J_S = I/C_{eff}$$
$$C_{eff} = C\sqrt{\frac{\pi b}{a}}$$

Where C = circumference of wing, a = wing chord, and b = wing thickness. The current and charge density along the leading and trailing edges of the wing (approximated as an ellipse) will be enhanced 2 or 3-fold above that for a cylinder of the same circumference.

The end result of the analysis of the lightning-airframe interaction is the charge and surface current densities over the conducting exterior surfaces of the airframe. These quantities are then used to obtain the fields at the location of wire bundles as described in the following Section.

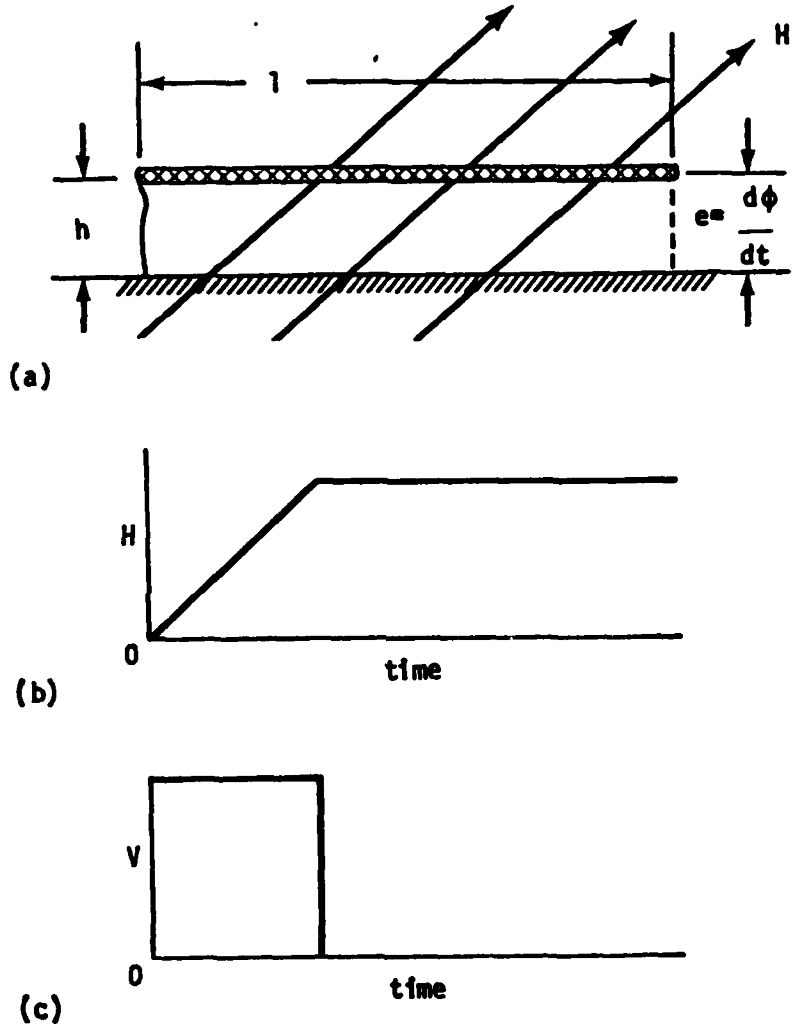
b. Wire Modeling

The geometry of aircraft wiring lends itself naturally to transmission line analysis. The transmission line parameters were obtained from computing self and mutual inductances and capacitances for the individual wires, along with wire and ground return resistances. These parameters were obtained from wire radius, wire-to-wire separation, height above ground plane, and dielectric constant of insulation, using textbook formulas. These line parameters were then entered, along with the sources, into the Boeing TRAFFIC code for computation of transients.

<u>Description of Magnetic Coupling</u>

Figure 3 depicts magnetic coupling of lightning surface currents to a wire. The voltage, e, is the open circuit voltage seen at the end of a wire which is grounded at the other end.

If only common-mode voltages without transmission effects are considered, the coupled transient voltage will be shown in equation 1. This voltage will appear between the end of the wire bundle and nearby airplane structure. For a wire which is terminated in circuit loads, this voltage will divide between the loads at the ends of the bundle inversely as the impedance of the loads.



(a) Physical circuit schematic
(b) Magnetic field waveshape
(c) Voltage waveshape

Figure 3 Open Circuit Voltage/Magnetic Field Dramatization

$$e = \frac{d\phi}{dt} = (\mu_o)(A)\frac{dH}{dt}, \qquad (1)$$

where A = area of loop: meters squared

μ_o = permeability of free space, $4\pi \times 10^{-7}$: henries per meter

ϕ = total flux linked: webers

H = magnetic field intensity: amperes per meter

t = time: seconds

e = voltage: volts

Expressed in inch units:

$$e = 8.11 \times 10^{-10}\,(l)(h)\left(\frac{dH}{dt}\right), \qquad (2)$$

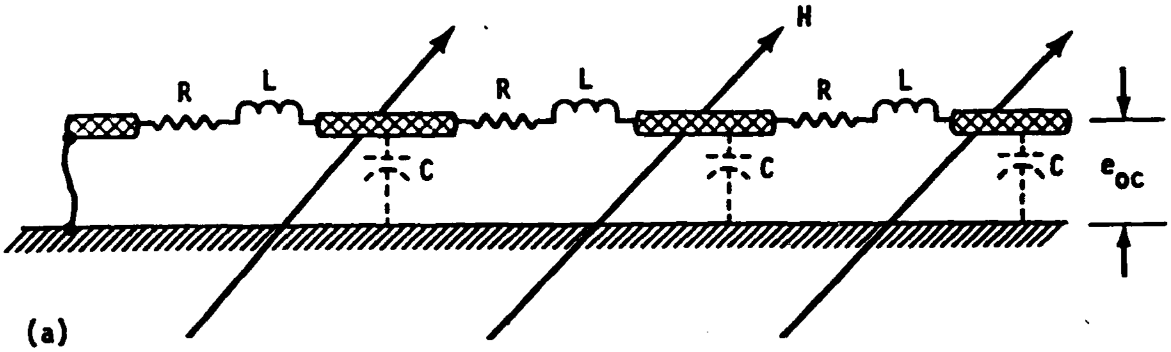
where l = length of cable bundle: inches

h = height above ground plane: inches

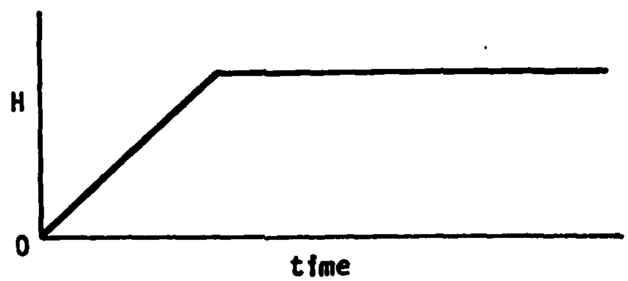
H = magnetic field intensity: amperes per meter

t = time: seconds

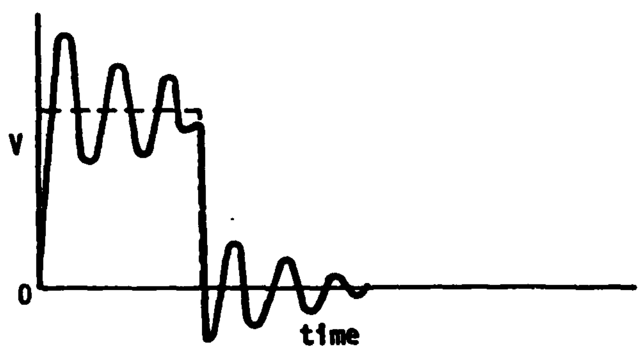
In the development of the models, the effects associated with the resonant response of the transmission line were included. Figure 4 shows the open circuit voltage and the open end of a magnetically excited, resonant line. In general, airplane wiring is grouped into bundles consisting of both short and long conductors, so when exposed to a magnetic field the resultant transient responses in the voltage waveshapes are more complex.



(a)



(b)



(c)

(a) 'hysical R,L,C circuit schematic

(b) Magnetic field waveshape

(c) Voltage waveshape

Figure 4 Open Circuit Voltage Response Caused by a Changing Magnetic Field

SECTION III

TECHNIQUES FOR INHERENT HARDENING

With the advent of composite aircraft, protecting the airvehicle electronic/electrical equipment from lightning transients has become a primary concern in the overall airplane design. Today's aluminum airframes, by virtue of their excellent conductivity, rarely suffer critical damage from lightning strikes; and these structures provide excellent protection for more vulnerable systems within. However, taking their place are aircraft constructed of fiber-reinforced plastics with light-weight and high strength properties but with poor electrical conductivity. The potential hazards generated by these new aircraft exposed to the lightning environment have prompted many studies of lightning effects and protection techniques.

Wire routing will be one of the first items to be designed into the airplane as more inherent airframe shielding will be utilized. Paragraph III.1 highlights the rules governing wire routing. After maximizing the inherent airframe shielding for equipment location and wire routing, the design engineer will be better prepared for judicious usage of shielding and other add on protection devices for the most flight critical equipment. This section of the design guide reviews the lightning effects on metallic structures and discusses the inherent hardening protection techniques applicable for the electrical system design. Also, this section reviews the lightning effects on non-metallic materials such as fiber-glass and advanced composites and the inherent hardening protection techniques applicable for the electrical system designed for installation within this type structure.

1. Wire Routing

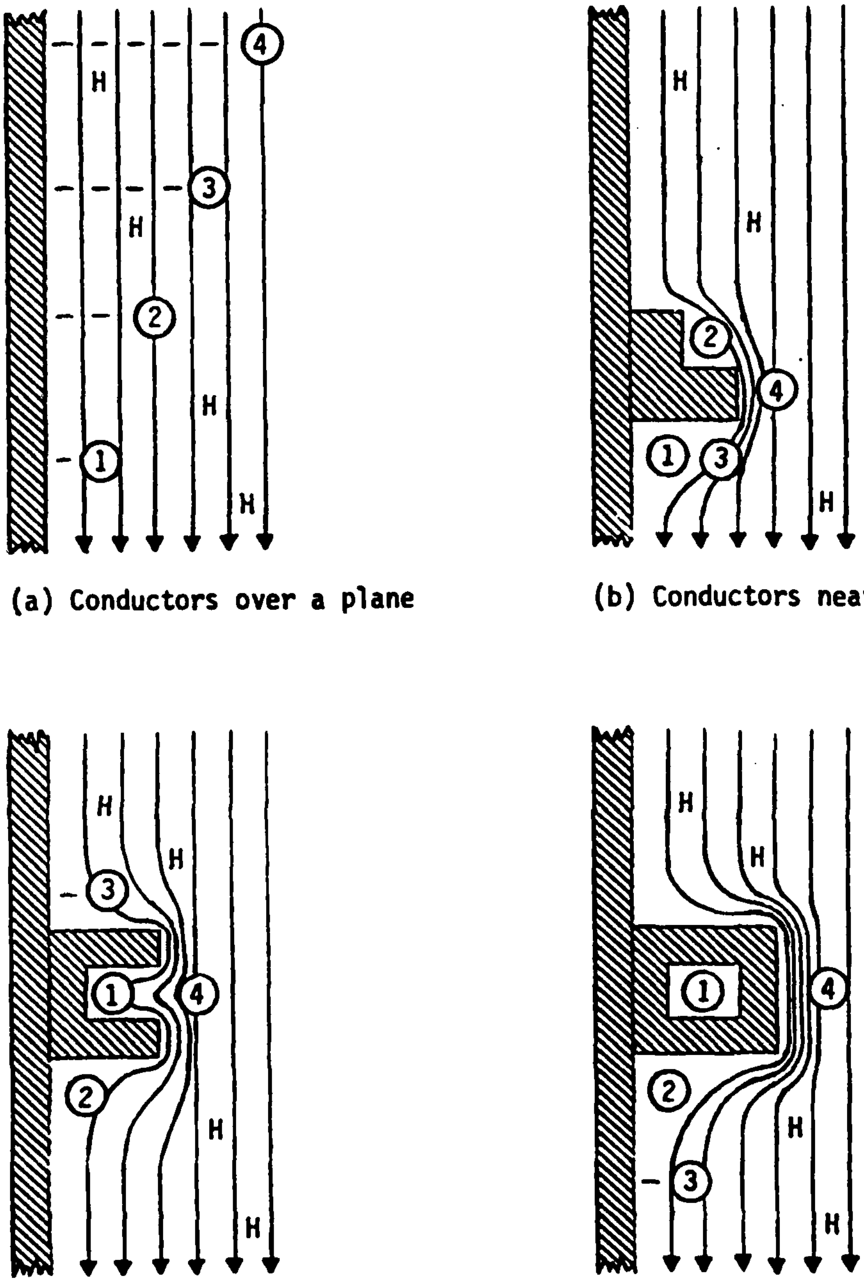
The primary reason for optimizing wire routing is to reduce the amount of electromagentic flux coupled onto the conductors. Wiring should be located as close as possible to the ground plane or structural frame. Route exposed wiring (e.g., wires underneath a leading edge of a poorly conducting material) close to the metal structure (e.g., aluminum front spar). The amount of flux that is coupled to a wire is proportional with the distance separating the two conducting mediums. Wiring should be located away from aperatures (e.g., windows) and regions where the radius of curvature of the airplane frame or outer skin is the smallest. In particular, do not route wiring across obvious slots (e.g., access doors). Magnetic fields are most concentrated at protruding structural framework points and tend to diverge inward producing a weaker field intensity in the corners. Inherent shielding is provided if the cable can be routed in a channel, and better yet inside an enclosed channel. Avoid using structural return for exposed power wiring. Figure 5 shows the deviation in magnetic flux linkage due to metallic obstruction with respect to conductor position (Reference 6).

For lightning protection and a good EMC design, subsystems should be grouped together as much as possible. That is, keeping units or equipment of the same function close together. The introduction of composites has brought a greater need for functional grouping of circuits, subsystems, and equipment. The aircraft has been a natural shielded enclosure which provided partitioning. With composite structures electrical equipment and interconnecting and distribution wiring must take into account new shielding and ground plane demands that were previously supplied by aluminum structure.

Since shielding will be less and coupling high, there is a greater need for interconnecting cables which are separated by energy categories (power, signal, rf, etc.). Where space is available, it is recommended that wiring be separated by signal/energy categories. Table 6 defines possible energy categories and wire separation distances (Reference 1).

Connectors

Definition of the total circuit is required; the driver, the wiring, the receiver, operating frequency and intercircuit connections. Identify all identical circuits. Identify all common circuits, common returns, every ground connection, capacitor or resistor connection. Determine output and input impedances, balanced and unbalanced impedances to ground. Draw and diagram the total circuit on one sheet of paper. Check for other current paths that are not intentionally designed.



(a) Conductors over a plane

(b) Conductors near an angle

(c) Conductors near a channel

(d) Conductors near a box

FIGURE 5 Magnetic Flux Linkage Versus Conductor Position

In each case pictured: Conductor 1 - lowest flux linkage: best
Conductor 2 - intermediate flux linkage: better
Conductor 3 - intermediate flux linkage: good
Conductor 4 - highest flux linkage: worst

TABLE 6 WIRE SEPARATION DISTANCES FOR ENERGY CATAGORIES

		EED VII	RF VI	AUD V	SIG IV	SW III	SC POWER II	400 Hz PWR I
400 Hz PWR I	I	2 IN.	4 IN.	4 IN.	2 IN.	2 IN.	2 IN.	-
DC PWR	II	2	4	4	2	2	-	
SW	III	2	4	4	4	-		
SIG	IV	2	2	4	-			
AUD	V	2	2	-				
RF	VI	2	-					
EED	VII	-						

TYPICAL BUNDLE CLASSIFICATIONS

CATEGORY	TYPE
I	AC power bus AC control circuits AC power to transformer rectifier unit
II	DC power DC control circuits
III	Switching circuits - DC or secondary AC Hydraulic valves Motor drives Fuel systems Inductive loads
IV	Digital circuits
V	Low level, sensitive circuits Audio, analog DC reference, DC secondary power (filtered) Tempest
VI	Communications RF, video
VII	EED

When all circuits and connections have been identified assign identical or common circuits to the same connector. Circuit currents should enter and return in the same connector. Low frequency (less than one megahertz) may return in aluminum structure. Evaluate circuits for coupling and immunity.

The following rules adhere to those developed for the wiring above:

- Separate power and signal (if power must be in same connector, separate power and signal by ground pins)
- Separate families of circuits by frequency: audio, digital, coax, video
- Position wires for shortest route to other equipment
- Assign connectors for optimum wire routing to other equipment
- Dedicate connectors where possible.

Return Current Rule

Signal currents should return in the same interconnecting cable. Currents below one megahertz may be designed to return in aluminum structure with special care and analysis given to frequencies above 50 KHz. Current paths returning in structure must be designed and allowed to follow immediately adjacent to the cable (an image path). (Currents should not be forced to take a wide path through distant connectors and structure.)

A current probe measuring the net current flow (to and from) in an interconnecting cable would indicate zero or would indicate the current returning in nearby structure. Figure 6 illustrates this concept. Low frequency current returning in structure works well because aluminum aircraft structure has such a low resistance and impedance at those frequencies.

Adhering to the return current rule will help in organizing and assigning signal lines and their returns. There is an important exception to signals that can return in structure; never use structure for an audio return.

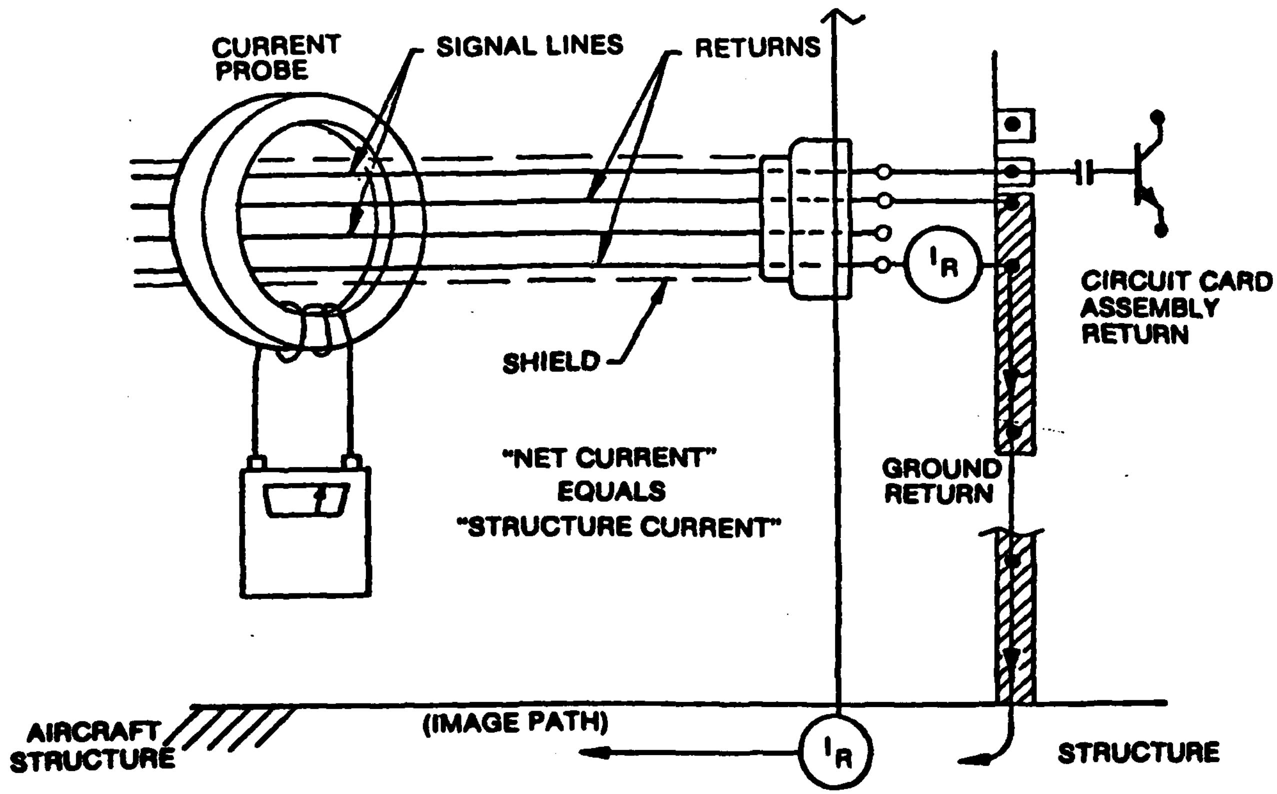


Figure 6 Return Current Rule in Aircraft Structure

Circuit and Shield Grounds

The structure return circuit shown in Figure 7 is susceptible to magnetic fields induced in the loop and should never be used for audio circuits. (It is also susceptible to capacitive coupled voltages and electric fields).

Adding a return lead and twisting the leads with only the receiver grounded offers excellent protection against magnetic fields. Grounding the circuit at both ends causes current flow that can result in interference. Twisted pairs also offer good protection to low impedance circuits for capacitive coupling.

Adding a shield (with the wires twisted) and grounding at the receiver and also provides protection against magnetic field. Figure 7 shows this circuit and the resulting induced voltage. The circuit and shield are at the same potential. The twisted pair cancels the magnetic field induced voltage. (Four amps at 400 Hz for 100 ft will induce less than 0.1 millivolt on either the twisted pair or the shielded twisted pair line shield grounded at the receiver).

Often it becomes necessary to ground the shield at both ends (or multiple locations) for containment of radio frequency (rf) fields or protection against rf fields and lightning transients. However, grounding the shield at both ends can degrade magnetic field protection. When the shield is grounded at both ends there is a potential difference between the shield and the circuit. When necessary, this situation must be evaluated with the possibility of using isolation or double shielding.

2. Equipment Location

The primary threat to equipment is the conducted threat delivered to the equipment by:

a. Exposed interconnecting wiring, or

b. Interconnecting wiring attached to an exposed element (e.g., windshield heater circuit).

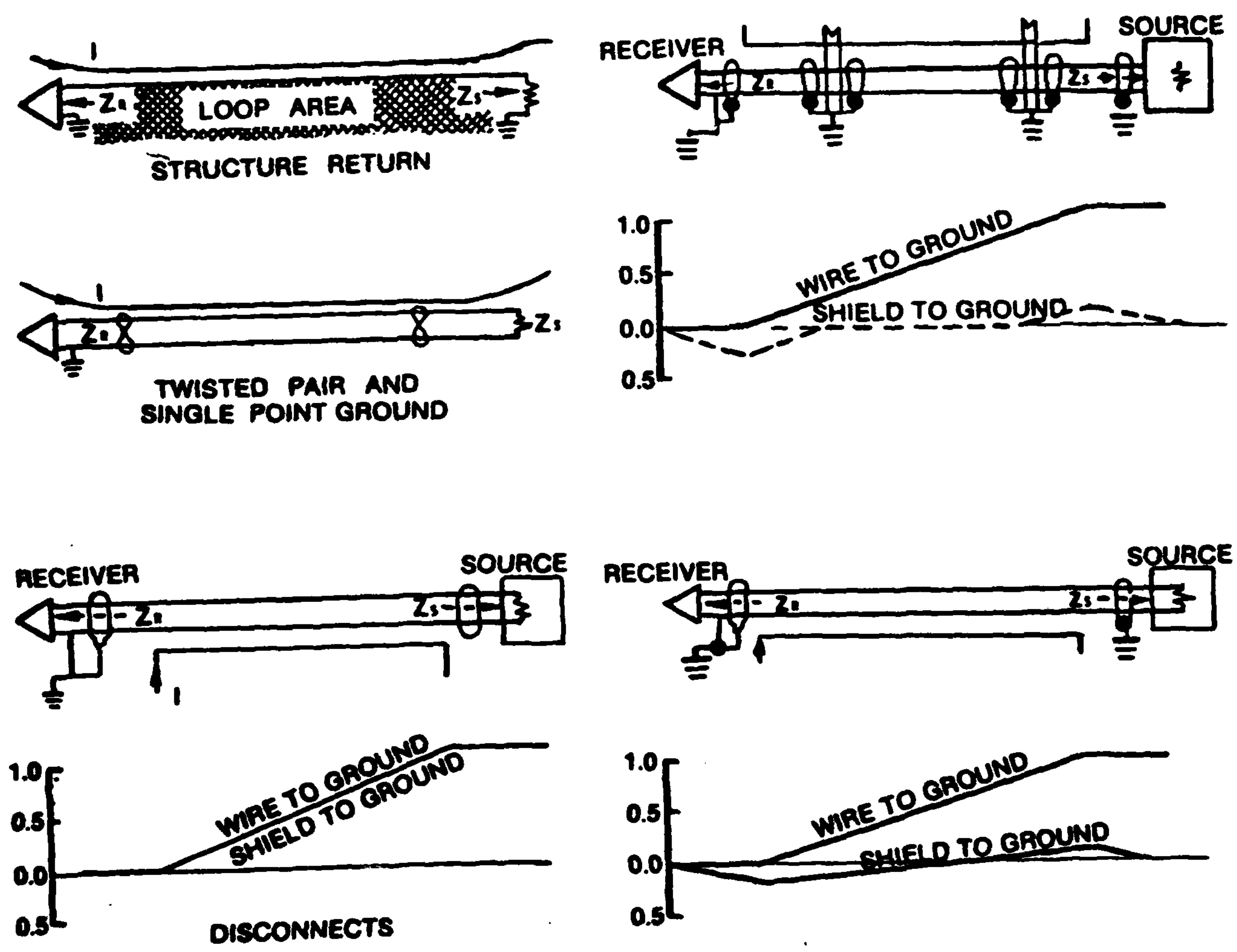


Figure 7 Structure Return Circuit and Its Induced Voltage

The only potential threat which depends upon the fields in the vicinity of the equipment is E-field coupling. (I.e., nearby electric fields may induce a voltage upon the wiring terminating in a poorly-grounded case.) In order of priority then, the rules for equipment placement are:

1. Locate equipment to minimize exposure of interconnecting wiring.
2. Locate equipment in areas which are shielded from electric fields induced by lightning. Note that, if the case is well grounded to structure, the E-field coupling problem is minimized.

Grounding of Equipment

Four hundred hertz power systems use structure for return currents in conventional aluminum aircraft. A wire return must be brought out of a unit of equipment so that the return current can be conducted to structure outside of the equipment prefereably at a centralized distribution box. See Section IV.4 for recommended designs of power current returns. Four hundred hertz power should not be grounded within a unit of equipment. There are a number of conventions implemented to establish a compatible and safe system through approved grounding techniques:

1. Isolate primary power and primary power return lines from chassis/structure.

2. Use at least two connector pins for power return lines

3. Connect chassis ground (internal to the unit) by a wire through the connector out to nearby external structure.

4. Provide electrical bond from case to structure or case to mounting plate to structure.

5. Isolate primary power from secondary power and signal circuitry by 1.0 megohm minimum.

6. Bring signal circuit ground out to a connector pin (for an optional tie to external structure ground).

Advanced composite (graphite/epoxy) structure is not suitable as a current return (ground) for AC or DC power systems. It may be feasible to ground some low current (under 5 amps) circuits which can tolerate the voltage drop and common mode coupling inherent in graphite/eopxy structural materials (Reference 1). See Section IV.4 for additional bonding information.

3. Fiber Optics as an Alternate Wiring Method

In areas of high vulnerability to lightning induced EMI, fiber optic transmission may be an attractive alternative to conventional wiring. The fiber optic signal transmission lines are electrically nonconductive and are not subject to electromagnetic coupling of lightning-caused or any other transients. Besides EMI/EMP immunity, the primary benefits of using fiber optics will be weight savings, increased bandwidth and elimination of ground problems. Fiber optic systems are well suited to either point-to-point links or data bus systems and can handle digital data transmission or analog signal transmission. The implementation of fiber optics will depend upon the benefits of fiber optics compared to some of the disadvantages which include interconnect problems, lack of standards, and lack of reliability data. Additional data on fiber optics can be obtained from Reference 10.

Table 7 describes the weight and bandwidth advantages of fiber optics. As shown, the weight savings is dependent upon the type of standard electrical cable to which it is being compared. Compared to a twisted pair (22 gauge), fiber optic cables offer approximately 22% savings in weight. For coaxial cable (higher data rate information), the savings is over 90%. Table 7 also addresses bandwidth, again as compared to a twisted pair and coaxial cable. At a standard loss of 4db/KM, the fiber optic cable (single strand graded index glass fiber) can operate up to 1 GHz. By comparison, both twisted pair and coaxial cables can operate only below 1 MHz. In this case, there are over ten orders of magnitude increase in bandwidth of a fiber optic cable as compared to a twisted pair or coaxial cable.

a. System Components

The primary components of various types of fiber optic links are summarized in

TABLE 7 COMPARISON OF FIBER OPTIC AND ELECTRICAL CABLES

CABLE TYPE	WEIGHT	BANDWIDTH (at 4 DB/Km Loss)	COST
Optical (single strand) (graded index glass)	22.8 Kg/Km	1 GHz	$0.25 to $1.00/ft
Twisted Wire Pair (22 gauge)	28.8 Kg/Km	150 KHz	$0.40 to $0.50/ft
Coaxial (RG-58/u)	43.5 Kg/Km	180 KHz	

TABLE 8 PRIMARY COMPONENT SELECTION

TYPICAL APPLICATION PRIMARY COMPONENT SELECTION

TYPE	SPEED	LENGTH	SOURCE	DETECTOR	FIBER	COMMENTS
POINT TO POINT	<50MHZ	<100M	LED	PIN	PCS	LOWEST IN COST AND CAPABILITY
POINT TO POINT	>50MHz	<100M	ILD	PIN	PCS	ILD REQUIRED FOR SPEED
DATA BUS	>50MHz	<100M	ILD	PIN	PCS	ILD REQUIRED FOR POWER NEEDS COUPLER DEVELOPMENT
POINT TO POINT	>50MHz	>100M	ILD	APD	GLASS ON GLASS	LONG LINE COMMUNICATIONS

Table 8. Low speed systems can be driven by light emitting diodes (LEDs) and detected by P-doped/intrinsic/N-doped (PIN) diodes. High speed applications will require the high frequency characteristics of injection laser diodes (ILDs) and avalanche photodiodes (APDs). All of the major fiber optic system components are discussed below.

b. Sources

There are two types of fiber optics sources, ILDs and LEDs. A summary of each is presented in Table 9.

There are two basic types of LEDs - edge emitters and surface (Burrus) emitters. Of the two, the Burrus diode is more widely used due to its generally better performance. It is also a more expensive device (as much as a factor of 100 times more expensive, depending on the quality). As the top of the Burrus diode is etched away to expose the active area, the devices normally comes pigtailed. Until recently, these devices were not hermetically sealed. One company now claims to have developed a hermetic pigtail Burrus diode.

Injection laser diodes (ILDs) are threshold devices. After a certain value of drive current, the output efficiency will dramatically increase. The point at which this increase occurs (the lasing threshold) varies from device to device even from the same manufacturer. Manufacturers normally supply a curve of output vs. drive current for each diode. ILDs are high priced devices. The reasons given for high price are the high development costs that need to be recovered, the complex structure, the high demand, and the low yields of the devices. One of the reasons for the low yields is that the structures are extremely complex but they are being standardized into 14-pin DIP package.

c. Connectors

Table 10 is a summary of data on connectors. Fiber optic connectors available today cover a very broad range from simple single contact fiber bundle or plastic fiber types to multicontact types capable of handling bundles, single fibers, and conventional wires in the same shell. Parameters of primary importance to connector performance include fiber alignment, protection, cable strain relief, size, and cost.

TABLE 9 INJECTION LASER AND LIGHT EMITTING DIODE ANALYSIS

COMPONENT: INJECTION LASER DIODES (ILD, DOUBLE HETEROSTRUCTURE GAALAS)	
RELIABILITY:	1%/1000 HOURS
STANDARDS (MILITARY/INDUSTRY):	1982 LARGE VARIETY OF DEVICES, NEW TECHNOLOGY
APPLICATIONS:	HIGH DATA RATE TRANSMISSION, HIGH EMI, EMP AREAS
FAILURE MODES AND MECHANISMS:	INFANT MOTALITY (FIRST 100-200 HOURS - CRYSTAL DEFECT RELATED). FACET DAMAGE (ELECTRICAL OVERSTRESS, CURRENT SPIKES - HIGH OPTICAL POWER DESTROYS FACETS). BULK DEGRADATION (GRADUAL MIGRATION OF DOPANTS INTO ACTIVE AREA, GRADUAL FACET EROSION - LIMIT OF DEVICE LIFE).
LIMITATIONS:	DEVICE IS TEMPERATURE SENSITIVE. SHOULD BE MAINTAINED AT 25°C OR LESS FOR MAXIMUM LIFETIME AND OUTPUT POWER. SENSITIVE TO ELECTRICAL OVERSTRESS, MUST BE PROTECTED FROM ANY CURRENT SURGES (EVEN OF LESS THAN 1NS).
COMPONENT: LIGHT EMITTING DIODES (LED, SURFACE EMITTER (BURRUS), EDGE EMITTER GAALAS)	
RELIABILITY:	1%1000 HRS
STANDARDS (MILITARY/INDUSTRY):	1981 CURRENTLY BEING GENERATED
APPLICATIONS:	LOW TO MODERATE (<50MHz) DATA RATE TRANSMISSION. LIMITED TO MODERATE LENGTHS (2Km OR LESS) TRANSMISSION. HIGH EMI, EMP AREAS. ANALOG APPLICATIONS.
FAILURE MODES AND MECHANISMS:	INFANT MORTALITY (FIRST 100-200 HOURS-CRYSTAL DEFECT RELATED). BULK DEGRADITION (GRADUAL MIGRATION OF DOPANTS INTO ACTIVE AREA COMMON TO ALL IC'S).
LIMITATIONS:	CURRENT DEVICES LIMITED TO <100MHz OPERATION. WIDE SPECTRAL WIDTH CAUSES DISPERSION PROBLEMS IN LONG LINKS.

TABLE 10 CONNECTOR ANALYSIS

COMPONENT: CONNECTORS (SINGLE TERMINATION, MULTITERMINATION)	
RELIABILITY:	NO DATA
STANDARDS (MILITARY/INDUSTRY):	1981 CURRENTLY BEING GENERATED
APPLICATIONS:	CONNECTIONS BETWEEN FIBER OPTIC COMPONENTS AND OPTICAL FIBERS.
FAILURES MODES AND MECHANISMS:	CONTAMINATES (SERIOUSLY IMPAIRS COUPLING EFFICIENCY) ADHESIVES FAILURE (BOND BETWEEN FIBER AND CONNECTOR FAILS UNDER ENVIRONMENTAL STRAIN).
LIMITATIONS:	DEVICES NOT DEVELOPED TO MIL/SPACE LEVELS DUE TO LACK OF MARKET AND LARGE EXPENSE. REQUIREMENTS SPECIFIC TO FIBER OPTIC CONNECTORS NEED TO BE DEFINED.

TABLE 11 CABLE AND FIBER ANALYSIS

COMPONENT: CABLE	
RELIABILITY:	NO DATA
STANDARDS (MILITARY/INDUSTRY):	1981 (CURRENTLY BEING GENERATED)
APPLICATIONS:	PROTECTION OF OPTICAL FIBER FROM HOSTILE CONDITIONS.
FAILURE MODES AND MECHANISMS:	BREAKAGE, KINKING, OUT GASSING (PHYSICAL DAMAGE TO FIBER)
LIMITATIONS:	CABLES ABLE TO MEET SPECIFIC MIL/SPACE REQUIREMENTS BUT NOT ALL REQUIREMENTS CONCURRENTLY. REQUIREMENTS SPECIFICALLY OF FIBER OPTIC CABLES NEED TO BE DEFINED.
COMPONENT: OPTICAL FIBER	
RELIABILITY:	NO DATA
STANDARDS (MILITARY/INDUSTRY):	1981 (CURRENTLY IN DEVELOPMENT)
APPLICATIONS:	LOW TO HIGH DATA RATE TRANSMISSION. SUITABLE FOR AREAS CLOSED TO ELECTRICAL WIRING. HIGH EMI, EMP AREAS. LOW BER.
FAILURE MODES AND MECHANISMS:	BREAKAGE OF FIBER.
LIMITATIONS:	TEMPERATURE EXTREMES. SOME FIBER TYPES MORE RADIATION RESISTANT THAN OTHERS. RESISTANT TO ADHESIVES USE.

d. Fibers/Cables

A summary of information on fibers and cables is given in Table 11. Ex:mples of cable construction are shown in Figure 8.

e. Dete‹ ‹ rs

A summary of detector data analysis is found on Table 12. This technology appears to be the most highly developed area of fiber optics. The detector chips are very durable and should last as long as other silicon diodes.

f. Fiber Optic Transmitter/Receiver Modules

Table 13 contains a summary of the transmitter/receiver modules data analysis. There is a large variety of fiber optic modules on the market. Most are designed for the commercial market although a few companies claim their modules will meet military specifications with the exception of the LED. One set of modules was designed under an Air Force contract.

The function of the modules is to be the interface between the electronics and the optical fiber. A typical transmitter module will contain an LED and the associated electronics necessary to drive it. The receiver module will be comprised of a photodiode and the electrical circuitry needed to translate the optical signal into an electrical signal. Usually, all that is necessary to operate the module is a supply voltage and an input (or output for the receiver) of the signal.

g. Couplers

A summary of the analysis on the coupler data is on Table 14. Couplers are a necessary part for use in data buses. A main disadvantage of fiber optics compared to conventional electrical wiring is the difficulty in splitting up the signal. At present, almost all fiber optic links are point-to-point systems, one output to one input. To increase the flexibility and utility of fiber optics, the ability to transmit one output into several inputs (or vice versa) will be necessary.

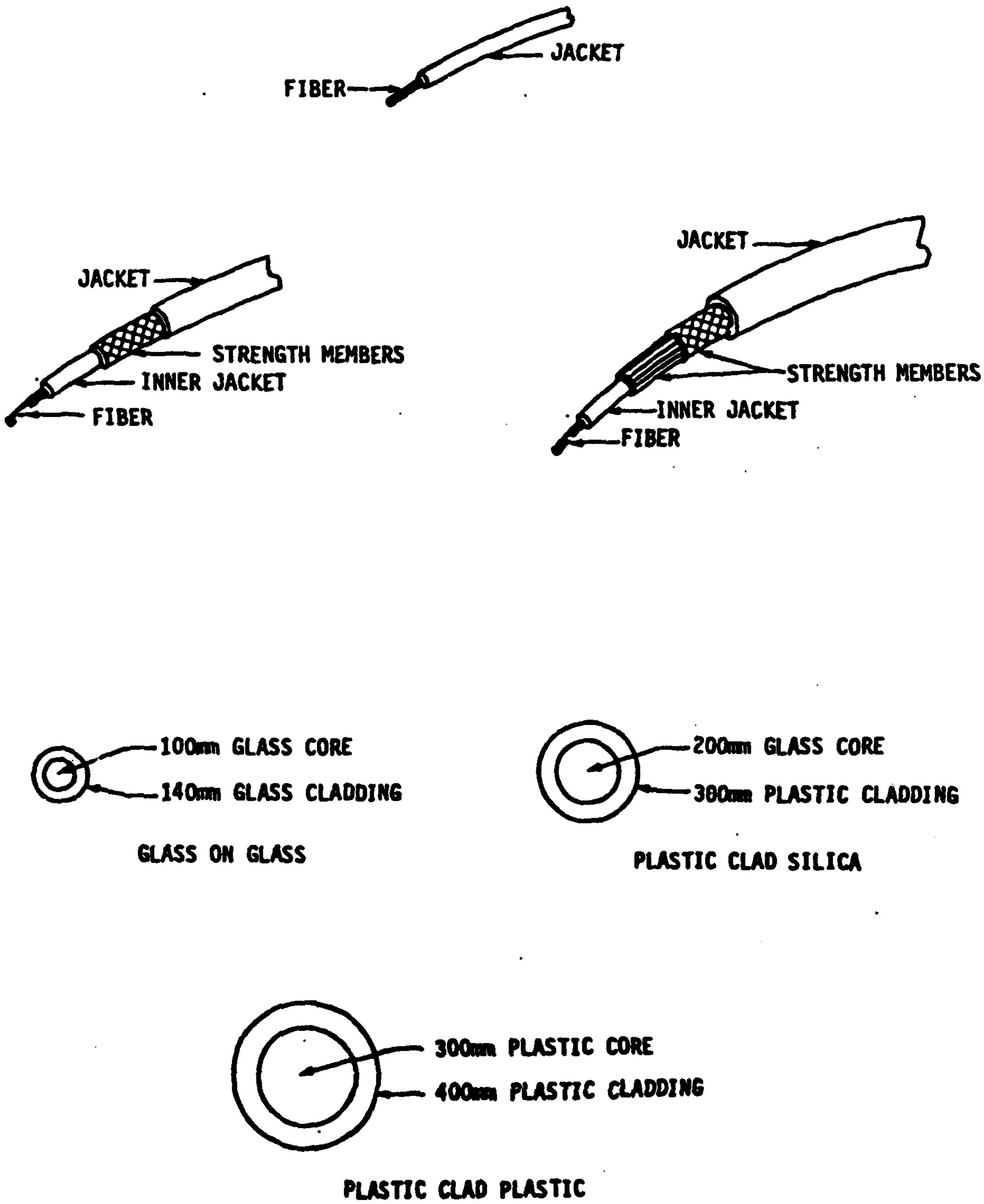


FIGURE 8 Cable Construction

TABLE 12   DETECTOR ANALYSIS

COMPONENT: DETECTORS	
RELIABILITY:	.1%1000 HRS
STANDARDS (MILITARY/INDUSTRY):	1981 (CURRENTLY BEING GENERATED)
APPLICATIONS:	ALL FIBER OPTIC LINKS
FAILURE MODES AND MECHANISMS:	ELECTRICAL OVERSTRESS. OPTICAL OVERSTRESS (EXTREMELY HIGH LEVELS NEEDED, UNLIKELY IN A FIBER OPTIC LINK)
LIMITAIONS:	PACKAGING IS NOT CURRENTLY OPTIMAL. APD'S GAIN TEMPERATURE AND VOLTAGE DEPENDENT. SILICON DETECTORS GOOD OUT TO 850 TO 900NM WAVELENGTHS

TABLE 13   MODULE ANALYSIS

COMPONENT: MODULES	
RELIABILITY:	2%1000 HRS
STANDARDS (MILITARY/INDUSTRY):	1981 (CURRENTLY BEING GENERATED)
FAILURE MODES AND MECHANISMS:	SUSCEPTIBLE TO FAILURES COMMON TO SOURCES, DETECTORS, IC'S, AND CONNECTORS
LIMITATIONS:	LOW DATA RATES (<10MHz). ENVIRONMENTAL LIMITATIONS (NONHERMETIC, TEMPERATURE RANGE)

TABLE 14   COUPLER ANALYSIS

COMPONENT: COUPLERS	
RELIABILITY:	NO DATA
STANDARDS (MILITARY/INDUSTRY):	1981 (BEING GENERATED)
APPLICATIONS:	DATA BUS REQUIREMENTS FOR USE IN FIBER OPTIC COMMUNICATION SYSTEMS
FAILURE MODES AND MECHANISMS:	INSUFFICIENT DATA
LIMITATIONS:	INPUT LOSSES ARE TOO HIGH. DYNAMIC RANGE OF OUTPUT TOO LARGE. DEVICES ARE BULKY AND FRAGILE.

4. Bonding and Grounding

It is standard practice in the aircraft industry to use the aluminum airframe as a ground return path for the AC and DC electrical systems and bonding techniques on conventional aluminum and other metal structures are well documented. However, bonding on composite aircraft structure requires methods in many instances that are currently being developed. Also, a composite structure aircraft will not perform the ground return function since the boron on graphite fibers are not continuous nor of sufficient conductivity to provide a current return (Reference 1).

Thus, one can readily see the problems confronting the design engineer, in that the type of structure used will determine the methods to be used in attaining adequate electrical bonds and grounds as well as the lightning protection techniques.

The electrical system designer must adhere to the bonding and grounding requirements established for the protection of the overall aircraft to ensure that a homogeneous grounding system is designed into the basic aircraft structure (Reference 11).

The achievement of reliable low impedance electrical bonds is of importance in advanced aircraft because of the following:

1. There is an increased use of high power electrical equipment where the potential for interference emission is high unless proper grounding is maintained.

2. There is an increased use of low voltage and low current signal transmission over a wide frequency band thus increasing susceptibility to EMI.

3. Military aircraft tend to have increased electrical/electronics packed into a smaller space and therefore less reliance can be placed on space attenuation for interference reduction.

4. The greater use of electrical and electronics equipment has brought about an increase in the number of control and signal lines again increasing the possibilities for EMI.

The following paragraphs address these problems and reference materials that will aide the design engineer in achieving good electrical bonding and grounding and provide system protection in a lightning environment.

a. Metallic Structured Aircraft

1) Methods of Bonding

There are three ways electrical hardware can be bonded to structures. These are listed below.

<u>Faying Surface Bond</u>

(1) All finishes which are non-conducting must be removed from the interfacing, contact area of the parts involved in the ground path prior to assembly of the parts.

(2) Faying surface bonds must be capable of carrying the maximum fault current until the circuit breaker interrupts, while complying with the bond resistance levels as determined from Table 15 and Figure 9. An exception to this requirement would be that equipment which has an additional case ground - via a wire or bonding jumper - and is <u>not</u> installed in a Fire Prevention or Protection Flammable Zone.

(3) Metals from mating parts should be electrochemically compatible. If this cannot be accomplished, since the materials involved are inherently corrosion-susceptible, then the interface bond should be protected from environmental exposure.

TABLE 15 TYPICAL RESISTANCE VALUES FOR BONDING EQUIPMENT TO STRUCTURE

SYSTEM: Electrical, Electronics

ITEM	CONNECTION	MAXIMUM RESISTANCE, (OHMS)
Connectors, Electric [2]	Jumper	0.0025
Dischargers, Electro-static (Base)	Faying	0.100
Equipment Shelves	Faying or Jumper	0.0025
Interphone Amplifiers	Faying or Jumper	0.0025
Panels	Jumper	0.0025
Radio Noise Filters	Faying	0.0005
Relays	Faying or Jumper	0.0025
Switches	Faying or Jumper	0.0025
Transformers	Faying or Jumper	0.0025
Transformer-Rectifier Units	Faying or Jumper	0.0025
Electrical Connection Allowable Resistance Values		
Antenna Mounts	Faying Jumper	0.0005 0.0010
Arresters, Lightning	Faying	0.0005
Battery Cases	Faying or Jumper	0.0025
Circuit Breakers	Faying	0.0025
Conduit	Jumper	0.0025

[2] If shell is used for grounding of shields.

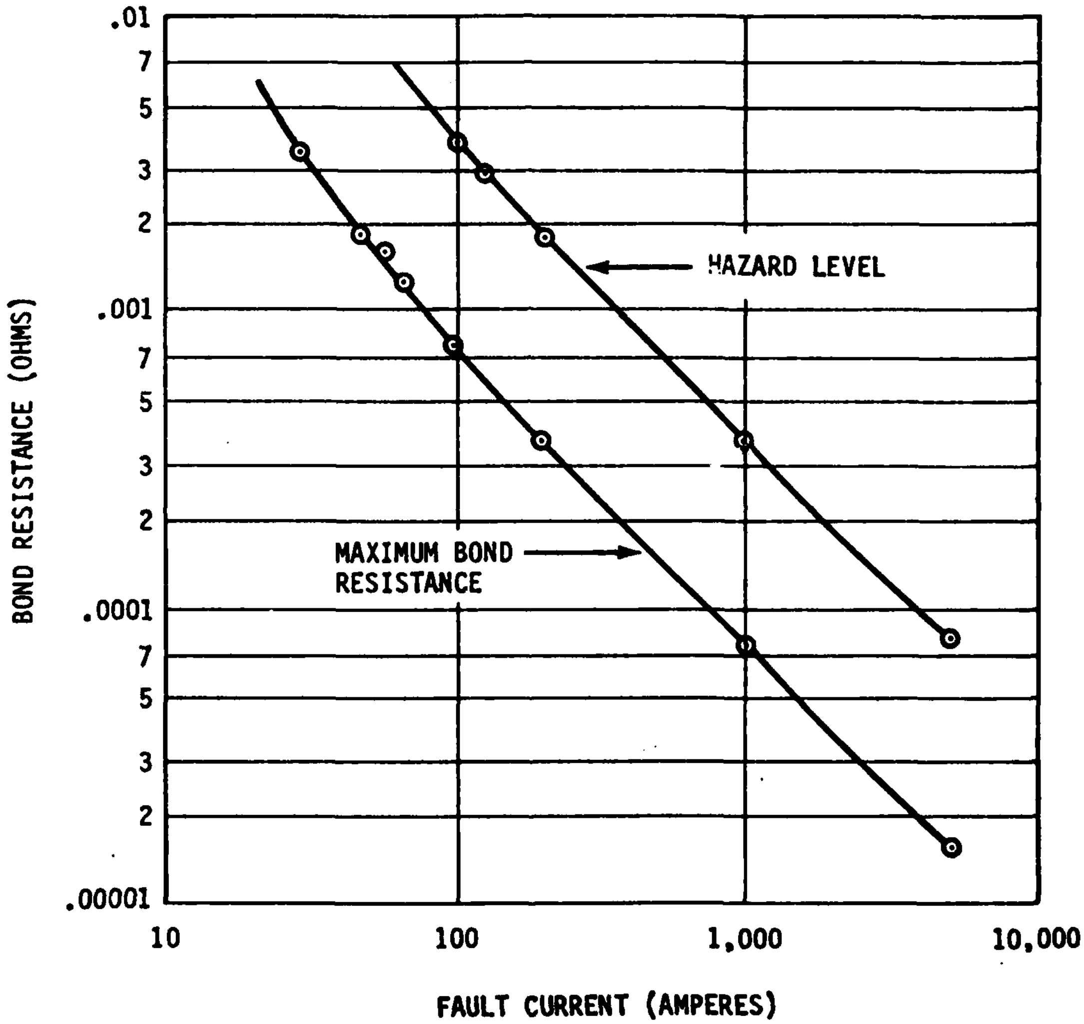


Figure 9 Bond Resistance Values in Hazard Areas

Grounding the Case Through Connector Contacts or Terminal Studs

(1) Wire, connector contacts and/or terminal studs must be capable of carrying the fault current from the largest circuit breaker protecting the wire and equipment until the breaker interrupts. (The external wire will be defined the same as any wire in the circuit and will be sized to equal the maximum fault characteristics of the equipment and power source.)

(2) The case ground should be isolated from, and independent of, the current return grounds.

(3) The internal case ground connection should be at a point on the case which is as physically close to the current carrying parts as practical and should be optimized to provide proper bonding for all internal components, but should not be identified with any internal circuit ground.

(4) If the equipment utilizes voltages in excess of 30 volts (Aerospace Industries Association Personnel Hazard Limit) and has more than one electrical connector which may be disconnected independently, then a case bond wire should be routed through each connector per the above (1) and (2) controls.

Bonding Jumper or Strap

(1) The jumper and attachment hardware must be capable of carying the fault current from the largest circuit breaker protecting the equipment, until the breaker interrupts. Tables 16 and 17 summarize data available on the current capabilities of jumper and attachment hardware.

(2) The jumper and attachment hardware must be capable of withstanding the associated temperature and vibration environments.

TABLE 16 STANDARD BONDING JUMPER DATA FOR METAL AIRCRAFT

Material to be bonded	Bac No.	Useful Temp Range	Smallest Lug	Largest Lug	Shortest Jumper Inches	Longest Jumper Inches	Wire Size CM	Continuous Current Rating Amperes (1)	Resistance ohms/in, Length (2)
Aluminum	BACJ40A		#6	3/8	2	15	6125	35	0.00016
	BACJ40C	-65°	1/4	3/8	3	13	14600	60	0.00010
to	BACJ40D		#10	5/8	1.5	13	42000	13.5	0.00003
	BACJ40E	to	#10	5/8	1.5	12	84000	200	0.000015
Aluminum	BACJ40F		#10	1/4	2	12	14600	60	0.00010
	BACJ40K	300°F	#10	3/8	3	24	6125	35	0.00016
Aluminum to Titanium or Stainless Steel	BACJ40AC	-65° to 300°F -65° to 450°F	#4	3/8	2	12	6125	35	0.00017
Titanium to Titanium or Stainless Steel to Stainless Steel	BACJ40AD	-65°F to 300°F -65° to 450°F	#4	3/8	2	12	6125	35	0.00017

(1) Also largest circuit breaker size with which jumper can be used. (2) at 68°F

TABLE 17 CURRENT CAPABILITIES OF FASTENERS

FASTENING TO ALUMINUM AND/OR COPPER PARTS	
FASTENER SIZE & THREAD/INCH MINIMUM	CONTINUOUS CURRENT CAPABILITY AMPERES (MAX) [1]
#6 - 32	10
#8 - 32	17
#10 - 32	73
1/4 - 28	135
3/8 - 24	245

FASTENING TO STEEL, STAINLESS STEEL OR TITANIUM			
FASTENER SIZE & THREAD/INCH MINIMUM	CONTINUOUS CURRENT CAPABILITY AMPERES (MAX) [1] -65°F TO 220°F	CONTINUOUS CURRENT CAPABILITY AMPERES (MAX) [1] -65°F TO 350°F	CONTINUOUS CURRENT CAPABILITY AMPERES (MAX) [1] -65°F TO 450°F
#8 - 32 #10 - 32 1/4 - 28 3/8 - 24 1/2 - 20 5/8 - 18	73	73	35

[1] THIS RATING INCLUDES THE TOLERANCE OF CIRCUIT PROTECTION. FOR EXAMPLE, A 10 AMP BREAKER PROTECTION WILL ALLOW 14 AMPERES CONTINUOUS, THUS A #18-32 FASTENER IS MINIMUM STUD SIZE.

(3) The jumper attachment shall be at a point on the case which is as physically close to the current carrying parts as practical.

(4) The materials used in the jumper and attachment hardware must be electrochemically compatible. Figure 10 shows electrical bonding jumpers for different metals at different temperature ranges.

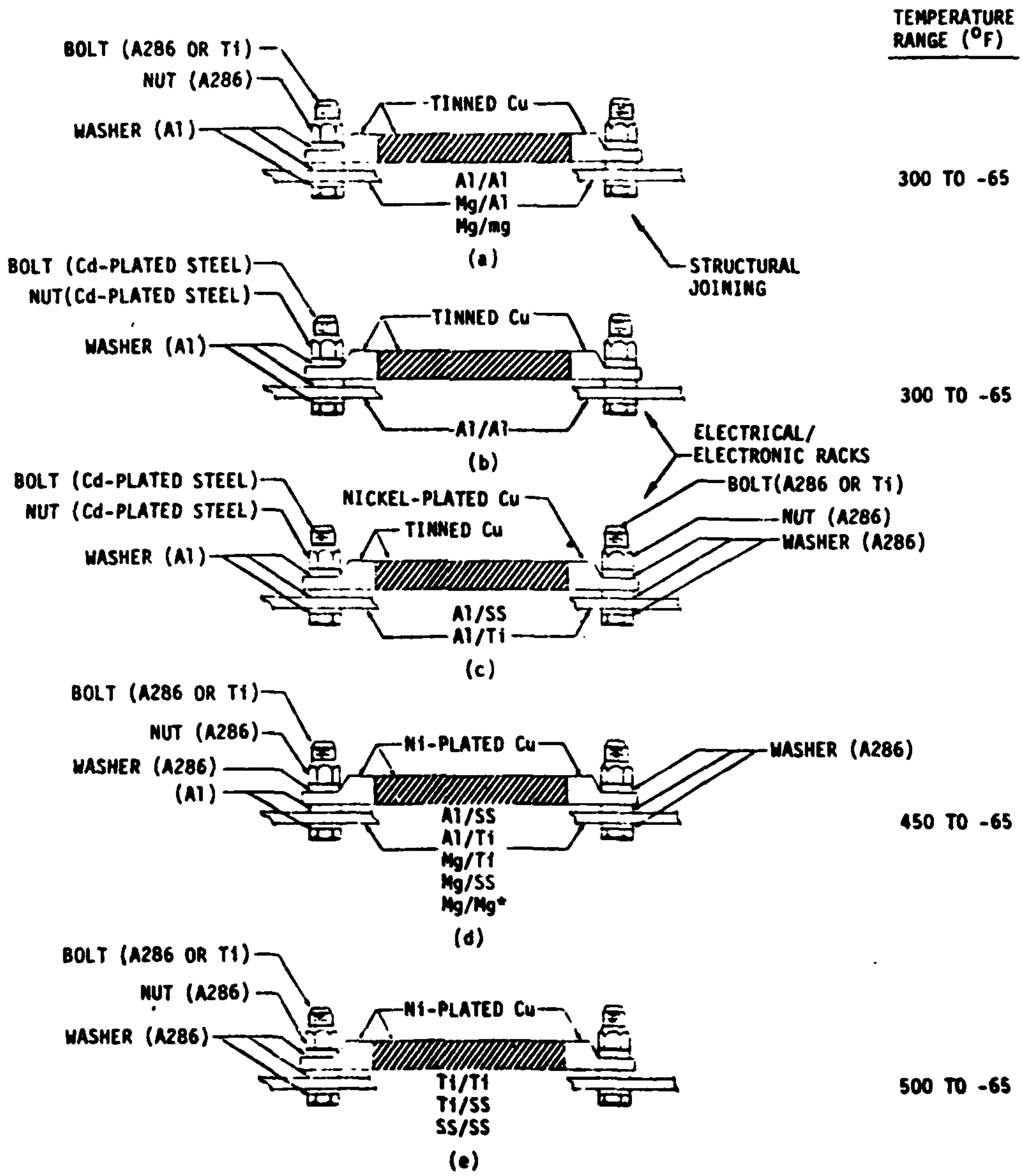
2) Current Returns

There probably is no other area in bonding and grounding considerations where the designer will find himself more in a difficult situation than in his consideration of current returns. On the one hand, he will be concerned with the maximum degree of safety that can be provided and on the other hand he will strive to design his equipment with the minimum susceptibility to interference. These two considerations are not always compatible. It is in this area, then, that the designer may need to thoroughly investigate state-of-the-art advances and evaluate these through extensive testing.

The following "rules" should constitute the basis for all current return considerations; however, - especially where electronic circuitry packaging is concerned - each individual case would have to be evaluated on its individual merits.

(1) AC and DC current returns (both for circuits utilizing airplane power system inputs and those in which AC or DC is generated within a subsystem) should be brought out of the equipment separately (see Figure 11). It should be a design objective on new equipment designs that the case not be used as a current return (except for EMI filters, which may be connected to current return and chassis).

(2) There shall be no single, physically common, tie point, either internal to the equipment or external in the ships wiring, where a single failure could result in mixing the airplane's AC and DC voltages (see Figure 11).



* USE LEFT STACK-UP FOR BOTH SIDES WHEN BOTH STRUCTURES ARE MAGNESIUM.

NOTE: CLEAN TITANIUM AND STAINLESS STEEL WITH BMS 3-2 TYPE I OR II SOLVENT; ALUMINUM AND MAGNESIUM REQUIRE ROTARY BRUSH CLEANING AND SEALING WITH SRF PRIMER (EXCEPT LEFT SIDE OF (d) REQUIRES HIGH-TEMPERATURE FINISH) AFTER STACK-UP COMPLETE.

Figure 10 Electrical Bonding Jumpers for Different Metals

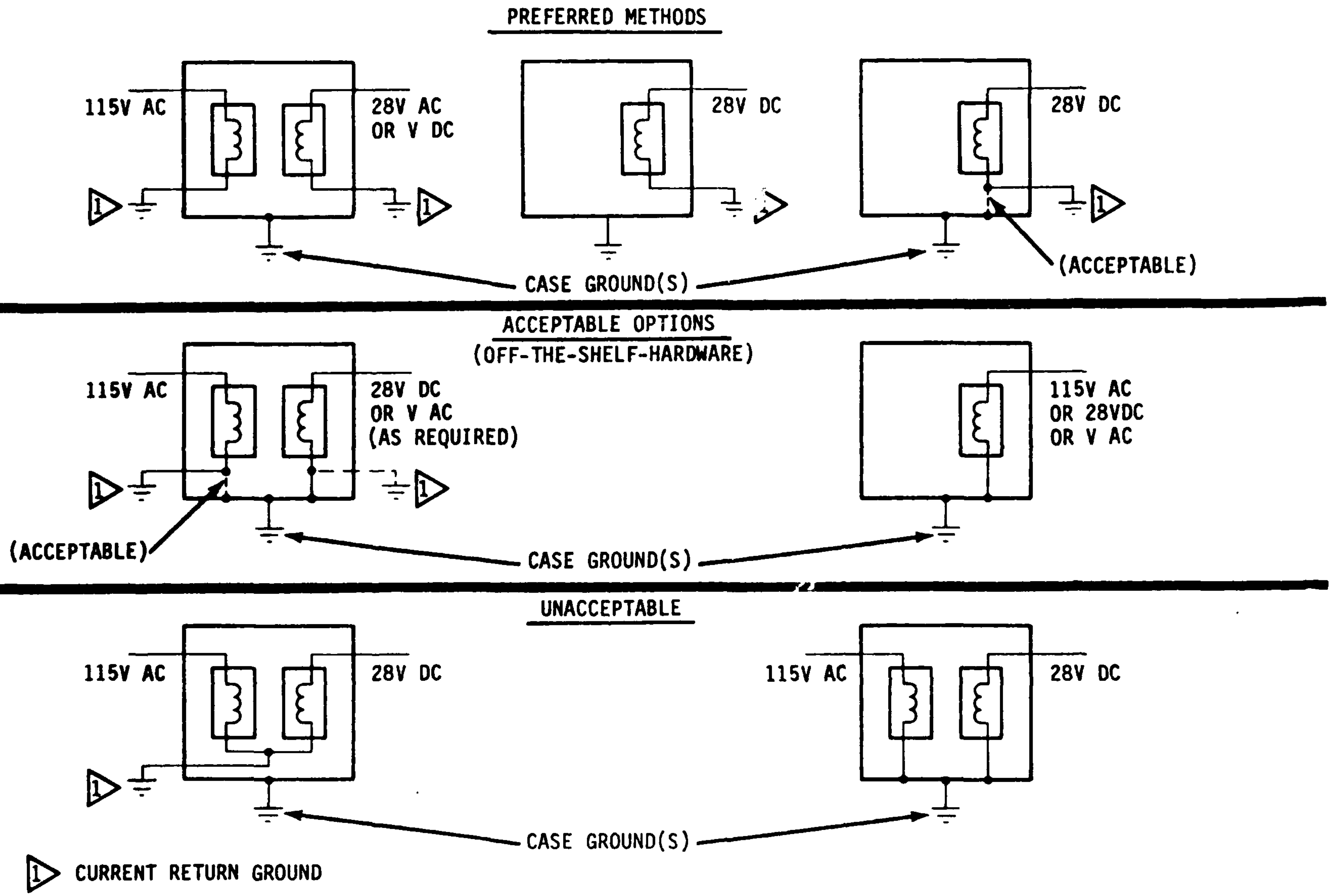


Figure 11 Current Return Grounding Options

(3) Separate current return leads - sized for current carrying capacity so that they are protected by the input circuit protectors - should be provided. This current return should be brought out of the equipment through a connector contact or wire attached to a stud (via terminal lug). Refer to Table 17.

(4) In Fire Prevention and Protection Flammable Zones an applicable dual ground termination is required. Dual ground implies that separate grounding means, such as faying surface bond and internal case ground are provided, each independently meeting the resistance requirements of Figure 9.

b. Composite Structured Aircraft

The use of composite structure has required the development of new electrical bonding techniques. New bond designs that do not comply with minimum safety (resistance) requirements in fuel hazard areas will require augmenting the conductivity of the composite structure by adding conductive materials or it will be necessary to use separate ground return and conduit for wire runs. All of which result in a significant cost and weight penalty.

1) Methods of Bonding

For a composite airplane where internal structure remains aluminum, a continuous path for current return can be provided by metal-to-metal construction. When the continuous metal path is broken by either plastic structure or where adhesive bonding methods are used, alternate current paths must be provided. Ways in which the current path can be provided are:

a) Providing a ground bus system
b) Usage of a ground return wire

The alternate current paths will prevent or minimize the electrical use of the fibers in the eopxy, since even low current levels could cause structural damage or composite degradation. (See Reference 1)

Also, for a composite aircraft where internal structure is not metal, the conductive ground plane will be gone and these alternate methods in addition to those suggested in Reference 1 will have to be evaluated. These include design concepts that use a method of embedding a wire screen in the graphite plies at the joint to provide a good electrical connection.

Figures 12 and 13 display some of the possible bonding techniques. The joints with the multiple intereleaved screens (Figure 12) provide a large amount of screen contact area and prove to be a better electrical bond than those with fewer screens. However, the addition of more screens reduces the structural area and increases the fabrication costs. Additional bonding problems arise with special requirements such as accessibility, maintainability, and repairability. The upper and lower surfaces of the wings provide a good example. In most cases at least one wing surface must be removable and in fuel areas the joints must be sealed. Present methods of using mechanical fasteners and a sealant groove are not acceptable in most cases for a sound electrical joint. Figure 14 shows an example of a grounded fastener concept to be considered.

2) Current Returns

Composite materials will not permit the use of aircraft structure for power return. The infinite ground plane as seen in all metal aircraft is not available. Also this loss of aluminum as a safety element may require a safety return system that parallels the power supply lines. Lightning currents and fault currents should be attracted to and conducted along these safety grounds. The installation of lightning diverters on the aircraft will increase circuit protection (See Section VI.4).

With the loss of the infinite ground plane, balanced circuits are viable alternatives for low cost and lightweight designs. Balanced circuits are immune to high levels of common mode voltages: they reject rf fields and transients and they tolerate relatively large ground shifts. Different types of balanced loading are shown in Figure 15.

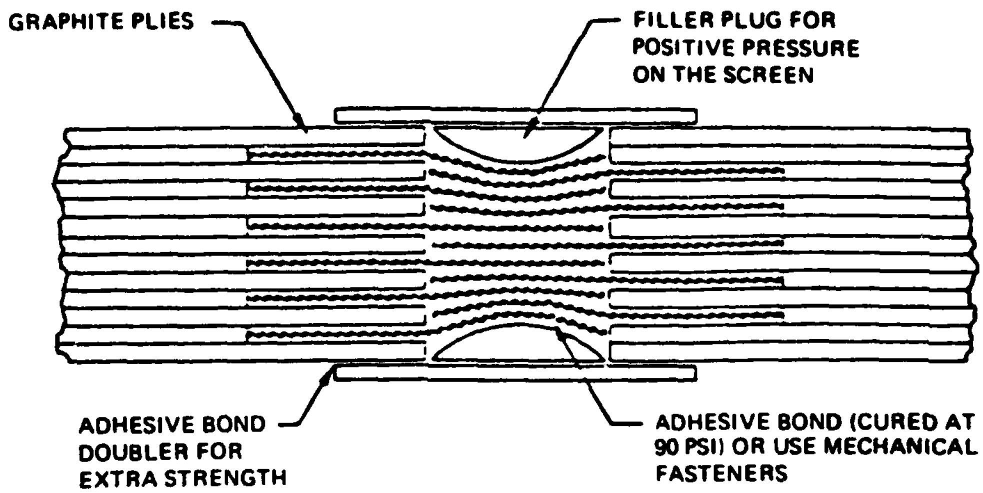


Figure 12 Multiple Screen Interleaved Lap Joint

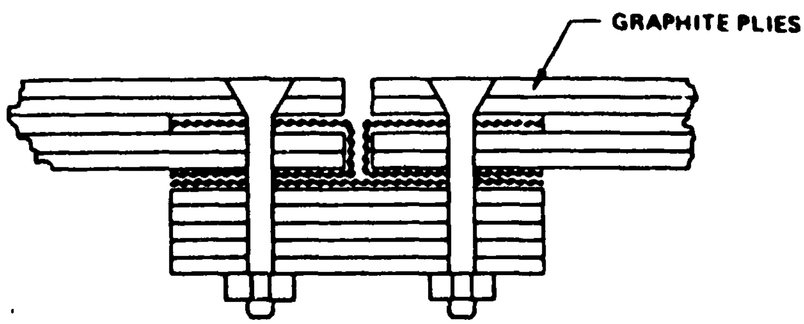
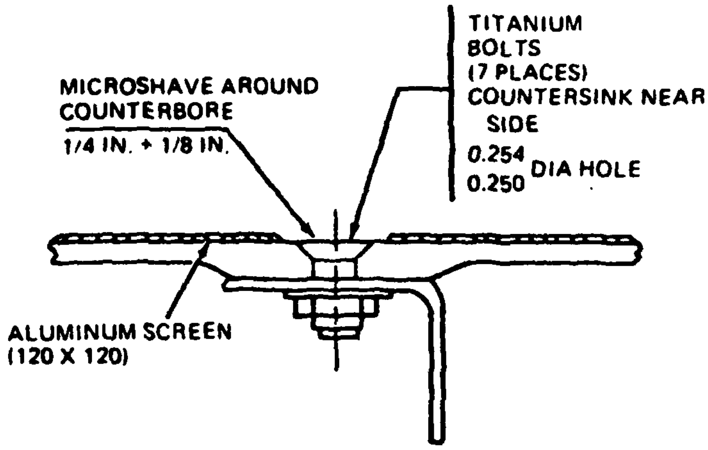
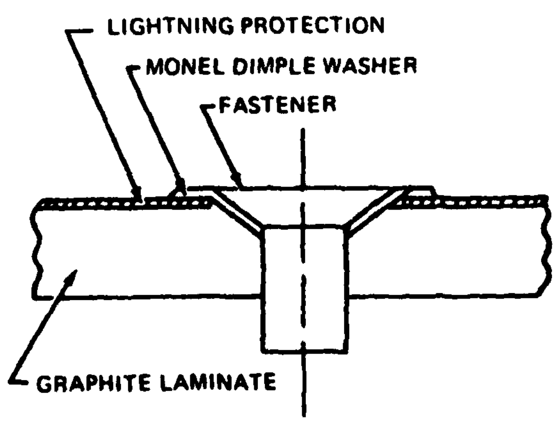


Figure 13 Folded Single Center Screen Mechanically Fastened Lap Joint



ISOLATED FASTENER CONCEPT



DETAIL A
GROUNDING DETAILS

Figure 14 Isolated and Grounded Fastener Concept

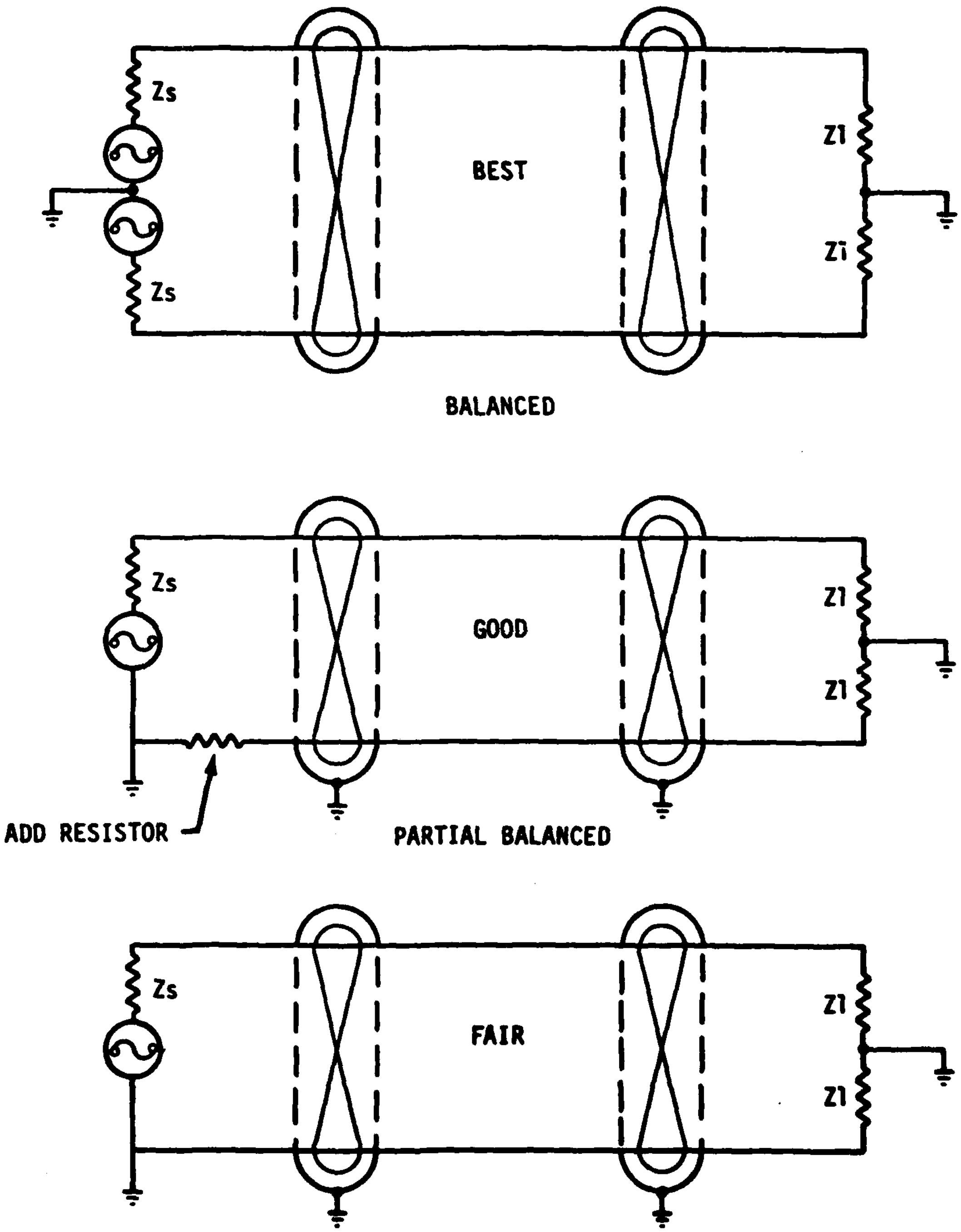


Figure 15 Balanced Loading Concepts

Since composite structure will not provide the fault current and lightning current conductance available with aluminum, separate grounding systems should be initiated. The grounding system would provide the appropriate current paths for lightning, fault, power, and signal. There will still be a need for minimum common impedances between power and signal supplies and lines of distribution of secondary power and return. There will also be a significant weight penalty in those areas where these grounding systems must be incorporated. Particular attention must also be paid to the interconnection and bonding of the ground system and any metal structure used for ground return.

SECTION IV

SYSTEM EVALUATION WITH INHERENT HARDNESS

This section of the design guide provides the systems engineer with data to compute the lightning threat as it effects the electrical system. Typical aircraft circuits are developed for analysis. First, the threat is calculated using the equations developed in Section II. Second, this threat is applied to the circuit model developed here and in Reference 1 using the Presto Traffic computer program.

The computer routine used in the evaluation of the circuits examined was developed for the Defense Nuclear Agency in 1978. The TRAFFIC modeling library is used with the PRESTO applications code (Reference 13) for the frequency-domain modeling and analysis of cables, antennas and other distributed conducting structures.

The modeling programs and subroutines model the pickup and propagation of signals on electrical systems and conducting structures. The pickup and propagation characteristics are analyzed using models of transmission lines and antennas. This includes intentional signal paths such as communication and control cables, and unintentional signal paths such as power systems and other conducting structures.

An example of the equations required for the computer analysis of the electrical system developed in the paragraphs below are shown in Figure 16. These equations form a subroutine that describes a magnetically coupled exposed conductor with input and output parameters defined in Table 18. The output of the subroutine is in the form of an N-node Norton equivalent circuit, i.e., a short circuit current and source admittance. All subroutines developed for analysis in this section are listed in Reference 1.

The design guide looks at several electrical circuits that are part of, or interface with the electrical power subsystem. Each of the following circuits are analyzed for their ability to withstand lightning transients at various threat levels:

The equations listed below were used to calculate the amount of magnetically coupled voltage on the leading edge wire bundle for an all aluminum wing with a figerglass leading edge.

```
W=2.*PI*FM*1.E6
IL=PEAKI*(1./(ALPHA+J*W)-1./(BETA+J*W))
VEL=3.E8
RHO=(RL-ZC)/(RL+ZC)
GAML=CEXP(J*W*L/VEL)
CAMLX=CEXP(J*W*(L-X)/VEL)
ZIN= C*(GAML+RHO/GAML)/(GAML-RHO/GAML)
TX=(GAMLX-RHO/GAMLX)/(CAML-RHO/GAML)
I=((2.*RL)/(RL+ZIN))*TX*IL
V=J*W*U*I*PI*PRAM(1)*PRAM(2)*PRAM(4)/PRAM(3)
Y(1,1)=(1.E6,0.)
Y(2,2)=Y(1.1)
Y(1,2)=(-1E6,0.)
Y(2,1)=Y(1,2)
C(1)=1E6*V
C(2)=-1E6*V
```

Figure 16 Magnetically Coupled Exposed Conductor Subroutine Equations

TABLE 18

MAGNETICALLY COUPLED EXPOSED CONDUCTOR SUBROUTINE DEFINITIONS

INPUT PARAMETERS

Physical Quantity Name	Description	Units
ALPHA	Fall Time Constant For Lightning Current	Seconds -1
BETA	Rise Time Constant For Lightning Current	Seconds -1
C	Output Current Vector	Amps
FM	Frequency	Megahertz
J	Imaginary Operator Of Complex Number	
L	Length Of Lightning Path Through Airframe	Meters
PEAKI	Peak Current Amplitude Constant For Lightning	Amps
PI		3.14159
PRAM 1	Wire Route Length	Meters
PRAM 2	Wire Height Above Ground Plane	Meters
PRAM 3	Wing Circumference	Meters
PRAM 4	Concentration Factor	
RL	Lightning Channel Characteristic Impedance	Ohms
U	Permeability of Free Space	Henries/Meter
VEL	Velocity Of Light	Meters/Second
X	Distance From Attachment Point To Source	Meters
Y	Output Admittance Matrix	Mhos
ZC	Airframe Characteristic Impedance	Ohms

OUTPUT PARAMETERS

GAML	Phase Shift Parameter	
GAMLX	Phase Shift Parameter	
I	Lightning Current In Airframe At X	Amps/Rad
IL	Lightning Current Spectrum	Amps/Rad
RHO	Reflection Coefficient For Airplane/ Lightning Column Mismatch	
TX	Transfer Function Ratio Of Input Current To Current At X	
V	Output Voltage	Volts
W	Frequency	Rad/Sec
ZIN	Input Impedance For Aircraft Transmission Line	Ohms

a. VSCF Circuit with Generator and Converter on Wing
b. VSCF Circuit with Generator on Wing, Converter in Fuselage
c. Generator on Wing Circuit
d. F15 Generator Circuit
e. Beacon Light Circuit
f. Window Heater Circuit
g. Upper Surface Blowing Actuator Circuit

1. VSCF Generator and Converter Circuit

The VSCF electrical power schematic shown in Figure 17 and examined here was originally designed for the F-18 aircraft. The generator is a wound rotor salient pole brushless machine rated 55 KVA, 165 volts, and delivers six phase, 1660 Hz to 3500 Hz power to three identical legs of the cycloconverter that convert the variable frequency power to a constant 400 Hz, three phase power. There are 12 thyristors in each cycloconverter leg that are gated by modulators to form the 400 Hz output (Reference 8). Each cycloconverter leg is followed by a filter (the interphase transformer and capacitor) to remove the cycloconverter ripple frequency. The system was examined in three different configurations, a. Both the generator and converter located out on the wing, b. The generator located out on the wing with the converter in the fuselage and c. The generator located out on the wing without the converter.

a. VSCF Cenerator and Converter on Wing

The baseline VSCF generator and converter circuit for this evaluation consisted of the generator and converter package located 12 meters out on the wing connected via feeders to the bus located in the fuselage. Figure 18 is the one line diagram and Figure 19 is the modelled equivalent circuit. The one line diagram displays the VSCF system as the circuit was broken down into blocks and modelled in the computer simulation. Test points were taken at the generator/converter output and the bus input for severe lightning threats. Figure 19, the modelled equivalent circuit, shows the various component parameters used within the simulation blocks. The generator neutral wire is grounded to the nearest spar 3 meters from the generator. Using the common mode configuration, which assumes balanced loading, simplified the analysis by

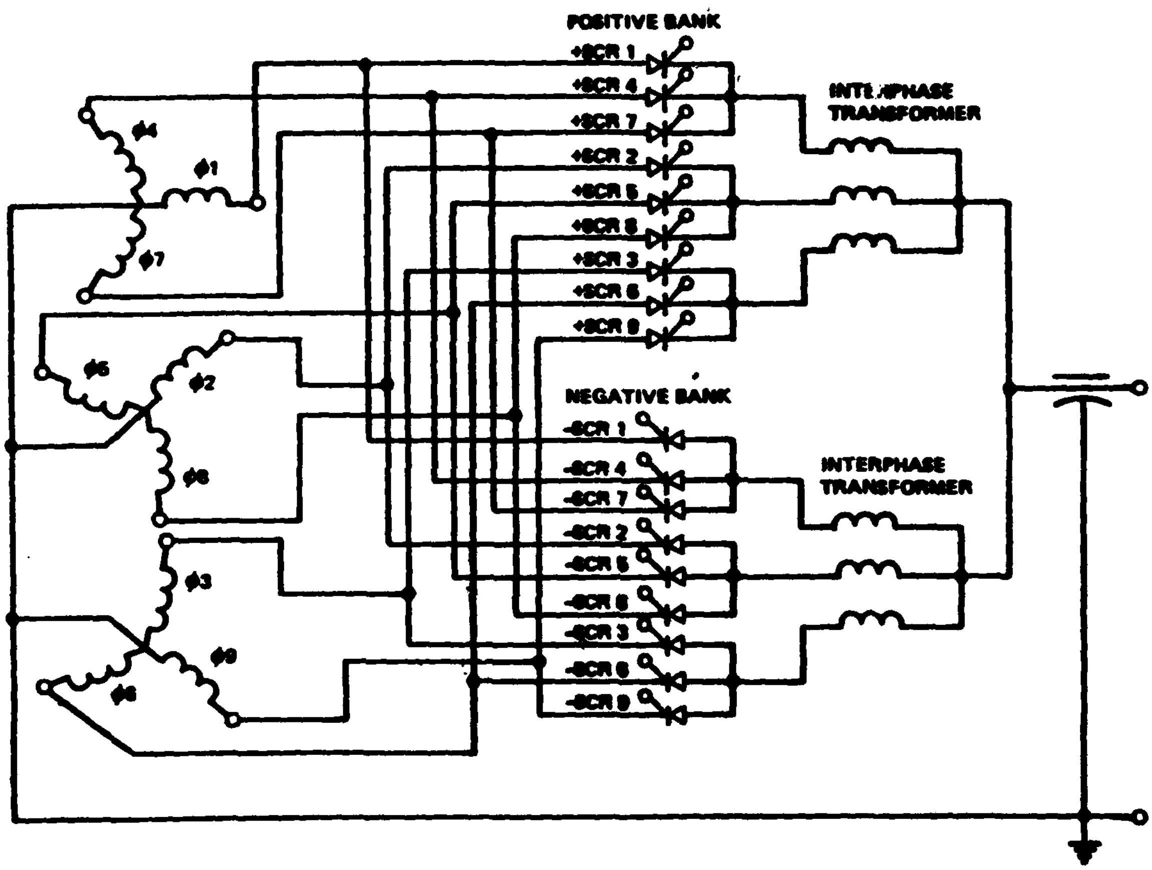


Figure 17 VSCF Power Circuit With Shielding

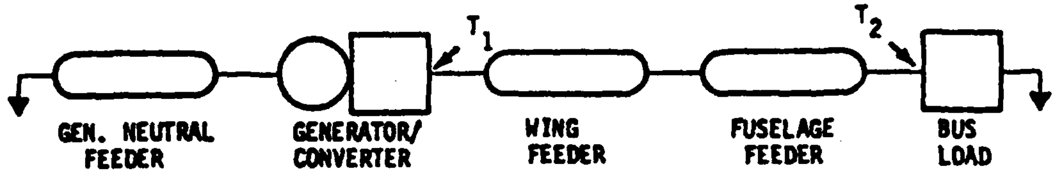


Figure 18 VSCF Generator/Converter on Wing Block Diagram

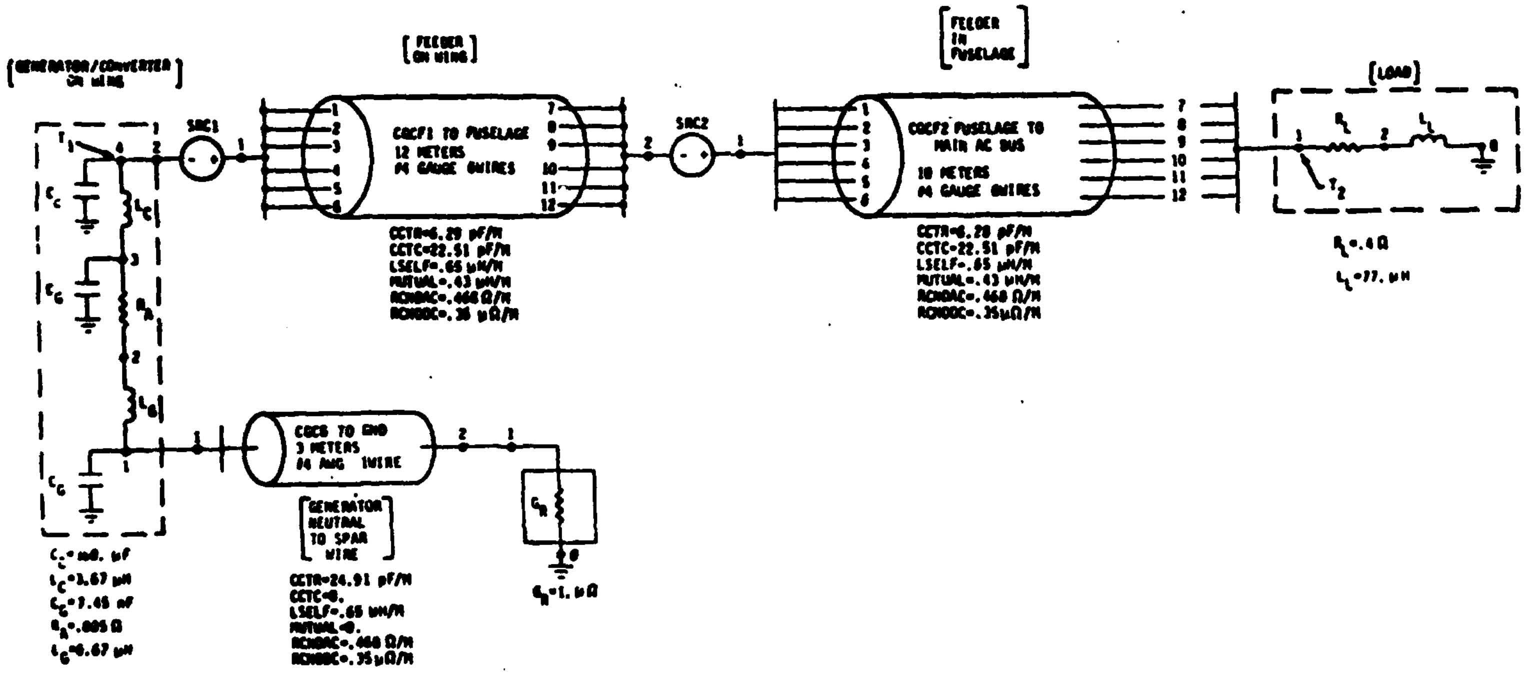


Figure 19 VSCF Generator/Converter on Wing Equivalent Circuit

allowing the phases to be paralleled into equivalent impedances. The lightning strike attaches to the wing tip and travels toward the fuselage. The threat is magnetically coupled to the wing feeder, between the generator located out on the wing and the load bus located inside the fuselage, at nodes SRC1 and SRC2 in Figure 19. Inside the fuselage, the feeder model connecting the converter to the bus is not directly exposed to the lightning current.

Fiberglass Wing Leading Edge

Using the circuit described above, a bundle of six number four gauge feeder wires were excited via magnetic coupling of the lightning transient as they feed a half loaded bus and then a full load. The bundle was located two inches above the leading edge spar of an all aluminum wing and behind a fiberglass leading edge. The lightning equations and definitions are given in Figure 16 and Table 18. The length of the excited feeder was varied from the baseline 12 meters to 6 and 18 meters. Table 19 lists the severe threat transients first for the half load and then full load case transients monitored at the two test points (T1, T2) shown on Figures 18 and 19. The test case labels in Table 19, 6MF, 12MF, and 18MF correspond with the length of excited feeder. Figures 20 and 21, plot the positive amplitude voltage and current peaks versus feeder length for the two cases.

Graphite/Epoxy Wing Leading Edge

In the development of the graphite epoxy leading edge, an extremely low frequency response in the VSCF circuit, primarily caused by the generator, resulting in the domination of the low frequency spectral content of the threat waveform was found. The lightning threat equations and definitions are similar to those given in Figure 16 and Table 18 and defined precisely in Reference 12. In comparison of the equations for the graphite epoxy and fiberglass leading edge cases, a change in the conductivity and thickness of the leading edge material was the difference.

The test points, (T1 and T2), were the same as in the previous case. The first three blocks of data in Table 20, namely test cases 12GE35, 12GE45, and

TABLE 19 VSCF/1 PEAK TRANSIENTS FIBERGLASS LEADING EDGE

TEST CASE	TEST POINT/ NAME	TRANSIENT DURATION	POSITIVE AMPLITUDE	NEGATIVE AMPLITUDE	DC OFFSET
			(50% LOAD)		
6MF	T1/VCON	1.0 mS	13.5 V	-15.5 V	+0.2 V
6MF	T1/ICON	1.0 mS	92.0 A	-62.0 A	+1.8 A
6MF	T2/VLOAD	5.0 uS	42.0 KV	-36.0 KV	-8.0 KV
6MF	T2/ILOAD	.15 mS	148.0 A	-16.0 A	+6.0 A
12MF	T1/VCON	1.0 mS	27.0 V	-30.0 V	+0.5 V
12MF	T1/ICON	1.0 mS	180.0 A	-120.0 A	+4.0 A
12MF	T2/VLOAD	8.0 uS	65.0 KV	-40.0 KV	0.0 V
12MF	T2/ILOAD	.15 mS	289.0 A	0.0 A	0.0 A
18MF	T1/VCON	1.0 mS	38.0 V	-44.0 V	+0.4 V
18MF	T1/ICON	1.0 mS	260.0 A	-175.0 A	+6.4 A
18MF	T2/VLOAD	8.0 uS	99.0 KV	-68.0 KV	-14.0 KV
18MF	T2/ILOAD	.15 mS	425.0 A	-45.0 A	+15.0 A
			(100% LOAD)		
6MF	T1/VCON	1.0 ms	24.0 V	-28.0 V	0.0 V
6MF	T1/ICON	1.0 ms	160.0 A	-100.0 A	+5.0 A
6MF	T2/VLOAD	6.0 us	38.0 KV	-19.0 KV	-8.0 KV
6MF	T2/ILOAD	0.6 ms	280.0 A	-35.0 A	+10.0 A
12MF	T1/VCON	1.0 ms	46.0 V	-52.0 V	0.0 V
12MF	T1/ICON	1.0 ms	300.0 A	-200.0 A	+12.7 A
12MF	T2/VLOAD	8.0 us	58.0 KV	-36.0 KV	+15.0 KV
12MF	T2/ILOAD	0.6 ms	550.0 A	-60.0 A	+30.0 A
18MF	T1/VCON	1.0 ms	64.0 V	-74.0 V	0.0 V
18MF	T1/ICON	1.0 ms	440.0 A	-280.0 A	+10.0 A
18MF	T2/VLOAD	10.0 us	78.0 KV	-50.0 KV	+19.0 KV
18MF	T2/ILOAD	0.7 ms	750.0 A	-90.0 A	+50.0 A

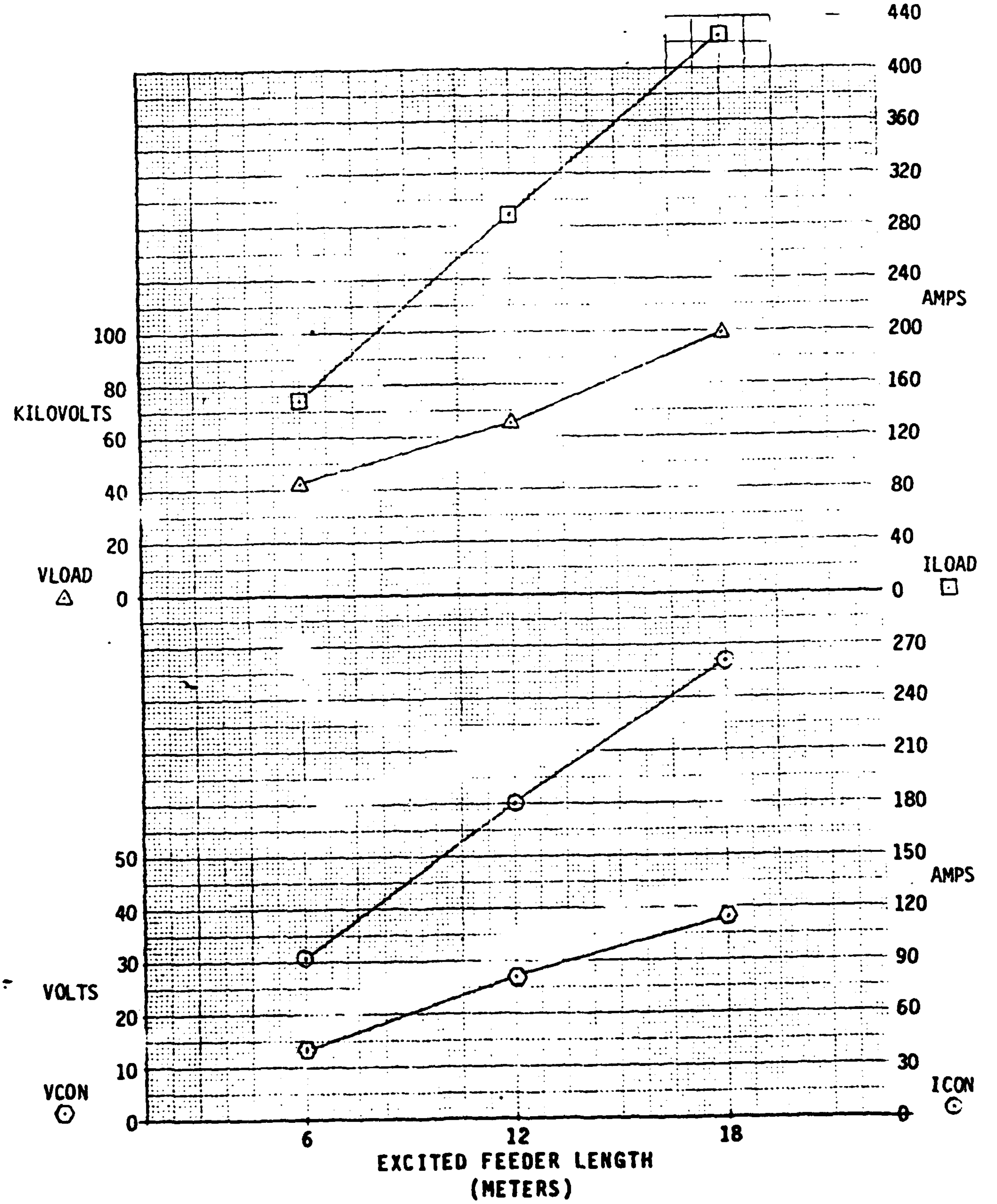


FIGURE 20 Fiberglass Leading Edge 50% Loaded Bus

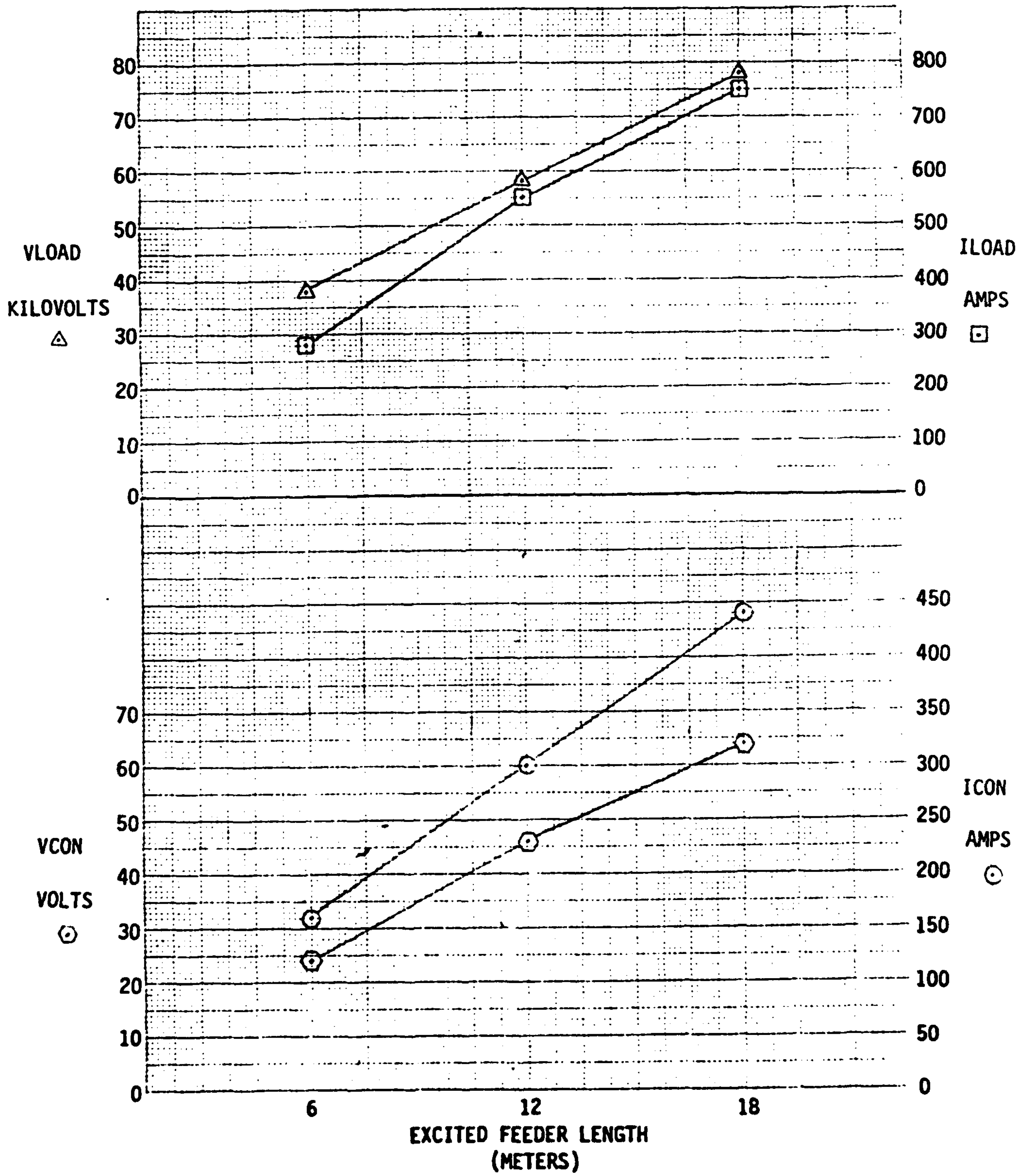


FIGURE 21 Fiberglass Leading Edge 100% Loaded Bus

TABLE 20 VSCF/1 PEAK TRANSIENTS GRAPHITE EPOXY LEADING EDGE

TEST CASE	TEST POINT/ NAME	TRANSIENT DURATION	POSITIVE AMPLITUDE	NEGATIVE AMPLITUDE	DC OFFSET
12GE35	T1/VCON	1.0 mSec	24.0 V	-47.0 V	+2.0
12GE35	T1/ICON	1.0 mSec	435.0 A	-70.0 A	+12.0
12GE35	T2/VLOAD	1.0 mSec	410.0 V	-35.0 V	+85.0
12GE35	T2/ILOAD	1.0 mSec	305.0 A	-62.0 A	+5.0
12GE45	T1/VCON	1.0 mSec	18.0 V	-37.0 V	+1.5
12GE45	T1/ICON	1.0 mSec	340.0 A	-60.0 A	+10.0
12GE45	T2/VLOAD	1.0 mSec	320.0 V	-25.0 V	+60.0
12GE45	T2/ILOAD	1.0 mSec	235.0 A	-50.0 A	+5.0
12GE50	T1/VCON	1.0 mSec	16.0 V	-33.0 V	+1.3
12GE50	T1/ICON	1.0 mSec	305.0 A	-50.0 A	+10.0
12GE50	T2/VLOAD	1.0 mSec	285.0 V	-25.0 V	+50.0
12GE50	T2/ILOAD	1.0 mSec	215.0 A	-45.0 A	+5.0
12GE51	T1/VCON	1.0 mSec	32.0 V	-68.0 V	+2.0
12GE51	T1/ICON	1.0 mSec	610.0 A	-100.0 A	+10.0
12GE51	T2/VLOAD	1.0 mSec	570.0 V	-50.0 V	+100.0
12GE51	T2/VLOAD	1.0 mSec	420.0 A	-90.0 A	+10.0
12GE52	T1/VCON	1.0 mSec	65.0 V	-135.0 V	+5.0
12GE52	T1/ICON	1.0 mSec	1.22 KA	-200.0 A	+20.0
12GE52	T2/VLOAD	1.0 mSec	1.14 KV	-100.0 V	+200.0
12GE52	T2/VLOAD	1.0 mSec	840.0 A	-180.0 A	+20.0

12GE50 compare the results of varying the thickness of the graphite epoxy material on the leading edge. The thickness, a function of the number of .005 inch plies, was varied from 0.175 to 0.225 to 0.25 inches for each respective case. Figure 22 plots the positive amplitude voltage and current peaks with respect to the change in leading edge thickness.

Test cases 12GE50, 12GE51, and 12GE52 compare the results of varying the distance between the graphite composite leading edge and the excited wire bundle. The wire bundle was positioned two inches above the ground plane. Distances used for each respective case were 2.0, 1.0 and 0.5 feet. Figure 23 plots the positive amplitude voltage and current peaks with respect to the change in the distance between the leading edge and the bundle.

b. VSCF Generator on Wing, Converter in Fuselage

The VSCF circuit examined in this case consisted of the 55KVA synchronous generator, described in Section IV.1, positioned on the wing twelve meters from the fuselage and VSCF converter. The unshielded feeder model included a return neutral wire from the generator to the converter ground. The system one line diagram and equivalent circuit modelled are shown in Figures 24 and 25, respectively. Impedance values for the generator, feeders, converter and a 50% bus load tied in a common mode configuration were put into the TRAFFIC analysis routine format for computation.

Fiberglass Wing Leading Edge

Using the circuit described, a bundle of seven number ten gauge wires twelve meters long were excited by the magnetic field of first a moderate and then a severe lightning transient. The feeder bundle located two inches above the leading edge spar of an all aluminum wing and behind a fiberglass leading edge was connected to a 50% loaded bus. An unexcited feeder bundle of six number four gauge wires twelve meters long tied the converter to the power bus. The lightning equations and definitions used are given in Reference 12. Table 21 lists the moderate and severe threat transients as monitored at the three test points; T1, the generator output terminals, T2, the converter input terminals, and T3, the bus input terminals, shown in Figures 24 and 25.

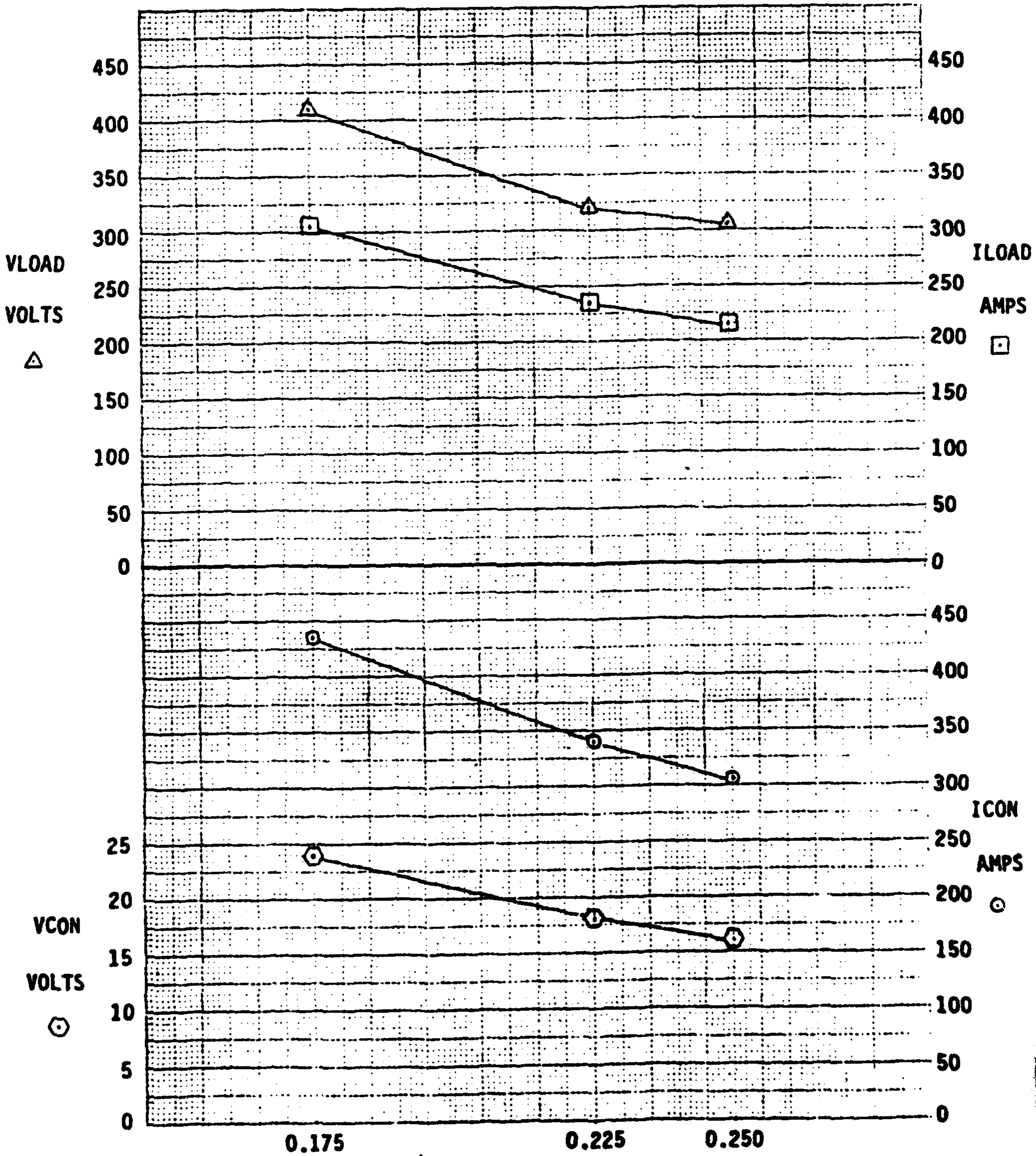


FIGURE 22 Graphite/Epoxy Leading Edge—Thickness (Inches)

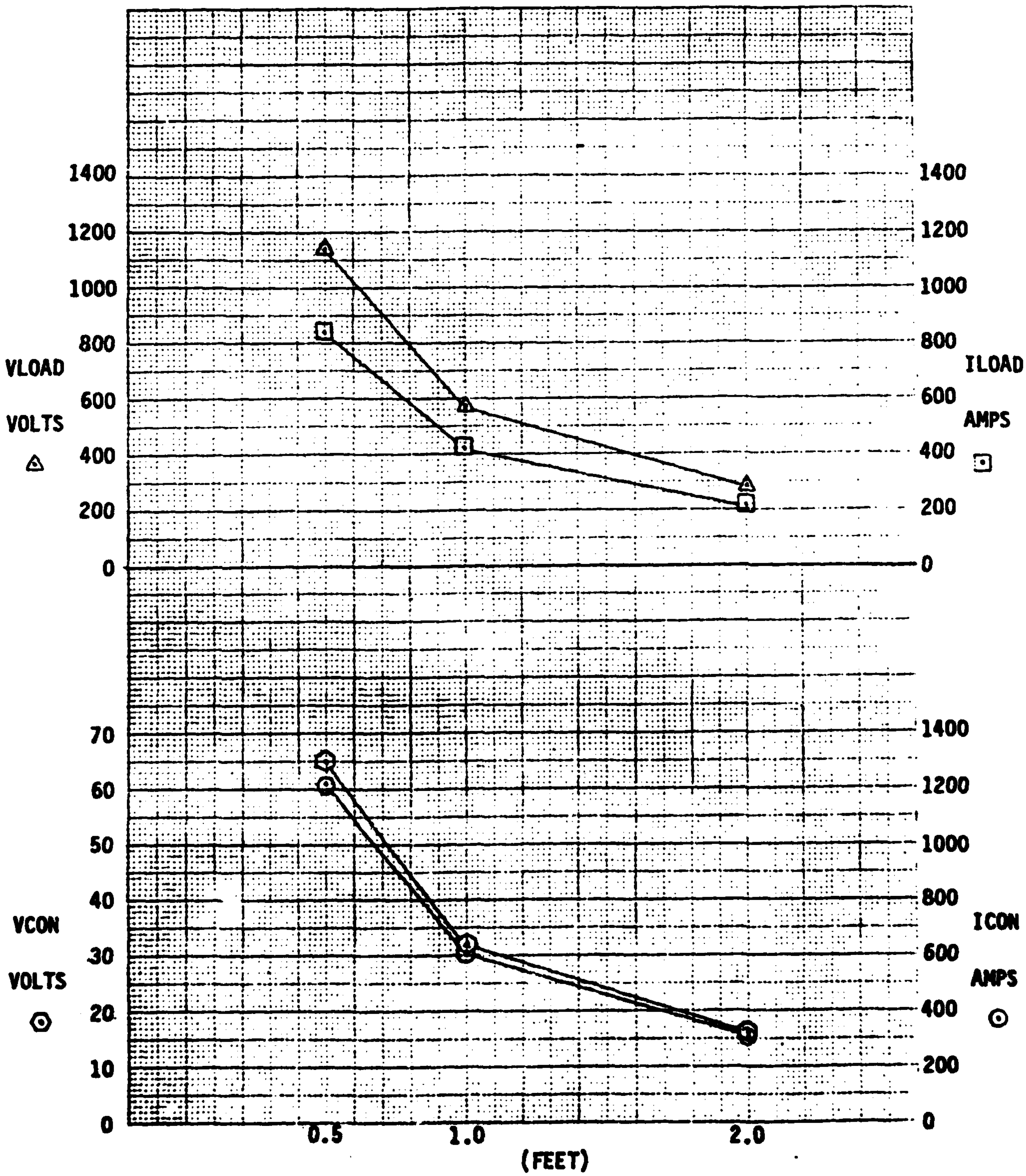


Figure 23 Graphite/Epoxy Leading Edge - Wire Separation

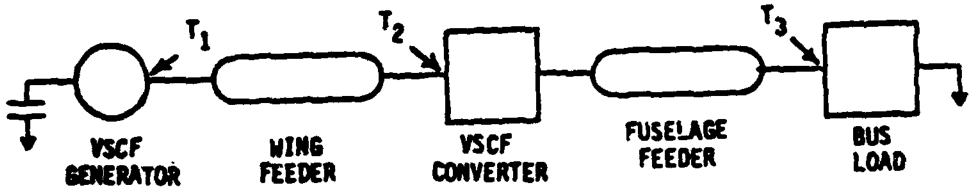


Figure 24 VSCF Generator on Wing Converter in Fuselage Block Diagram

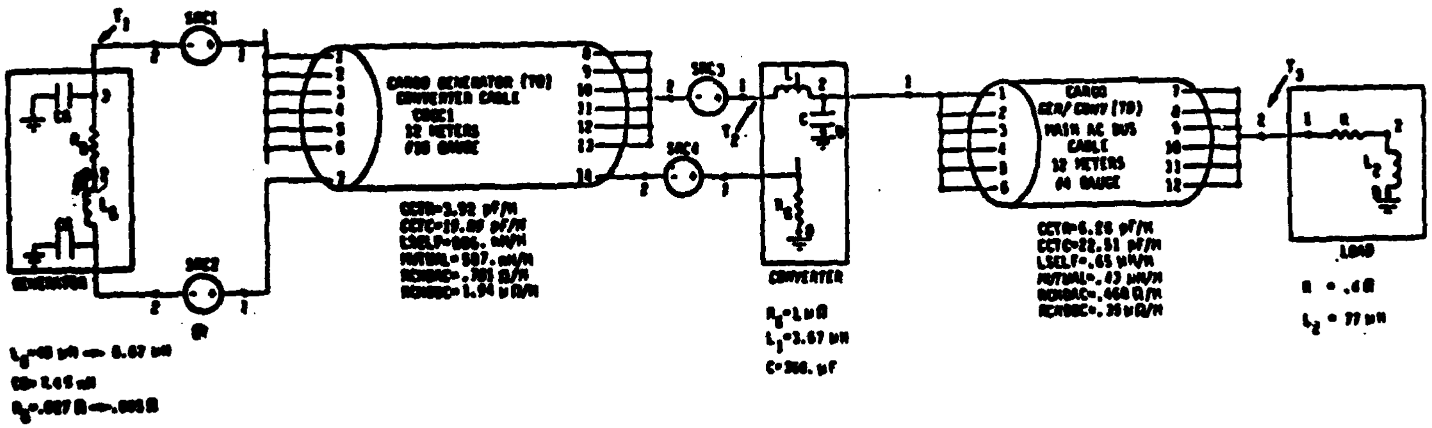


Figure 25 VSCF Generator on Wing Converter in Fuselage Equivalent Circuit

TABLE 21 VSCF/2 PEAK TRANSIENTS FIBERGLASS LEADING EDGE

TEST CASE	TEST POINT/ NAME	TRANSIENT DURATION	POSITIVE AMPLITUDE	NEGATIVE AMPLITUDE	DC OFFSET
			(MODERATE)		
12MF	T1/VGEN	5 uSec	2.2 KV	12.3 KV	+200.0 V
12MF	T1/IGEN	5 uSec	16.5 A	11.0 A	+1.0 A
12MF	T2/VCON	5 uSec	1.05 KV	1.18 KV	-50.0 V
12MF	T2/ICON	5 uSec	20.0 A	18.0 A	-3.0 A
12MF	T3/VLOAD	5 uSec	6.5 mV	4.5 mV	-0.8 mV
12MF	T3/ILOAD	>10 uSec	110.0 uA	14.0 uA	0.0 A
			(SEVERE)		
12MF	T1/VGEN	3u Sec.	2.0 KV	53.0 KV	+1.0 KV
12MF	T1/IGEN	5u Sec.	65.0 A	45.0 A	+4.0 A
12MF	T2/VCON	5u Sec.	4.2 KV	4.5 KV	-200.0 V
12MF	T2/ICON	5u Sec.	76.0 A	68.0 A	-12.0 A
12MF	T3/VLOAD	5u Sec.	27.0 mV	16.0 mV	-3.0 mV
12MF	T3/ILOAD	>10u Sec.	94.0 uA	10.0 uA	0.0 A

TABLE 22 VSCF/GEN PEAK TRANSIENTS FIBERGLASS LEADING EDGE

TEST CASE	TEST POINT/ NAME	TRANSIENT DURATION	POSITIVE AMPLITUDE	NEGATIVE AMPLITUDE	DC OFFSET
12MFG	T1/VGEN	20.0 us	2.8 KV	-4.8 KV	-800.0 V
12MFG	T1/IGEN	150.0 us	600.0 A	-340.0 A	+20.0 A
12MFG	T2/VLOAD	8.0 us	58.0 KV	-40.0 KV	+12.0 KV
12MFG	T2/ILOAD	150.0 us	280.0 A	-35.0 A	+5.0 A

TABLE 23 F15 GENERATOR FEEDER PEAK TRANSIENTS

SEVERE THREAT ALUMINUM - APERTURE COUPLING					
TEST POINT	TEST POINT NAME	POSITIVE AMPLITUDE	NEGATIVE AMPLITUDE	DC OFFSET	TRANSIENT DURATION
T1	VGEN	560. V	-700. V	20. V	40 msec
T1	TGEN	36. A	-37. A	-33. A	9 msec
T2	VGENNEU	3400. V	-4000. V	600. V	10 msec
T2	IGENNEU	290. A	-300. A	-280. A	10 msec
T3	VBUSLOAD	3200. V	-3200. V	-600. V	6 msec
T3	IBUSLOAD	7 A	-7. A	-7.4 A	30 msec

c. Generator on Wing, No Converter

This case consisted of removing the converter from the circuit described in Section IV.1.a and shown in the one line diagram and equivalent circuit of Figures 18 and 19, respectively. Test points were taken at the generator output terminals, T1, and bus input terminals, T2, for a severe lightning strike.

Fiberglass Wing Leading Edge

Using the circuit described, a bundle of six number four gauge feeder wires twelve meters long were excited by the magentic field of a lightning strike transient traveling from the wingtip attachment point toward the fuselage as they feed a half loaded bus. The bundle was located two inches above the leading edge spar of the all aluminum wing and behind a fiberglass leading edge. The lightning equations and definitions are given in Figure 16 and Table 18. Table 22 lists the severe threat transients monitored at the two test points, T1 and T2.

2. F15 Generator Circuit

The F15 generator system is typical of most fighters with a 40/50 KVA generator and feeders located inside the fuselage. The main generator feeder bundle is 2 meters long and is made up of 24 #12 AWG wires, 6 wires per phase and 6 wires for the neutral. The neutral is grounded at the end of the 2 meter run. Routed forward from the generator to the engine firewall (2 meters in length) are the feeders and the neutral. The feeders penetrate the firewall, where the neutral is grounded, and are routed to the main bus 10 meters from the firewall. This segment was considered to be unexposed to the lightning threat. This is a valid assumption since much of the run is at right angles to the lightning path (assuming a tail-to-nose strike) and because the feeder, once past the firewall, is well shielded by the aircraft structure. The transients induced on the generator system are assumed to originate on the 2 meter feeder segment (24 #12 AWG bundle) in the engine compartment. In the case of the graphite/epoxy fuselage, this run is varied in length from 2 to 15 meters. Figures 26 and 27 show the F15 circuit block

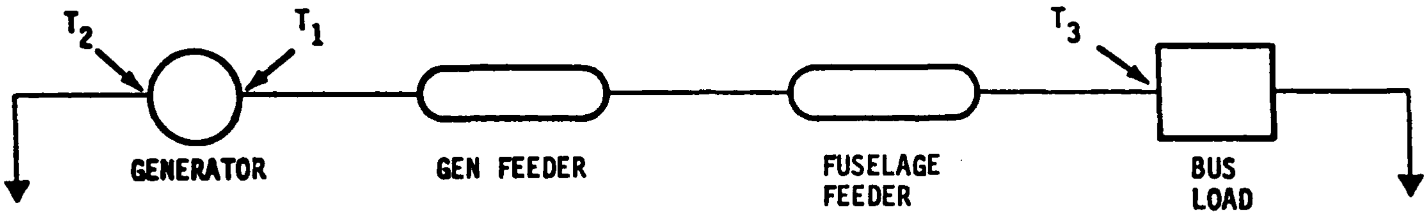


FIGURE 26. F15 Model Block Diagram

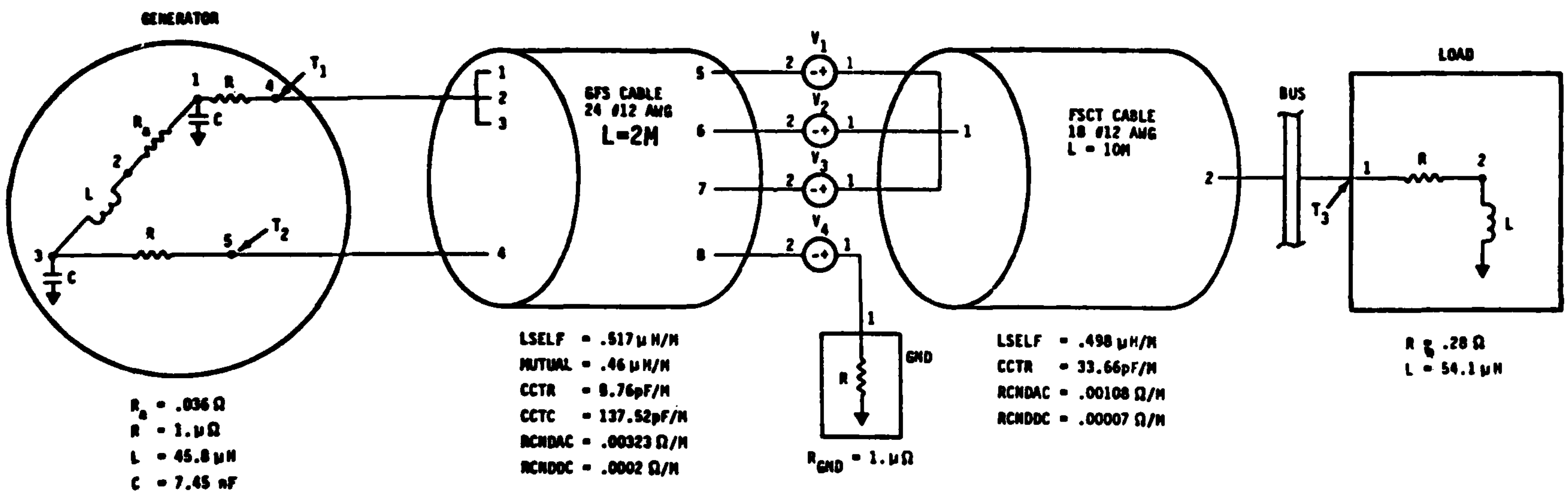


FIGURE 27. F15 Model Circuit Diagram

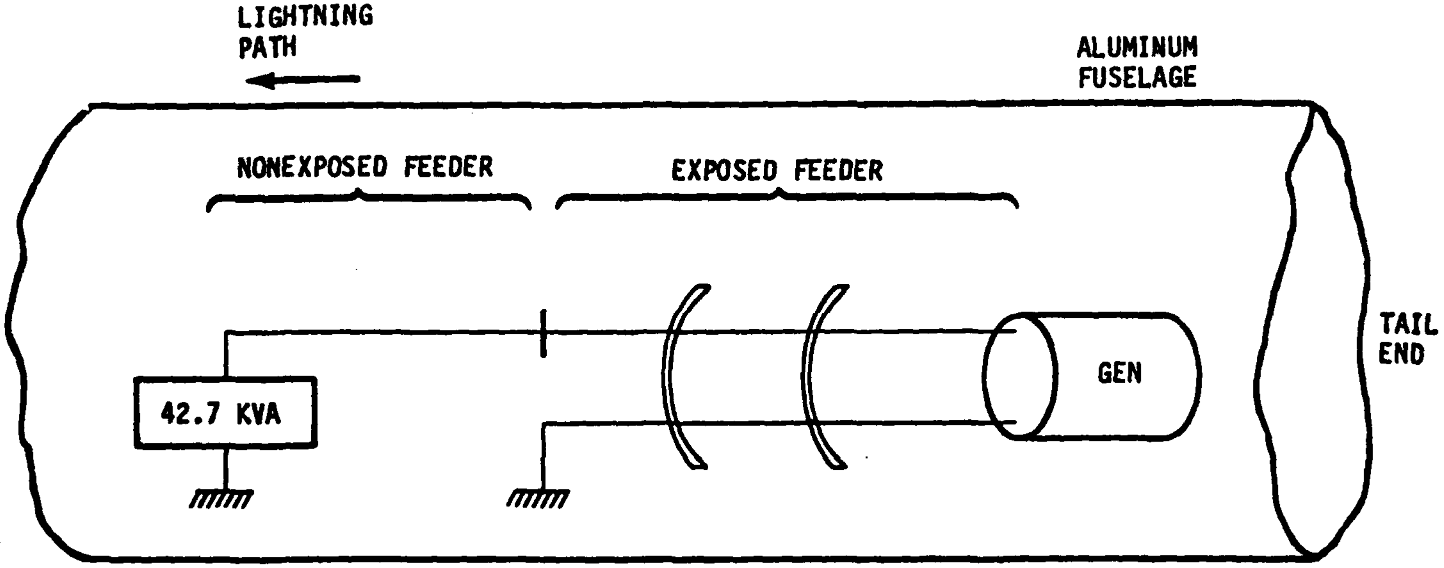
diagram and modelled equivalent circuit, respectively. The lightning source used in the F15 analysis was the "severe threat" (200 KA strike).

a. Aluminum Fuselage

An aluminum fuselage provides a good shield for the generator feeders; however, any openings in the aluminum will allow electric fields to penetrate into the fuselage and couple onto the feeders. These openings exist in the engine compartment area in the form of gaps in the access door seals. The model used to simulate the F15 is shown in Figure 28. Two slots, perpendicular to the lightning path and running across the feeders, provide the source of the lightning induced transients on the feeders. These slots represent gaps in the access door seals. Results of the computer simulation run shown in Table 23 were made with a full load on the bus. The maximum voltage transient seen at the bus was 3200 volts and decayed to 10 percent of the maximum within 6 microseconds. The maximum voltage transient at the generator output terminal was -700 volts. The transient voltages were calculated using the magnetic field aperture coupling equations defined in Reference 12.

b. Graphite/Epoxy Fuselage

To investigate the effects of a graphite/epoxy composite fuselage on lightning induced transients, the F15 model was modified to represent a fuselage made of graphite/epoxy. Only the feeder section in the engine compartment (from generator to firewall) was assumed to be exposed to the lightning threat. Since graphite/epoxy is not a good conductor, magentic fields produced by the lightning current flowing on the fuselage will penetrate into the interior of the aircraft. The penetrating magnetic field couples onto the feeder (diffusion coupling) producing voltage and current transients on the feeders. In the analysis of the graphite/epoxy fuselage model, the exposed feeder length was varied from 2 to 15 meters. The induced voltage is related to the length of the feeder since the magnetic field is penetrating the fuselage wherever the lightning current is flowing.



NONEXPOSED FEEDER - 10 METERS

EXPOSED FEEDER - 2 METERS

WIDTH OF APERTURES - .1 INCH

LENGTH OF APERTURES - .56 METERS, .37 METERS

FIGURE 28 F15 Aluminum - Generator Feeder Configuration

Computer simulations of a lightning strike were made for four lengths of exposed feeder, 2, 5, 10 and 15 meters. The configuraton of the model is shown in Figure 29. As the length was increased, the voltage and current transients increased. The results of the computer analysis are summarized in Table 24. The relation between the induced transient and the length of the exposed feeder is shown in Figure 30, at the generator terminals, and in Figure 31, at the main bus. The induced transients, as was expected, increased as the length of the exposed feeder increased. The equations used to calculate the transient voltage are developed in Section II and Reference 12.

3. Beacon Light Circuit, Cargo Airplane

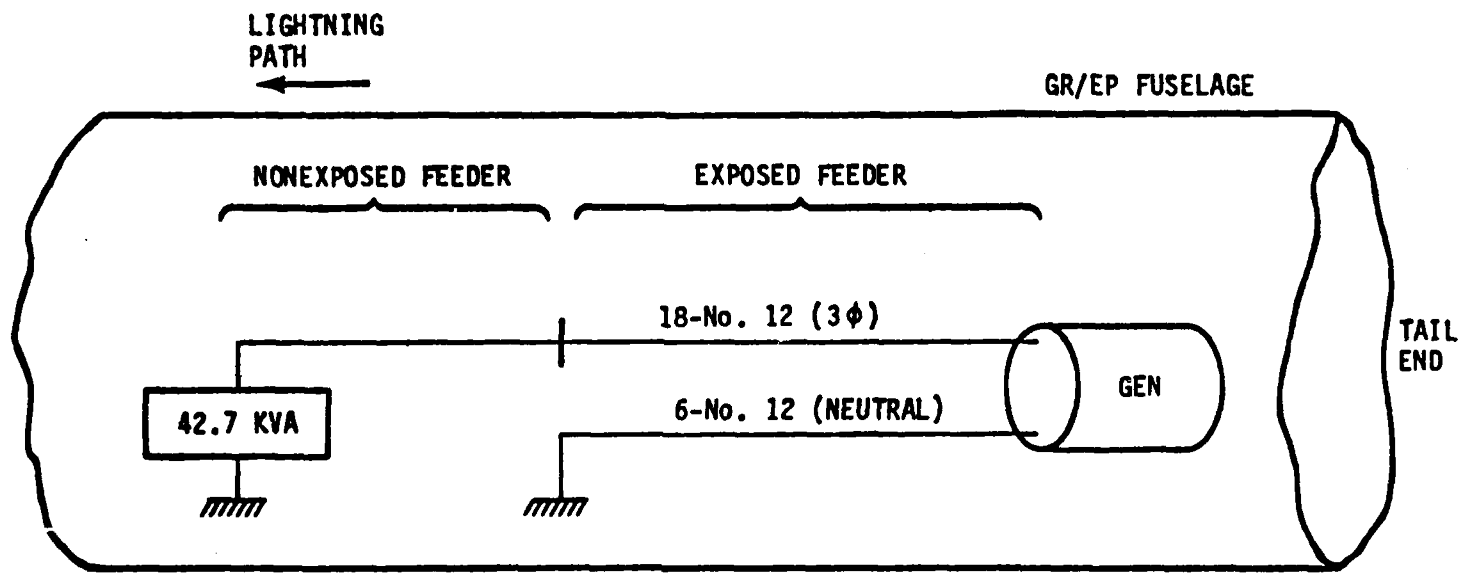
The beacon light was modelled as shown in the one line diagram of Figure 32 and the equivalent circuit in Figure 33. This circuit consisted of a pair of 20 gauge wires running along the front spar connecting the bus circuit breaker to the beacon light transformer at the wing tip. Resistance, inductance, and capacitance values for each block including a 50% loaded bus are recorded on Figure 33, the modelled equivalent circuit. Peak transient voltage to ground and line current test points were taken at the beacon light transformer primary (T1) and at the input side of the bus (T2).

<u>Fiberglass Wing Leading Edge</u>

Using the circuit described, the pair of 20 gauge wires were excited by the magnetic field of a lightning transient traveling from the wing tip attachment point toward the fuselage. As is shown in Figure 33, the excited wing section of the circuit was broken into three sections, each 4.66 meters in length. The wire pair was located behind a fiberglass leading edge two inches above the ground plane or front spar of an all aluminum wing. The lightning equations and definitions used in the TRAFFIC computer analysis routine and described in Figure 16 and Table 18 and Reference 12. Table 25 lists the moderate and severe transients monitored at the two test points, T1 and T2.

4. Window Heater Circuit, Cargo Airplane

The windshield heater circuit was modelled with the aircraft nose being the



NONEXPOSED FEEDER - 10 METERS

EXPOSED FEEDER - 2,5,10,15 METERS

FIGURE 29 F15 Graphite/Epoxy - Generator Feeder Configuration

TABLE 24 F15 GENERATOR FEEDER PEAK TRANSIENTS

SEVERE THREAT - GRAPHITE/EPOXY - DIFFUSION COUPLING				
2 METERS				
TEST POINT	TEST POINT NAME	POSITIVE AMPLITUDE	NEGATIVE AMPLITUDE	DC OFFSET
T1	VGEN	20. V	-670. V	-170. V
T1	IGEN	1.75 A	-1.75 A	.25 A
T2	VGENNEU	-15. V	-435. V	-15. V
T2	IGENNEU	5. A	-4.5 A	-1.0 A
T3	VBUSLOAD	260. V	-270. V	-150. V
T3	IBUSLOAD	2.35 A	-2.25 A	-.8 A
5 METERS				
T1	VGEN	-180. V	-1280. V	-180. V
T1	IGEN	2.3 A	-2.9 A	.2 A
T2	VGENNEU	40. V	-1120. V	20. V
T2	IGENNEU	8.5 A	-11. A	1.25 A
T3	VBUSLOAD	310. V	-340. V	-200. A
T3	IBUSLOAD	3. A	-2.6 A	.8 A
10 METERS				
T1	VGEN	1100. V	-3500. V	1100. V
T1	IGEN	5. A	-7.8 A	-2.2 A
T2	VGENNEU	50. V	-2300. V	50. V
T2	IGENNEU	26. A	-34. A	5. A
T3	VBUSLOAD	1400. V	-1450. V	950. V
T3	IBUSLOAD	15. A	-14. A	-2. A
15 METERS				
T1	VGEN	1700. V	-5800. V	1500. V
T1	IGEN	12. A	-17.5 A	4. A
T2	VGENNEU	900. V	-4300. V	800. V
T2	IGENNEU	54. A	-56. A	18. A
T3	VBUSLOAD	2500. V	-2500. V	700. V
T3	IBUSLOAD	27. A	-26. A	-7. A

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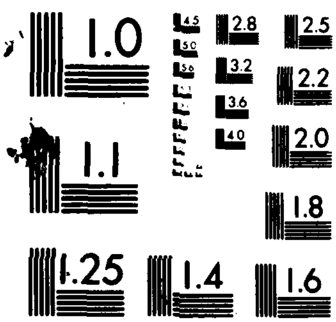

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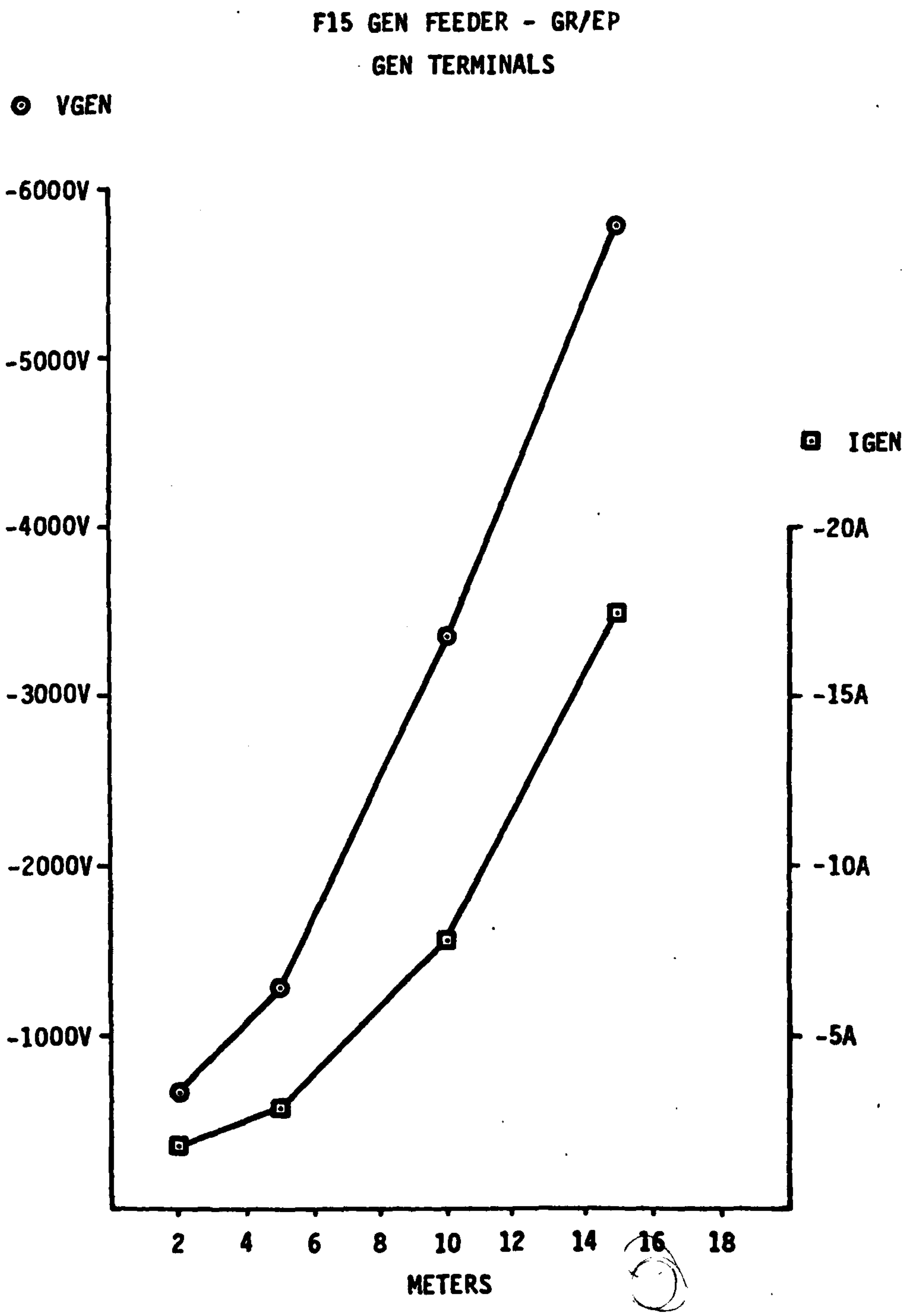


FIGURE 30 F15 Graphite/Epoxy - Voltage Vs Current Curves

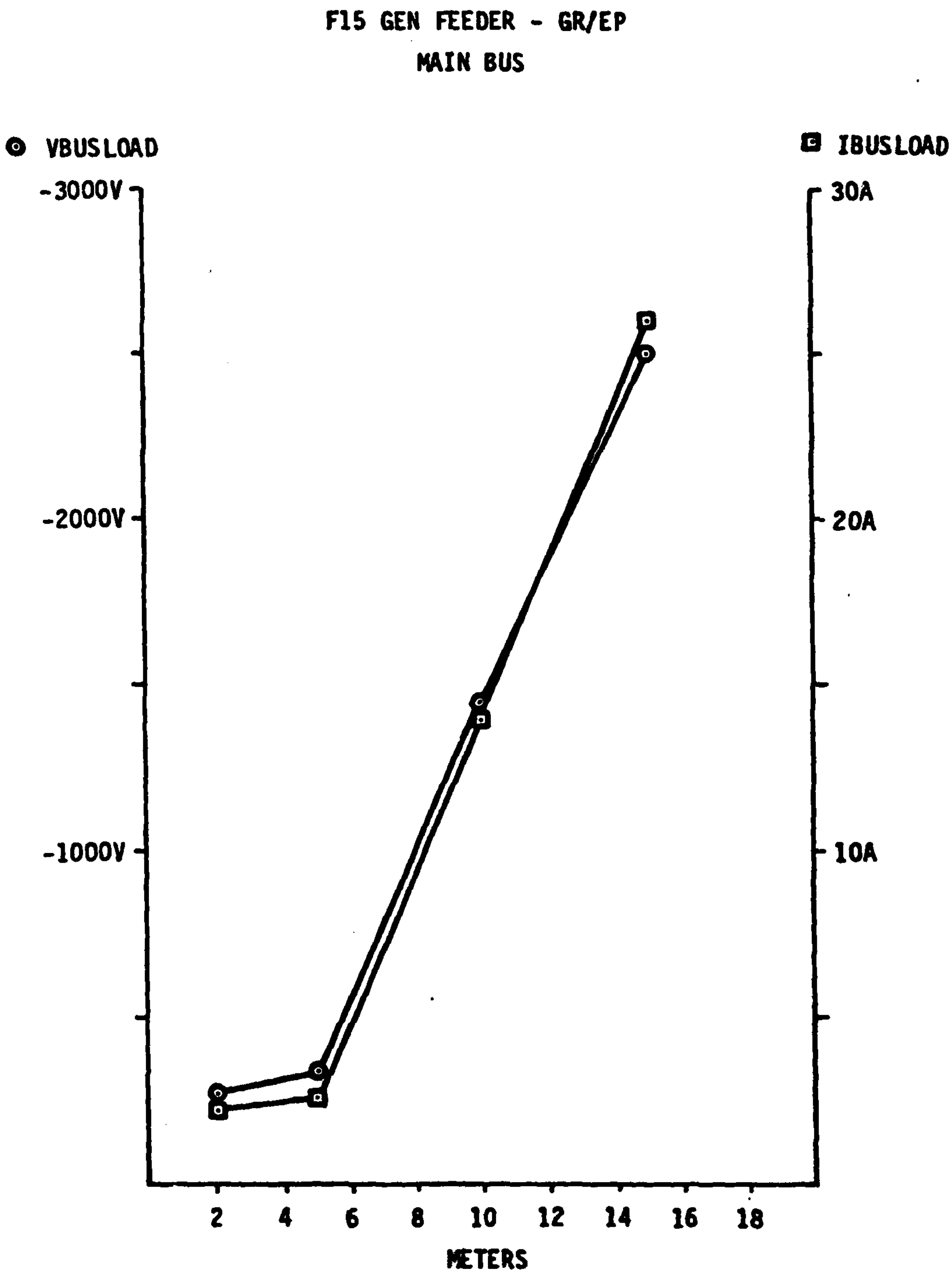


FIGURE 31 F15 Graphite/Epoxy - Voltage Vs Current Curves

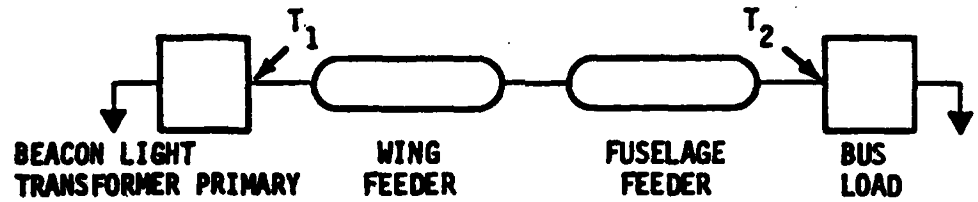


Figure 32 Beacon Light Block Diagram

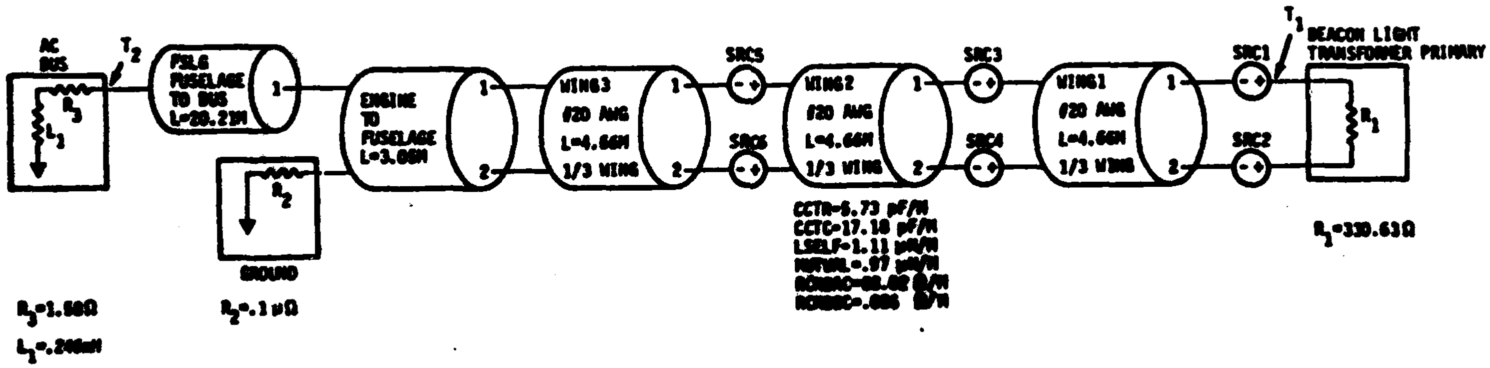


Figure 33 Beacon Light with Equivalent Circuits

TABLE 25 PEAK TRANSIENTS BEACON LIGHT

TEST CASE	TEST POINT/ NAME	TRANSIENT DURATION	POSITIVE AMPLITUDE	NEGATIVE AMPLITUDE	DC OFFSET
			(MODERATE)		
BL MOD	T1/VLIGHT	1u Sec.	18.0 KV	0.0 KV	+5.25 KV
BL MOD	T1/ILIGHT	2u Sec.	1.1 mA	-1.4 mA	-0.45 mA
BL MOD	T2/VBUS	2u Sec.	0.6 KV	-0.62 KV	-80.0 V
BL MOD	T2/IBUS	2u Sec.	0.26 A	-0.52 A	-.05 A
			(SEVERE)		
BL SEV	T1/VLIGHT	4u Sec.	81.0 KV	0.0 KV	+21.0 KV
BL SEV	T1/ILIGHT	4u Sec.	4.6 mA	-7.8 mA	-2.4 mA
BL SEV	T2/VBUS	1u Sec.	2.2 KV	-2.8 KV	-0.4 KV
BL SEV	T2/IBUS	3u Sec.	0.8 A	-2.6 A	-0.25 A

TABLE 26 PEAK TRANSIENTS WINDOW HEATER

TEST CASE	TEST POINT NAME	TRANSIENT DURATION	POSITIVE AMPLITUDE	NEGATIVE AMPLITUDE	DC OFFSET
			(MODERATE)		
WH MOD	T1/VCONLNA	>50u Sec.	48.0 V	-37.0 V	+1.0 V
WH MOD	T1/ICONLAI	10u Sec.	15.0 A	-2.4 A	-0.6 A
WH MOD	T2/VCONLNB	>50u Sec.	170.0 V	-35.0 V	-10.0 V
WH MOD	T3/ICONLAO	10u Sec.	2.1 A	-0.5 A	+0.1 A
WH MOD	T4/VBUSLNA	>50u Sec.	45.0 V	-34.0 V	+3.0 V
WH MOD	T4/IBUSLA	>50u Sec.	0.7 A	-0.7 A	0.0 A
WH MOD	T5/VBUSLNB	>50u Sec.	185.0 V	-30.0 V	-17.5 V
WH MOD	T5/IBUSLB	>50u Sec.	0.7 A	-0.7 A	0.0 A
			(SEVERE)		
WH SEV	T1/VCONLNA	>50u Sec.	420.0 V	-330.0 V	+20.0 V
WH SEV	T1/ICONLAI	>50u Sec.	74.0 A	-11.0 A	-2.0 A
WH SEV	T2/VCONLNB	>50u Sec.	865.0 V	-340.0 V	-60.0 V
WH SEV	T3/ICONLAO	>50u Sec.	11.0 A	0.0 A	+0.4 A
WH SEV	T4/VBUSLNA	>50u Sec.	400.0 V	-340.0 V	+20.0 V
WH SEV	T4/IBUSLA	>50u Sec.	7.8 A	-6.8 A	0.0 A
WH SEV	T5/VBUSLNB	>50u Sec.	920.0 V	-320.0 V	-80.0 V
WH SEV	T5/IBUSLB	>50u Sec.	7.4 A	-6.4 A	0.2 A

lightning attachment point. Surface charge on the airframe exterior from the lightning strike capacitively coupled onto the heater element. A pair of number 12 gauge power wires connected the heater element through a controller to the bus. Shown in Figure 34 is the circuit one line diagram. Figure 35, displays the modelled equivalent circuit of the interconnection of the feeders with the windshield to the controller and bus. Impedance values in terms of capacitance, resistance, and inductance for each circuit element and the 50% loaded bus are noted on the equivalent circuit.

Using the circuit described, the pair of twelve gauge power feeders were excited with a simulated moderate and then severe lightning transient. Test points for phase to ground voltage and line current were taken at five locations: Phase A and B controller inputs (T1, T2), phase A controller output (T3), and phase A and B bus inputs (T4, T5). The lightning source Fortran subroutine equations and definitions are given in Section II and Reference 12. Table 26 lists both moderate and severe threat transients.

5. Upper Surface Blowing Actuators, Cargo Airplane

One upper surface blowing actuator was modelled in series with an interface unit and AC and DC buses. A strike to the wing was assumed to generate a lightning transient traveling down the wing producing magnetic coupling on the 20 gauge power wiring located along the rear spar. The one line diagram is shown on Figure 36. The impedance values for each circuit element and a 50% loaded bus are listed on the modelled equivalent circuit diagram, Figure 37.

Using the circuit described, a bundle of ten number twenty gauge power wires 3.66 meters long were excited by the magentic field of a moderate and then a severe lightning strike. This excited wire bundle was connected on one end to the AC and DC loads and to an unexcited bundle on the other end. From the interface unit, one number twelve gauge wire fed each respective bus as is shown in Figure 37. Test points for phase to ground voltage and line current were sampled at six locations: input to the AC and DC loads (T1 and T2), input of one AC and DC wire to the interface unit, (T3 and T4), and input to the AC and DC buses (T5 and T6). The lightning equations and definitions are given in Reference 12. Table 27 lists both moderate and severe transients.

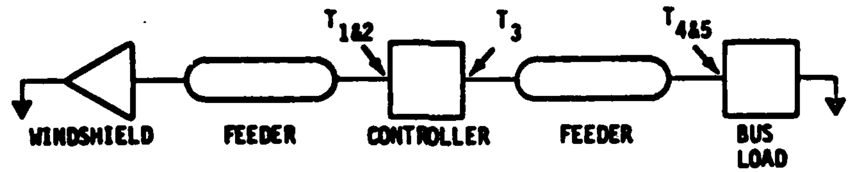


Figure 34 Windshield Heater Block Diagram

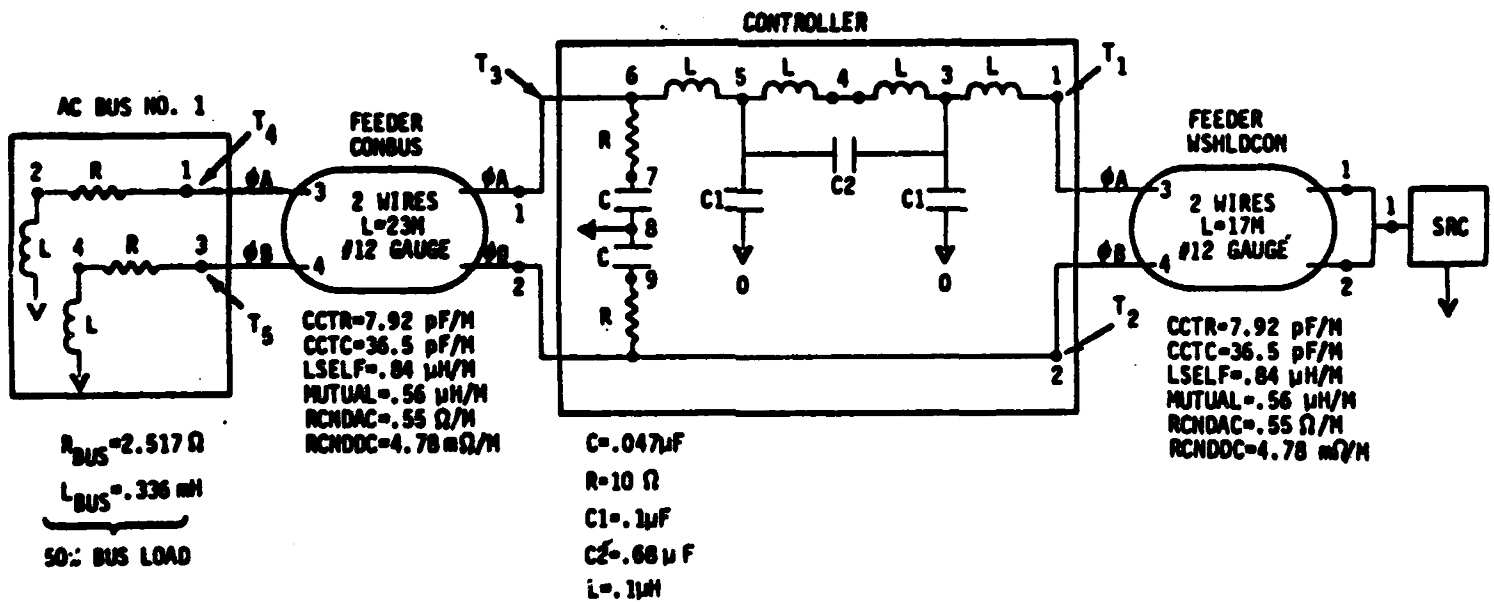


Figure 35 Windshield Heater Equivalent Circuit

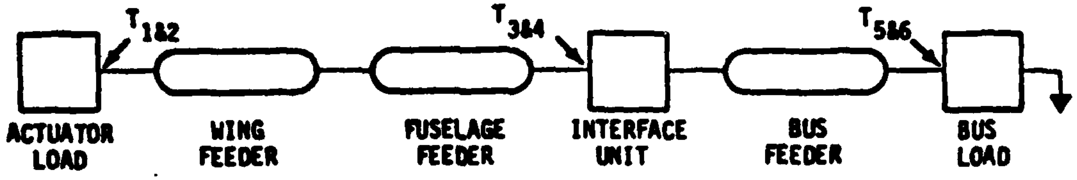


Figure 36 Upper Surface Blowing Block Diagram

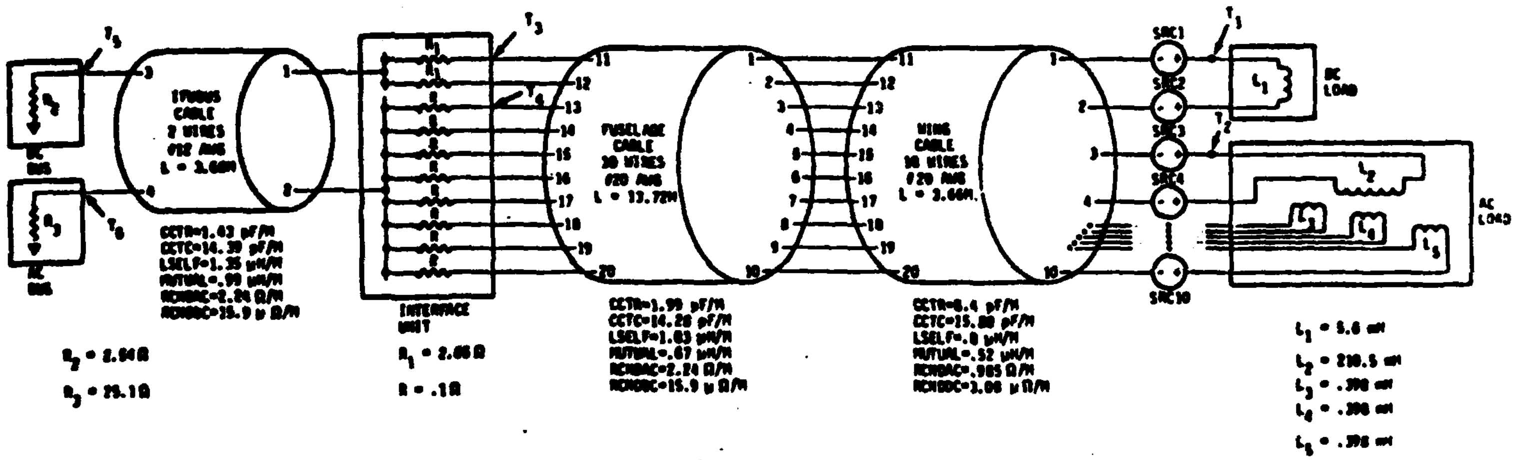


Figure 37 Upper Surface Blowing Actuator Equivalent Circuit

TABLE 27 PEAK TRANSIENTS UPPER SURFACE BLOWING ACTUATOR

TEST CASE	TEST POINT/ NAME	TRANSIENT DURATION	POSITIVE AMPLITUDE	NEGATIVE AMPLITUDE
		(MODERATE)		
USB MOD	T1/VDCLOAD	2u Sec.	18.8 KV	0.0 V
USB MOD	T1/IDCLOAD	>10u Sec.	0.42 uA	-0.25 uA
USB MOD	T2/VACLOAD	2u Sec.	18.8 KV	0.0 V
USB MOD	T2/IACLOAD	>10u Sec.	0.5 nA	0.8 nA
USB MOD	T3/VIFUDC	>10u Sec.	20.0 mV	-40.0 mV
USB MOD	T3/IIFUDC	>10u Sec.	12.0 uA	-160.0 uA
USB MOD	T4/VIFUAC	>10u Sec.	8.0 mV	-50.0 mV
USB MOD	T4/IIFUAC	>10u Sec.	0.16 mA	-0.02 mA
USB MOD	T5/VDCBUS	>10u Sec.	20.0 mV	-40.0 mV
USB MOD	T5/IDCBUS	>10u Sec.	16.0 uA	-24.0 uA
USB MOD	T6/VACBUS	>10u Sec.	8.0 mV	-50.0 mV
USB MOD	T6/IACBUS	>10u Sec.	0.0 uA	-68.0 uA
		(SEVERE)		
USB SEV	T1/VDCLOAD	4u Sec.	82.5 KV	0.0 V
USB SEV	T1/IDCLOAD	>10u Sec.	1.0 uA	-1.4 uA
USB SEV	T2/VACLOAD	4u Sec.	82.5 KV	0.0 V
USB SEV	T2/IACLOAD	>10u Sec.	3.5 nA	-5.4 nA
USB SEV	T3/VIFUDC	>10u Sec.	0.15 A	-0.3 A
USB SEV	T3/IIFUDC	>10u Sec.	70.0 uA	-92.0 uA
USB SEV	T4/VIFUAC	>10u Sec.	0.0 V	-0.34 V
USB SEV	T4/IIFUAC	>3m Sec.	0.77 mA	-0.1 mA
USB SEV	T5/VDCBUS	>10u Sec.	0.15 V	-0.29 V
USB SEV	T5/IDCBUS	>10u Sec.	0.13 mA	-0.19 mA
USB SEV	T6/VACBUS	>10u Sec.	0.0 V	-0.34 V
USB SEV	T6/IACBUS	>10u Sec.	0.0 A	-690.0 uA

6. Inherent Hardness Assessment

In each example stated the circuit was developed to provide the designer with some useful data to predict potential threat levels for his particular application. The data is not by any means intended to be all inclusive, however, some obvious conclusions can be made.

In each case, the circuits were terminated with appropriate impedances at both ends and at intermediate points of the circuits to represent typical aircraft systems. The induced transients at various points were computed using the TRAFFIC computer program. A summary of the results for the VSCF circuit with generator and converter on the wing and anticipated transient data at the bus located in the fuselage is shown in Table 28. As can be seen, the most severe transient coupling occurs with the generator feeders routed in the fiberglass leading edge of the wing.

A second set of evaluations was conducted with the same circuit but with the leading edge of the wing being a graphite epoxy composite material with varying number of plies. Again the induced transients are reduced by two orders of magnitude by virtue of the fact that the graphite epoxy has some conductivity even though it is about 1000 times less than aluminum. Also, routing the wiring close to metallic structure reduces the amount of electromagnetic energy that can be coupled onto the wiring. The induced voltage levels are approximately proportional to the height of the wire above the metallic structure.

From the detailed examination of power circuits, protection is required from the severe lightning threat for nearly all cases. The transient levels coupled onto the power bus exceed MIL-STD-704B and MIL-E-6051D requirements. The transients must therefore be reduced to values below the military specifications by various methods (i.e., shielding cables, add on protection, changing skin material composition and thickness, re-routing wiring, etc.).

Also, the investigation of graphite epoxy structure determined that electrical power systems in composite structure aircraft must be protected by either structural shielding, wire shielding, voltage suppression devices, or a combination of these.

TABLE 28 SEVERE LIGHTNING STRIKE TRANSIENTS SUMMARY DATA

TEST CONDITIONS	VOLTAGE PEAK	TRANSIENT DURATION	CURRENT PEAK	TRANSIENT DURATION
An all aluminum wing with fiberglass leading edge, 22 meters from the power bus				
Bus Open Circuit	75 KV	7 mS		
Bus Short Circuit			2.65 KA	0.7 mS
50% Loaded Bus	65 KV	8 mS	289 A	0.15 mS
100% Loaded Bus	58 KV	8 uS	550 A	0.6 mS
An all aluminum wing with a graphite epoxy leading edge, 22 meters from the power bus				
50% Loaded Bus, 35 Plies	410 V	1 mS	305 A	1 mS
50% Loaded Bus, 45 Plies	320 V	1 mS	235 A	1 mS
50% Loaded Bus, 50 Plies, L.E. is 2 ft ahead of feeder	285 V	1 mS	215 A	1 mS
50% Loaded Bus, 50 Plies, L.E. is 1 ft ahead of feeder	570 V	1 mS	420 A	1 mS
50% Loaded Bus, 50 Plies, L.E. is 1/2 ft ahead of feeder	1.14 KV	1 mS	840 A	1 mS

SECTION V

IDENTIFICATION OF ELECTRICAL SYSTEM SPECIFICATION REQUIREMENTS FOR AIRCRAFT

1. COMPARISON OF THREAT LEVELS WITH EXISTING STANDARDS

The threat levels defined in Section II produce voltage transients that exceed the transient withstanding requirements of the present military equipment specifications. The summation of applicable specifications for lightning transients on power systems is shown on Table 29. MIL-STD-704 and RTCA document DO-160 specify that equipment attached to the power system be capable of withstanding a 600 volt transient test. The purpose of the test is to ensure that the electrical equipment will not be damaged by switching transients. MIL-E-6051D has a power system requirement which limits voltage transients to 50 percent of the nominal line voltage for the AC system and +50 and -150 percent of nominal line voltage for the DC system. By specifications, electrical equipment is tested for 600 volts open circuit and is not required to withstand larger transients.

2. ELECTRICAL SYSTEM DESIGN SPECIFICATIONS

This section lists some of the specifications and federal design constraints that impact the design of a lightning hardened electrical system. The two major power quality standardization constraints are the RTCA document DO-160 and MIL-STD-704 both compared above.

a. Military Constraints

The Air Force Systems Command Design Handbook DH 2-3, Design Note 5A3 is a summary of the active military specifications required for the design control of electrical power systems. The following list identifies most of the related specifications:

TABLE 29 APPLICABLE TRANSIENT SPECIFICATION REQUIREMENTS

PARAMETER	MIL-STD-704B	MIL-STD-704C	MIL-E-6051D	DO-160
AC VOLTAGE SPIKE	±600 v. peak 1 usec rise t. test<500 usec		±50% of nominal volts test<50 usec	±600 v. peak 2 usec rise t. test
DC VOLTAGE SPIKE	same as AC		+50%, -150% of nominal volts test<50 usec	
AC VOLTAGE SURGE	180 v. rms >500 usec	180 v. rms >50 usec		
DC VOLTAGE SURGE	50 v >500 usec	50 v >50 usec		

SPECIFICATIONS

MIL-E-25499	Electrical System, Aircraft, Design and Installation of, General Specification For.
MIL-STD-704	Electrical Power, Aircraft, Characteristics and Utilization of.
MIL-E-7016	Electrical Load and Power Source Capacity, Aircraft, Analysis of.
MIL-G-21480	Generator System, 400 Hertz Alternating Current, Aircraft, General Specification For.
MIL-E-23001	Generating System, Variable Speed Constant Frequency, Aircraft, General Specification For.
MIL-E-7080	Electric Equipment, Aircraft, Selection and Installation of.
MIL-I-7032	Inverter, Aircraft, General Specification For.
MIL-G-6162	Generator, 30 Volt, Direct Current, Aircraft Engine Driven General Specification For.
MIL-B-83769	Battery, Storage, Lead Acid.
MIL-P-26517	Power Supply, Transformer-rectifier, Aircraft, General Specification For.
MIL-W-5088	Wiring, Aircraft, Selection and Installation Of.

Additional related specifications are:

MIL-B-5087	Bonding, Electrical, and Lightning Protection For Aerospace Systems.
MIL-STD-461	Electromagnetic Characteristics Requirements for Equipment.
MIL-STD-454	Standard General Requirements For Electronic Equipment.

The design engineer is advised to refer to AFSC DH 2-3, Design Note 5A3 for potential new replacement specifications, and should call out the latest active revision for all military airplane applications, unless special program directives exist to require particular prior specification controls. Also, the extent to which the military design constraints are made applicable to a military derivative of a commercial model airplane are normally negotiated for each derivative project.

b. Federal Constraints

The following federal design constraints have an impact on the electrical power system design for commercial transport and/or military airplanes and should be thoroughly reviewed and understood by the design engineer:

1. FAR Part 25, "Airworthiness Standards: Transport Category Airplanes."

2. FAR Part 91, "General Operating and Flight Rules."

3. FAR Part 121, "Certification and Operations: Domestic, flag, and Supplemental Air Carriers and Commercial Operators of Large Aircraft."

4. FAR Part 135, "Air Taxi Operators and Commercial Operators of Small Aircraft."

5. DOT Advisory Circular 120-28A, "Criteria for Approval of Category IIIA Landing Weather Minima."

6. Air Force Systems Command Design Handbook DH 2-3 "Propulsion and Power," Design Note 5A3 "Electrical Systems." (See Military Constraints above)

The power quality requirements of FAR 25.1351b-3 and 25.1351-4 require only that the voltage and frequency at all essential load terminals be maintained within the limits for which the equipment is designed and that the system transient conditions preclude inoperative essential loads, smoke or fire hazard. A particular "voltage and frequency" is not required, as long as the power quality and the essential load ratings are compatible. However, cost effectiveness and airplane maintainability considerations demand that the voltage and frequency limits be standardized for an airplane.

SECTION VI

IDENTIFICATION OF ADD-ON PROTECTION

To the design engineer, whose job is to prevent, minimize, or eliminate the effect of lightning transients that may cause permanent equipment damage, this section of the design guide will be most beneficial. It is more productive to design electrical/electronic equipment to withstand transients on input and output leads prior to manufacturing than it is to retrofit and provide protection to an existing system. Trade-offs must be made between the cost of providing equipment capable of withstanding lightning transients and the cost of shielding equipment and interconnecting wiring. The designer should take advantage of the inherent shielding provided by the aircraft structure and avoid placing equipment and wiring in locations that will be exposed to the electromagnetic fields generated by lightning strikes as pointed out in Section III.

1. SHIELDING OF POWER CABLES AND SIGNAL WIRES

An unshielded conductor exposed to the magnetic field of a lightning current traveling from the wingtip to fuselage will have high voltage transients induced onto the power feeders or adjacent signal wires. Shielding against magnetic fields requires the shield to be grounded at both ends in order to carry a circulating current that will cancel the magnetic fields which produce common mode voltages.

Some general circuit shielding types that may be used are:

- Single shields
- Overall bundle shields
- Double overall bundle shields (braid on braid)
- Solid conduit

Extra shielding provides much better protection at rf frequencies.

Circuits that are generally shielded for various reasons other than lightning protection are shown in Table 30. The table should help in evaluating the overall electrical system shielding requirements.

In these circuits conditions that set the grounding of shields vary, but there are a number of requirements that must be emphasized. They are:

1. Ground audio shield (and circuit) at receiver end only.
2. Ground video wideband shields at both ends.
3. Ground shields that contain or protect against rf fields and transients at both ends.

Note that the "audio shield" and "rf shield" grounding requirements conflict. Audio lines combined with rf shielding always require EMC analysis to determine the best overall design approach.

Figure 38 shows the amount of shielding obtained on a typical eight foot length of cable by a single shield. Although, the actual shielding effectiveness varies because of the wire length, tuning of shielded enclosures, equipment, set-up and measuring variables, Figures 39 through 43 give representative levels of shielding. At one gigahertz there is almost no shielding with the use of a two-inch pigtail. Figure 43 shows some standard connector shielding levels without the effect of pigtails. Double shield braid substantially improves shielding as shown in Figure 39.

Of the different types of shields, the solid shield inherently provides better shielding than does a braided shield, while a spiral-wrapped shield is less effective than a braided shield. Figure 44 gives relative shielding effectiveness for several types of shields.

a. Conduits As Shields

Conduits may provide electromagnetic shielding, however, they are used more for mechanical protection than for electrical protection of conductors. Conduits for mechanical protection are physically mounted in clamps that use rubber gaskets to prevent mechanical vibration and wear, and only if the

TABLE 30 CABLE SHIELDING MATRIX

	GROUP	SIGNAL RF & VIDEO	ANALOG	DIGITAL	DISCRETE ④	POWER DC ④	AC ④
		6	5	4	3	2	1
1	AC Power ④	No Special Shielding Required	Shield Both ①	Shield Both ①	Shield 5V Discretes & AC Excitation Only	Shield AC & DC Excitation & AC Measuring Only	Shield AC Excitation Only
2	DC Power ④	No Special Shielding Required	Shield Both ②	Shield Both ②	Shield 5V Discretes & DC Excitation Measuring Power Only	Shield Excitation Measuring Power Only	
3	Discrete Signals ④	No Special Shielding Required	Shield Both ③	Shield Both ③	Shield 5V Discretes Only		
4	Digital Signals	No Special Shielding Required	Shield Analog Only	Shield 5V Digitals Only			
5	Analog Signals	OK Only If Shielded Analog Is D' Arsonval Movement	Special Shielding Not Required				
6	RF & Video Signals	No Special Shielding Required					

① Exception - Shield neither if the only AC power to be cabled is the low voltage AC excitation power from which the analog signal was derived.

② Exception - Shield neither if the only DC power to be cabled is the low voltage DC excitation power from which the analog signal was derived.

③ Exception - Shield neither if the only discrete signal(s) to be cabled is 5V

④ AC and DC power and discrete signal circuits are assumed to have on/off transients.

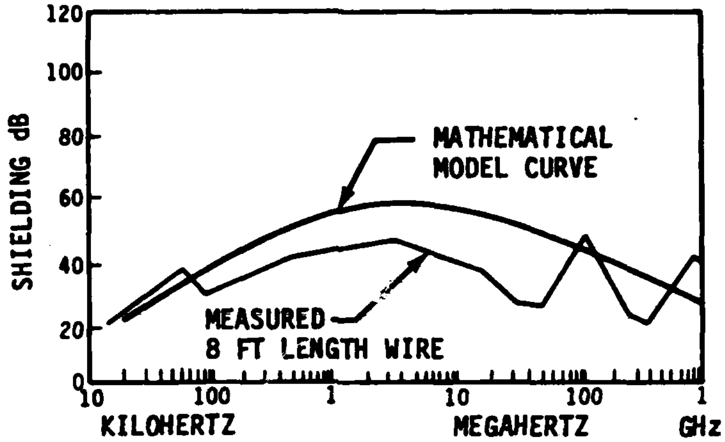


Figure 38 Wire Shielding

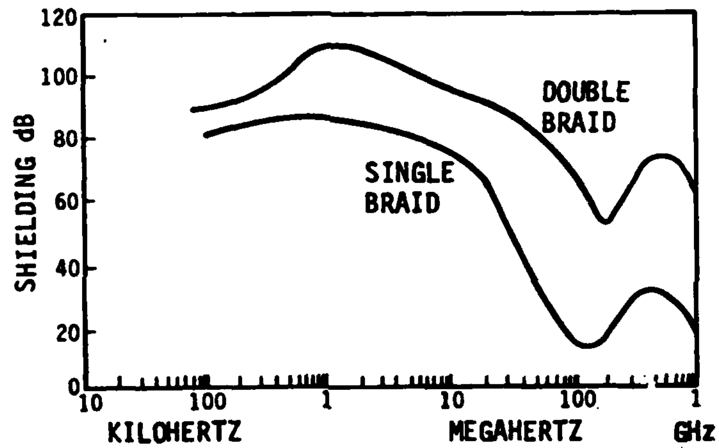


Figure 39 Double Braid vs Single Braid Shielding

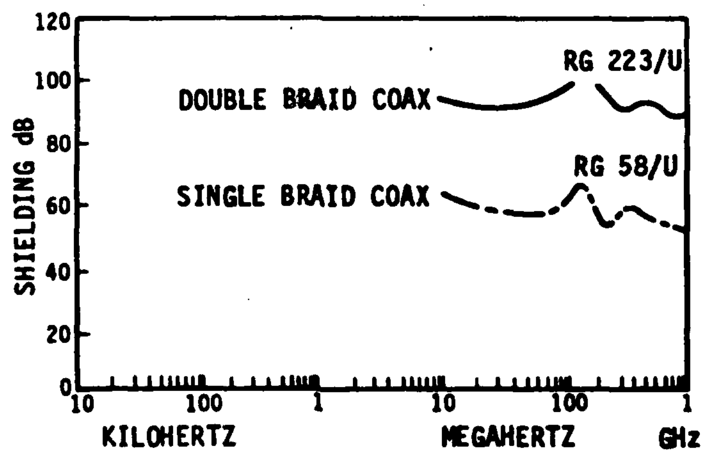


Figure 40 Coaxial Braid Shielding

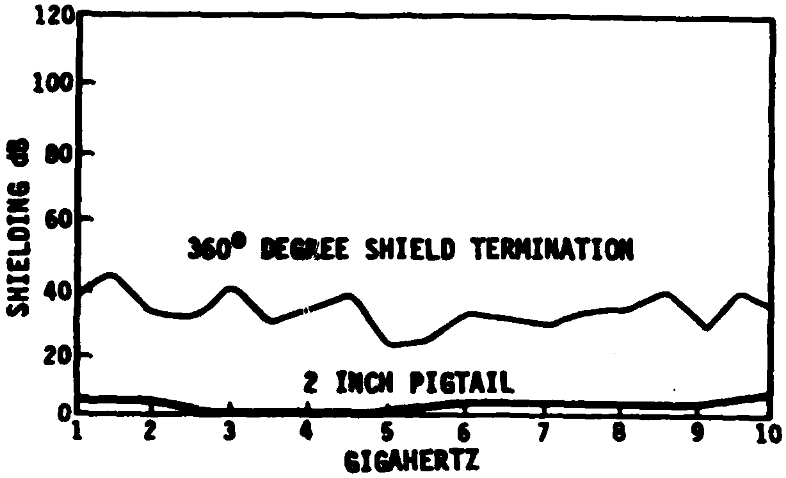


Figure 41 Shielding Loss from Pigtails

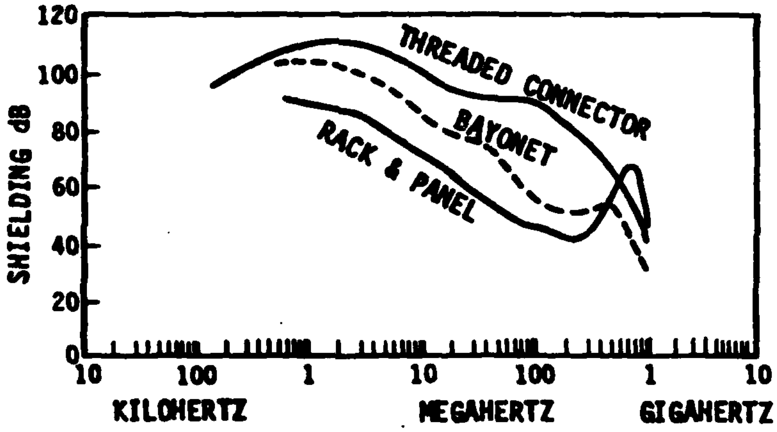


Figure 42 Connector Shielding

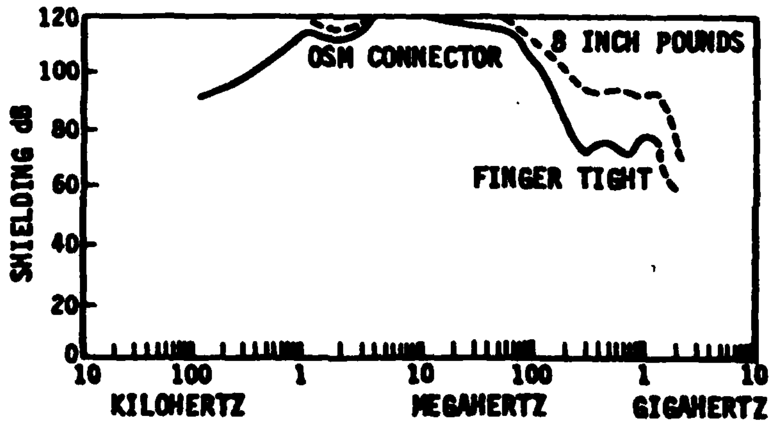


Figure 43 OSM Connector Shielding

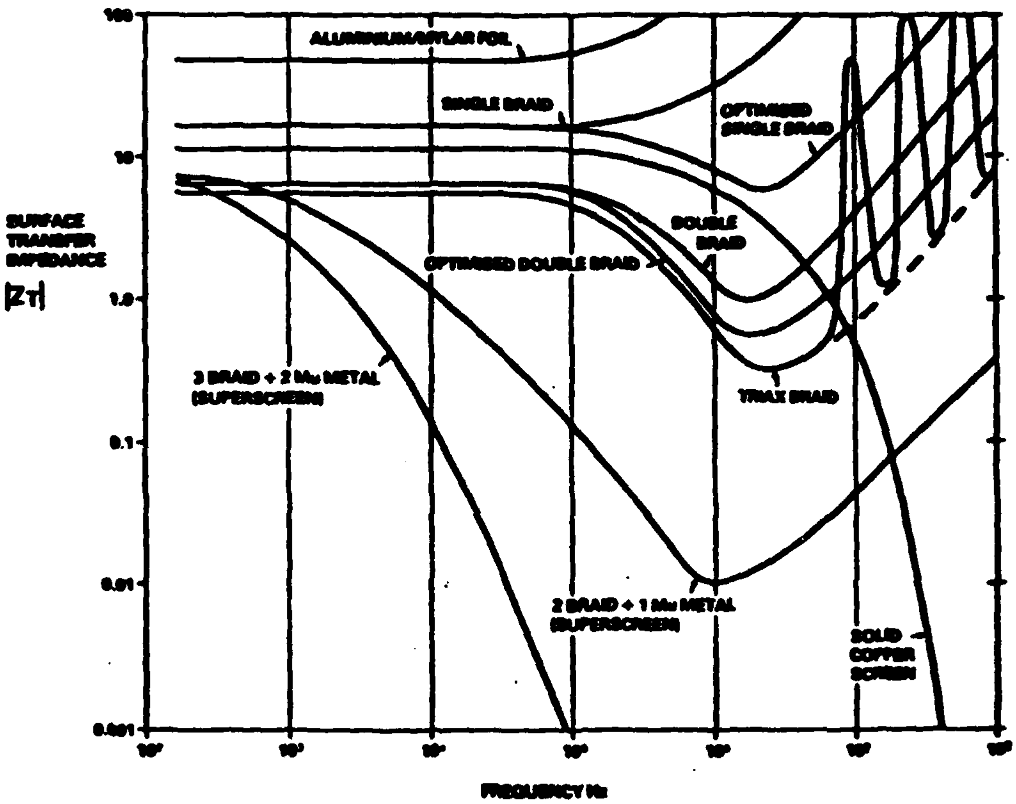


Figure 44 Comparison of Typical Shields

conduit is electrically connected to the framework of the airplane at both ends will it be able to carry current and provide shielding for the conductors within.

b. Tape Wound Shields

Tape wound shields are often used where flexibility of the shielded cable is required. The shield may be formed either from a narrow metal sheet spiraled around the core or from a carrier of fine wires, again spiraled around a core. Flexible armour and flexible conduit, which is normally used for mechanical protection, may be analyzed as tape wound shields. The tape-wound, or spiral-wound, shield is rather a poor shield for preventing coupling of current from the shield onto the internal conductor because the shield tends to behave as a solenoid wound about the internal conductors. There is thus a rather large mutual coupling term relating the internal voltage to the shield current. As stated in Reference 6, the mutual inductance of the tape-wound shield was calculated to be on the order of 10^4 greater than the mutual inductance obtained for a braided-wire shield.

c. Thin-Walled Tubular Shield

The thin-walled tubular shield consists of a metal tube of uniform cross section and uniform wall thickness. Coupling through the shield can occur only by diffusion of the electromagnetic fields through the walls of the tube.

The transfer impedance characteristic as stated in Reference 6 decreases with increasing frequency. Accordingly, the internal electric field will, in response to a step function current, increase according to the pulse penetration time constant.

d. Cable Trays/Raceways as Shields

Cable trays are most often used for mechanical protection of wires, but if viewed as shields, they may also provide electrical protection. The characteristics of a cable tray that make for good electrical protection are the same as those for any other shield:

1. It must be able to carry current along its axis.

2. It should be made of low-resistance material.

3. It should completely surround the conductors.

4. It should have a minimum number of openings through which magentic fields may leak.

5. It should have as few joints as possible, and such joints should be made in such a manner as to provide minimum resistance and leakage of magnetic fields.

The transfer characteristics of the tray by itself would be about the same as those of the solid tubular shields. This comparison assumes the tray to be of solid metal and fitted with a well sealed cover.

Trays are most commonly built in short sections and jointed by splices or transition sections. Such sections frequently provide for thermal expansion and contraction and are, at any rate, seldom designed either to provide good electrical continuity or to protect against magnetic leakage. When joints are considered, the transfer characteristic of the tray is found to depend almost entirely on the treatment of the joints.

e. Grounding of Shields

The aircraft structure serves as the ground return circuit unless system consideration requires separate ground return wiring. Refer to Section III for grounding requirements and procedures.

Caution should be exercised in the use of shields for return currents. Shields should not be used to conduct return currents for circuits (e.g., sensitive low voltage circuits). Shields sometimes cannot be prevented from carrying fault currents. In these instances, where safety grounding for equipment is involved, check for adequacy of current carrying capacity.

Wire shields must continue as close to connectors or terminals as possible. In connectors, circuits which are shielded are separated from source circuits by grounded contacts.

Terminate shields of all antenna leads to the antenna ground plane. Under no circumstances are shields or wires extended into the antenna cavity.

Shield ends must be supported in a manner to prevent intermittent contact with structure or other grounds.

When a multi-conductor shielded cable is connected to a terminal block, the conductors should be twisted after they are broken out of the shield, and arranged on the terminals to allow only the smallest possible pickup loop.

When designing electrical cables and wire bundles requiring dead-ending of shields, the following design alternatives, listed in order of desirability, should be considered:

- o Terminate shield on both ends (use one unused connector pin) so the continuity test can be made.
- o Terminate with breakout pigtails to be dead-ended after pre-pot test.
- o Terminate with temporary pigtail to be removed after test. In some design combinations, this is a manufacturing option.

The typical low frequency shield, because it is ordinarily grounded at only one point, is usually not adequate to provide shielding for the high frequency lightning transients. Both sets of requirements can be met by supplying two separate shields, one for each type of interference.

The method of grounding the shield can have a great impact, an order of magnitude or more, on its effectiveness in protecting against lightning generated transients. The best method is the circumferential or 360° connection to the back shell of the connector (see Figure 45). The connector itself should have a low dc resistance with respect to its mating panel connector. For a good 360° connection between the shield connector and the mating panel, paint and other lacquers should be stripped down to metal.

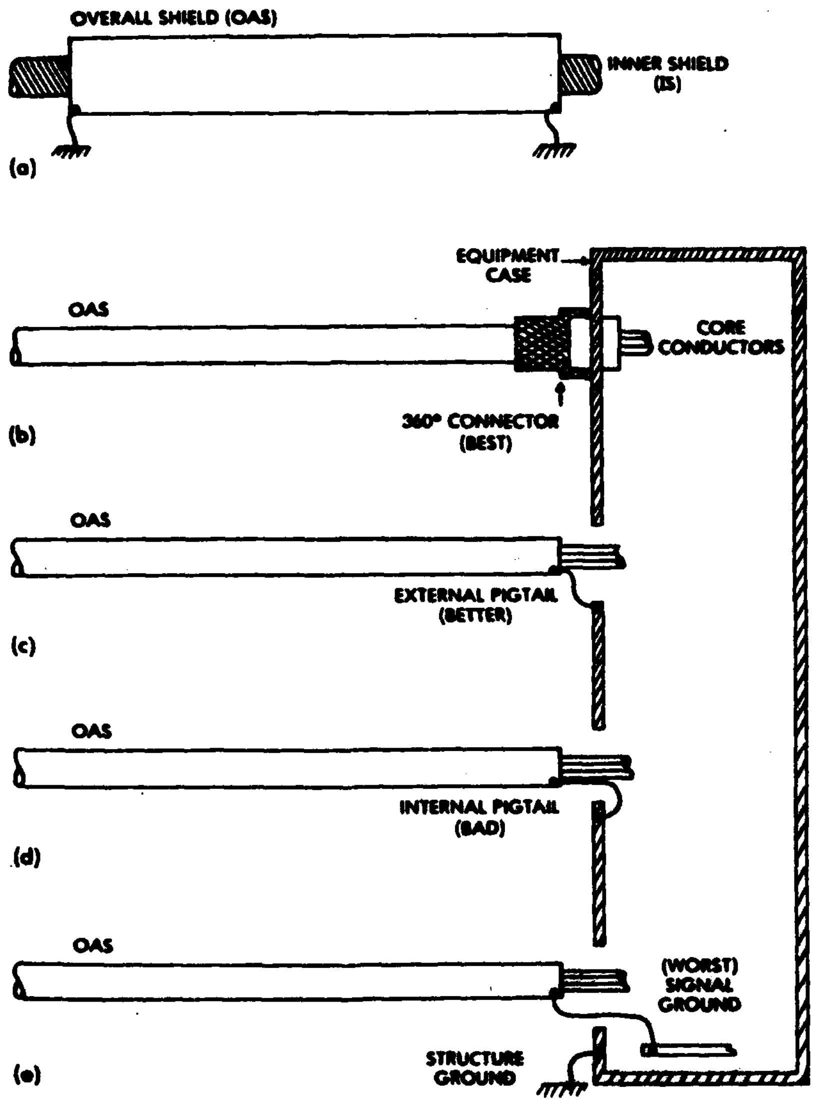


Figure 45 Types of Grounding for Shields

Frequently, pigtails are used in grounding shields but are inferior to the circumferential ground. The pigtails force the transient current to become concentrated at the pigtail enhancing the magnetic coupling to the feeders or conductors inside (Figure 46). If pigtails are used, they should be kept as short as possible and terminate on the outside of the equipment case. Grounding of pigtails to the inside of the equipment case is less effective and should be avoided. Never terminate a shield to a signal ground bus.

2. Nonlinear Devices for Protection: Tranzorbs™, Varistors and Zener Diodes

All types of overvoltage devices inherently operate by reflecting a portion of the transient energy back toward the source and by conducting the rest into another branch. Until exposed to an over voltage condition, these devices will maintain the operating voltage of the system. Then, according to their nonlinear voltage-current relationships, these devices will short the overvoltage and conduct the excess current to ground. When the transient subsides, device conduction turns off, and the system returns to its normal operating state. Resetting circuit breakers is not required when the voltage returns to its normal value.

A TransZorb™ is a silicon PN junction device designed for suppression of high voltage transients associated with power disturbances, switching, and induced lightning effects. The TransZorb is characterized by a $1x10^{-12}$ second response time and a low series resistance.

A varistor is a two-electrode semiconductor device with a voltage-dependent nonlinear resistance that drops markedly as the applied voltage is increased. The metal oxide varistor is characterized by a 50 nanosecond response time.

Zener diodes are two-layer polarized devices that when forward biased respond as an ordinary rectifier diode. If a voltage applied in the reverse bias direction exceeds the device's breakdown voltage, the device reacts in an avalanche fashion with respect to its current-voltage characteristics.

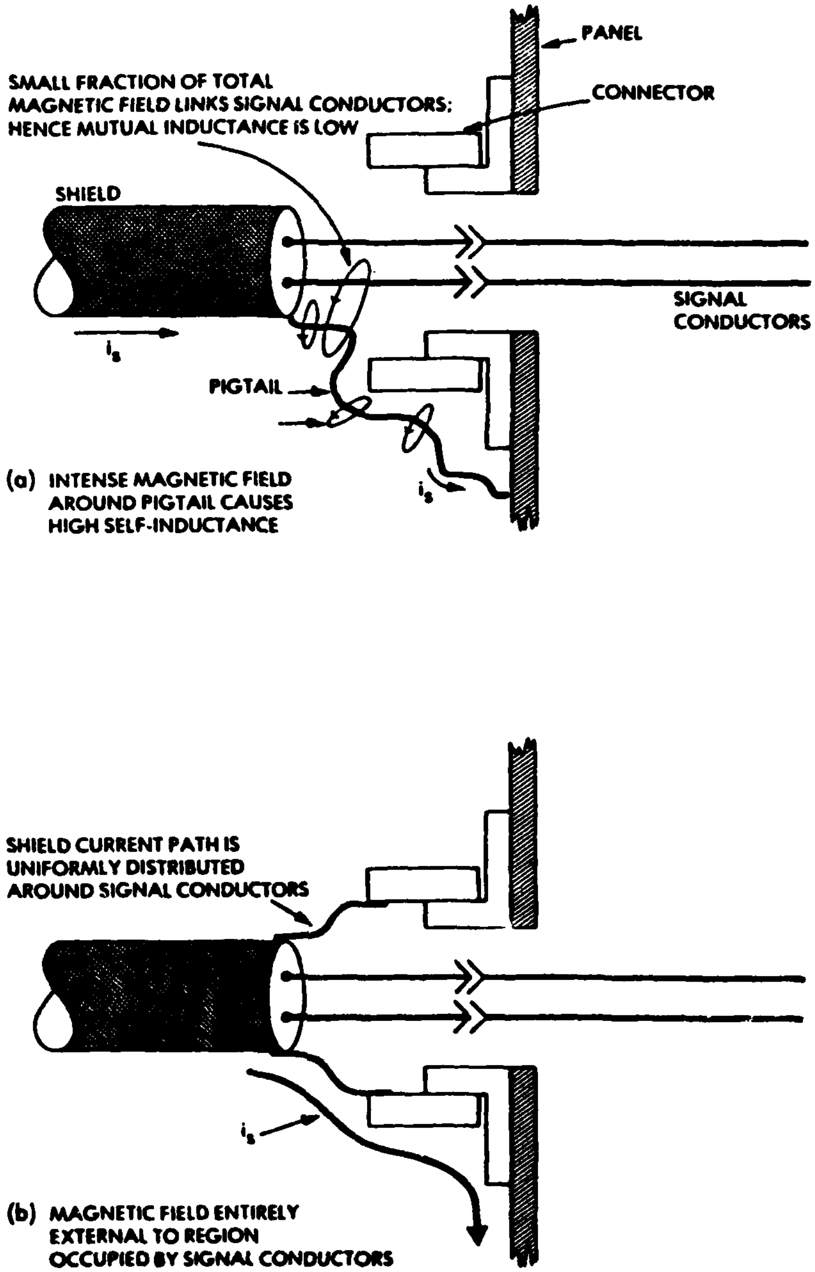


Figure 46 Magnetic Fields Around Shielding Terminations

a. Guidelines for TransZorb™ Selection

The TransZorb (Reference 13) was initially designed for providing protection for telecommunication equipment from transient voltages resulting from induced lightning. Applications for TransZorbs have subsequently expanded to include many other areas of protection encompassing transient voltages generated by inductive switching, high-voltage disconnects, static discharge, and EMP. In closed systems where voltage transients can be predicted and well defined, it is much easier to select a TransZorb to protect the more sensitive elements of the system. General guidelines for selecting the right TransZorb are listed below. Table 31 provides some typical TransZorb data.

DC Voltage Rating

- o Determine the maximum dc or continuous operating voltage, which should be the nominal circuit voltage plus its tolerance on the high side. This should be the maximum voltage of the circuit.

- o Select a TransZorb suppressor to have a reverse standoff voltage equal to or greater than the maximum circuit voltage, as defined in the paragraph immeidately above. This selection will allow for operating over the temperature range of -65° to +175°C.

Pulse Rating

- o Define the waveshape or source of the transient and duration of the pulse. Determine the maximum peak pulse power of the transient. If the pulse decays expoenetially, observe the pulse time for decay to 50% of the crest value.

- o Check the peak pulse current on the data sheet to assure that the current of the pulse is within the maximum rating of the suppressor for a 10x1000 pulse. For example: 286 A for the 15KP28 (28 V), and 70 A for the 15KP100.

TABLE 31 TYPICAL TRANSZORB™ DATA LISTINGS

GENERAL SEMI-CONDUCTOR PART #	REVERSE (1) STANDOFF VOLTAGE V_R	BREAKDOWN VOLTAGE @ 5 MA	MAXIMUM CLAMPING VOLTAGE @ I_{PP} 1 MSEC V_C	MAXIMUM PEAK PULSE CURRENT (AMP)
15KP28	28	31.1 → 38.0	52.4	286
15KP28A	28	31.1 → 34.4	47.5	316
15KP100	100	111 → 136	179	84
15KP100A	100	111 → 123	162	93
15KP120	120	133 → 163	214	70
15KP120A	120	133 → 147	193	78
15KP170	170	189 → 231	304	49
15KP170A	170	189 → 209	275	55
15KP220	220	245 → 299	393	38
15KP220A	220	245 → 271	356	42
15KP280	280	311 → 380	500	30
15KP280A	280	311 → 344	452	33

(1) A TransZorb™ is normally selected according to the reverse standoff voltage (V_R) which should be equal to or greater than the DC or continuous peak operating voltage level.

- If the pulse decays exponentially, but different than the 1 millisecond which is specified on the data sheet, check the data for maximum Peak Power (Pp) for that particular pulse duration.

- If the pulse is a nonrepetitive square wave, derate the transient suppressor to 66% of the maximum value under exponential decay conditions. If the pulse is a nonrepetitive one-half sine wave, derate the suppressor peak pulse power to 75% of the maximum capability.

- If the pulse is a rapidly damped sine wave or rapidly damped square wave with one time constant of five cycles or less, rate the device the same as if it were subject to only one pulse, as defined in the paragraph above.

Stacking TransZorbs™ for Higher Power

- If the incident Pp is greater than the rating of the TransZorb, devices may be stacked in series to increase power rating for voltage levels usually above 20 volts. An example of this could be a 1.5 kW, 100 V TransZorb, which is inadequate, and a 3 kW peak power dissipation is required. The most advantageous way to achieve this power level is to stack in series two each of a 50 V ±5% TransZorb. The total peak pulse power dissipation would then be twice that of a 1.5 kW device, or 3 kW. Stacking three each of a 33 V ±5% device would yield a 4.5 kW peak pulse power and stacking 4 each of the 25 V ±5% device would give a peak pulse power of 6 kW. TransZorbs can be stacked almost without limit.

  In practice, TransZorbs have been stacked in excess of 180 devices with good reliability. However, 5% tolerance devices of the same voltage must be used to insure even loading of the devices. When the power rating is doubled, notice that the current rating is doubled also.

- If it is impossible to achieve the necessary power rating by stacking the devices in series, parallel stacking can be done effectively for voltages below 20 V. Close matching, about 100 mV or less between each device, is necessary to assure even loading of the transient power between the suppressors. This is usually done at the factory for optimum results.

Clamping Voltages

Observe that the maximum clamping voltage is 1.33 x the breakdown voltage. If this maximum clamping voltage exceeds the circuit limitations, devices can be derated to reduce the clamping factor. For example, two devices in series have a clamping factor of approximately 1.2 as compared to the clamping factor of 1.3 for a single device.

High Frequency Applications

If the suppressor is used on dc or low frequency signal lines, the capacitance of the suppressor will not attenuate or alter the circuit conditions. However, if the frequency is quite high, and insertion loss occurs, methods of effectively reducing capacitance by adding low capacitance diodes in series have been developed.

b. Guidelines for Varistor Selection

Varistors (Reference 14) are voltage dependent, nonlinear resistors which have an electrical behavior similar to back-to-back zener diodes. The symmetrical sharp breakdown characteristics enable the varistor to provide excellent transient suppression performance. When exposed to high voltage transients the varistor impedance changes many orders of magnitude from a near open circuit to a highly conductive level, thus clamping the transient voltage to a safe level. The potentially destructive energy of the incoming transient pulse is absorbed by the varistor thereby protecting vulnerable circuit components.

Varistors are available with AC operating voltage from 10 V to 1000 V, with higher voltages limited only by packaging. Peak current handling exceeds 25,000 A and energy capability extends beyond 600 joules for the larger units.

To select the appropriate varistor for the particular application of interest a five step process has been developed:

1) Determine the necessary steady state voltage rating.

2) Establish the transient energy absorbed by the varistor.

3) Calculate the peak transient current through the varistor.

4) Determine any power dissipation requirements.

5) Select a model to provide the required voltage limiting characteristics.

This process requires a knowledge of the electrical environment, however, if it is not fully defined some approximations can be made.

Specifications shown in Table 32 are for GE varistors rated in the High Energy (HE) series and illustrate typical manufacturer characteristics. The V-I characteristics for various current rise times for these devices are shown in Figure 47a and the Static and Dynamic Impedance characteristics are shown in Figure 47c.

The energy absorbed by the varistor can be calculated from the following expression:

$$E = K \, V_c \, I \, \alpha$$

where I is the peak current applied, Vc is the clamp voltage, α is the impulse duration and K is a constant based on the pulse waveshape (for a sinusoidal transient decaying exponentially, K equals 0.86).

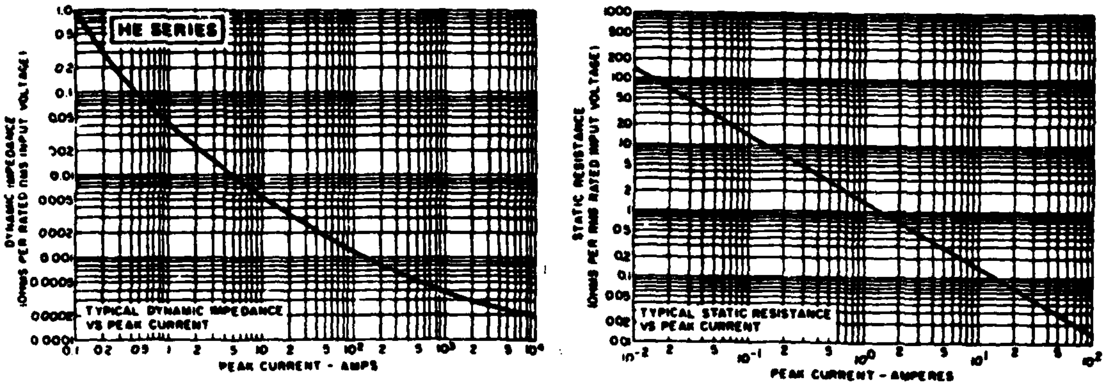
The rated peak current is the maximum allowable for a single pulse of 8 X 20

TABLE 32 SPECIFICATIONS FOR HE SERIES VARISTORS [1]

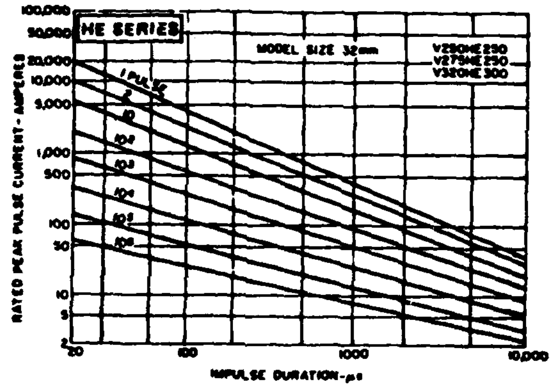
RATINGS AND CHARACTERISTICS TABLE

MODEL NUMBER	MAXIMUM RATINGS (25°C)				CHARACTERISTICS			
	CONTINUOUS		TRANSIENT		V_{NOM} VARISTOR PEAK VOLTAGE @ 1mA AC		MAXIMUM CLAMPING VOLTAGE, V_C @ 300 AMPS (8 x 20 μs)	TYPICAL CAPACITANCE
	RMS VOLTAGE	DC VOLTAGE	ENERGY (10 x 1000 μs)	PEAK CURRENT (8 x 20 μs)				
	V_{RMS}	V_{DCM}	W_{tm}	I_{tm}	MIN.	MAX.	V_c	f = 0.1-1 MHz
	VOLTS	VOLTS	JOULES	AMPERES	VOLTS	VOLTS	VOLTS	PICOFARADS
V130HE150	130	175	200	15,000	184	254	365	4700
V150HE150	150	200	220	15,000	212	282	425	4000
V250HE250	250	330	330	20,000	354	472	690	2500
V275HE250	275	369	360	20,000	389	522	760	2250
V320HE300	320	420	390	20,000	462	635	860	1900
V420HE400	420	560	400	25,000	610	800	1200	1400
V480HE450	480	640	450	25,000	670	914	1320	1300
V510HE500	510	675	500	25,000	735	970	1450	1200
V575HE550	575	730	550	25,000	805	1060	1600	1100
V660HE600	660	850	600	25,000	940	1265	1850	900

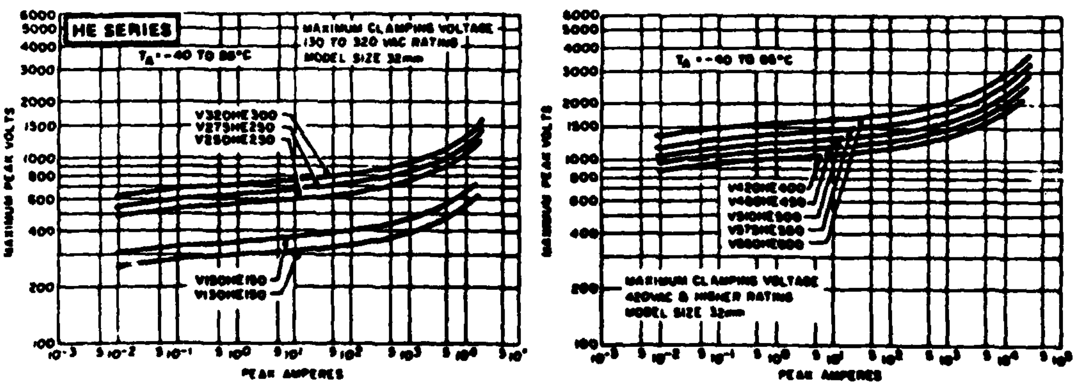
[1] THESE ARE GE-MOV™ II VARISTORS, REFERENCE 14



c. Static/Dynamic Impedance Characteristics



b. Typical Pulse Lifetime Ratings



a. Transient Characteristics for the HE Series Varistors

Figure 47 Typical Response Data for Varistors (Reference 14) sec exponential waveform. For longer duration pulses, the peak current rating should be derated to the curves in the varistor specifications. Typical derating curves are shown in Figure 47b. The designer must consider the total number of transient pulses expected during the life of the equipment and select the appropriate curve.

Series and Parallel Operation of Varistors

In most cases the designer can select a varistor that meets the desired voltage ratings to meet the requirement of the circuits to be protected. However, the varistors can be arranged in parallel or series to meet the system requirements due to voltage ratings or energy/current ratings.

Varistors are applied in series for one of two reasons: to provide voltage ratings in excess of those available, or to provide a voltage rating between the standard model voltages. Higher energy ratings are achieved with series connected varistors over an equivalent single device. Varistors can be connected in series providing they have identical peak current ratings (same disc diameter). The composite V-I characteristics, energy rating, and maximum clamp voltages are all determined by summing the respective characteristics and/or ratings of the individual varistors.

If application requirements necessitate higher peak currents and energy dissipation than available varistors provide, then the logical alternative is to examine the possibility of paralleling. At high current levels varistors have a prominent series resistance in the up-turn region of the V-I characteristic. It acts as a series balancing resistor to force a degree of current sharing. The manufacturer suggests that for practical application the varistors must be matched by means of high current pulse tests to make parallel operation feasible. Some guidelines are given on Table 33 for series and parallel operation of varistors (Reference 14).

c. Zener Diodes for Protection

This category includes all single-junction semiconductor devices such as rectifiers, in addition to Zener diodes. While other semiconductor devices,

TABLE 33 GUIDELINES FOR SERIES AND PARALLEL OPERATION OF VARISTORS

	SERIES	PARALLEL
Objective	• Higher Voltage Capability • Higher Energy Capability • Non-standard Voltage Capability	• Higher Current Capability • Higher Energy Capability
Selection Required By User	NO	YES
Models Applicable	• All, must have same I_{tm} rating.	LA, PA, ZA, HE Series
Application Range	• All voltages and currents.	• All voltages – only high currents, i.e., > 100 amperes.
Precautions	• I_{tm} ratings must be equal.	• Must use identical voltage rated models. • Must test and select units for similar V-I characteristics.
Effect on Ratings	• Clamp voltages additive. • Voltage ratings additive. • Current ratings that of single device. • Energy, W_{tm}, ratings additive.	• Current ratings function of current sharing as determined graphically. • Energy ratings as above in proportion to current sharing. • Clamp voltages determined by composite V-I characteristic of matched units. • Voltage ratings that of single unit.

such as PNPN devices and bipolar transistors, may have application as surge arrestors, they are not covered here because of the limited data available.

Zener diodes are basically polarized devices which exhibit an avalanche breakdown when the applied voltage in the reverse bias direction exceeds the devices specified breakdown, or Zener voltage of the device. Operated in an opposed series configuration, diodes can be used as effective suppression devices. Since Zener diodes are designed to operate in the breakdown mode, they usually can perform more effectively as terminal protection devices than can signal diodes. While the energy-handling capabilities of Zener diodes are modest when compared with those of spark gaps, they are very well adapted for protection of individual components or circuit boards.

The advantages of Zener diodes include the following:

- They are of small size.
- They are easily mounted.
- They have low "firing" voltage.
- They have low dynamic impedance when conducting.
- They are self-extinguishing. When applied voltage drops below the Zener level, they cease conduction.
- They exhibit low volt-time turnup, or impulse ratio.

The disadvantages of Zener diodes include the following:

- They may be expensive.
- They are not bilateral. To protect against both polarities, two diodes in series back-to-back configuration are necessary.
- Diodes have relatively high-junction capacitance; therefore, they may cause significant signal loss at operating frequencies above 1 MHz. (Special diode assemblies may extend the useful frequency to approximately 50 MHz.)
- They do not switch state between a conducting and a nonconducting mode. The voltage across the diode does not switch to a low value when conducting but remains at the Zener voltage. This characteristic accounts for their ability to cease conduction when the voltage falls below the Zener level, but it has a disadvantage thermally. During conduction, the power absorbed

by the diode is the product of the current through the diode and the voltage across the diode. The power absorbed for constant current, thus, is directly proportional to the diode voltage.

Partially offsetting this disadvantage, however, is the phenomenon that surge energy absorbed in the diode is energy that cannot be reflected back into the system to cause trouble elsewhere.

- They provide lower energy capabilities than do spark gaps. Since the Zener action takes place across a narrow P-N junction, the mass of the protecting junction is small and hence cannot store much energy. As a result, diode networks cannot be used where extremely high transient current or energy is predicted. For most hardening applications, this is not a serious limitation, since the induced surge-current levels are in the 1 to 100 A range at those locations where Zener diodes are most likely to be used.
- They are not available for voltage below about 5V.
- They are not normally available for voltages above a few hundred volts.

3. Filtering of Power Cables and Signal Wires

In using filters for lightning transient suppression, we must view the protective device behavior in terms of its ability to "reflect" incident transient energy "waves" away from the protected equipment. This concept is illustrated in Figure 48.

An "ideal" protective device would divide the transient voltage and totally reflect the incident energy wave, allowing none of it to reach the protected equipment. At the same time it should not affect normal operational signals. Real-world suppressors do allow transient energy to reach the protected equipment, and do have some effect on normal operational signals. In many cases the normal/transient performance requirements are actually conflicting. It is then the job of the system designer to choose devices providing a realistic compromise in normal/transient performance.

Incident transient waves can be reflected by either very low impedance (negative reflection coefficient) or very high impedance (positive reflection

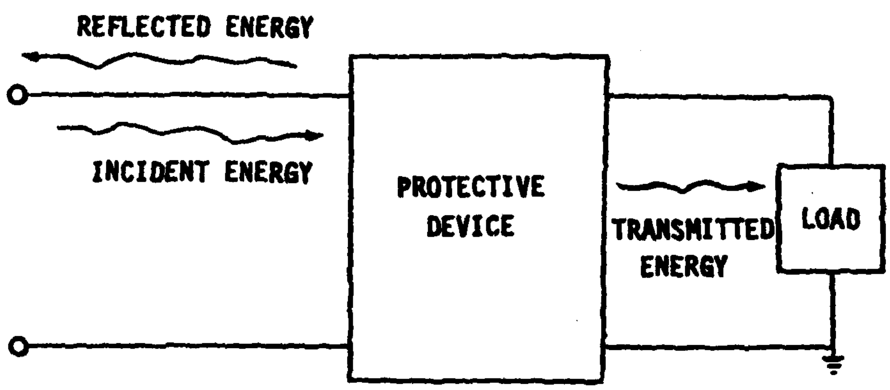


FIGURE 48 Reflective Protection Device Concept

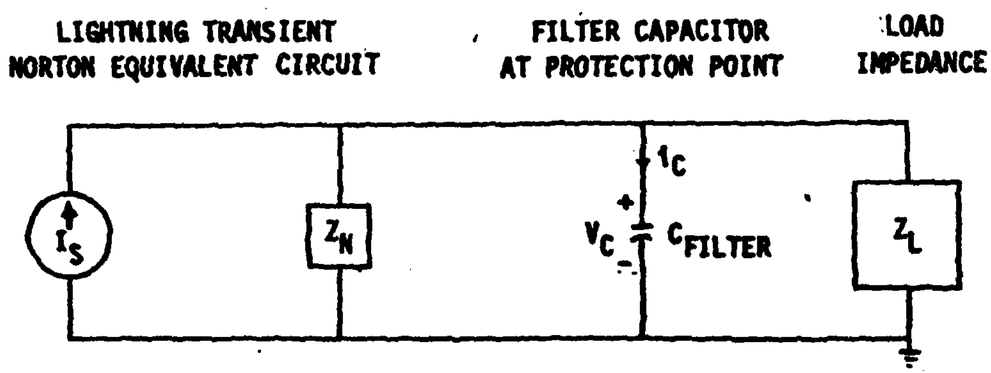


Figure 49 Transient Model With Filter Capacitor

coefficient) terminations. In power systems low transient impedances are obtained using capacitors or solid-state devices (such as diodes or TransZorbs). High transient impedance devices must also provide load isolation from the input terminals, and are normally obtained using LC filters.

A major drawback of high transient impedance protection schemes is that high voltages can exist in the immediate neighborhood of the protective device. This would likely result in arcing in wiring or connectors. The resulting large power system follow through current would trip the circuit breaker. A low transient impedance device would tend to keep these voltages low, thus avoiding the arcing problem.

All these protective schemes exploit differences between the lightning induced transients and the normal power signals: (1) level differences (nonlinear protective devices, such as TransZorbs), (2) spectral differences (linear devices, such as capacitor or LC filters), or (3) level and spectral differences (combintations of TransZorbs and capacitor or LC filters).

Filter Design Concepts

Consider the simplified power system transient model illustrated in Figure 49, including a Norton equivalent network representation of the lightning transient source, a capacitor filter connected to the protection point, and a load impedance.

If the Norton and load impedances are desirably high compared to the transient impedance of the capacitor then most of the short-circuit current (I_S) will flow through the capacitor. For an ideal capacitor

$$v_c(t) = \frac{1}{C}\int i_c(t)dt \qquad (3)$$

If the short-circuit current at the protection point has the form

$$I_s(t) = I_0 \exp(-t/\tau)u(t), \qquad (4)$$

then

$$v_c(t) = \frac{I_0\tau}{C}\left[1-\exp(-t/\tau)\right]u(t) \qquad (5)$$

is the transient induced component of the capacitor voltage (superimposed on the normal voltage).

Equations (3) through (5) are valid until a level is reached at which device breakdown occurs. At the onset of breakdown, the voltage drops and the current increases suddenly. The result of such a breakdown is to reduce the capacitor's leakage resistance and subsequent breakdown level by creating tracking paths in the insulation material or encapsulation (Reference 15). Capacitance change or device fracture may also occur. The short-pulse voltage level at which breakdown occurs will usually be several times greater than the d.c. voltage rating (typically four to six times for microsecond pulses).

If the Norton and load impedances are very high at low frequencies, the capacitor will discharge very slowly, and the voltage across the capacitor will decay according to the time constant. Low impedances (for low frequencies) would discharge the capacitor rapidly. The discharge rate determines the overvoltage factor at which the capacitor can be operated. For devices having unknown characteristics or for unknown discharge rates, it may be wise to conservatively design so that the direct current voltage rating is not exceeded.

In addition to transient performance, a designer must consider normal system operational performance. Capacitor reactance is defined as:

$$X_C = \frac{1}{2\pi f_{PWR} C} \qquad (6)$$

where C is the capacitance value and f_{PWR} is the power system frequency of operation (60Hz, 400Hz, etc.). There will normally be a maximum allowable capacitor "leakage" current (dictated by safety, power factor, or capacitor reliability considerations), which will in turn define an upper limit on the capacitance value:

$$C = \frac{I_{MAX}}{2\pi f_{PWR} V_{PWR}} \qquad (7)$$

where I_{MAX} is the maximum allowed power current and V_{PWR} is the power line voltage. The peak transient voltage is then approximated as:

$$V_{Peak} = \frac{2\, f_{PWR} V_{PWR}\, I_o \tau}{I_{MAX}} \quad (8)$$

where τ is the time constant rate of decay and I_o is the current at zero time.

4. Skin Materials and Coatings

Unfortunately aircraft (even "all metal" aircraft) are not, and cannot be perfect metal shells. The extremities, which most often serve as electrodes for the strike, are commonly covered with non-metallic radomes; antennas of various kinds project beyond the shield of the metal shell; and flight control surfaces are vulnerable because of their shape, their extreme location and bearing attachment to the shell. As might be expected these are the items that are most often damaged by lightning strikes and that couple lightning transients to the electrical wiring within.

a. Fiberglass Components

(1) Radomes

Non conductive shells such as radomes present difficult design problems and warrant some particular attention.

It is generally not feasible to alter the location of a radome or its material to provide lightning protection for the field of surveillance and/or the range of the radar would suffer. The only alternative is to divert the stroke to the metal skin or structure by a chosen path via a conductor placed so as not to interfere with the operation of the enclosed equipment. Diverters of two general types are in use, the consumable and the permanent (Reference 6).

For most applications, the consumable conductors (thin foil strips) are in the form of braided wire or narrow thin metallic strips, cemented longitudinally to the radome outer surface, and bonded to the metal skin or structure. The length of the strips, their location, and their cross sectional dimentions are determined by tests to be optimum for the particular application. That is to say, they are planned to provide the best balance between lightning protection and loss of performance from the enclosed equipment (Reference 16).

(2) Antennas

These are often instrumental in leading lightning into the electronic bay areas where it damages equipment and exposes operating personnel to hazardous voltage. For this reason, lightning suppression devices have been developed. These are located in the antenna lead-in adjacent to the aircraft skin. The arresters are expendable, that is, they must be expected to sustain some damage in diverting the heavy current, and should be frequently inspected to ensure that the correct spark-gap is maintained. Note that they are not intended to protect the external antenna, but are intended to provide a calibrated weak point in the antenna system which will break down and carry off the destructive peak voltage through a safe path rather than allowing the lightning to flashover to structure inside the fuselage. Arresters are not provided for all antennas in all locations. Generally only those which are likely targets because of their shape and location are fitted with arrestors (composite structured aircraft may require them in all locations).

(3) Control Surfaces

Rudders and elevators are prime lightning targets because of their location and are susceptible to damage because they are necessarily hinged and constructed of light-gauge material. There is no practical way to preclude all current transfer through the hinge bearing, but it can be reduced to a certain extent by providing bonding jumpers (Figure 50) between the fixed and the movable structure. This provides paths of low resistance in parallel with the hinges, so that a large proportion of the current is bridged safely. However, when high voltages are applied current will inevitably flow through the bearing.

Protection Guidelines Using Diverter Straps

As stated in Reference 6, the following guidelines should be followed to properly place diverters on a fiberglass structure:

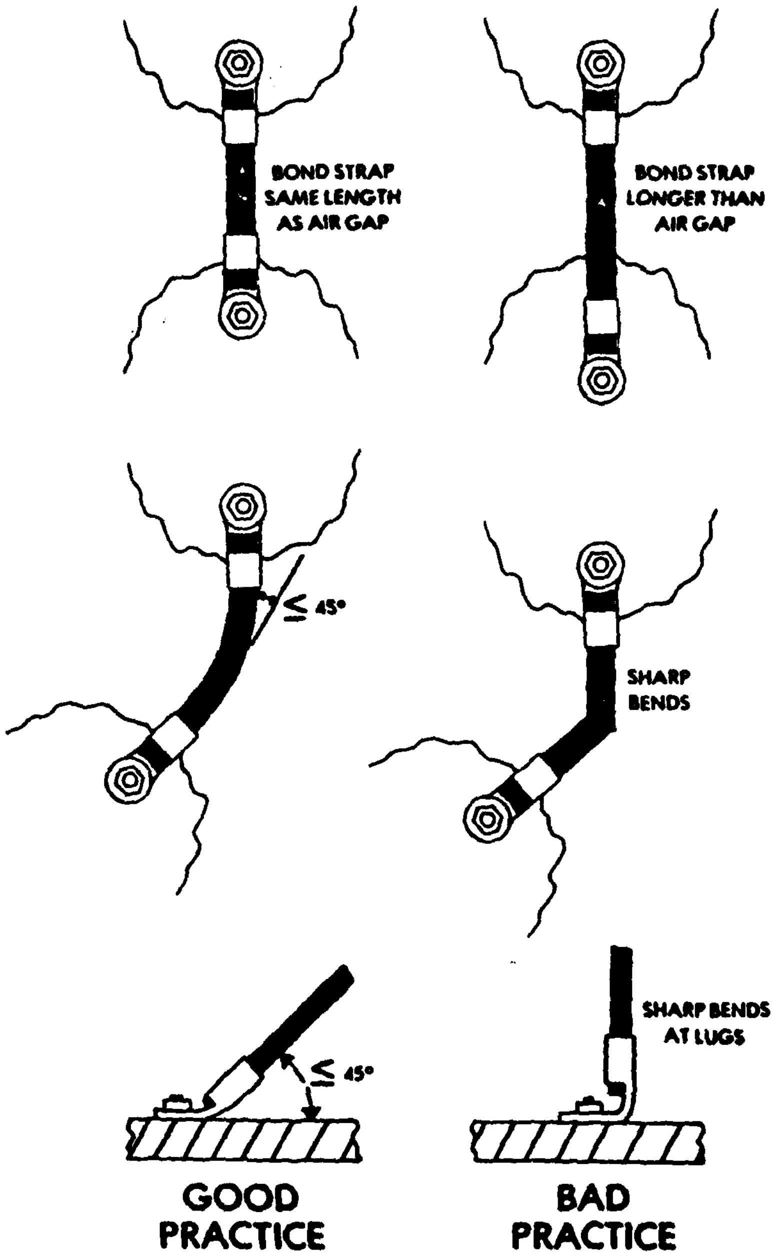


Figure 50 Design of Bonding Straps or Jumpers

1. Orient the diverters as nearly as possible in the line of flight so that flashes which originally strike the diverter can reattach farther aft on the same divertion as the aircraft moves forward.

2. While the above is desirable for reattachment purposes, an adequate path must be provided for lightning current to be conducted into the airframe. This requirement usually calls for some of the diverters to be oriented perpendicularly to the line of flight.

3. The surface flashover voltage from any point over the external surface to the nearest diverter strap must be less than the maximum voltage required to puncture the skin and attach to a conducting object beneath. Thus, the diverter must be within a maximum displacement distance from a point on the skin directly opposite the enclosed conductor. This relationship is defined as follows:

$$\text{Maximum displacement distance (cm)} \leq \frac{\text{Skin puncture voltage (KV)}}{\text{Surface flashover Voltage (KV/cm)}}$$

This criterion should be met for lighting voltage stresses of either polarity applied at up to 1000 KV/μ sec rate of rise.

4. The maximum voltage drop from the original attachment point to any other point on a lightning arc swept aft directly above a nonconducting surface must not exceed the skin puncture voltage from that point through the skin to any conducting objects inside. The maximum arc voltage drop will occur during a restrike formation in a multiple-stroke flash and can be assumed to be equal to or less than the free air breakdown voltage, or about 500KV/m of arc length.

5. The inductive voltage rise, V_L, along any diverter segment carrying lightning stroke currents to conducting structure must be less than the skin puncture voltage between the diverter and the nearest conducting object inside the structure. The inductive voltage rise, V_L, may be expressed as follows:

$$V_L = L \frac{dI_L}{dt}$$

where

L = diverter segment inductance

I_L = lightning current

t = time

In practice, L may be assumed to be 1 H/m for most diverter straps or foils, and dI_L/dt may be assured to be 100,000 A/µ sec.

b. Advanced Composites

Advanced composites, consisting of boron- or graphite-reinforced plastics are being used increasingly often as replacements for aluminum load bearing applications in aircraft. The high strength-to-weight characteristics of these materials make them attractive for structural applications, but because they are nonmetallic, they are inherently more vulnerable to lightning effects. Unlike fiberglass-reinforced plastics, which have no electrical conductivity, the boron filaments or graphite fibers are resistive conductors and will conduct some lightning currents, causing serious heating problems. the materials may not be able to dissipate the heat without some change in or distruction of physical properties. Simulated lightning-strike tests of typical composite laminates have demonstrated this problem (Reference 1, 17). Substitution of composites for aluminum also poses an additional threat to the electrical systems because composites do not possess the excellent shielding property of aluminum, with the result that the electrical system designer may have to provide his own protection. The problems are further compounded by the fact that these materials are relatively easy to construct, and have resulted in a proliferation of available composite materials.

(1) Protection Using Diverter and Foil Strips

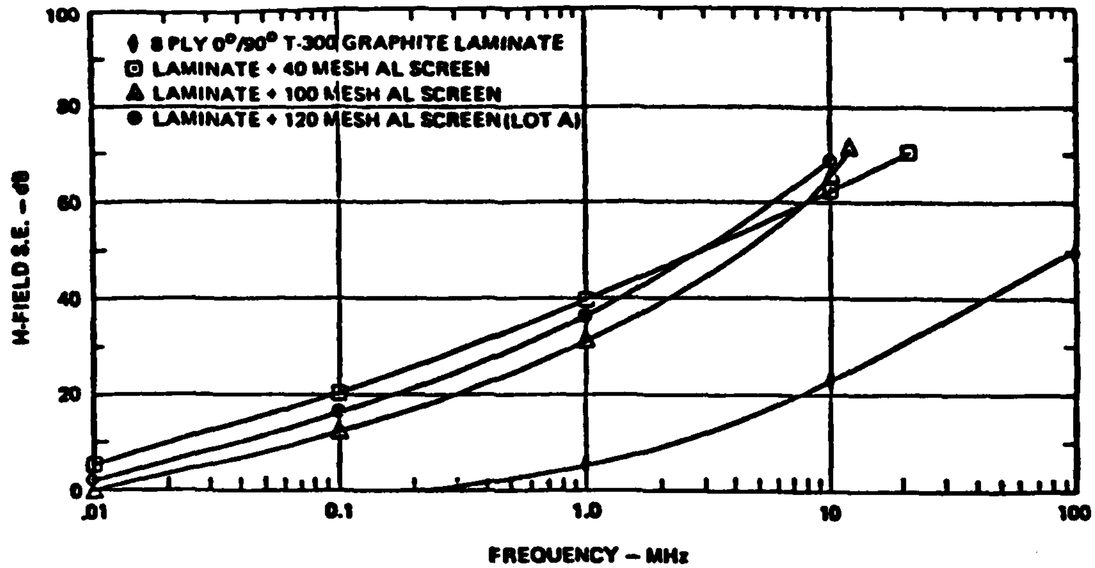
Advanced composites have some electrical conductivity - enough to supply the few milliamperes of current needed for a streamer. Thus, a metal diverter on a poorly conducting surface is not nearly as effective as it is on a nonconducting surface. Although the rules discussed above apply for installing diverters on composite materials as well, other means of protection must also be addressed.

(2) Add-on Coating Protection for Direct Attached Lightning

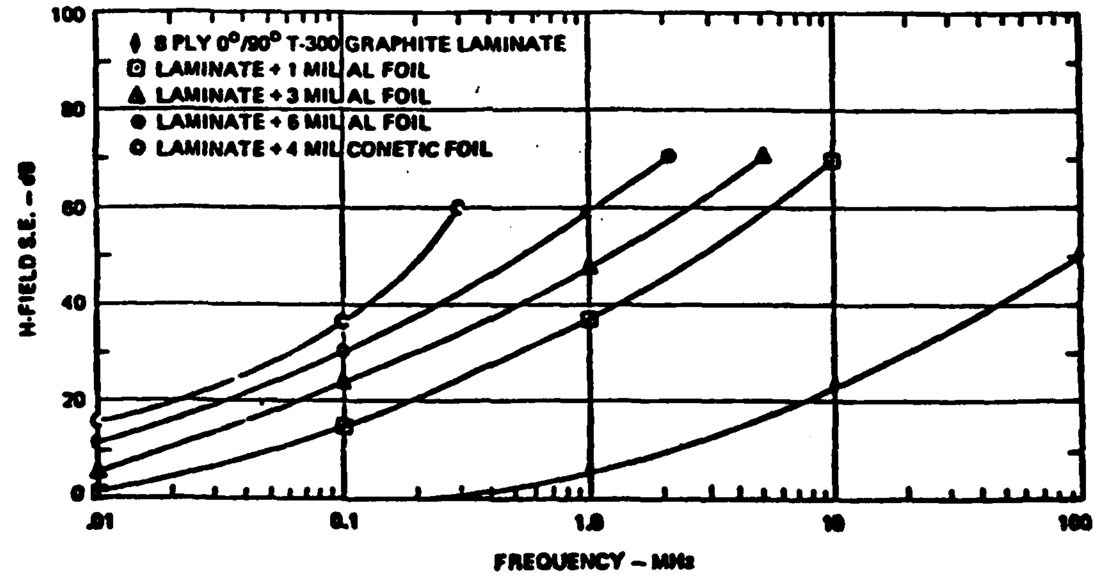
The shielding effectiveness of composites for magnetic (H) fields has been measured by Strawe and Piszker (Reference 17). Composite material systems and coating materials were selected for evaluation based upon their potential use and shielding quality. Evaluation was accomplished by a flat-plate magnetic field shielding effectiveness (MSE) test. Flat-plate MSE test data were used to rank the materials, since the MSE is a good indication of relative shielding quality. Joining concepts that are in current use in composites technology were evaluated (Section III and also see Reference 1). Others were developed specifically to improve the shielding quality of composite joints and to provide good electrical joints between coating materials. Twelve inch square flat-plate samples were tested using various graphite laminates, foils, screens, and coated graphites, Figure 51 displays a sample of the test results plotting the response of the magnetic field versus frequency.

An important factor which limits the effectiveness of add-on conductive coatings is the degree of electrical contact, across the frequency range of interest, between the perimeter of the conductive coating and underlying metal structure. The admittance of the joint between the conductive coating and metal structure is obtained by testing sample joints, using techniques described in Reference 17. The potential impact of poorly designed joints is analyzed in Reference 1, for the lightning threat. When the joint admittance is known, one may estimate induced transients on internal wiring by the techniques described in Appendix C of Reference 12.

A number of programs have been undertaken to develop suitable protective coatings for composites. Available lightning protection coatings and possible sources for the various materials are listed on the following pages. The order in which the protection coatings are listed does not reflect any specific preference or rating. However, the first three were determined to provide the best aircraft lightning protection coating, as detailed in Reference 7. Weights and a ranking of manufacturing difficulty are given in Table 34 for the various protection coatings. In addition, Table 35 shows the coating thicknesses and weight penalties for various fixed shielding available (Reference 18).



(a)



(b)

Figure 51 Shielding Effectiveness of Graphite Laminates

TABLE 34 SUMMARY TABLE OF PROTECTION COATINGS

PROTECTION SYSTEM	WEIGHT, LB/FT^2 WITH ADHESIVE	WEIGHT, LB/FT^2 WITHOUT ADHESIVE	MANUFACTURING RANKING ①
Aluminum metal flame spray, 4-6.9 mil, 100% coverage	0.036	–	9
Aluminum metal flame spray, 4-6.9 mil, 50% coverage	0.018	–	8
120 x 120 Aluminum wire screen, 100% coverage	0.140	0.070	6
200 x 200 Aluminum wire screen, 100% coverage	0.080	0.060	7
Aluminum foil, 2 mil, 100% coverage	0.060	0.030	2
Aluminum foil, 2 mil, 50% coverage	0.030	0.015	3
Aluminum Foil Tape, 2 Mil Adhesively Backed, 100% Coverage	0.034	–	2
Aluminum Foil Tape, 2 Mil Adhesively Backed, 50% Coverage	0.017	–	3
Aluminum foil, 3 mil, 100% coverage	0.075	0.045	4
Aluminum foil, 3 mil, 50% coverage	0.038	0.022	5
Aluminum Foil Tape, 3 Mil, Adhesively Backed, 100% Coverage	0.050	–	2
Aluminum Foil Tape, 3 Mil, Adhesively Backed, 50% Coverage	0.025	–	3
Kapton film, 2 mil, + 2 mil foil strips	0.044	0.014	1

① 9 = Easiest to apply and repair
1 = Most difficult to apply and repair

TABLE 35 COATING THICKNESS AND WEIGHT PENALTY

Shielding	Conductivity, (Ω/m)	Coating Thickness in mils $20 \log_{10} Z_{st}$ 40 dB	60 dB	72 dB
Aluminum Foil	3.12×10^7	0.1259	1.259	5.0121
Copper Foil	7.29×10^7	0.054	0.54	2.1451
Titanium Foil	2.1×10^6	1.87	18.7	74.46
Nickel Foil	1.28×10^7	0.31	3.1	12.217
Tin Foil	8.78×10^6	0.45	4.47	17.81
Aluminum Flame Spray	2.46×10^6	1.6	16.0	63.6
Graphite/Epoxy	10^4	392.8	3928.0	15638.0

Shielding	Density (lb/ft^2) for 1 mil coating (lb)	Weight Penalty/ft^2 Applied Coating (lb) $20 \log_{10} Z_{st}$ 40 dB	60 dB	72 dB
Aluminum Foil	0.014	0.00177	0.0177	0.0702
Copper Foil	0.04665	0.00252	0.0252	0.100
Titanium Foil	0.024125	0.45	0.45	0.797
Nickel Foil	0.0405	0.0126	0.126	0.495
Tin Foil	0.0365	0.016	0.16	0.65
Aluminum Flame Spray	0.00243	0.004	0.04	0.155

1. Aluminum Metal Spray Protective Coating, 4.0-6.9 mil Thickness, 0.036 lb/ft^2 (Nominal Weight)

This coating provides good lightning protection for Zone 1 and 2 (Section II) conditions. It can be applied to simple or complex shaped parts either in a cocure operation or secondarily applied to cured composite surfaces. This coating requires specialized application equipment and trained personnel to obtain a good uniform coating.

Materials	Possible Source
Pure Aluminum Wire 1/8-in. diameter, Per AMS 4180B	Metco, Inc. 307 East Fourth Street Cincinnati, OH 45202
Sealer Resin FR-40 Hardener 5413C	Fiber Resin Corporation 170 Providencia Ave. Burbank, CA 91503
Potting compound FR 8840 Parts A and B	Fiber Resin Corporation 170 Providencia Ave. Burbank, CA 91503

2. Aluminum Metal Flame Spray Strips (50% Coverage), 4.0-6.9 mil Thickness, 0.018 lb/ft^2 (Nominal Weight)

This coating is used in Zone 2 applications to protect large composite surface areas. The metal strips are typically 3 inches wide with 3 inch spacing. Comments from 1. above are applicable here.

3. Aluminum Wire Screen (120 x 120) Protective Coating, 0.14 lb/ft^2 (Nominal Weight with Adhesive)

This coating provides good lightning protection in Zone 1 and Zone 2 conditions. Good quality application restricts this system to simple contour shaped parts. Screen width is limited to 36 inches, which complicates application because of screen splicing requirements for large surface areas.

Materials	Possible Sources
120 x 120 Wire Screen, 0.004-in. diameter 1100 Aluminum wire 36-in. width rolls	Cal-Metex Corporation 509 Hindry Avenue Ingelwood, CA 90301
Adhesive AF-143 or AF-147 or equivalent 0.05-0.08 lb/ft^2, 18 in wide. Sold in 3-roll minimum order, 36 yds per roll.	3M Company 3M Center St. Paul, MN 55101 (612) 733-1110

4. Aluminum Wire Screen (200 x 200) Protective Costing, 0.08 lb/ft^2 (Nominal Weight with Adhesive)

This protection coating can provide limited protection in Zone 2 conditions. Limitations discussed in 3. above also apply to this system.

Materials	Possible Sources
200 x 200 Aluminum Wire Screen, 0.0021-in. diameter 1100 wire, 36-in. width. Sold by the roll	Cal-Metex Corporation 509 Hindry Avenue Inglewood, PA 90301
Adhesive AF-143 or AF-147 or equivalent, 0.05-0.08 lb/ft^2 18-in. width. Sold in 3-roll minimum order, 36 yards per roll.	3M Company 3M Center St. Paul, MN 55101 (612) 733-1110

5. Aluminum Foil (2 mil) Cocured Protective Coating, 0.060 lb/ft^2 (Nominal Weight with Adhesive)

Aluminum foil (2 mil) offers limited protection in Zone 1 and Zone 2 applications. Good quality surface finish is difficult to obtain except for simple flat surfaces. Foil width is limited to 36 inches, which forces noncontinuous splice areas on large surfaces.

Materials	Possible Sources
Aluminum Foil (2 mil)	Any major aluminum manufacturer
Adhesive AF-143 or AF-147 or equivalent 0.03 lb/ft^2 18-in. width. Sold in 3-roll minimum order, 36 yards per roll.	3M Company 3M Center St. Paul, MN 55101 (612) 733-1110

6. Aluminum Foil (2-mil, Adhesive Backed) Secondarily Applied Protective Coating, 0.034 lb/ft^2 (Nominal Weight)

This coat is best applied to the cured composite structure surface. It conforms reasonably well to complex shapes. It offers limited protection in Zone 1 and Zone 2 applications. The 3-in. width limitation requires close attention to splices for continuous coverage.

Materials	Possible Source
Scotch Aluminum Foil No. 431 Linerless, Tape, 2 mil, acrylic adhesive backed 3-in. width sold by the case, 12 rolls 60 yds each roll.	3M Company 3M Center St. Paul, MN 55101 (612) 733-1110

7. Aluminum Foil (3-mil) Concured Protective Coating, 0.075 lb/ft^2 (Nominal Weight with Adhesive)

Aluminum foil (3-mil) offers adequate protection in Zone 1 and Zone 2 application. Manufacturing comments and materials information are as listed in 5. above.

8. Aluminum Foil (3-mil, Adhesive Backed) Secondarily Applied Protective Coating 0.050 lb/ft^2 (Nominal Weight)

This coat offers adequate protection in Zone 1 and Zone 2 applications. Other comments as to manufacturing complexity are found in 7. above.

Materials	Possible Source
Scotch Aluminum Foil No. 425, linerless tape, 3-mil, acrylic adhesive backed, 3-in. width sold by the case, 12 roll 60 yds each roll.	3M Company 3M Center St. Paul, MN 55101 (612) 733-1110

9. Aluminum Foil Tape Strips (3-mil, Adhesively Backed), 3-in. width with 3-in. spacing, Protection Coating 0.025 lb/ft^2 (Nominal Weight)

This coat is best applied to the cured composite structure surface. It is intended for Zone 2 swept-stroke conditions only. Comments as to manufacturing complexity and materials are found in 7. and 8. above.

10. Kapton Film (2-mil) Plus Aluminum Foil Strips (2-mil, Adhesive Backed) Protective Coating, 0.044 lb/ft^2 (Nominal Weight with Adhesive)

This coat is the most complex to incorporate (cocured) into the composite surface and is the most difficult to repair. Kapton film is limited to simple contour or flat surfaces, and must be overlap spliced for areas greater than 36 inches wide.

Materials	Possible Sources
Kapton Film, 2 mil 36-in. width sold by the pound	Fralock 15441 Carbillo Rd. Van Nuys, CA 91406 (213) 873-6665

Materials	Possible Sources
Scotch Aluminum Foil No. 431 linerless tape, 2-mil, acrylic adhesive backed, 3-in. width sold by the case, 12 rolls 120 yards.	3M Company 3M Center St. Paul, MN 55101 (612) 733-1110
Adhesive AF-143 or equivalent. 0.05 lb/ft^2 18-in. width. Sold in 3-roll minimum order, 36 Yards per roll.	3M Company 3M Center St. Paul, MN 55101 (612) 733-1110

SECTION VII

SYSTEM EVALUATION WITH ADD-ON PROTECTION

This section of the design guide evaluates the various add-on protection devices and techniques discussed in Section VI as they apply to the electrical system design. Most devices are application oriented, that is, more effective in one aspect of the design than another. Each electrical system design to be lightning tolerant will therefore, use more than one scheme or type of protection device or technique.

As shown in Section IV, by utilizing the appropriate inherent design techniques the lightning transient can be significantly reduced. A need still remains, however, for additional attenuation of the transient. Table 36 displays the moderate and severe threat lightning transients for typical circuits computed using the equations developed in Section II and in Reference 12. These computed open circuit voltages and short circuit currents can help the designer predict transients for similar circuits in his design. Also, as shown in Section IV, the transients are more severe with the use of composite materials in the structure.

The following design goals are considered as each of the system lightning protection techniques are assessed:

1. Achieve a design that prevents the effects from causing irreversible physical damage.

2. Eliminate that interference which provides an imminent hazard to the safety of the aircraft or one that prevents completion of the mission.

3. Design electrical equipment that can accept transient signals on input and output terminals at the outset rather than relying on retrofit program to protect existing systems.

4. Design electrical systems around the capabilities of existing and proven protective devices and techniques.

TABLE 36 MODERATE AND SEVERE THREAT LIGHTNING TRANSIENT SUMMARY

CIRCUIT	MODERATE THREAT Peak V_{oc}	MODERATE THREAT Peak I_{sc}	SEVERE THREAT Peak V_{oc}	SEVERE THREAT Peak I_{sc}
C-14 USB ACTUATOR				
AT ACTUATOR	7.6 KV[2]	36 A[3]	30 KV[2]	305 A[3]
AT INTERFACE UNIT	Negligible*	37 A[3]	Negligible*	305 A[3]
C-14 WING TIP BEACON				
AT TRANSFORMER	11 KV[1]	30 A[4]	52 KV[1]	320 A[4]
AT POWER BUSS	1.1 KV[1]	30 A[4]	4.4 KV[1]	320 A[4]
C-14 WINDSHIELD HEATER AT POWER BUSS	30 KV[3]	18 A[1]	300 KV[3]	90 A[1]
C-14 VERTICAL STABILIZER	21 V[1]	0.06 A[3]	80 V[1]	0.6 A[3]
F-111 PITOT HEATER AT FORWARD BULKHEAD	27 KV[2]	280 A[2]	105 KV[2]	1100 A[2]
F-111 COCKPIT MAP READING LIGHT AT POWER BUSS	220 V[2]	94 A[4]	860 V[2]	940 A[4]
F-15 PITOT HEATER AT ESSENTIAL POWER BUSS	136 V[3]	5.4 A[3]	1360 V[3]	54 A[3]
F-15 EXTERNAL FUEL TANK QUANTITY INDICATOR**	16 KV[1]	Not Available**	62 KV[1]	Not Available**
F-15 GENERATOR FEEDERS AT CIRCUIT BREAKER	37 V[2]	1.4 A[4]	140 A[1]	15 A[4]

1. Waveform dominated by circuit resonance.
2. Waveform follows time derivative of lightning current.
3. Waveform follows lightning current.
4. Other low frequency waveform (none of the above).

Note: Arcing through wire insulation will limit voltages to 20-50 KV maximum for most circuits.

* Negligible voltage because of loading effects (both ends of wire bundle were open circuit).

** Levels are for transient voltage appearing across gap between fuel tank and fuselage. This voltage will appear as a source in wiring crossing the gap.

5. Conduct trade-offs between the cost of providing electronic equipment capable of withstanding lightning induced transients and the cost of shielding interconnecting wiring from the electromagnetic effects of lightning.

6. Take advantage of the inherent shielding that aircraft structures are capable of providing and avoid placing equipment and wiring in locations that are most exposed to the electromagnetic fields produced by lightning.

1. Shielded Cable Selection

It is generally accepted that the effectiveness of a shield can be determined by measuring the surface transfer impedance of the shielded harness or cable. The surface transfer impedance, Z_T, relates the open circuit voltage (V) developed inside the shield to the disturbing current (I) flowing on the outside of the shield by the relationship

$$Z_T = \frac{V}{I}$$

Figure 52 shows the curves of Z_T vs. frequency for some typical shield constructions (Reference 19).

For single braided shields the shape of the curve is different in that, after a certain frequency, Z_T tends to increase with frequency. The reason is that there are two uncoupled mutual inductances present. One of these inductances is due to the holes in the woven shield and the other is due to the wave like variation in distance of the braid wires from the center conductor as they weave over and under each other. The phase of these two inductances oppose each other. The result being that the braid optical coverage does not solely determine shielding effectiveness. Shielding effectiveness is also dependent on the interaction of the impedances which can be optimized for the most effective shield. In Figure 52, the results of optimization of braids are shown.

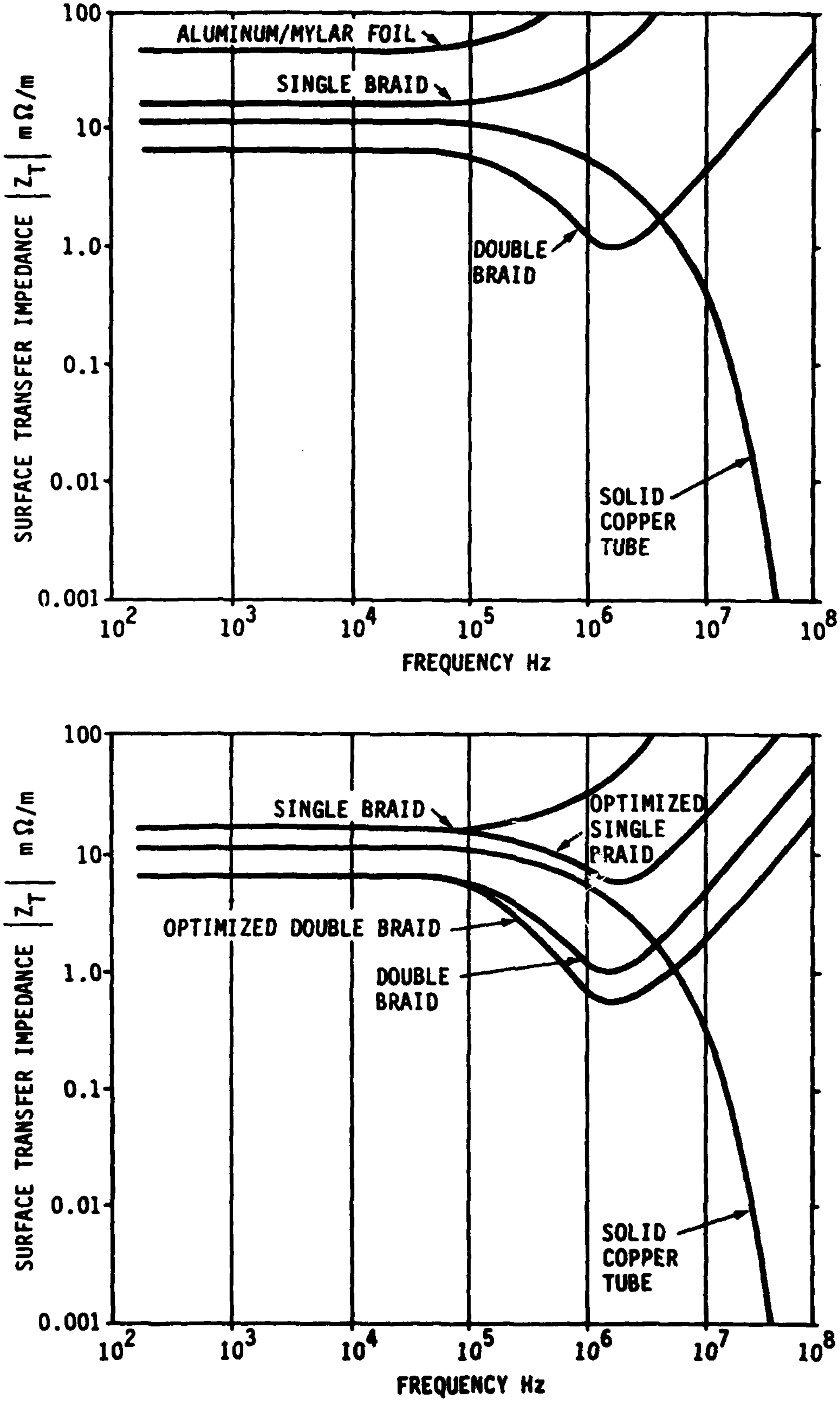


Figure 52 Surface Transfer Impedance vs. Frequency of Typical Shields

One source of coupling is via capacitive leakage through the holes in the shield as shown in Figure 53. Another source of coupling is via magnetic leakage which appears to have the greatest impact on the conductor (Reference 6). The factors that affect the voltage between the conductor, the shield and ground are the resistance of the shield, the degree to which the shield allows magnetic fields to leak to the inside, and the degree to which the shield allows electric fields to leak to the inside.

A braided shield typically has the appearance shown in Figure 54. The characteristics of the shield may be described in terms of the following symbols:

- a - the radius of the shield
- c - the number of carriers
- N - the number of wire strands per carrier
- P - the number of picks, or carrier crossings, per unit length
- d - the diameter of the individual wires
- α - the weave angle

The optical coverage of the shield relates to the size of the small holes not covered by the carriers. The greater the optical coverage the better the electrical performance of the shield.

Also note that, if there are multiple conductors in the core, each conductor will develop nearly the same voltage between that conductor and the shield. This holds true whether the conductor is located adjacent to the shield or in the center of the bundle of conductors comprising the core. Accordingly, the voltage between any pair of conductors in the core will be small. Present analytical tools do not seem of sufficient accuracy to predict with any assurance the magnitude of line-line voltages; they are best determined by actual measurement. Line-line voltages are much more strongly influenced by load impedances to which the conductors are connected than by the position of the conductors within an overall shield.

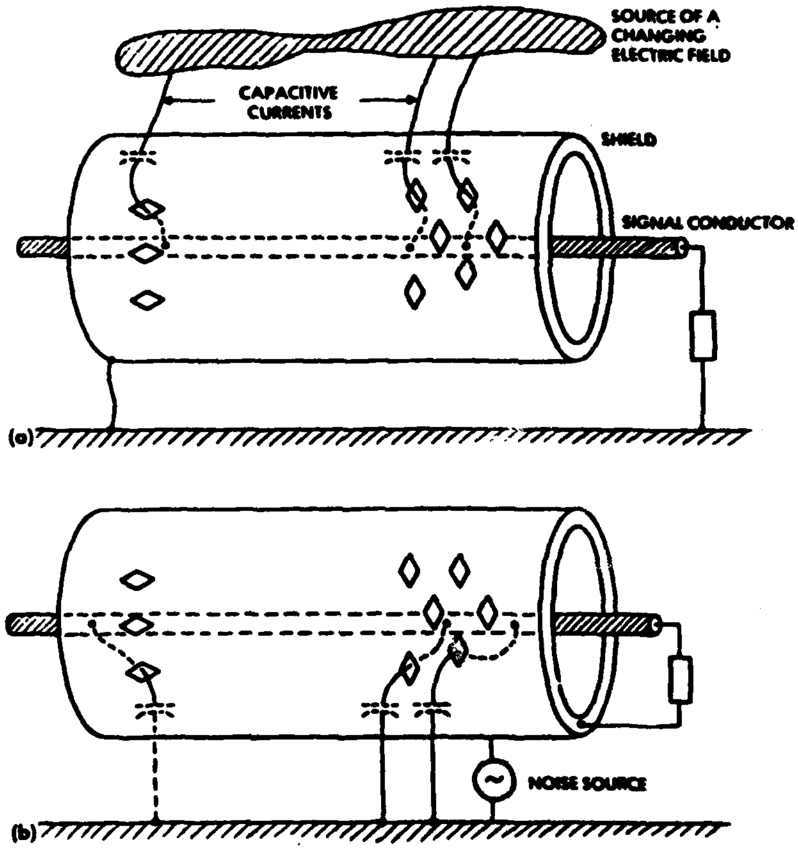


Figure 53 Coupling Via Capacitive Leakage

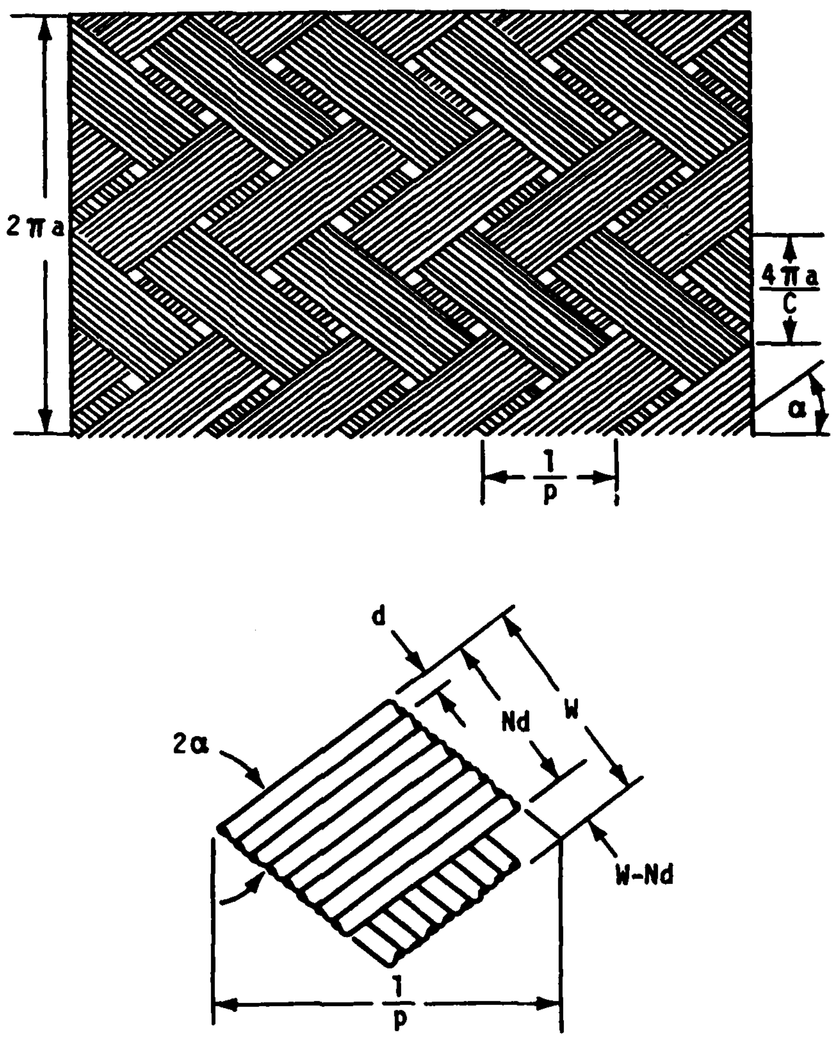


Figure 54 Typical Shield Braid Construction

a. *Computer Optimization of Cable Shielding*

One method of optimizing the specific cable shield requirement was developed by Dr. A. R. Martin of the RayChem Corp. (Reference 20). He developed a concept called the Critical Transfer Impedance (CTI). The CTI is defined as the ratio of the voltage that just causes an electrical device to fail, when applied to its terminals, to the current induced on the shield of a cable by a specified radiation field, at a particular frequency. The critical transfer impedance can then be compared directly with the surface transfer impedance of a proposed shield construction, to see if it is adequate.

To find the Critical Transfer Impedance, the device failure voltage (V_f) and the shield current must be developed. The failure voltage is defined as the voltage which just causes the equipment to fail as a function of frequency. In the early design of the system this can be chosen as some typical or approximate set of values.

The shield current can be determined by measurement, on either an actual or a simulated installation, when the interconnect system is subjected to the specified radiated field. Also, for preliminary analysis the shield current can be computed using the equations developed in Section II. The radiated field would be dependent on the Zone to which the lightning strike attaches and the coupling that the designer would expect to see at that point.

Having determined V_f and I_s at all frequencies of interest, the ratio then becomes the Critical Transfer Impedance (Z_{tc}). If the shield transfer impedance (Z_t) exceeds the CTI at any point, the system will fail. The particular shield that meets the shielding requirement for the system, can be selected from a chart similar to that shown in Figure 55. A complete description of this technique is given in Reference 20.

b. Connectors and Grounding of Shields

Most connectors that are used for shielded cables have a transfer admittance that is negligible due to their 100% optical coverage. In addition most bulkhead or panel-mounting connectors are located at points where the shield

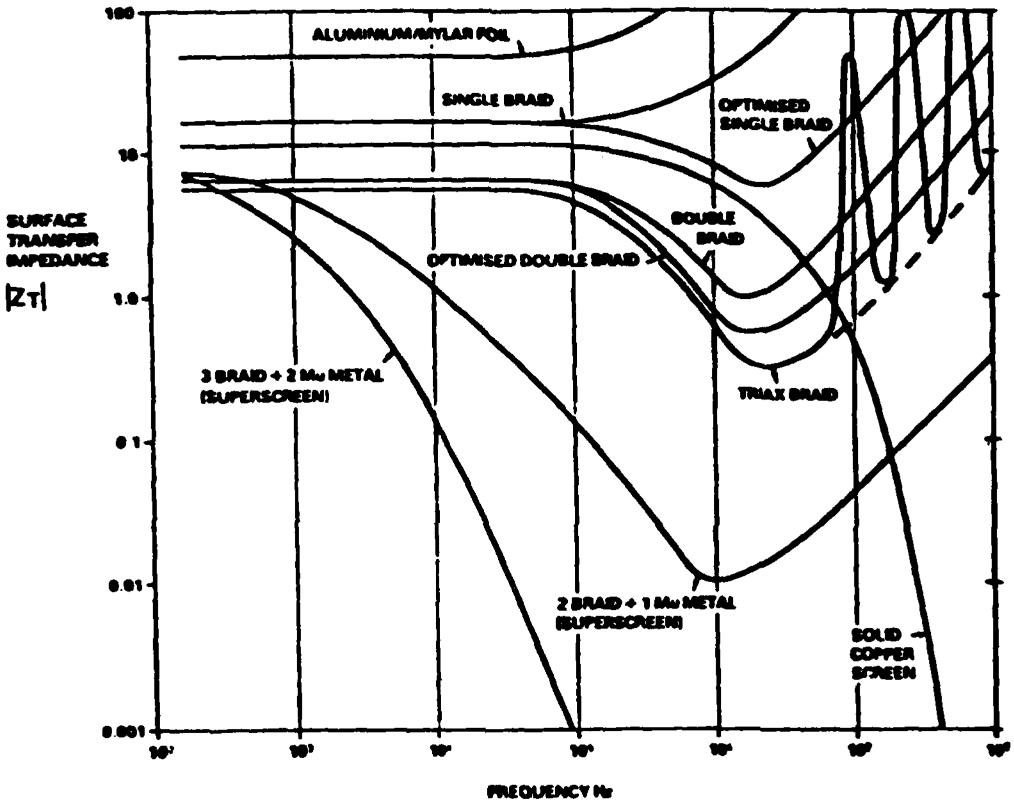


Figure 55 Shielding Selection Chart

voltage `` a minimum, so that excitation of the internal conductors by the transfer admittance is small even if the transfer admittance itself is not small. Some typical values of the resistance measured across the connectors and of the mutual inductance between the external shield circuit and the internal conductor of the cable are listed in Table 37 (Reference 6).

Additional transfer impedances may be produced by the manner in which the cable shield is connected to the connector. Even slight inattention to detail may introduce into the circuit transfer impedances far greater than the impedance of the connector or possibly far greater than that of the rest of the cable shield. A common treatment of a shield at a connector is to insulate the shield with tape and connect it to the back shell through a pigtail as shown in Figure 56. (See Section VI.1 for limitations.)

c. Shielding VSCF Generator and Converter Power Feeders

After examining the circuit described in Section IV (Figure 18, the baseline VSCF generator and converter located out on an all aluminum wing with 12 meters of excited feeder running behind a fiberglass leading edge toward the fuselage), and finding the coupled lightning transients at the power bus to exceed the acceptable voltage and current levels, the effect of shielding the feeders was examined. Two types of shielding were incorporated into the model. The first case included a braided shield with 6 inch pigtails at each end of the shield. The second case incorporated circumferential terminations at the ends of the braided shield. Reference 12 describes the subroutine equations for the two cases. The only difference in the two models is the resistance and inductance of the shield terminations. For compairson, shown in Table 38, are the severe transient levels recorded at the generator/converter output terminals and the 50% bus load input terminals for the baseline case, 12 MF, the pigtail shielding case, 12MPT, and the circumferential case, 12MCG. It should be noted that, compared to the unprotected case, two orders of magnitude transient suppression is obtained with the use of the circumferential grounded shield and one order of magnitude suppression is obtained with the pigtail grounded shield. For the circumferential case, the resultant voltage and current levels are acceptable. However, the bus/load voltage in the pigtail case is unacceptable.

TABLE 37 RESISTANCE AND MUTUAL INDUCTANCE OF CABLE CONNECTORS

Connector	Identification	R_o (ohms)	M_{12} (H)
Multipin Aerospace connectors (Threaded)	Burndy NA5-15863	0.0033	5.7×10^{-11}
	Deutch 38068-10-5PN	0.15	2.5×10^{-11}
	Deutch 38068-18-31SN	0.005	1.6×10^{-10}
	Deutch 38060-22-55SN	0.023	1.1×10^{-10}
	Deutch 38068-14-7SN	0.046	5.0×10^{-11}
	Deutch 38060-14-7SN	0.10	8.2×10^{-11}
	Deutch 38060-14-7SN	0.023	6.7×10^{-11}
	Deutch 38068-12-12SN	0.0033	3.0×10^{-11}
	Deutch 38068-12-12SN	0.012	1.3×10^{-11}
	Deutch 38068-12-12SN	0.012	1.3×10^{-11}
	Deutch 38060-12-12SN	<0.001	2.5×10^{-12}
	Deutch 38068-12-12SN	0.014	3.5×10^{-11}
	AMP	0.0067	1.6×10^{-11}
	AMP	0.0067	1.5×10^{-11}
	AMP	0.0033	1.9×10^{-11}
Type N	UG 21B/U-UG58A/U	*	*
Type BNC (Bayonet)	UG 88C/U-UG1094/U	0.002	$4\text{-}8 \times 10^{-11}$
Anodized	MS 24266R-22B-55	5×10^4	$\omega M < R_o$ @ 20 MHz
Open shell	MS 3126-22-55	0.5-1	$\omega M < R_o$ @ 20 MHz
Split shell	MS 3100-165-1P MS 3106A-	0.001	$\approx 20 \times 10^{-11}$

*Too small to measure in presence of 4 inches of copper tube used to mount connector.

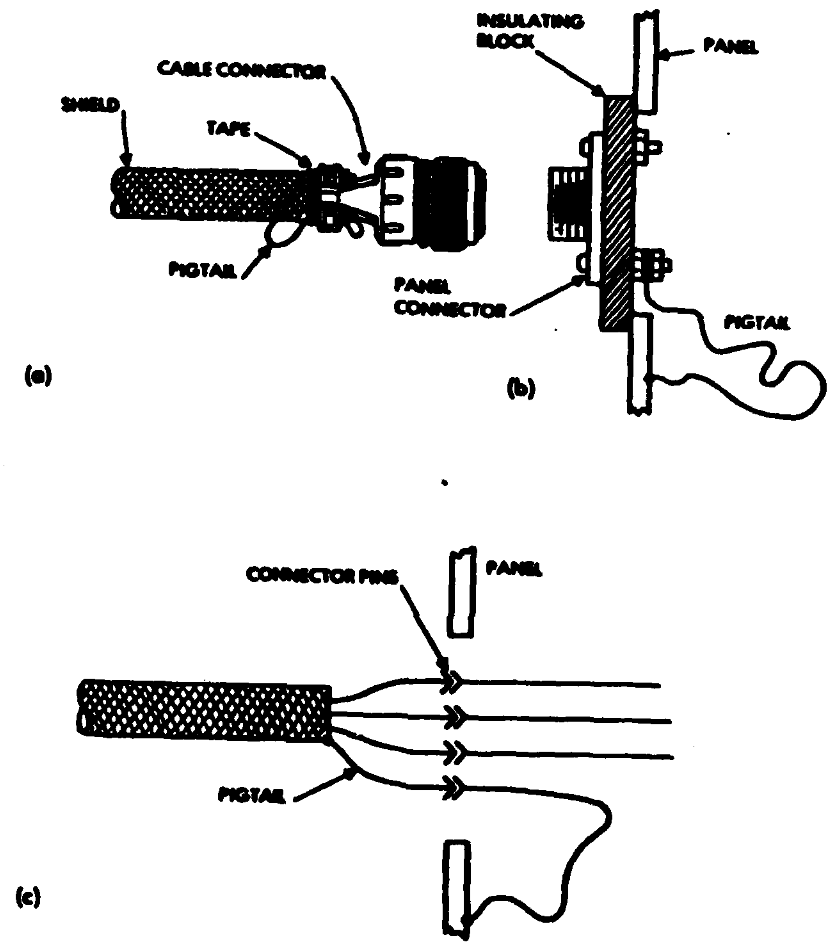


Figure 56 Typical Connection of Connector to Backplane via Pigtails

TABLE 38 PEAK TRANSIENTS WITH SHIELDING PROTECTION

Test Case	Test Point	Test Point Name	Transient Duration	Positive Amplitude	Negative Amplitude
12MF	T1	VCON	1. mS	27. V	-30. V
12MF	T1	ICON	1. mS	180. A	-120. A
12MF	T2	VLOAD	8. uS	65. KV	-40. KV
12MF	T2	ILOAD	.15 mS	289. A	0. A
12MPT	T1	VCON	1. mS	18.5 V	-21.5 V
12MPT	T1	ICON	1. mS	155. A	-80. A
12MPT	T2	VLOAD	.5 mS	5.4 KV	-3.3 V
12MPT	T2	ILOAD	1. mS	132. A	-34. A
12MCG	T1	VCON	1. mS	14.5 V	-17. V
12MCG	T1	ICON	1. mS	122.5 A	-65. A
12MCG	T2	VLOAD	.4 mS	295. V	-30. V
12MCG	T2	ILOAD	1. mS	104. A	-26. A

TABLE 39 PEAK TRANSIENTS WITH TRANSZORBS™ PROTECTION

TEST CASE	TEST POINT/ NAME	TRANSIENT DURATION	POSITIVE AMPLITUDE	NEGATIVE AMPLITUDE	DC OFFSET
12MF	T1/VCON	1.0 ms	27.0 V	-30.0 V	+0.5 V
12MF	T1/ICON	1.0 ms	180.0 A	-120.0 A	+4.0 A
12MF	T2/VLOAD	8.0 us	65.0 KV	-40.0 KV	0.0 V
12MF	T2/ILOAD	0.15 ms	289.0 A	0.0 A	0.0 A
12MFT	T1/VCON	0.5 ms	105.0 V	-145.0 V	-10.0 V
12MFT	T1/ICON	0.5 ms	660.0 A	-360.0 A	+40.0 A
12MFT	T2/VLOAD	0.5 ms	285.0 V	-50.0 V	+25.0 V
12MFT	T2/ILOAD	0.6 ms	82.0 A	-18.0 A	+10.0 A

TABLE 40 PEAK TRANSIENTS WITH 3 MIL FOIL ON FIBERGLASS LEADING EDGE

TEST CASE	TEST POINT/ NAME	TRANSIENT DURATION	POSITIVE AMPLITUDE	NEGATIVE AMPLITUDE	DC OFFSET
12M3MF	T1/VCON	1.0 mSec	0.6 V	-1.3 V	0.0
12M3MF	T1/ICON	1.0 mSec	12.0 A	-2.0 A	0.0
12M3MF	T2/VLOAD	1.0 mSec	11.2 V	-1.0 V	+2.4
12M3MF	T2/ILOAD	1.0 mSec	8.5 A	-2.0 A	0.0

2. TransZorb™ Selection

a. Hand Calculation Design of Lightning Protection Using TransZorbs™

The following steps give the designer hand calculations for estimating the number of TransZorbs required to protect a three phase load. A TransZorb is normally selected according to the reverse "Stand Off Voltage" (V_r) which should be equal to or greater than the DC or continuous peak operating voltage level (Reference 21).

STEP (1) Approximate the short-circuit current at the protection point as an exponential having peak value I_T and half-value falltime of t_d. To protect the circuit from both positive and negative transient spikes, two TransZorbs must be placed back to back in series, as is shown in Figure 57. Each forward biased series element contributes negligibly to the total voltage and dissipates very little power.

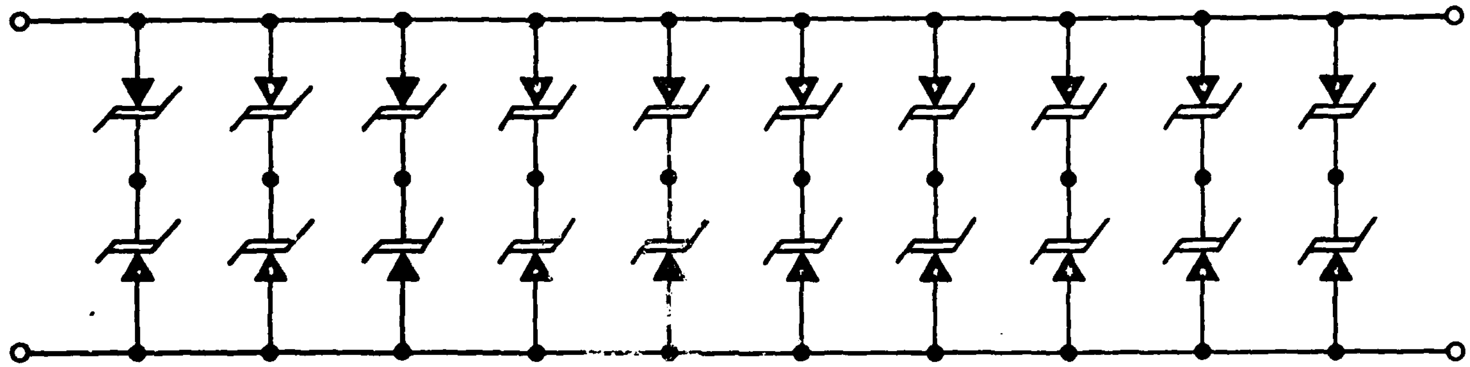
STEP (2) Choose the maximum allowable voltage transient acceptable in the system or the reverse biased device voltage, V_d. In order to determine the number of devices, n, required to meet the power specification, refer to the manufacturers data sheet for the necessary electrical parameters to satisfy equation (9) below.

$$n = \frac{I_T\ (V_c - Vb)}{I_{pp}\ (V_d - Vb)} \qquad (9)$$

In selecting a number of devices, n, and satisfying the data sheet parameters in equation (10), the resultant reverse biased device voltage, V_d, can be computed.

$$V_d = Vb + \left(\frac{I_T}{n}\right) \left(\frac{V_c - Vb}{I_{pp}}\right) \qquad (10)$$

V_d = reverse biased device voltage
V_c = maximum clamping voltage @ I_{pp} (1m Sec)
I_{pp} = maximum peak pulse current



20 DEVICES, DEVICE TYPE 15KP280A

FIGURE 57 TRANSZORB SUPPRESSOR ASSEMBLY USED ON EACH OF THREE PHASES

Vb = breakdown voltage
I_T = approximate short circuit current
n = number of TransZorbs

STEP (3) Compute the current, Id, and power, Pd, for each device per equations (11) and (12) respectively. Calculate the safety margin, SM, as is shown in equation (13). P_p, the peak pulse power is obtained from the peak pulse power versus pulse time, t_d, waveform. If the device current, power, or safety margin values are unsatisfactory, iterate on the device type or device number for the particular application.

$$I_d = \frac{I_T}{n} \quad (11)$$

$$P_d = V_d I_d \quad (12)$$

$$SM = 10 \log_{10} \left(\frac{P_p}{P_d}\right) \quad (13)$$

b. Computer-Aided Design of Lightning Protection Using TransZorbs™

STEP (1) From the computed short-circuit current and open-circuit voltage at the protection point, synthesize a Norton equivalent circuit.

STEP (2) Use the 2-terminal damage model to simulate the TransZorb protective array. Connect this model to the Norton equivalent circuit, along with models for other system loads at this point.

STEP (3) Using CIRCUS-2, run the overall model. Plot the desired waveforms, including V_{cl}. The safety margin is given by equation (14).

$$SM = 10 \log_{10} \frac{1}{V_{cl\ (peak)}} \quad (14)$$

STEP (4) If the TransZorb array voltage response is low enough and the safety margin is high enough, the design is adequate. If SM is much larger than that calculated by hand, it may be possible to use fewer or lower-power devices to provide the required protection.

c. VSCF Generator/Converter Power Feeders with TransZorbs™

Transzorbs were examined as an alternative to shielding for add on protection in the VSCF generator/converter system described in Section IV. The philosophy incorporated within the model development, applied add on protection to suppress the transient before the transient became superimposed on the power bus. The type of Transzorb used was a series of high power medium voltage transient voltage suppressors. These devices are rated for a peak pulse power of 15,000 watts for 1 millisecond. Table 39 compares the results of the unprotected case with the Transzorb protection case. The design procedure for examining this and similar protective devices is described below.

Computer Aided Design Example: VSCF Gen/Conv Wing AC Bus Fuselage

STEP (1) System waveform approximations; see Figure 58 and 59.

Open-circuit voltage

$$V(t) = Ae^{-\ t} \sin 2\ ft\ u(t)$$

$$f \quad \frac{5 \text{ cycles}}{1.85 \times 10^{-6} \text{ sec}} = 2.7 \text{ MHz}$$

$$n = \# \text{ cycles to } \frac{1}{e} \text{ point} \quad 9.5 \text{ cycles}$$

$$= \frac{f}{n} = \frac{2.7 \times 10^{6}}{9.5} = 2.84 \times 10^{5}$$

$$A = 80 \text{ kV}$$

Short-circuit current

$$i(t) = I_T\ e^{-t/\ } \ u(t)$$

$$I_T = 2600 \text{ amperes}$$

$$= 37 \text{ microseconds}$$

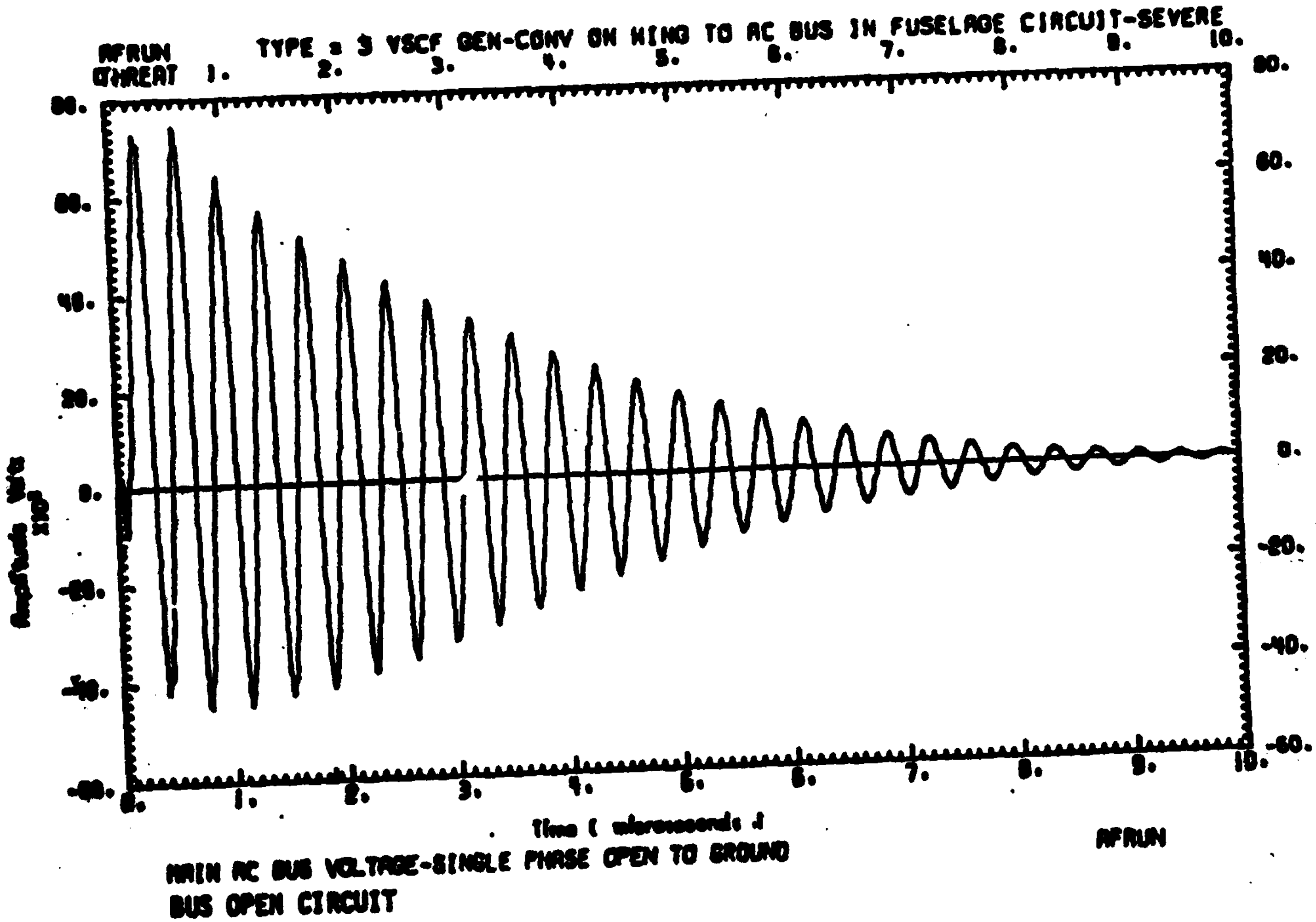


Figure 58 Open Circuit Voltage for Transorb Design

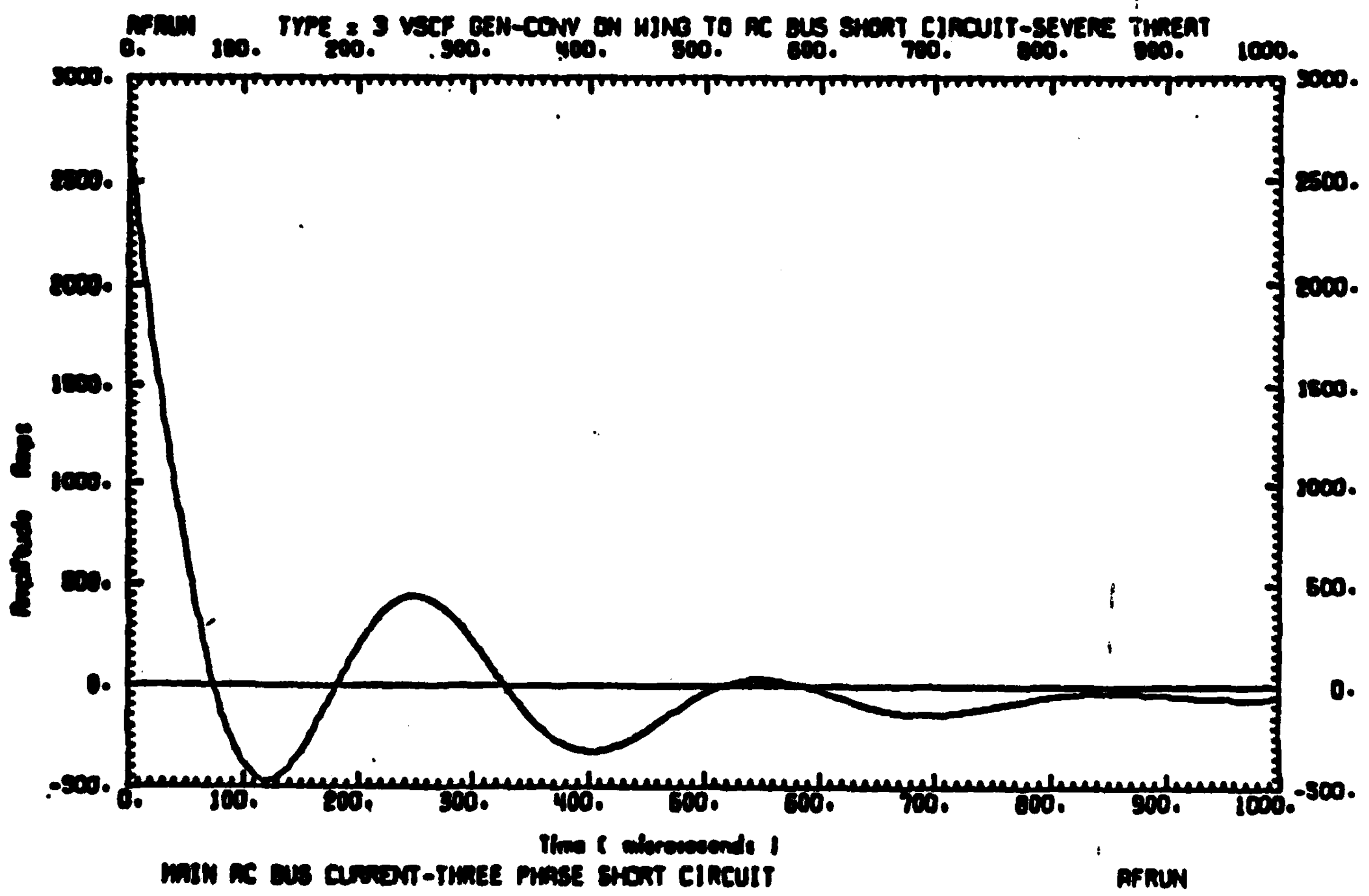


Figure 59 Short Circuit Current for Transorb Design

STEP (2) Choose device and configuration.

The device used here was the 15KP280A shown on Table 31. The suppressor array consisted of ten sets of back-to-back devices, as illustrated in Figure 57, protecting each of the three phases at the power bus. Using the equations defined above, the following computations are made.

$$P_p = 60 \text{ kW}$$

$$V_d = 330 + \left(\frac{2600}{30}\right)\left(\frac{452-330}{33}\right) = 650 \text{ volts}$$

$$I_d = \frac{2600}{30} = 86.7 \text{ amperes}$$

$$P_d = (650)(86.7) = 56.4 \text{ kW}$$

$$SM = 10 \log_{10} \frac{60}{56.4} = 0.3 \text{ dB}$$

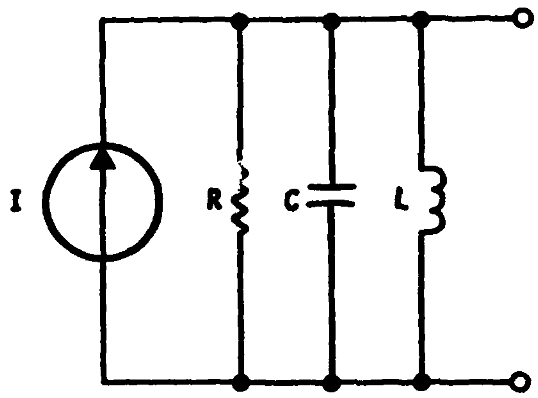
STEP (3) Norton equivalent circuit.

The Norton equivalent circuit should have the parallel RLC form illustrated in Figure 60. Values for L and C are determined by the equations shown. The value for R is found by running the Norton circuit and adjusting (L and C must follow) to obtain the correct peak voltage.

The CIRCUS-2 short-circuit current and computed open-circuit voltage for this example are shown in Figures 61 and 62, respectively.

STEP (4) Computer analysis results.

A 2-terminal damage model representing the suppressor assembly was connected to the Norton equivalent circuit described above. Plots of the resulting computed suppressor voltage and V_{C1} (representing normalized temperature rise) are shown in Figures 63 and 64.



$$f = \frac{1}{2\pi\sqrt{LC}}$$

$$\alpha = \frac{1}{2RC}$$

$$\approx \frac{f}{\#\ \text{CYCLES TO}\ \frac{1}{e}\ \text{POINT}}$$

R=8.0 KΩ

C=0.22 nF

L=16.0 µH

Figure 60 Norton Equivalent Circuit for Transorb Design

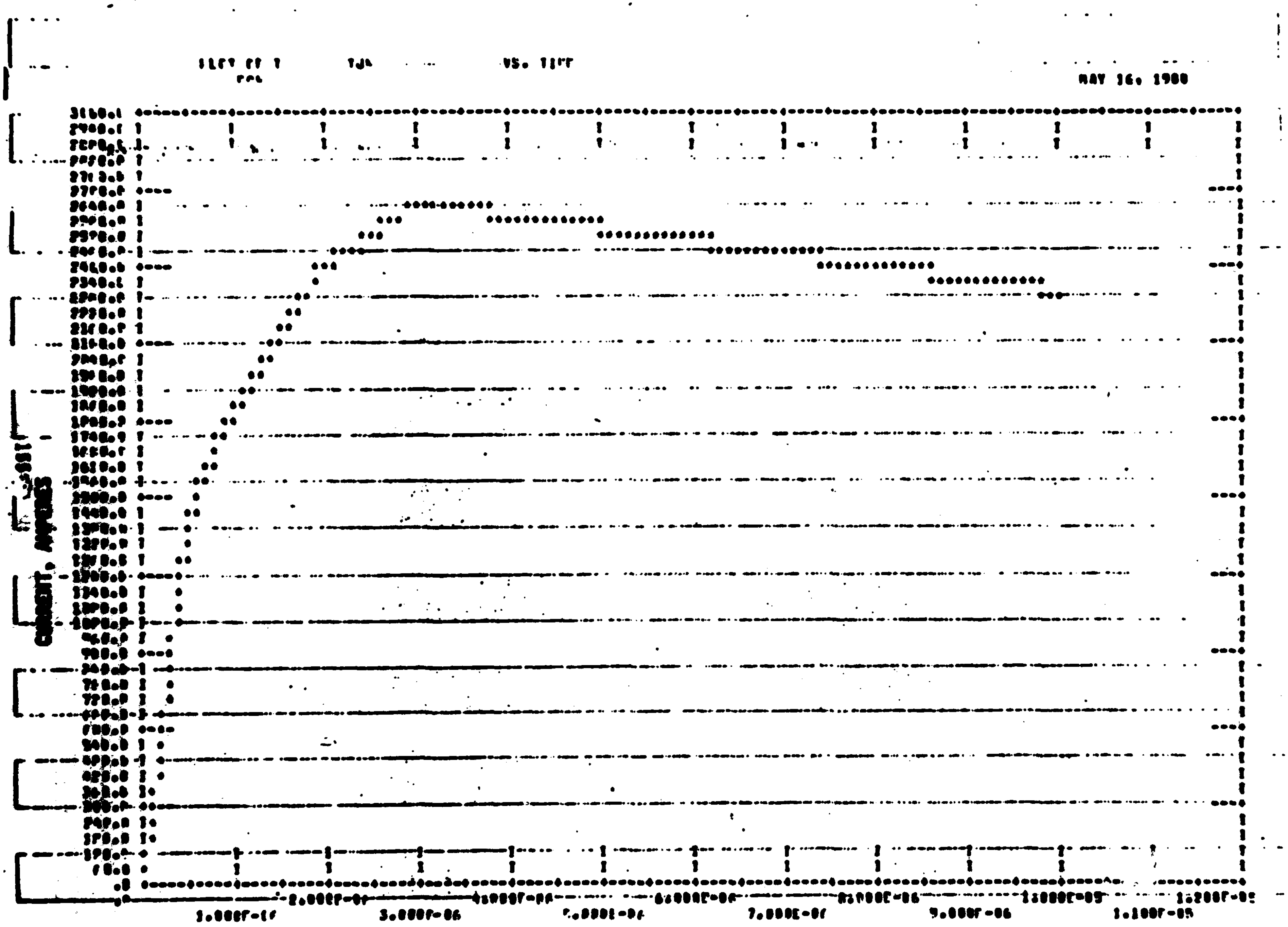


Figure 61 Short Circuit Current for Computer-Aided Design

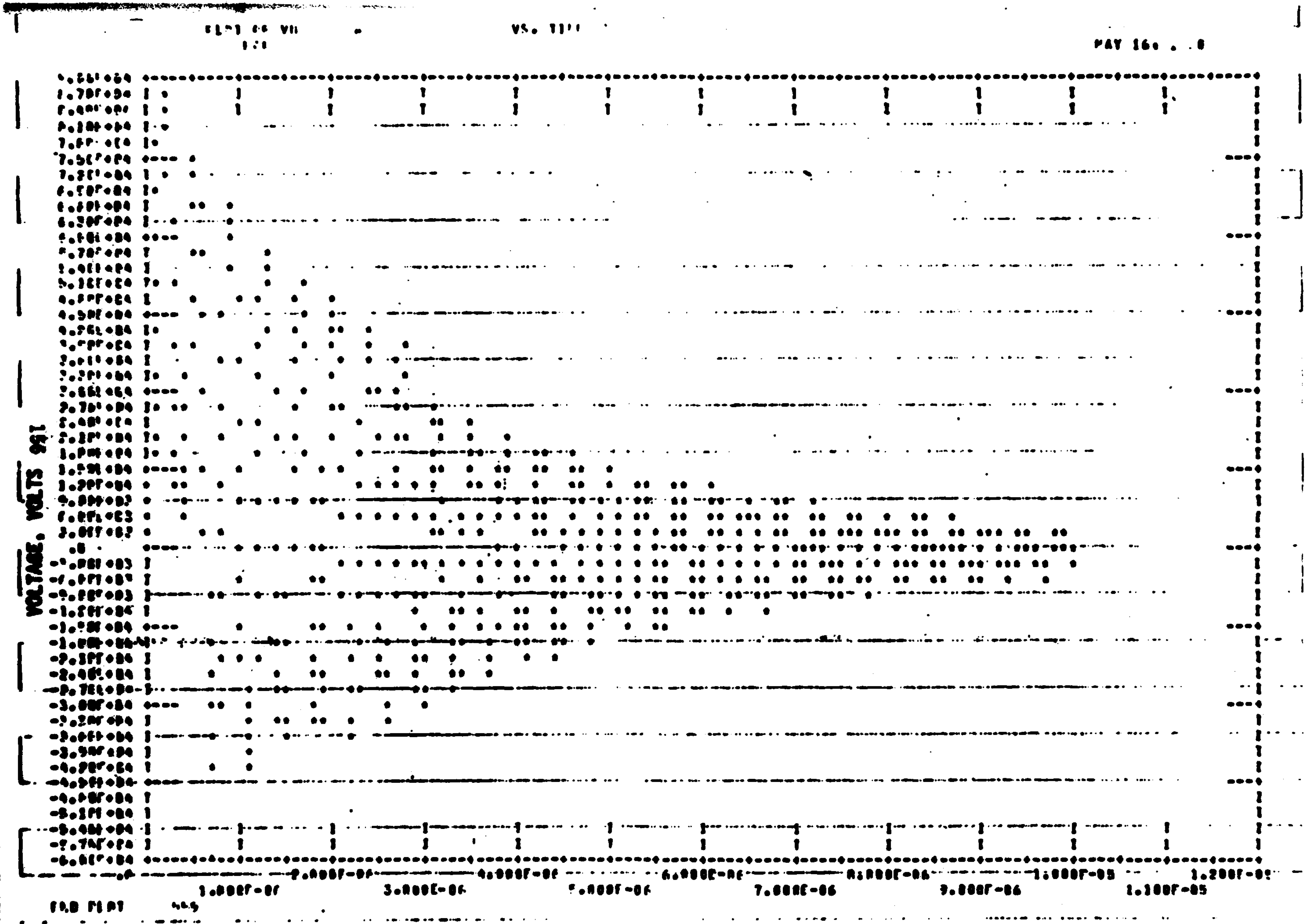
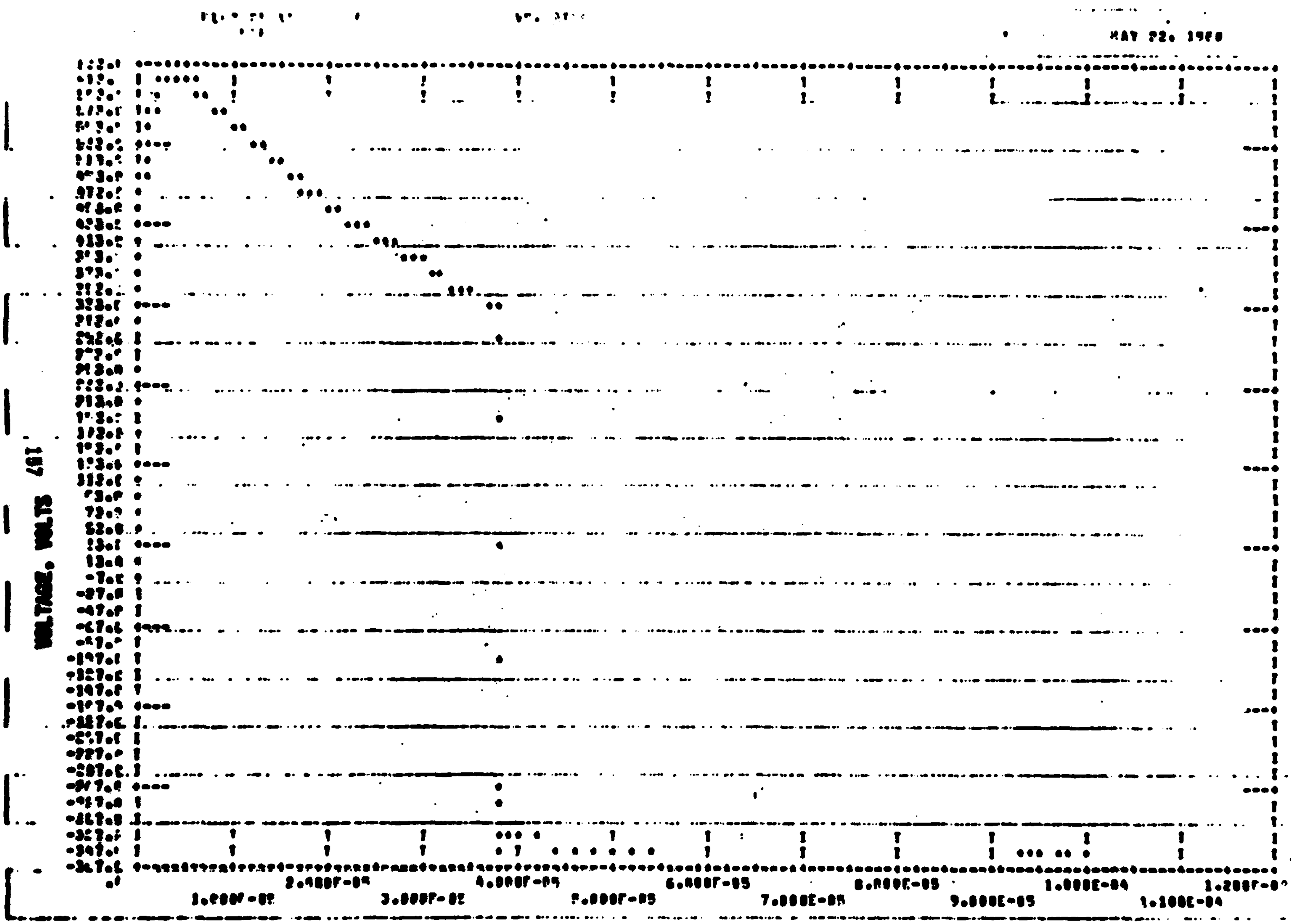


Figure 62 Computed Open Circuit Voltage



TIME, SECONDS

Figure 63 Computed Suppressor Assembly

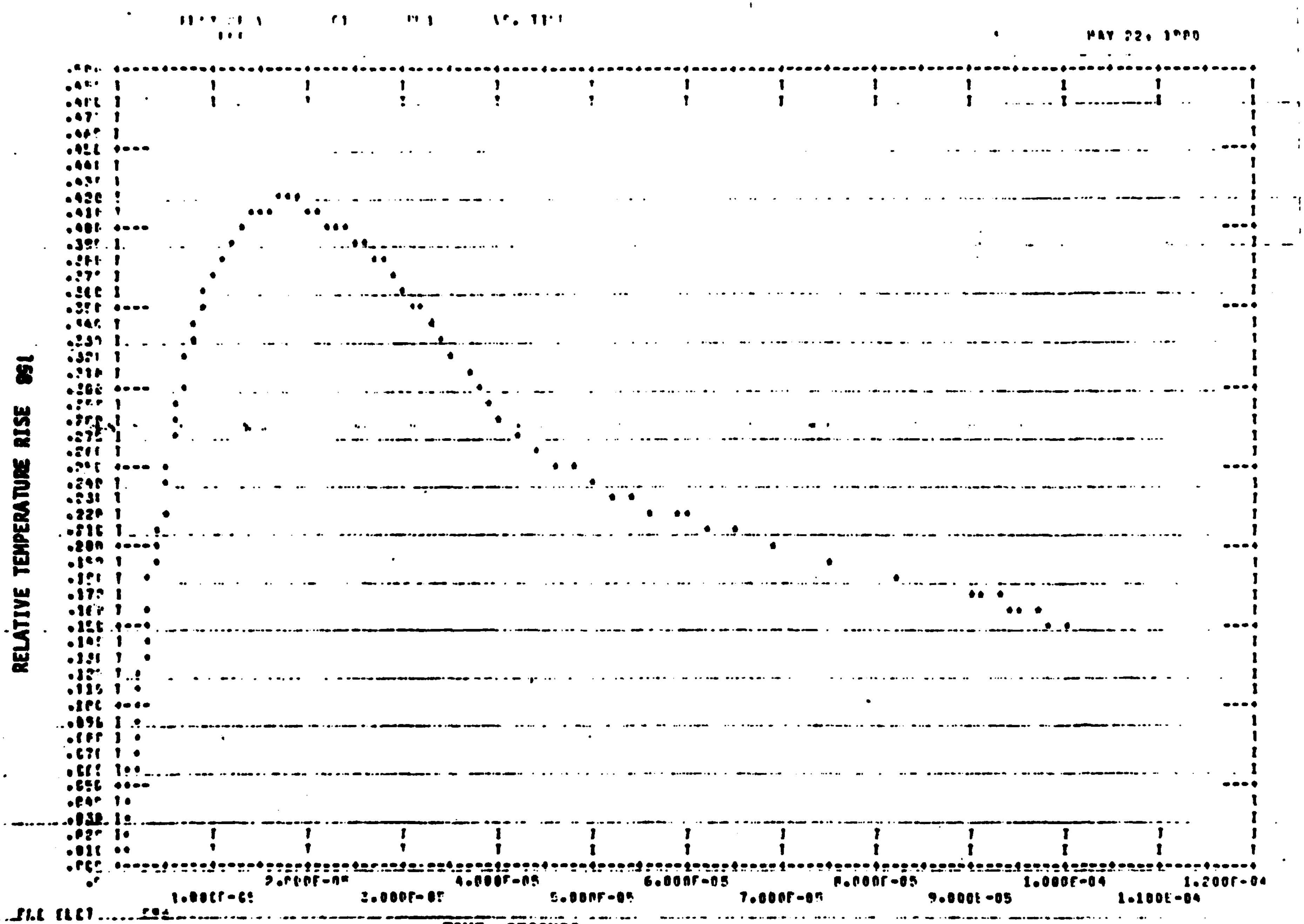


Figure 64 Computed Normalized Temperature Rise in Suppressor Assembly

We get:

$$V_d = 633 \text{ volts}$$

$$SM = 10 \log_{10} \frac{1}{0.42} = 3.8 \text{ dB}$$

3. Varistor Selection

a. Hand Calculation Design of Lightning Protection Using Varistors

This section is based in part on the G.E. "Transient Voltage Suppression Manual" second edition (Reference 14), to provide some helpful design data regarding varistors.

The five major considerations for varistor selections were described in Section VI. The final choice of a varistor is a balance of these factors with a device cost trade-off. In some applications, as with the lightning strike case which has a high peak pulse current, a high energy capability requirement forces the selection of one type of varistor or suppresor device.

An example is presented for selecting varistors to protect a power supply against line transient damage (Reference 14).

Using the circuit shown in Figure 65 with an input voltage of 117 vac and a 2.5 KV transient impressed upon it, the following selection process is suggested.

STEP (1) Steady-state voltage

If a 110% high line condition is assumed the closest steady-state voltage rating available would be 130 volts.

STEP (2) Energy and current

The 100 H input inductor will appear to be about 30 ohms to the transient.

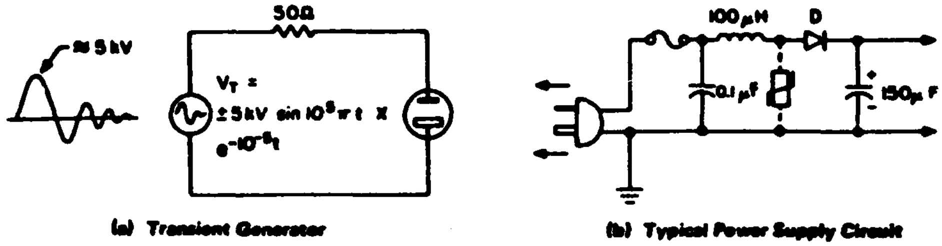


Figure 65 Power Supply Protection Technique

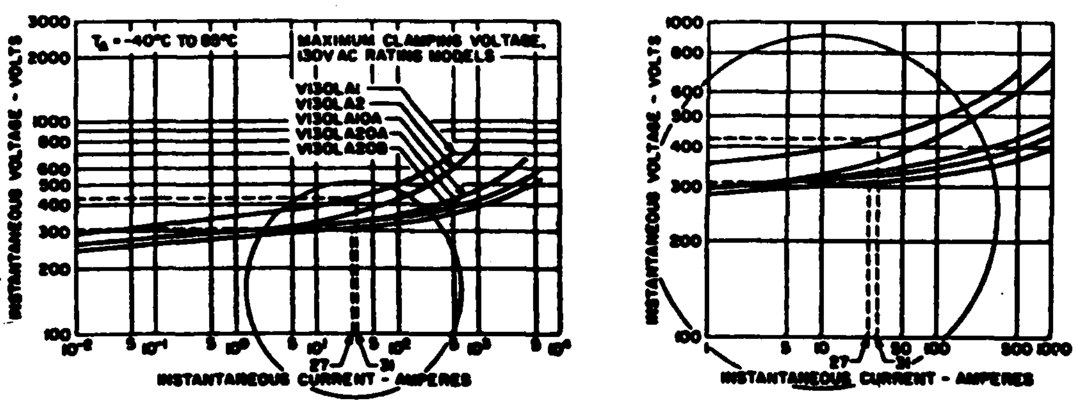


Figure 66 130-Volt Varistor V-I Characteristics

Assuming a 50 ohm source impedance with a frequency of $10^5 \pi$ radians, then a first estimate of the peak varistor current will be, 2500 volts/ 80 ohms = 31 amps.

From Figure 66 a current of 31 amps yields a voltage from 325 volts to 430 volts depending on the model size.

Revising the estimate,
I = (2500 V - 325 V)/80 ohms = 27.2 A

For model V130LA20B, 27.2 A coincides closely with a 320 V clipping level.

An energy figure can be arrived at by knowing the transient peak current, transient duration and clamping voltage. Assuming a sawtooth current waveform of 27 A peak dropping to zero in 20μ sec, energy is then roughly:

$$E = (27\ A \times 320\ V \times 20\mu\,sec)^2$$
$$= 0.086\ joules$$

This energy value is well within the capability of the varistor selected above which is rated at 50 joules.

STEP (3) Model Selection

The actual varistor selection is a trade off between the clamped voltage desired and the number of transient current pulses expected in the life of the equipment. Also, the clamp voltages determine the cost of power supply rectifiers by determining the voltage rating required. A smaller lower cost varistor may result in a more expensive higher voltage rectifier diode.

4. Capacitor Filter Selection

A general approach to capacitor filter design was discussed in Section IV. The design (through use of quick hand calculation methods) of lightning transient suppressors using capacitor filters can be outlined as follows:

STEP (1) Approximate the short-circuit current at the protection poi- an exponential having peak value I_0 and e-field fall time of τ.

STEP (2) Choose a candidate series/parallel capacitor configuration.

STEP (3) Compute the resulting capacitor peak voltage, power frequency current, and safety margin:

$$V_P = 1.4\ V_{PWR} + \frac{I_0 \tau}{C}$$

$$I_{PWR} = 2\pi f_{PWR} C V_{PWR}$$

$$SM = 20 \log_{10} \frac{V_{DAMAGE}}{V_P}$$

Here V_{DAMAGE} will normally be one to six times the direct current rating. For microsecond voltage pulses an overvoltage factor of three is often used. For devices of unknown characteristics, or voltage pulses of unknown length, a factor of one may be called for to ensure a safe design.

STEP (4) Iterate, as necessary, on device type/value until an acceptable compromise between capacitor peak voltage, safety margin, and power frequency current is achieved (or until it is determined that an acceptable design using capacitors is not possible).

5. Shielding Fiberglass Wing Leading Edge With 3 mil Foil

The baseline system described in Section V (VSCF generator and converter located out on an all aluminum wing with 12 meters of excited feeder running behind a fiberglass leading edge running toward the fuselage) was also examined with the addition of 3 mil foil to the fiberglass leading edge. The twelve meter length of excited feeder was connected to the 50% loaded bus. Table 4C lists the severe transients monitored at the generator/converter output terminals and bus input terminals, T1 and T2, respectively.

6. Add-on Protection Assessment

Protection of the electrical system as well as the overall aircraft against the effects of lightning induced voltages and currents is difficult to achieve when attempting to minimize weight, maintainability, reliability and cost penalties. The most common practice in recent years has been to harden the external structure to prevent rf energy from penetrating the aircraft. The techniques developed to achieve this end as identified in Reference 22 are:

(1) The use of fine wire mesh in cockpit and other windows.

(2) The use of rf gaskets and special corrosion protection techniques around doors and access covers.

(3) The use of filters on cables that go outside the fuselage.

(4) The use of improved bonding on coax shields, waveguide, hydraulic lines, pneumatic lines and some mechanical shafts.

(5) The use of ferrite cores around control lines and some mechanical shafts to absorb and reflect transients.

(6) The use of a separate wire return for the neutral on power lines rather than using the structure.

(7) The use of shielding on some exposed cables in the wings, wheel wells, empennage and under the nose radome.

As applied to new aircraft with composite materials, these techniques provide the designer with a basis to trade-off the protection methods to be used in his system. It is also apparent that each design will incorporate several methods of protection.

In examining add on protection in this section of the design guide, several techniques were described to best protect the electrical system. The following paragraphs compare the effectiveness of these devices to provide the design engineer with some additional data for making a selection for his particular application.

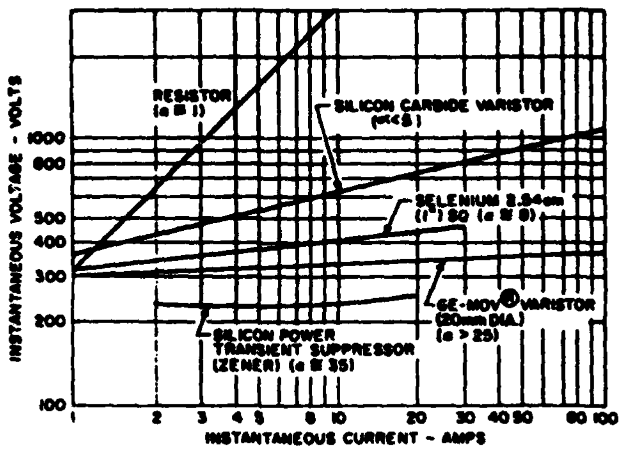
A comparison of the various transient suppressors other than TranZorbs™ is provided in the GE Transient Voltage Suppression manual (Reference 14). A graph (Figure 67) taken from this reference shows the relative volt-ampere characteristics of four devices. A curve for a resistor is included for comparison. Note that the alpha term represents the nonlinearity of the conduction. A linear resistance has an alpha (referred to as clamping factor) equal to one. High alphas are desirable for clamping applications which require operation over a wide range of currents. Tables 41 and 42 show typical suppressor characteristics including device response times and peak-current capabilities.

The amount of steady state power dissipation that a circuit can tolerate may be the deciding factor in the selection of a suppressor. Table 43 lists the most common suppressor devices with their major advantages and disadvantages.

Several transient suppressor devices were tested by G. E. with the results documented in Reference 14. The candidate suppressors were connected to an impulse generator which gave a 5 KV open circuit voltage pulse, and subjected them to 10 impulses. The suppressor protective levels are given in Table 44.

Table 44 is also a comparison of the candidate suppressors that survived the tests. From these, G. E. concluded that the protection of electrical/electronic equipment containing solid-state components that are conductively connected to power buses can be done at different levels for varying costs. In general the most effective protection has the highest price with the exception of capacitors. However, size constraints and the risk associated with using linear protection devices make capacitors impractical for many applications. The non-linear devices displayed very similar voltage response characteristics with the TransZorbs™ providing the lowest protection level and the highest cost.

One of the areas of greatest research at present, the incorporation of a conductive material into the manufacture of the composite material, may prove



SUPPRESSOR TYPE	IDLE CURRENT mA	PEAK CURRENT ● 1 ms A	PEAK POWER ● 1 ms kW	PEAK ENERGY JOULES	VOLTAGE CLAMPING RATIO ● 10 A	VOLTAGE RANGE DC
GE-MOV ● Varistor (20 mm diameter)	1	120	40	50	1.7	14-1200
Zener (1 W)	.005	5.5	1.5	2	1.65	5-200
Selenium (1" Sq.)	12	30	9	9	2.3	35-700
Spark Gap	–	>500	–	–	2.4-8.8*	90-1400
Silicon Carbide (0.75" diameter)	5	–	–	50	4.6	15-300

Figure 67 Comparison of Suppressor Characteristics

TABLE 41 TYPICAL SUPPRESSOR CHARACTERISTICS

PARAMETER	GAS DISCHARGE TUBE	SPARK GAPS	VARISTOR DEVICES	ZENER DIODES	TRANSZORBS™
Typical Surge Current Capability (Amps)	40,000	10,000	1000-25K	To 500	30-500
Response Time (Sec)		10^{-8}	10^{-8}	10^{-9}	10^{-12}
Capacitance (farad)	10^{-12}	10^{-12}	10^{-12}	10^{-10}	10^{-9}
AC Voltage Range (Volts)		90 and higher	40-1000	2-300	17-280
Failure Mode	Short	Short	Short	Short	Short
Activated State	Short Circuit	Short Circuit	Clamped	Clamped	Clamped

TABLE 42 LINEAR AND NON-LINEAR DEVICE COMPARISON DATA

	Reaction Time [1]	Voltage Range	Peak Current [1]
I. Linear Devices			
o Spark Gaps (linear before breakdown)	Fast	90V & Up	Very large
o Crow bars (triggered gaps)	Intermediate	*	Very large
o Fuses	Very slow	to 100kv	Medium
o Shorting Stubs	*	*	Very large
o Filters	*	*	*
o Circuit design	*	*	*
o Isolation Transformers			
II. Semi-Conductor Devices			
o Zener Diodes	Very fast	2-300	Medium
o Variable Resistors			
Selenium	Very fast	40-700	Medium
MOVs	Very fast	150-1500	Large
o Crow bars (SCR's)	Intermediate	100kv	Very large
o Solid State Diodes	Very fast	Few volts	Large
III. Hybrid Systems			
o Lightning Suppressor GE M185	Very fast	Clumps to 100V	Very large
o Lightning Suppressor Boeing 60B40082			

Reaction Times [1]

10^{-8}	- very fast
$10^{-8} - 10^{-7}$	- fast
$10^{-6} - 10^{-4}$	- intermediate
$10^{-3} - 10^{-1}$	- slow
$10^{-1} - 1$	- very slow

Current Handling Capabilities [1]

5KA - 3KA	very great
3KA - 1KA	great
1KA to 100A	medium
100 to 10A	low
10A	Very low

* Not applicable

TABLE 43, COMPARISON OF PROTECTION DEVICES

DEVICE	ADVANTAGES	DISADVANTAGES
Transzorb	1. Large surface area for good energy handling capability (compared with Zener diode) 2. Restores to initial state, no follow on power 3. Tight voltage control 4. Fast response 5. Small size, easily mounted	1. May fail under normal operation if line voltage frequently exceeds rated voltage 2. Requires recovery time after firing 3. Limited power-handling capability 4. Low energy absorbing capability 5. Large capacitance
Metal Oxide Varistor	1. Restores to initial state, no follow on power 2. Energy absorbed through out device volume 3. Fast response/low impulse ratio 4. Small size, easily mounted 5. Self extinguishing 6. High ratio of energy absorbed to energy reflected	1. Low impedance and high capacitance 2. Low energy absorbing 3. Limited power handling capability 4. Operating voltage proportional to material thickness 5. Requires recovery time after firing
Zener Diode	1. Restores to initial state no follow on power, self-extinguishing 2. Low firing voltage and tight voltage control 3. Low dynamic impedance when conducting, low capacitance 4. Absorbs energy in the device 5. Fast Response 6. Small size, easily mounted	1. Are not bilateral 2. High junction capacitance 3. Low energy absorbing capability 4. Limited power handling capability 5. Absorbs energy in junction surface 6. May fail under normal operation if line voltage frequently exceeds rated voltage 7. Requires recovery time
Spark Gap	1. High current, large power handling capability 2. High impedance, low capacitance 3. Bilateral operation 4. No recovery time required 5. Simple and reliable	1. High turn on voltage 2. Does not extinguish follow current, may draw follow on power after turn on 3. Absorbs little power
Gas Discharge Tube	1. Low capacitance 2. Absorbs energy in the device 3. High current and power capability 4. Fails short to indicate need to replacement	1. Slow response time 2. Variable breakdown voltage 3. May age with leakage of gas 4. May draw follow on power after turn on

TABLE 44 PROTECTION LEVEL VERSUS COST

TYPE DEVICE	THREAT LEVEL	PROTECTION LEVEL	PROTECTION LEVEL WITH AN EMI FILTER	UNIT COST (50M QUANTITY)
<u>Spark Cap</u>				
Signalite CG2-350ALT	5 K Volts	810 Volts	400 Volts	$.75
<u>Varistors</u>				
GE-MOV-V220MA2A	5 K Volts	1250 Volts	600 Volts	.22
GE-MOV-V130LA10A	5 K Volts	690 Volts	430 Volts	.38
<u>Transorbs</u>				
General Semi-Conductor - 1.5 KE200C	5 K Volts	320 Volts	195 Volts	1.55
<u>Capacitor Suppressors</u>				
Sprague Film .5 F 600 VDC 160P6TM-P50	5 K Volts	300 Volts	--	.22
GE Film 61F .1 F 100 VDC	5 K Volts	840 Volts	--	.08

to be the most effective method of lightning protection. As shown in Section VIII.5, the graphite/epoxied material with 3 mil foil attached provides a maximum amount of attenuation against the severe threat lightning strike. Not only is the electrical system protected, but the structure itself is protected by allowing the lightning generated current to disperse over the entire surface. There are, of course, several problem areas with laminate materials including methods of connecting joints and other apertures, and the method of incorporating the foil material to prohibit corrosion, etc. These problem areas are being addressed in several study programs to hopefully develop suitable solutions (References 6 and 23).

Of course not all areas of the aircraft structure which utilize composite materials can make use of the 3-mil foil technique. In these areas shielding of the signal or power cables must be used. Table 45 suggests protection concepts for protecting the aircraft electrical system from lightning strike. Each concept is identified with a particular application and function that should be considered for the individual system to be designed. Table 46 evaluates the protection concepts as to their relative shielding effectiveness. As can be seen from this table the conducting skin enclosure provides the greatest attenuation and therefore has generated the greatest interest. Further research and study are required to resolve the reliability question and provide the necessary data.

TABLE 45 PROTECTION CONCEPTS AND THEIR APPLICATION

CONCEPT	APPLICATION	FUNCTION
Enclosures: System skin Bays Racks	Protection of electronics subsystems by classical shielding of radiated environments from outside the system and within the system.	Reflection and attenuation of electromagnetic fields. Reduction of coupling of surface currents via apertures and penetrations.
Cable shield assemblies	Protection of the interconnecting paths between and among electronic subsystems.	Reduction of electromagnetic energy coupled to wires within cables. Reduction in coupling of currents induced on one cable to other cables.
Fiber optic data links	Protection of the interconnecting paths between and among electronics.	Nonmetallic interconnect virtually immune to coupled radiation.
Terminal protection device: e.g., Zener diode spark gap Surge arrestor	Protection of interfaces to electronic subsystems. Applied at the subsystem or enclosure interface.	Amplitude selective reduction of the conducted voltage/current transient appearing on wires or cables; nonlinear operation.
Filters	Protection of interfaces to electronic subsystems. Applied at the subsystem or enclosure interface. Can be used in conjunction with with terminal protection devices.	Frequency selective reduction of the conducted voltage/current transient appearing on wires or cables; linear operation.
Electro-optical Isolators	Protection of interfaces to electronic subsystems. Usually applied at the subsystem. May apply at bay, rack, drawer interface.	Reduces the common-mode transient coupled to two-wire circuits.
Procedures: Grounding Bonding Routing	System-wide usage to reduce coupling of electromagnetic energy.	Provides for a reduction in the distribution of electromagnetic energy within the system. Increases the shielding performance of other elements.

TABLE 46 PROTECTION CONCEPT PERFORMANCE CHARACTERISTICS

CONCEPT	NOMINAL PERFORMANCE	VARIABILITY	RELIABILITY	COST
ENCLOSURES				
PERMANENT SEAMS	55 dB	± 25 dB	-20 dB	(8-12) X C_M
ACCESS SEAMS	45 dB	± 15 dB	-20 dB	(24-28) X C_M
SMALL APERTURES	54 dB	± 36 dB	-20 dB	(24-28) X C_M
PENETRATIONS	68 DB	± 22 dB	-20 dB	(24-28) X C_M
NONCONDUCTING SKIN	23 dB	± 17 dB	Unknown	(24-28) X C_M
CONDUCTING SKIN	90 dB	± 10 dB		
INTERCONNECT				
CABLE SHIELDS	70 dB	± 30 dB	-20 dB	(24-28) X C_M
CABLE CONNECTORS	72 dB	± 28 dB	-20 dB	(24-28) X C_M
FIBER OPTIC LINKS	>100 dB	small	> 5 X 10^3 hours	(8-12) X C_M
TERMINAL				
FILTERS	35 dB	± 30 dB	10^5 - 10^6 hours	(24-28) X C_M
TPDs	30 dB	± 16 dB	10^4 - 10^6 hours	(24-28) X C_M
ELECTRO-OPTIC ISOLATORS	23 dB	± 13 dB	≥ 5 X 10^3 hours	(8-12) X C_M

NOTE: C_M = COST OF MATERIALS

SECTION VIII

SELECTION OF HARDENING TECHNIQUES FOR AN ADVANCED ELECTRICAL SYSTEM

1. Advanced Electrical System Description

Basic system:

- Single channel VSCF (cycloconverter) with rare-earth permanent magnet generator.
- Micro-processor-based controls of generator and buses.
- Multiplex data bus control of power generation and distribution.
- Power bus switching by contactors with solid state sensing and control.
- Distribution system protection and switching by solid-state power controllers.

This section of the design guide describes the airplane electric power system that will be used as the example for applying hardening techniques to protect it from lightning hazards. As described initially, no special lightning protection is included.

The power generation system consists of two 60 KVA VSCF channels. Only one channel will be described for hardening (See Figure 68). The samarium cobalt PMGs are mounted on the engine accessory drive gear boxes on the wing-mounted engines, and the cycloconverters are mounted in the fuselage. A typical aircraft housing this electrical system is shown in Figure 69. the system lightning protection design is based upon an electrical system being installed in this aircraft configuration.

The power feeder between the generator and the frequency converter consists of

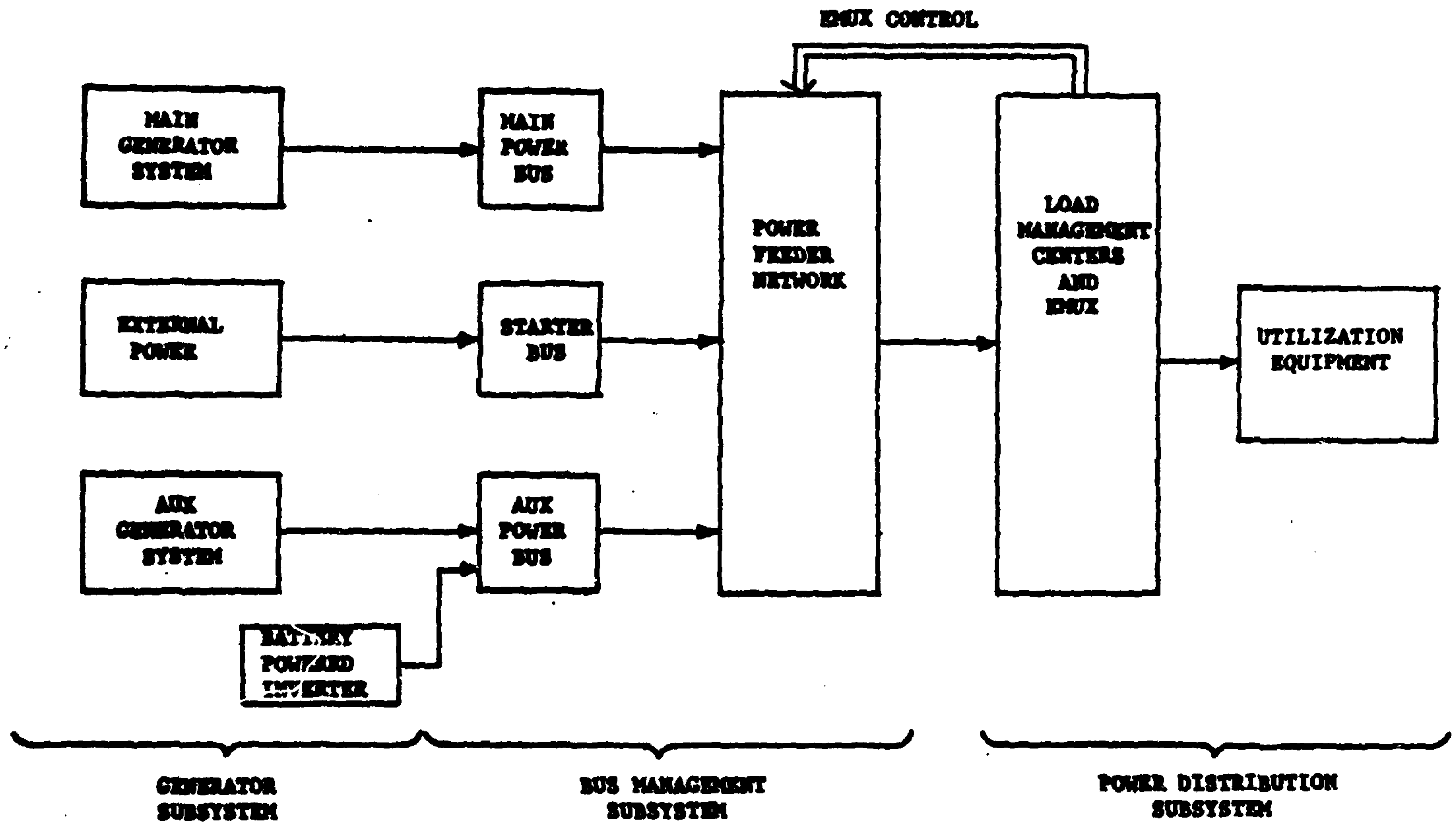


Figure 68 Single Channel Electrical System

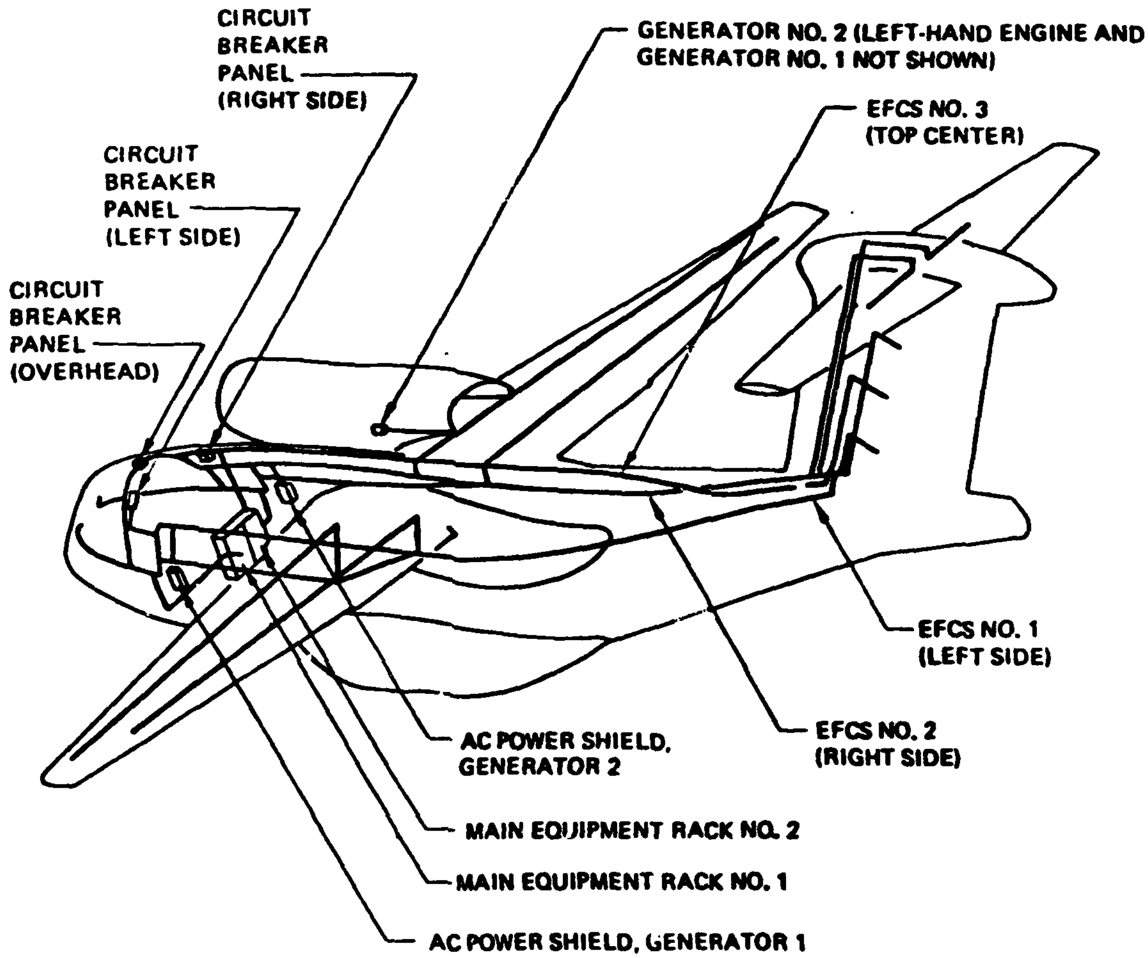


Figure 69 Aircraft Configuration for Advanced Electrical System

AD-A112 707 BOEING MILITARY AIRPLANE CO SEATTLE WA F/G 1/3
PROTECTION OF ELECTRICAL SYSTEMS FROM EM HAZARDS - DESIGN GUIDE--ETC(U)
SEP 81 D L SOMMER F33615-79-C-2006
UNCLASSIFIED D180-26154-3 AFWAL-TR-81-2118 NL

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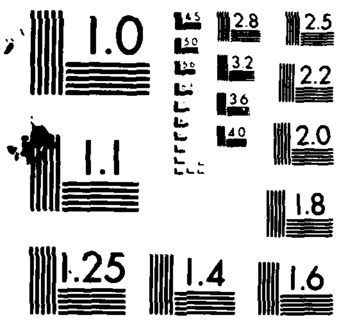


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

three No. 10 AWG copper wires for each of the six phases plus three wires of the same size for the neutral, or 21 wires total. EMI shielding is required on these wires due to the voltage spikes that result from the high-frequency switching in the cycloconverter. EMI shielding, in this context, is braided jacket, pigtail-grounded at only one end. To simplify installation, the feeder is arranged in three shielded bundles of seven wires each; i.e., one wire for each phase and one neutral wire. These bundles are routed from the generator through the firewall via fireproof connectors, thence through the engine strut to the wing, and along the front face of the front spar to the fuselage and thence to the cycloconverter which is located in the electrical/electronic equipment bay.

The alternative, if space is a available in the nacelle, is to mount the cycloconverter on the generator, thus eliminating the 21-wire 6-phase shielded feeder between the two assemblies. In its place is installed a 3-phase power feeder bundle from the cycloconverter to the power shield in the fuselage. This 3-phase 400 Hz bundle does not require EMI shielding.

The generator control unit (GCU) functions in VSCF generation systems normally are contained within the cycloconverter package, as they are in this design. Bus power control functions are separated and housed separately, since only one set of controls is needed for the complete system. Logic for all of these control functions is contained in the software of microprocessors. For the generator systems these microprocessors are contained in the cycloconverter packages. The bus control microprocessor is in the bus power control unit (BPCU).

All communication between GCUs, as well as between a GCU and a BPCU, is transmitted via multiplex data buses.

Bus switching is accomplished by means of contactors, using solid-state sensing of power quality characteristics such as voltage, frequency, magnitude of load current, and other characteristics used in determining the need for bus switching operation. Contactor position status sensing and position control also is by solid state circuitry. Power distribution wiring protection and individual load switching is accomplished by solid state power controllers (SSPCs). All communication between GCUs, EPCU, or the electrical system control panel at flight crew stations and the distribution system SSPCs is transmitted by multiplex data buses.

2. Threat Assessment to the Electrical System

The assumed threat as described in Section II will either be a direct attachment strike to the engine nacelle, to the wing tip travelling transversely across the aircraft, or to the nose/tail travelling fore and aft along the fuselage. The threat to the electrical system components in first a composite aircraft with various structure configurations and in second an all metal aircraft. In each case both the baseline and alternative electrical systems are described. The electrical circuit configurations are considered with the inherent hardness techniques of Sections III and IV applied. Applicable reference sections and paragraphs are listed with the circuit descriptions.

a. Composite-Structure Airframe

1) Generator in nacelle, cycloconverter in fuselage (Section *II.1.b* and II.2):
    a. Graphite-epoxy or fiberglass cowling:
       Generator directly exposed to lightning field via engine inlet and exhaust ports, and to diffusion field penetration in graphite-epoxy skin.
    b. Graphite-epoxy or fiberglass skin on engine strut:
       Generator feeders protected from lightning by EMI-shielding.
    c. Graphite-epoxy or fiberglass leading edge on wing:
       Generator feeders protected from lightning by EMI-shielding.
    d. Graphite-epoxy skin on fuselage:
       Cycloconverter internal circuits shielded from induced transients by metal housing (standard).

2) Alternative: Generator and cycloconverter in nacelle:
   Generator to cycloconverter feeders, very short--no shielding.
   Conditions 1b, 1c, 1d apply here to unshielded 3-phase power feeders, cycloconverter to power shield.

3) Power shield in fuselage (Section II.2):

a. Graphite-epoxy skin:

Power feeders from cycloconverter to power shield, exposed to inductive coupling of lightning transients, via apertures in the skin, joints in structure, e.g., leading edge flaps, and diffusion of field into structure and skin.

Equipment in power shield, subject to conducted transients on feeders from cycloconverters and on distribution feeders to loads.

4) Distribution wiring from power shield:

Feeder wiring from power shield to loads subject to inductive coupling of lightning transients. Coupling may be by any or all of the mechanisms identified in Section II.

a. Upper surface blowing actuator:

Wiring exposed to two primary coupling mechanisms, i.e., direct exposure to lightning fields (especially when flaps are extended) and diffusion penetration of fields into composite structure spar and skin.

b. Wing tip beacon light:

Wiring exposed to same coupling mechanisms as upper-surface blowing actuator wiring, above, except installed along front spar instead of rear spar. Some direct exposure when leading edge flaps (if any) are extended.

c. Windshield heater:

Primary exposure is direct (capacitive) coupling between the heater element and the external [illegible] induced electric field. This exposure is the same as in the me[illegible]ic airframe.

d. Vertical stabilizer (rudder) actuator:

The threat in this circuit is similar to the assessment in b above since that analysis assumed installation in a non-metallic composite structure location.

b. Metal-Structure Airframe

1) Generator in nacelle, cycloconverter in fuselage (Section II.2):

   a. Metal cowling:
      Generator directly exposed to lightning field via engine inlet and exhaust ports.

   b. Metal skin on engine strut:
      Skin serves as lightning shield. Braided jacket shield, required on generator feeders for EMI shielding (to contain internally-generated EMI), being grounded at only one end, does not protect against coupling of lightning transients onto feeders.

   c. Metal wing skin and leading edge:
      Generator feeders protected from lightning transients by metal skin as well as by braided jacket EMI shielding.

   d. Metal skin on fuselage:
      Cycloconverter internal circuits shielded from induced transients by metal housing (standard).

2) Alternative: Generator and cycloconverter in nacelle:

   Generator-to-cycloconverter feeders--very short--no shielding required. In this configuration, conditions A2, A3, A4 apply to unshielded 3-phase power feeders, cycloconverter to power shield. No extra shielding (lightning protection) required, since metal skin shields from induced transients.

3) Power shield in fuselage (Section II.2):

   a. Metal skin:
      Power feeders from cycloconverter to power shield, exposed to inductive coupling of lightning transients, via apertures in the skin, joints in structure e.g., leading edge flaps, windows, slots around doors (may be plugged, air tight, by rubber or other non-conductive material which does not provide shielding).

      Equipment in power shield, subject to conducted transients on feeders from cycloconverter and on distribution feeders to loads.

4) Distribution wiring from power shield:

a. Metal skin:

Feeder wiring from power shield to loads subject to inductive coupling of lightning transients. Coupling may be by any or all of the mechanisms identified in Section II. Coupling by induction of fields diffused into structure is a threat only to circuits using structure for the current return path.

- Upper surface blowing actuator:
  Wiring exposed to only one primary coupling mechanism, i.e., direct exposure to lightning fields, especially when flaps are extended).
- Wing tip beacon light:
  Wiring exposed to same coupling mechanism as upper-surface blowing actuator wiring, above, except installed along front spar instead of rear spar. Some direct exposure when leading edge flaps (if any) are extended.
- Windshield heater:
  Exposure same as in composite-structure airframe, and same as described in Section IV.
- Vertical stabilizer (rudder) actuator:
  Same as for upper surface blowing actuator above.

3. Electrical System Protection

The electrical system described above will require additional protection as stated in Section III and IV of the design guide. Inherent hardening of the system is not sufficient to protect against the severe threat lightning strike described in Section II. The electrical system described in paragraphs 1 and 2 above will therefore require the additional protection suggested in the following paragraphs.

Specific techniques used to provide lightning protection of the aircraft and therefore also of the electrical system in addition to the inherent shielding provided by the airplane structure (described in Section III and IV) are:

- Component Location

  Protection provided by this method is accomplished by locating items out of the direct or swept stroke zones (Section III.2).

- Alternate Current Paths

  This technique diverts lightning discharge currents around components or devices which cannot sustain the passage of lightning discharge currents (e.g., electrical bonding jumpers on hinges and control surface actuators) (Section VI.4).

- Stroke Diversion

  This method provides an alternate preferred path for the direct lightning strokes. One form of diverter consists of thin metallic strips installed on a di-electric surface and well grounded to the airframe. Another form consists of a long protuberance attached to the exterior of the aircraft in the immediate area of concern (Section IV.4).

- Electromagnetic Shielding

  This method prevents the transmission of detrimental transients into the aircraft electrical system by shielding wires lying near, or adjacent to, areas subject to lightning discharge current flow (e.g., conduit on radome mounted pitot heater wires which are adjacent to the air data lines - these data lines will carry a major portion of the discharge currents resulting from a lightning strike to the pitot boom) (Section VI.1).

- Penetration Resistant Material

  Protection by this technique prevents lightning stroke penetration by providing adequate material thickness for lightning current conduction (Section VI.4).

a. Composite-Structure Airframe

1) Generator in nacelle, cycloconverter in fuselage

The design guide (Section VI.4 and VII.5) suggests that the best approach here is to shield the entire wing and nacelle area with a 3-mil foil. This technique is presently being used on the new generation aircraft which utilize composite materials. Any areas of the aircraft, such as in the nacelle, that cannot be shielded in this manner and house unshielded electrical conductors, could be shielded with diverter straps or pigtails as are being used on the new generation Boeing aircraft. These can divert the lightning stroke and reduce the coupling to the electrical wiring.

2) Alternative: Generator and cycloconverter in nacelle

The same situation applies here as described in paragraph 1) above. However, the unshielded feeders routed between the nacelle and fuselage must be shielded either by the 3-mil foil technique or by cable shields. The preferred technique is the former, in this case, as described in Section VII.6. The lightning induced currents are reduced by two orders of magnitude. The designer must take precautions to prohibit coupling through apertures in the skin.

3) Power shield in fuselage

The interconnect system requires shielding both for EMI and the lightning threat (Sections IV, VI.1, and VII.1). Although shielded itself due to EMI, the power shields interconnect system must be protected. Cables should be routed near any ground plane.

4) Distribution wiring from power shield

Here the protection scheme is dependent on the location of the wiring and the electrical component it is interconnecting. For example the windshields are located in either a direct or swept (Section II.1.b) lightning strike zone. Since the windshields are electrically heated and shielding of heater elements is not practical due to the necessary exposure of the heater elements, surge suppressors must be provided for lightning protection (Section VI.2 and VII.2). Also, any wiring in the vicinity of the windshield must be shielded to provide protection against the concentrated magnetic fields. Section IV.4 found the transients to exceed 1200 V peak-to-peak. These transients could be reduced by a suppression device using TransZorbs™ by up to two orders of magnitude (Section VII.2).

This description of the windshield applies to both metallic and non-metallic structures.

The beacon lights must be protected against direct attachment lightning strikes which can induce voltages up to 80 kV (Section IV.3). To prevent coupling of the severe transient to internal electrical circuits the lights must be protected with surge suppressors. Here again a TransZorb™ type device can provide the attenuation, however, with such large voltage transients a spark gap device with a good structure ground to handle the current could be used more effectively (Section VII.6). Also the interconnecting wiring must be shielded (Sections VI.1, VI.2, and VII.1). Similarly circuits and wiring in the Vertical stabilizer and near the upper surface blowing actuation must be protected.

b. Metal Structure Airframe

The all metal airframe provides an excellent shield for the electrical circuits which reside within. However, the airframe is not a perfect metal shell (Section VI) and therefore protection from lightning strike may be required in the highly susceptible attachment zones (Section II.1.b). External hardware prove to be the most susceptible to lightning strike. External hardware includes air data probes, antennas, radomes, navigation lights, windshields, canopies and other objects mounted on the external surface of an aircraft. Since many of these objects are in lightning strike zones, they must be designed to safely conduct lightning currents and to prevent surges from being coupled into associated electrical wiring, if present.

For example the beacon light case described in paragraph A.4) above: If the light is located in a lightning strike zone, the housing must be grounded to the metallic structure in such a way as to conduct the large lightning currents. If this is not possible, then surge suppressors must be provided to assure that lightning currents are not conducted to the internal circuits.

Also, the windshield heaters must be protected as described above in paragraph A.4). Any interconnect wiring exposed near the heater must be shielded.

SECTION IX

RELIABILITY AND MAINTAINABILITY FOR PROTECTION HARDWARE

Reliability is a problem at all levels of complex system design, from materials to operating systems. Reliability engineering is concerned with the time degradation of materials, equipment design and system analysis (Reference 24).

This section of the design guide looks at some of the lightning protection system components that may affect the reliability of the electrical system. The reliability of the overall electrical system must be reassessed at the time of design.

Predictions of electronic component reliability are given in MIL-HDBK-217C, "Reliability Prediction of Electronic Equipment". From the handbook reliability of electronic surge suppressor devices can be predicted. The part failure rate models in the handbook include the effects of part electrical stress, thermal stress, operating environment, quality level and complexity. Each type of suppressor using electronic components (zener diodes, capacitors, inductors, transistors, etc.) can be assessed as a series system for part failure rate calculations.

The following paragraphs provide reliability analysis data for varistor and transzorb type suppressors. Shielding reliability data is well documented in Mil-Std Handbooks and not included here. Reliability data from graphite/epoxied materials with mil-foil applications is presently being studied under various military programs. Further studies must be done to assess the reliability and maintainability problems of these advance composite materials.

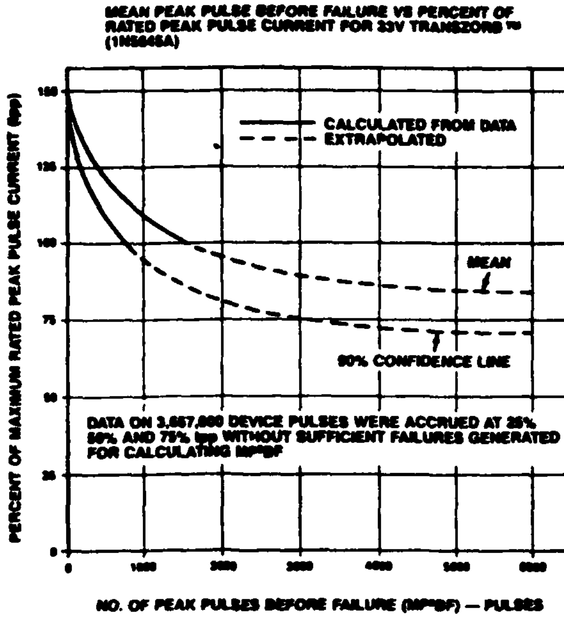
1. TransZorbs™ *(Based on the data generated by General Semiconductor Inc.)*

The reliability of the TransZorb™ was studied extensively under NASA Contract Nos. NAS8-30811 and NAS8-31547 in which more than 12,500,000 test pulses were generated. Twelve hundred devices were used in the tests with 50 units per test group. Test pulse magnitudes for two voltage types, 33V, and 190V, were applied in increments of 25% from and up through 150% of the maximum peak current rating of the TransZorb™. The Mean Number of Peak Pulses Before Failure (MP^2Bf) is used as a more accurate measure of reliability for a transient suppressor than Mean Time Beofre Failure (MTBF). Figure 70 represents the reliability curves in terms of percent of maximum rated peak pulse current versus the number of peak pulses before failure.

2. Varistors (Based on the GE-MOV™ varistor data)

The majority of the applications for the varistor are as transient suppressors on the ac line. The varistor is connected across ac line voltage and biased with a constant amplitude sinusoidal voltage. If the varistor current increases with time, the power dissipation will also increase, with the ultimate possibility of thermal runaway and varistor failure. Because of this possibility, an extensive series of statistically designed tests have been performed to determine the reliability of the GE-MOV™ varistor under ac bias combined with temperature stress. This test series contained over one million device hours of operation at temperatures up to 145°C. The average duration of testing ranges from 7000 hours at low stress to 495 hours at high stress. The results of this test have shown the GE-MOV™ varistor to be an excellent fit to the Arrhenius model, i.e., the expected life is logarithmically realted to the inverse of the absolute temperature ($MTBF = e^{C + K/T}$). The definition of failure is a shift in V_{NOM} exceeding ± 10%. Although the GE-MOV™ varistor is still functioning normally after this magnitude of shift, devices at the lower extreme of V_{NOM} tolerance will being to dissipate more power. As previously explained, this could ultimately lead to failure. This choice of failure definition, in combination with the lower stresses found in applications, should provide life estimates adequate for most design requirements. Figure 71 illustrates the arrhenius model plot for the line voltage and the low voltage GE-MOV™ varistor.

This type of statistical model allows a prediction of the reliability level that can be expected at normal operating temperatures. The usual ambients are well below the temperature levels chosen for accelerated testing. For example, a V130LA10 operating at 130V ac in a 55°C environment has a mean



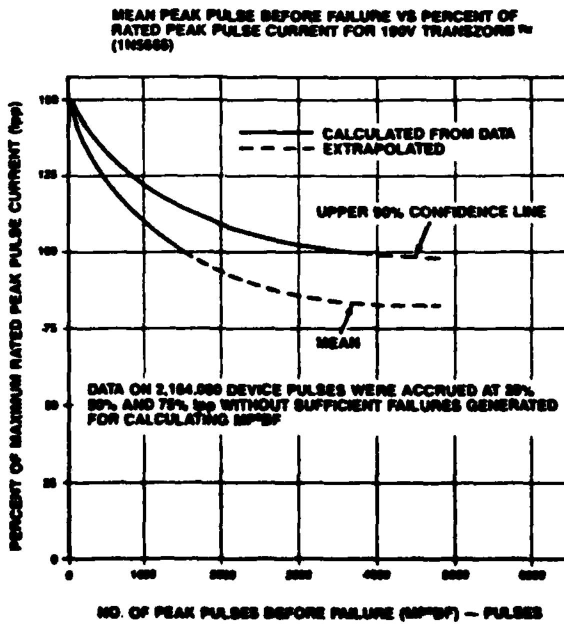


Figure 70 TransZorb™ MTBF Curves

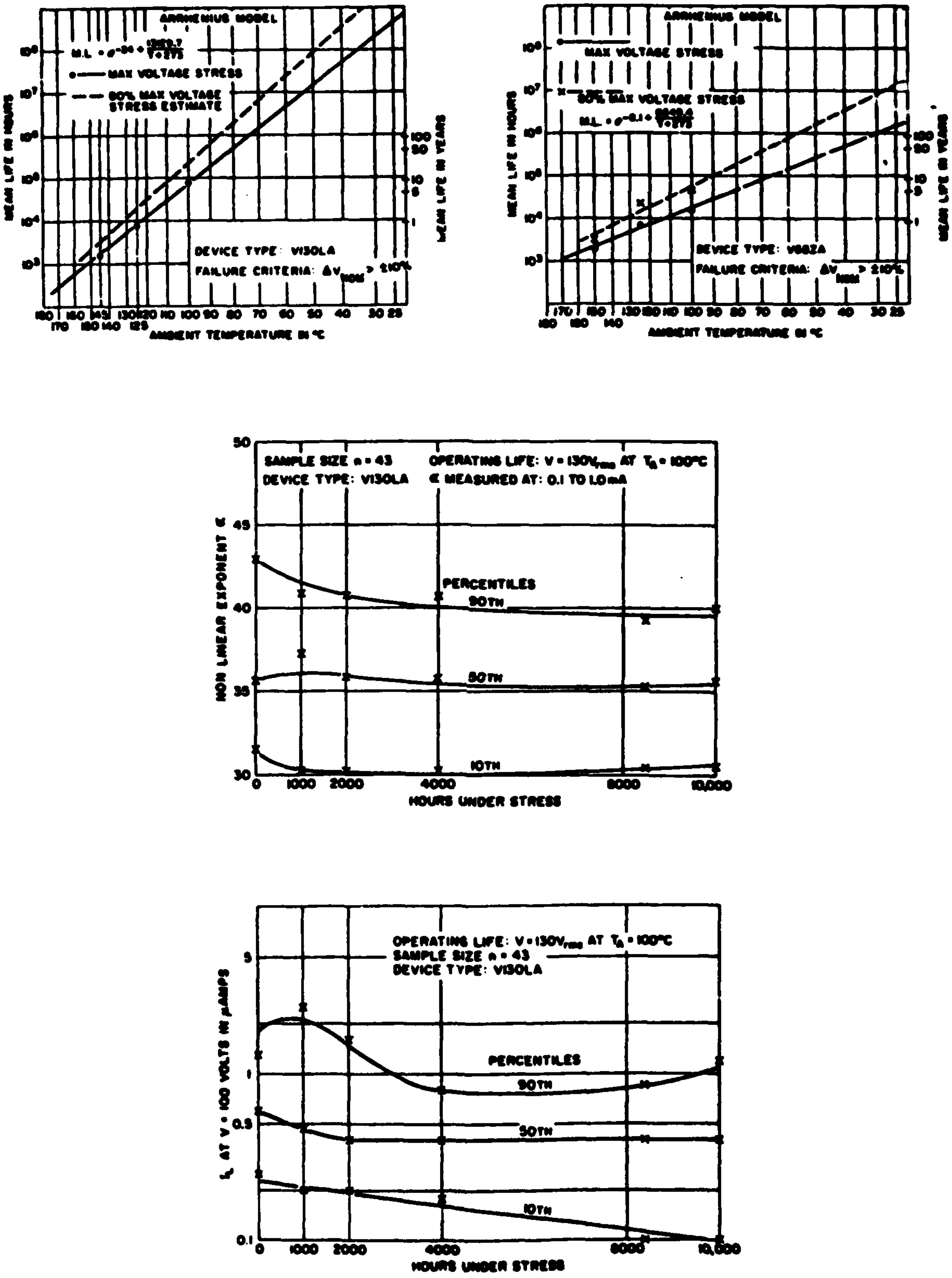


Figure 71 Varistor Mean Life Curves

life, from Figure 71, of about 10,000,000 hours (≈ 1140 years!). Using the equation gives a more precise estimate of 9,142,824 hours (1045 years). Note that at lower bias voltage even longer mean life is expected. Although the V130LA and V68ZA type devices are specifically described, the results are representative for all GE-MOV™ varistors. Additional evidence of the conservative ratings of the GE-MOV™ varistor is the absence of systematic or repeated field failures in over seven years of product use. As far as is known, all field failures of the GE-MOV™ varistor to date have been caused by misapplication or by exceeding the transient energy capability of the varistor.

It is noted the mean life curves have a steep slope. This indicates a high activation energy. As operating temperature is dropped, the mean life increases rapidly. Also, as the voltage stress is lowered, life will increase as well. The maximum stress curve represents the worst-case condition of a model at its lowest voltage limit operated at the maximum allowable rating. In usual practice, the median of a population of devices will operate closer to the 80% voltage stress curve.

For some applications the circuit designer requires other stability information to assess the effects of time on circuit performance. Figure 71 also illustrates the stability of additional GE-MOV™ varistor parameters when operated at maximum rated voltage and 100°C for 10,000 hours (≈ 1.15 years). The graphs indicate upper decile medium and lower decile response, furnishing useful design information on the stability of V_{NOM}, idle power drain, and non-linear exponent.

SECTION X

SAFETY

Throughout the design guide safety concerns are stressed as fundamental design concerns. All lightning protection schemes are based upon the safety and therefore survivability of the airplane and personnel within. These concerns are paramount for the all-weather mission capabilities of advanced military aircraft. Specifically protection criteria developed for aircraft include:

a) Safety of flight
b) Mission success
c) Maintenance economics - Repair costs vs protection costs

To this end several design steps can be taken which increase the probability that system failures can be avoided. One of the most important initial design efforts is to assure that the major entry points are mechanically strong enough to withstand the lightning magnetic forces. Additionally, all wiring entry points should have protection devices that can handle the residual currents which bypass the primary protection of aircraft lightning arrestors or shunt conduction protection. These design considerations are essential in the all composite structural areas where the inherent protection of the metal airframe is not available (Reference 25).

SECTION XI

DESIGN TO COST

Consideration was given to a specific design-to-cost effort in the design guide. All decisions relative to protecting the electrical system from lightning strike contained basic design-to-cost criteria.

Primary criteria (Reference 26) for providing a cost effective lightning protection design scheme include the following (which are described in detail throughout the design guide):

1. Determine the Lightning Strike Zones

Determine the aircraft surfaces, or zones, where lightning strike attachment to the aircraft is probable, and the portions of the airframe through which lightning currents must flow between these attachment points.

2. Establish the Lightning Environment

Establish the component(s) of the total lightning flash current to be expected in each lightning strike zone. These are the currents that must be protected against.

3. Identify Vulnerable Systems or Components

Identify systems and components that might be vulnerable to interference or damage from either the direct effects (physical damage) or indirect effects (electromagnetic coupling) produced by lightning.

4. Establish Protection Criteria

Determine the systems and/or components that need to be protected, and those that need not to be protected, based upon importance to safety-of-flight, mission reliability or maintenance factors. Establish lightning protection pass-fail criteria for those items to be protected.

5. Design Lightning Protection

Design lightning protection measures for each of the systems and/or components in need of protection.

6. Verify Protection Adequacy by Test

Verify the adequacy of the protection designs by laboratory qualification tests simulating the lightning environments established in step 2 using the pass-fail criteria of step 4.

Decisions relative to short versus long term production and production values are also critical in a development program. Tooling costs, mask charges and assembly techniques can be absorbed on a larger production program. Further studies would concern production hardware and installation techniques and their impact.

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