NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT 317

TRANSIENT PROTECTION, GROUNDING, AND SHIELDING OF ELECTRONIC TRAFFIC CONTROL EQUIPMENT

H. W. DENNY and J. P. ROHRBAUGH
Georgia Tech Research Institute
Georgia Institute of Technology
Atlanta, Georgia

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST:

Maintenance
Operations and Traffic Control
(Highway Transportation)

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C.

JUNE 1989

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NCHRP REPORT 317

Project 10-34 FY'86

ISSN 0077-5614

ISBN 0-309-04614-9

L. C. Catalog Card No. 89-50190

Price $11.00

NOTICE

The project that is the subject of this report was a part of the National Cooperative Highway Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council. Such approval reflects the Governing Board's judgment that the program concerned is of national importance and appropriate with respect to both the purposes and resources of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation officials, or the Federal Highway Administration, U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical committee according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

Special Notice

The Transportation Research Board, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Printed in the United States of America

FOREWORD

By Staff
Transportation
Research Board

Transportation engineers and technicians responsible for the design, specification, installation, and maintenance of traffic signal and related types of electronic equipment will be interested in the findings and recommendations of this report. The research reported herein addresses the problem of damage to traffic control equipment caused by electrical noise and transients (voltage spikes and surges) due to lightning, switching, and radiated electromagnetic interference (EMI) from radio and TV stations, radar, and mobile radio transmitters.

The research reported herein provides procedures, practices, test methods and specifications for the protection of not only traffic control equipment but also other types of equipment operated by transportation agencies such as traffic counters deployed for planning purposes, vehicle classifiers, weigh-in-motion systems, warning devices, and the like. In short, the material in this report can be applied to almost any type of electronic hardware that is exposed to damaging transients.

The problem of electrical transient damage to electronic control equipment may be minimized and, in most cases, eliminated by proper application of existing technology; in other words, currently available devices may be able to provide sufficient protection against equipment malfunction and deter damage. However, there are currently no widely accepted specifications or procedures for the transient protection of traffic control equipment. NCHRP Project 10-34, "Transient Protection, Grounding, and Shielding of Electronic Traffic Control Equipment," was initiated in response to this need. Researchers at the Georgia Tech Research Institute, Atlanta, Georgia, conducted the study, drawing on their extensive experience with protection of equipment in the fields of residential and industrial electrical power, computers and telecommunications, and military and aerospace applications.

The researchers began their work with an examination of typical traffic controllers, breaking them down into subparts of equipment cabinet, terminal blocks, internal components, and associated input and output wiring. This was followed by an in-depth review of protection devices and grounding, shielding, and bonding techniques currently employed in the traffic control field and in related fields. Existing specifications of the Institute of Electrical and Electronics Engineers (IEEE) and the National Electrical Manufacturers Association (NEMA) were reviewed for their applicability and appropriateness for traffic control equipment. Discussions were held with traffic system operating personnel in high lightning incidence areas such as Atlanta, Georgia, and Tampa and Sarasota, Florida. Manufacturers of protection devices were surveyed and descriptive material, costs and performance data were obtained.

This report is comprised of six chapters and an appendix which contains recommended modifications to the NEMA Standards Publication TS1-1983, *Traffic Control Systems.* The main body of the report is a comprehensive state-of-the-art document expected to serve as an in-depth technical reference for years to come. The appendix recommends changes that would be appropriate to allow equipment complying with NEMA TS1-1983 to meet a nominal lightning protection requirement. Readers are cautioned that the recommended modification to NEMA TS1-1983 may not be the most appropriate for their particular case because many localities do not have the lightning problems that others do. Imposing a stringent transient requirement on NEMA equipment would create added expense for many that may be unjustified.

Another product of the research, expected to be available late in 1989, is a video training tape including both user's and instructors' notes. These materials are intended to provide (non-electrical) engineers and traffic control technicians with practical advice and guidance that will facilitate implementation of the wealth of technical information contained in the report. Availability, cost, and ordering information may be obtained by writing to: Director, Cooperative Research Programs, Transportation Research Board, 2101 Constitution Avenue, N.W., Washington, D.C. 20418

Implementation of the findings of this research should help to improve the reliability of electronic equipment in both new and existing transportation installations.

CONTENTS

ACKNOWLEDGMENTS

This report was prepared by the Electronics and Computer Systems Laboratory of the Georgia Tech Research Institute under NCHRP Project 10-34. Hugh W. Denny, Chief, Electromagnetic Compatibility Division, was the principal investigator. Mr. Denny directed the effort and coauthored the report with Mr. John P. Rohrbaugh. Dr. Peter S. Parsonson, Professor, School of Civil Engineering, Georgia Institute of Technology, also contributed to the effort and to the report.

TRANSIENT PROTECTION, GROUNDING, AND SHIELDING OF ELECTRONIC TRAFFIC CONTROL EQUIPMENT

SUMMARY

Electronic traffic control equipment is subjected to a wide range of electromagnetic threats, including lightning, electrostatic discharge, internally and externally generated inductive switching transients, and radiated electromagnetic interference (EMI) from radio, TV, radar, and mobile communication transmitters. Lines providing electrical power and cables interconnecting equipment to sensors, communications systems, or peripheral hardware provide a direct path for the conduction of disruptive and damaging electrical transients and other EMI into traffic control equipment.

The objectives of the research program under which this report was prepared are: (1) review current practices and develop recommended procedures for the transient and electromagnetic interference protection, grounding, shielding, and filtering of power and signal conductors, cabinets, and equipment associated with traffic control to assure the proper operation and extended life of the electronic equipment, and (2) develop and document recommended performance specifications and test methods for protective devices and traffic control equipment. Additionally, the research effort was to develop video training tapes and user's and instructor's notes based on the material developed and documented in this report. The video tapes and the user's notes require no special background in electrical engineering or electronics to be applied. The video tapes are a summary of the basic information contained in this report.

The material is organized into two sections: the main body of the report contained in Chapters One through Six, and the Appendix. The main body of the report is intended as a technical reference document and is addressed to traffic system engineers and skilled traffic controller technicians. Although the majority of the key information should be readily usable by individuals without an electrical engineering or electronics background, some portions do presume basic familiarity with electrical technology. This document is the compilation of the necessary technical information for protecting electronic traffic controllers against transient and electromagnetic interference.

The Appendix presents recommended modifications to the National Electrical Manufacturers Association (NEMA) Standard TS 1-1983 to cover lightning and transient protection.

The most severe electromagnetic threat to traffic control equipment is lightning. To determine the level and extent of protection required against lightning-induced transients, the traffic control professional must know the lightning threat levels at traffic controller inputs, the rates-of-occurrence of lightning transients, and the effects of the lightning discharges on electronics within traffic control equipment. The lightning threat levels will vary depending on the type of interface, the length of the interconnecting lines or cables, and whether the lines are shielded or not. The approach taken in establishing the lightning threat levels at traffic controller inputs and outputs was to determine what measurements and analyses have been performed in related

areas and extrapolate the results to traffic control interfaces. This approach was necessary because no measurements to determine the incident lightning voltages, currents, or waveforms on traffic controllers were identified.

The Institute of Electrical and Electronics Engineers (IEEE) Standard 587-1980 (now ANSI C-62.41-1980), "Guide for Surge Voltages in Low-Voltage AC Power Circuits," was used as a guide for defining the lightning threat levels at ac power inputs. IEEE Standard C62.31-1984, "IEEE Standard Test Specification for Gas-Tube Surge-Protective Device," and "Part 15, Subpart J of the Code of Federal Regulations, Title 47(47CFR)" were used to establish the lightning threat levels at telephone and dedicated communication terminals of traffic controllers. The lightning threat levels at sensor and other inputs and outputs were determined by analysis and by extrapolation from equipment experiences in similar situations.

In addition to establishing the lightning threat levels, methods of predicting the lightning rate-of-occurrence from geographic location and local thunderstorm activity are given. Also presented are the effects of lightning on traffic control equipment, particularly the effects on solid state electronics within traffic control equipment.

Recommended modifications to the National Electrical Manufacturers Association (NEMA) Standard TS 1-1983 to add lightning and transient test specifications are presented in the Appendix. The modifications are a suggested starting point for establishing a test specification for traffic control equipment. NEMA TS 1-1983 was chosen primarily because of its wide use in the traffic control community. It is recognized that NEMA TS 1-1983 may not be the optimum document to employ to impose lightning and transient test specifications and that a separate document may be required. The recommended changes illustrate a possible form for the specifications, however.

An in-depth review of electromagnetic protection practices for traffic control equipment is given. Topics covered include: (1) grounding, (2) shielding of equipment and cables, (3) bonding and corrosion control, (4) terminal protection using filters and amplitude limiters, (5) communication interface practices such as the use of balanced inputs (shielded-twisted-pairs) to provide high common-mode interference signal rejection and the use of fiber optics to eliminate conductor penetration paths, and (6) guidelines for configuration control and retrofitting.

CHAPTER ONE

INTRODUCTION

1.1 PROJECT STATEMENT

Electronic traffic control equipment is highly susceptible to disrupted operation and even permanent damage caused by electrical noise and transients (voltage spikes and surges) associated with connected service and signal lines. Lines providing electrical power and cables interconnecting equipment to sensors, communications systems, or peripheral hardware provide a direct path for the conduction of disruptive and damaging electrical transients from externally generated electrical noise. Lightning, switching transients, and other electromagnetic interference (EMI), including radio frequency interference (RFI), may be conducted on electrical and signal lines connected to traffic control equipment. Some disruptive noise may even originate from companion equipment located within the traffic control cabinet.

The problem of electrical transient damage to electronic control equipment may be minimized and in most cases eliminated by proper application of existing technology, i.e., currently available devices may be able to provide sufficient protection against equipment malfunction and deter damage. However, there are no widely accepted specifications or procedures for application of such devices to the control equipment cabinet, terminal blocks, and associated wiring. There is a need to develop such specifications and procedures and to make them available to operating agencies to obtain maximum benefit from the protection devices.

1.2 OBJECTIVES

The overall objectives of NCHRP Project 10-34, "Transient Protection, Grounding and Shielding of Electronic Traffic Control Equipment," are to: (1) review current practices and develop recommended procedures for the transient protection, grounding, shielding, and filtering of power and signal conductors, cabinets, and equipment associated with traffic control to assure the proper operation and extended life of the electronic equipment; (2) develop and document recommended performance specifications and test methods for protective devices and traffic control equipment; and (3) develop video training tapes and user's and instructor's notes based on the material developed and documented in this report.

The objectives were accomplished and the results are documented as follows.

1.3 ORGANIZATION OF REPORT

The main body of the report is addressed to the traffic engineer with a background in electrical engineering or a skilled electronics technician. It is intended as a summary technical reference document on transient and electromagnetic interference control for traffic control applications. Chapter Two discusses how the traffic control system's configuration affects its exposure and susceptibility to transient and electromagnetic interference. Chapter Three describes and defines the electromagnetic threat to traffic control equipment. The electromagnetic threat includes: (1) lightning, (2) electrostatic discharges, (3) internally and externally generated inductive switching transients, and (4) radiated interference from radio, TV, radar, and mobile communications transmitters. The final chapter, Chapter Four, discusses methods and techniques to protect traffic control equipment from upset or damage due to the electromagnetic threats discussed in Chapter Three. Topics covered in Chapter Four include: (1) grounding, (2) shielding of equipment and cables, (3) bonding and corrosion control, (4) terminal protection using filters and amplitude limiters, (5) communication interface designs using balanced inputs (for example, shielded twisted-pairs) to provide high common-mode interference signal rejection and the use of fiber optics, and (6) guidelines on configuration control and retrofitting.

The Appendix provides recommended modifications to the National Electrical Manufacturers Association NEMA TS 1-1983 (*1.1*) to include lightning test requirements. The modifications presented are based on the material in Chapter Three and represent a starting point for establishing a lightning test specification for traffic control equipment. NEMA TS 1-1983 was chosen primarily because of its wide use in the traffic control community. It is recognized that an alternative to modifying NEMA TS 1-1983 may be the preparation of a separate document on lightning testing, although the responsible organization (e.g., the Institute of Electrical and Electronics Engineers (IEEE), NEMA, American National Standards Institute (ANSI)) has not been identified.

1.4 GLOSSARY

ANSI	American National Standards Institute
CATV	coaxial cable
CMOS	complementary metal oxide semiconductor
CMR	common-mode rejection
CMRR	common-mode rejection ratio
DIP	dual in-line package
ECL	emitter-coupled logic
EMF	electromotive force; also electrochemical series
EMI	electromagnetic interference
ESD	electrostatic discharge
IC	integrated circuit
IEEE	Institute of Electrical and Electronics Engineers
ILD	inductive loop detector
LED	light emitting diode
LPF	low-pass filter
MOV	metal-oxide varistor
NEC	National Electrical Code
NEMA	National Electrical Manufacturers Association
PC	printed circuit
RF	radio frequency
RFI	radio frequency interference
SAS	silicon avalanche suppressor
SCR	silicon-controlled rectifier
TPD	terminal protection device
TTL	transistor-transistor logic

REFERENCE

1.1 "Traffic Control Systems." NEMA TS 1-1983, Revision No. 2, National Electrical Manufacturers Association, Washington, D.C. (Oct. 1985).

CHAPTER TWO

TRAFFIC CONTROL SYSTEM

2.1 SYSTEM DESCRIPTION

Traffic control systems provide regulation of vehicle and pedestrian movement through one or more intersections. Although some traffic engineers reserve the word "system" for an interconnected series of two or more signals, herein the practice of the National Electrical Manufacturers Association (NEMA) is followed by using the term more broadly.

A traffic-control system can range widely in complexity. Simple, stand-alone, fixed-time, controllers with motors and gears have been used for decades. Unlike solid-state models, they are highly resistant to electrical disturbances. Typically such a controller will regulate but one intersection from its cabinet on the street corner. At the other extreme, a sophisticated, computer-based system may use a state-of-the-art distributed-processing scheme to control hundreds of interconnected intersections traffic, responsively.

A typical, noninterconnected ("isolated") signalized intersection is illustrated in Figure 1. It is more than one-half mile from the nearest signalized intersection, so no improvement in traffic operation would be gained by going to the considerable expense of installing an interconnect and a coordinator. The traffic control equipment is located in a cabinet mounted on a pole or on a concrete pad or base. At busy intersections, the cabinet is typically base-mounted because a pole-mounted model would not be large enough to hold the needed equipment. The control cabinet has lines coming in from ac power fed from overhead or buried distribution transformers, the four loop detectors, and the eight pedestrian detectors. Field wires to the overhead signals are the output lines from the cabinet.

In Figure 1 each vehicle loop detector, or "inductive loop detector" (ILD), is made up of several turns of insulated wire sealed into a rectangular slot sawed a few inches deep into the

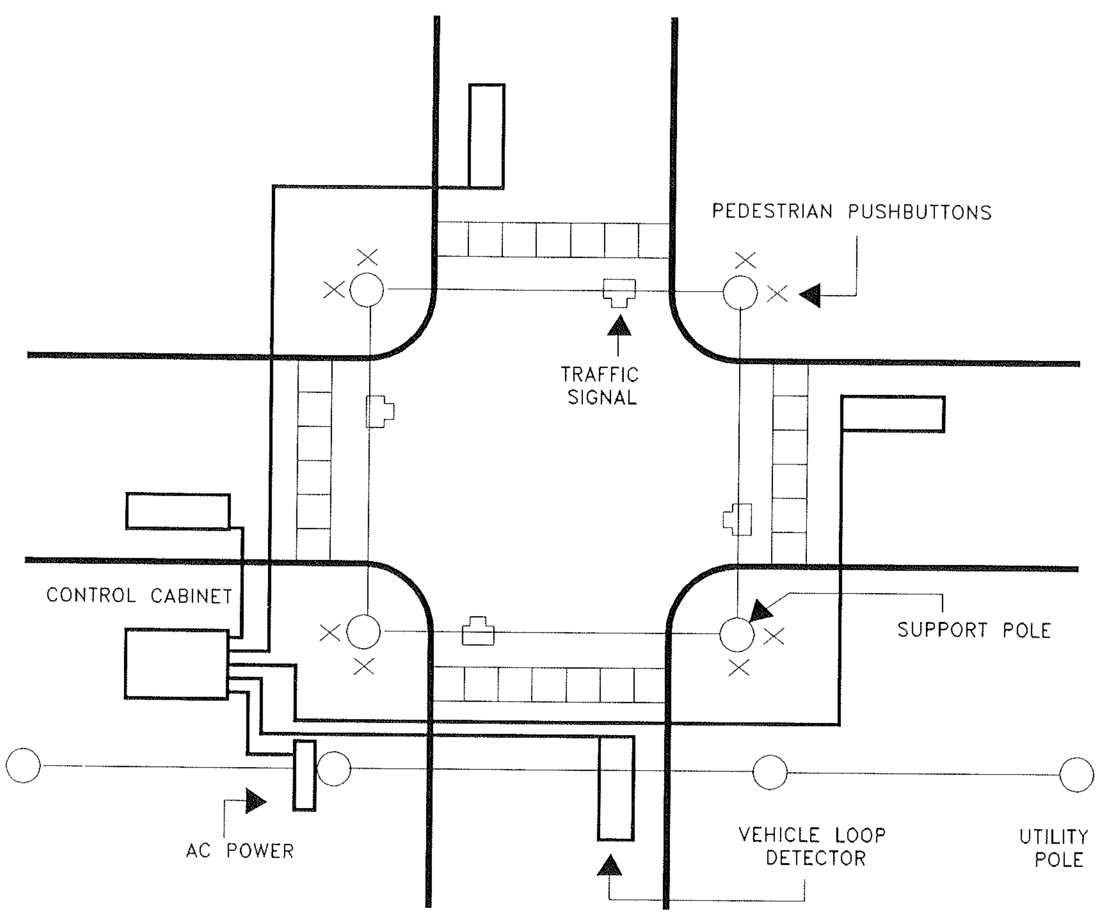


Figure 1. Typical traffic intersection.

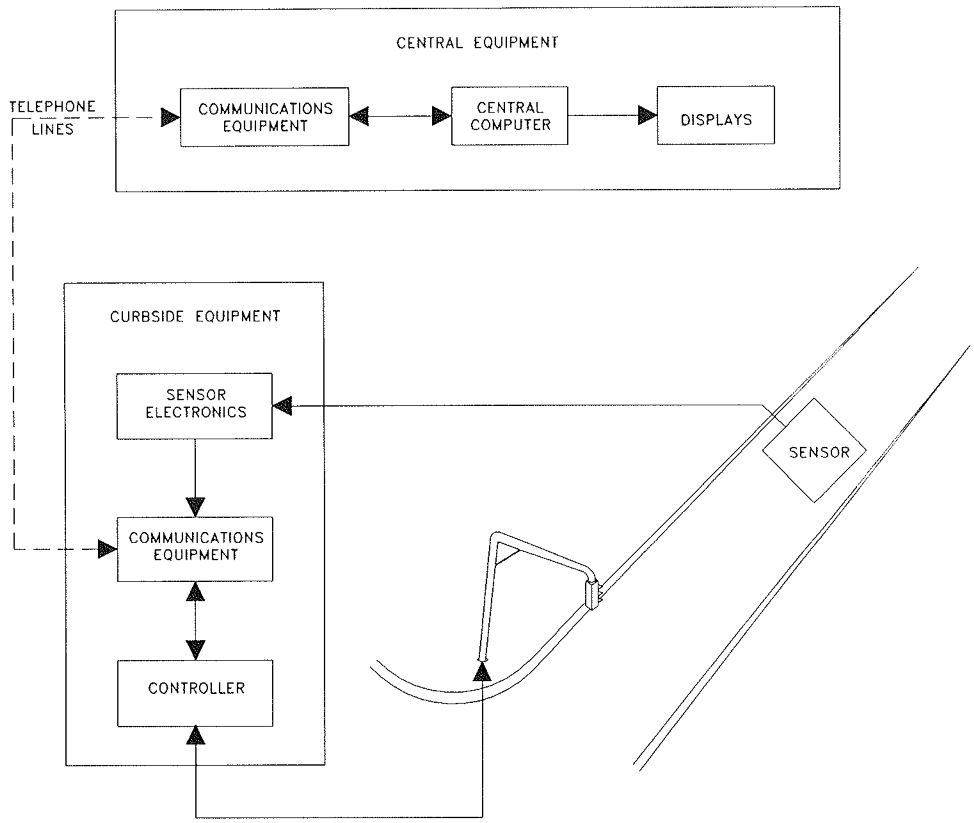


Figure 2. Centralized traffic-signal system.

pavement. The loop is connected to the curbside cabinet by means of electrical cable running overhead or underground.

The figure makes it clear that the intersection equipment is subject to electrical disturbances that could enter the cabinet through the ac power lines, the loop-detector wire, the pedestrian detectors, or the field wiring. Protection is needed at or near the points where these lines enter the cabinet.

Figure 2 shows the major components of a centralized traffic signal system. A car approaching a signalized intersection has just passed over a sensor buried in the road several hundred feet from the intersection. The sensor electronics, actuated by the passage of the car over the loop, inputs the call to communications equipment, which may be based on a time-division-multiplexing arrangement. The call is sent over miles of leased telephone lines or city-owned cable to a master computer that could be located at a control center at City Hall or a signal shop. There the computer processes input from many other sensors and selects a signal-timing plan intended to minimize stops and delay. The master communicates back to the intersection the appropriate commands to make the signal change. The potential for transient-induced damage is greater in Figure 2 than in Figure 1 because of the longer lead-in cable from the sensor to the cabinet and because of the interconnect with its long communication lines. They are long because the intersection may be miles from the control center, and because the system may include hundreds of intersections spread over many square miles of the community. Like ac power lines, communication lines will be routed overhead or buried, depending on local ordinances and local surroundings. The wiring can be affected by the electromagnetic fields created by the various industries, tall buildings, and rail-transit lines, in the areas through which the signal system extends.

Figure 2 shows that a curbside cabinet may contain much equipment in addition to the controller, or "controller unit," that uses a timing mechanism of one kind or another to make the signals change. The complete electrical mechanism, including the electronics for the sensors, communications, load relays, and conflict monitor, constitutes the "controller assembly" and is mounted in the "controller cabinet."

By the mid-1980's many communities had determined that it was not cost-effective to install the centralized systems so popular in the 1970's. Smaller "closed-loop" systems became popular for arterials and even grid networks. A typical design (Figure 3) includes a local system supervisor unit, along with the controller unit, at the intersection. Dedicated (full-time) communications lines connect that location to an on-street master in another field cabinet. Only a standard dial-up telephone service connects the master to an inexpensive microcomputer or personal computer at the office and/or the signal shop. The communication links between controllers, and from controller to master, can take a variety of forms. The most common links use metallic, shielded, twisted pairs. Coaxial cables (CATV) are also used.

The traffic control system can extend over large geographical areas, ranging up to several miles in all directions. Hundreds of individual intersections and controllers can be involved. Consequently, a particular controller could be exposed to electromagnetic signals that range from the intense RF radiation produced by an airport radar to the benign power line excursions likely to occur in a distant residential suburb. In between these extremes are the environments associated with high rise downtown office buildings, heavy industry such as electric furnaces and rolling mills, light industry, shopping centers, and suburban office parks. The characteristics of the electromagnetic signals

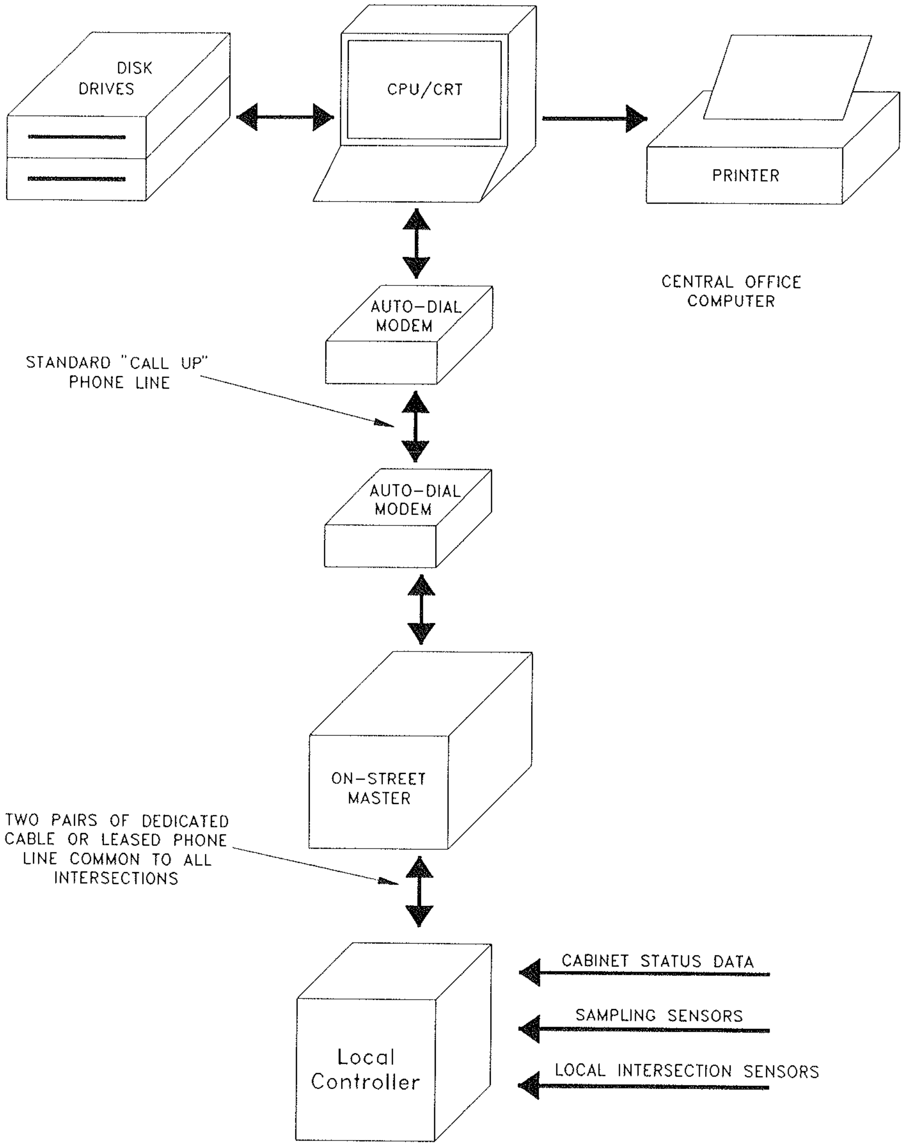


Figure 3. "Closed-loop" signal system.

incident on the controllers will vary markedly, depending upon the location. For example, those controllers located in heavy industrial areas are likely to experience large fluctuations in the ac supply voltage; in addition, large transients from electromechanical and electronic circuit breakers, switches, regulators, and speed controllers can be expected. Even in light industrial areas, and near office parks and shopping centers, large numbers of power and signal line transients can be anticipated. In suburban and rural residential areas, transients and other forms of electromagnetic energy will also be seen by the controller, although the severity is likely to be less than in built-up metropolitan areas.

2.2 LIGHTNING AND ELECTROMAGNETIC INTERFERENCE

Lightning is a serious threat to traffic control equipment. A traffic control system's degree of exposure to lightning varies with its relative geographic location. As shown later, the different regions of the United States vary significantly in the annual number of thunderstorms, with the Southeast having the greatest number. Lightning poses a particularly severe threat to the traffic control equipment because a single discharge to a building, tower, or tree may damage one or more controllers in the general vicinity of the strike. If the affected equipment happens to be a master controller, several intersections may be disrupted. Over the general metropolitan area, there are likely to be tens or even hundreds of strikes to earth during a typical thunderstorm. Thus, the potential is high that several controllers will be disrupted or damaged during a single thunderstorm.

The type and degree of protection required against these electromagnetic threats depend on several factors. The factors that must be considered include the criticality of an intersection to maintaining efficient traffic flow, the safety degradation as a result of the loss of the intersection, the cost-to-repair versus the cost-to-protect the control equipment, and the relative severity of the threat. For a critical intersection the cost-to-repair versus the cost-to-protect consideration may be irrelevant. For most systems, a trade-off analysis to determine whether protection devices should be installed on some or all controllers within the system is likely appropriate.

The lightning and EMI threat severity varies widely across the nation and, possibly, even within a local control district. During a single thunderstorm, the probability of any single controller being affected is likely to be quite low. However, if a large number of controllers are involved in the system and a large number of severe thunderstorms are likely to be experienced, the probability of several controllers being upset or damaged during any given storm season is likely to be high. If only a few storms occur in a year or if very few controllers are present in the system, the cost-to-repair may be less than the cost-to-protect. The type of protection required may also vary widely between different portions of a system. For example, controllers located in industrial areas or near TV, radio or radar transmitters may experience upset on a daily basis, and may require substantial protection to achieve reliable performance.

2.3 SUMMARY

Traffic control systems can range in complexity from a few stand alone controllers operating independently in a low traffic density area to a fully distributed network control system involving hundreds of controllers. The need for protection against lightning and other electromagnetic threats depends on the severity of a threat and its likelihood of occurrence, the criticality of the equipment to maintaining traffic flow and safety, and the cost-to-repair versus the cost-to-protect. Information presented in the following chapters is intended to aid in determining the EMI threat to traffic control equipment and the protection techniques that can be employed.

CHAPTER THREE

THE ELECTROMAGNETIC THREAT

3.1 SOURCES OF ELECTROMAGNETIC THREATS

Electromagnetic threats to traffic control equipment can arise from a wide variety of sources. As illustrated in Figure 4, sources of electromagnetic interference include lightning, power line transients, power system faults, electrostatic discharges, radiated emissions from mobile and fixed communications equipment, radar, and radiated and conducted interference from electronics within the traffic control equipment itself. These sources may be present at all times or may occur intermittently. Examples of continuously present sources include emissions from internal electronics and nearby fixed communications equipment and radar sites. Lightning, static discharges, emissions from mobile communications equipment, power line transients and power system faults will occur intermittently. It is difficult to predict and measure accurately the voltages and radiated electromagnetic field levels from intermittent sources.

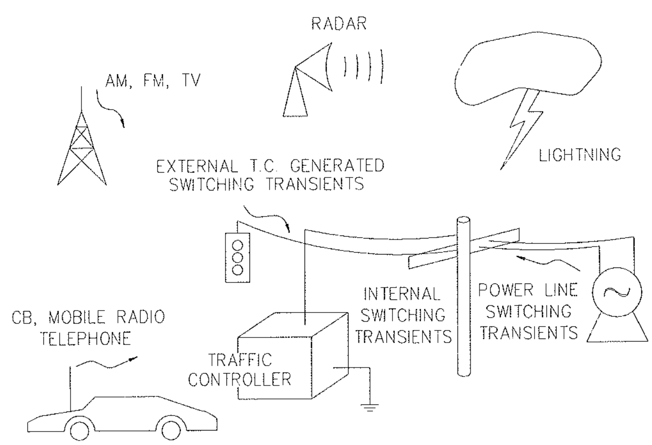


Figure 4. Sources of electromagnetic and transient interference.

3.2 NONLIGHTNING THREATS

In this section, electromagnetic interference from RF transmitters (fixed and mobile), electrostatic discharges, inductive switching transients, and power system faults will be discussed. Lightning-induced interference is treated in Section 3.3.

3.2.1 RF Transmitters

Table 1 gives various sources of radiated continuous wave (CW) and transient interference, the frequency ranges of concern, and the typical field strengths for each. Note that near airports the radiated field strength from radar transmitters can approach 1,400 volts/meter (V/m). Although traffic control equipment does not operate at radar frequencies (with the exception of radar vehicle detectors), the high frequency radar pulses can couple into sensitive electronics by coupling to interconnecting cables, through holes in shields, and so on. Once the radar signal reaches a sensitive piece of electronics, the high frequency radar pulses can be rectified at semiconductor device PN junctions as illustrated in Figure 5. The rectified pulse train can have a repetition rate comparable to the digital data rate

Table 1. External electromagnetic fields. (Ref. 3.1)

Source	Frequency	Distance (meters)	Field Strength
Broadcast Signal			
AM (Commercial)	535 - 1605 kHz	160	40 V/m @ 50 kW
FM (Commercial)	88 - 108 MHz	160	10 V/m @ 100 kW
TV (UHF)	470 - 806 MHz	160	76.1 V/m @ 5000 kW
Radar	1 - 10 GHz		
Military		310	200 V/m
Airport		600	1378 V/m
Mobile Radio			
HF - VHF	25 - 50 MHz	2	27 V/m @ 100 W
VHF	150 - 174 MHz		
UHF	406 - 512 MHz		
Power Transmission Lines	20 Hz to 1 kHz	underneath the line	greater than 1 V/m (values as high as 1000 V/m @ 60 Hz)
Industrial Sources			
Arc Welders	2 - 3 MHz	300	0.1 mV/m
Wood Gluer	10 - 20 MHz	300	1.0 mV/m
Fluorescent Lamp	10 kHz	1	0.1 V/m
Lightning	1 kHz - 18 kHz	500 1000	1700 V/m 1000 V/m

Hz = Hertz (one cycle per second)
Khz = kilohertz (one thousand cycles per second)
MHz = megahertz (one million cycles per second)
GHz = gigahertz (one billion cycles per second)
V/M = volts per meter
mV/m = millivolts per meter
kW = kilowatts (one thousand watts)

in the traffic control equipment. The rectified radar signal can be added to the normal data stream causing upset, or even damage, depending on the rectified signal level and the sensitivity of the electronics.

As a further example of how RF can couple to traffic controller circuits, consider the case of a 100 watt (W) land mobile transmitter operating at 900 megahertz (MHz) and feeding an antenna mounted on the trunk of an automobile. The closest approach distance between an automobile passing through an intersection and the traffic control cabinet can be taken to be 2 m and thus the field strength given in Table 1 applies directly. Assuming that the traffic control cabinet provides 30 decibels (dB) of shielding (a reduction factor of 31.6), then the field strength is reduced to 0.85 V/m at internal circuits. The power delivered to a specific IC can be estimated by considering the input pin to be connected to a tuned dipole antenna (*3.2*). The power level is then given by:

$$P_T = (V^2/377)\,(0.13)(\lambda^2) = 0.028 \text{ mW} \qquad (1)$$

where λ = wavelength in meters, and V = field strength in volts per meter.

The power to cause upset in TTL integrated circuits which are solid state devices typical of those employed in traffic controllers has been estimated to be 10 milliwatts (mW) (*3.3*). (Upset power level is a function of frequency and varies with IC technology, i.e., TTL, CMOS, ECL, etc.) In this situation, upset is not likely to occur. On the other hand, consider a controller located near an airport radar where field levels greater than 1,000 V/m can occur. Coupled levels in this case could

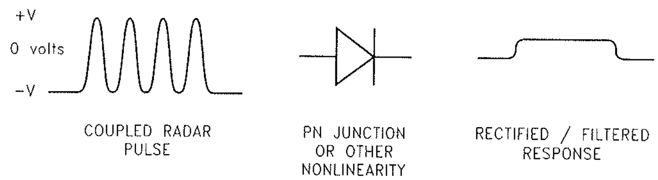


Figure 5. Illustration of RF rectification in a PN junction.

exceed 30 mW with a resultant high likelihood of causing upset to controller logic circuitry.

3.2.2 Electrostatic Discharge

An electrostatic discharge (ESD) occurs when a statically charged body touches or closely approaches another oppositely charged, grounded, or conductive object. ESD transient rise times of a few nanoseconds and peak voltages as high as 35 thousand volts are possible (*3.4*). An electrostatic discharge can occur during maintenance, repair, installation, or operation of traffic control equipment. ESD can be particularly hazardous to high impedance, low current solid state components such as CMOS digital integrated circuits. CMOS devices are so susceptible to static discharge damage that they can be destroyed simply by mishandling during maintenance activities. Protection against ESD-induced damage includes the use of transient protection devices at sensitive inputs (normally incorporated by the IC manufacturer), the use of effective grounding, and the following of proper handling procedures. Normal grounding techniques are adequate for ESD protection when circuits are energized. During maintenance and repair, personnel should use grounded tools, discharge themselves and tools prior to touching printed circuit boards and IC's by simply touching the grounded control cabinet, and by transporting PC boards and IC's in conductive foam. ESD-sensitive IC's can be damaged by simply touching unpowered PC boards or the individual IC's. Additional information on how to handle ESD sensitive devices and proper maintenance and shop procedures can be found in Ref. 3.4.

3.2.3 Inductive Switching Transients

Transient voltage spikes on 120 Vac power lines can range in amplitude from harmless values just above the normal operating voltage to thousands of volts. Transients on ac power lines are caused by motor startups, relay and switch closures, transformer energization and deenergization, and various other inductive charging/discharging actions. Energy stored in an inductive load produces transient overvoltages according to the time rate of change of current through the inductor and the inductance value. Traffic controllers located near large industrial sites are frequently subjected to numerous transients from inductive load switching. In addition, there are many inductive loads within the traffic control equipment cabinet itself. Typical loads such as relays, fan motors, and flashers function as internal noise sources. Adequate protection of sensitive devices against the various offending sources must be incorporated to prevent system upset or damage.

To illustrate inductive switching transients, consider the relay switching circuit shown in Figure 6(a). The peak voltage drop across the relay coil during transistor switching is given by the time rate of change in current, *di/dt*, and the coil inductance, *L*, according to:

$$V = L\frac{di}{dt} \tag{2}$$

If the coil inductance is 1 milliHenry (mH) and the current through the transistor changes at the rate of 100 milliampere/microsecond (mA/μsec), the peak voltage across the coil is given by:

$$V = (10^{-3})(100)(10^{-3}/10^{-6}) = 100 \text{ volts} \tag{3}$$

This peak voltage far exceeds the dc supply voltage of 24 V. A breakdown voltage of 40 V to 60 V is typical of low power switching transistors that are used in applications such as the one shown in Figure 6(a). The 100-V transient could destroy the drive transistor unless a protective amplitude limiter is placed across the relay coil or drive transistor as shown in Figure 6(b) and (c).

3.2.4 Power System Faults

A power system fault is either a direct short or an arc in a power distribution system and its associated electrical equipment. Power faults can result from a number of causes including water infiltration, moisture in combination with dirt on insulator surfaces, breakdown of insulation caused by thermal cycling and overloads, environmental contaminants, damage during installation or repair, and system age deterioration. A fault can cause potentially hazardous potentials to exist between equipment chassis and earth if a power lead touches the equipment chassis and if the earth electrode resistance is not low enough to cause the fuse or breaker to trip. A power fault can induce a high amplitude surge directly in circuits if it occurs to printed circuit traces or interconnect wires within an equipment chassis. Upset and damage can occur from overvoltages on a faulted line or from excessive voltage differentials occurring between equipment grounds if the fault occurs to a ground trace.

3.3 LIGHTNING

Of the various transient threats to traffic control equipment, lightning-induced transients on ac power, communications and sensor leads will likely be the most severe. Lightning can be coupled directly into sensitive controller electronics by a direct strike to the system, an indirect strike to power or communication lines, or by radiated coupling to exposed power, communication or sensor cables. The need for protection against lightning depends on component susceptibility levels, the lightning rate-of-occurrence, equipment criticality, and the cost-of-protection versus the cost-of-repair. If lightning occurrences are rare, as for example in Southern California, the cost of protecting equipment against lightning-induced upset or damage may be more than the cost-to-repair equipment that may only rarely be damaged by lightning.

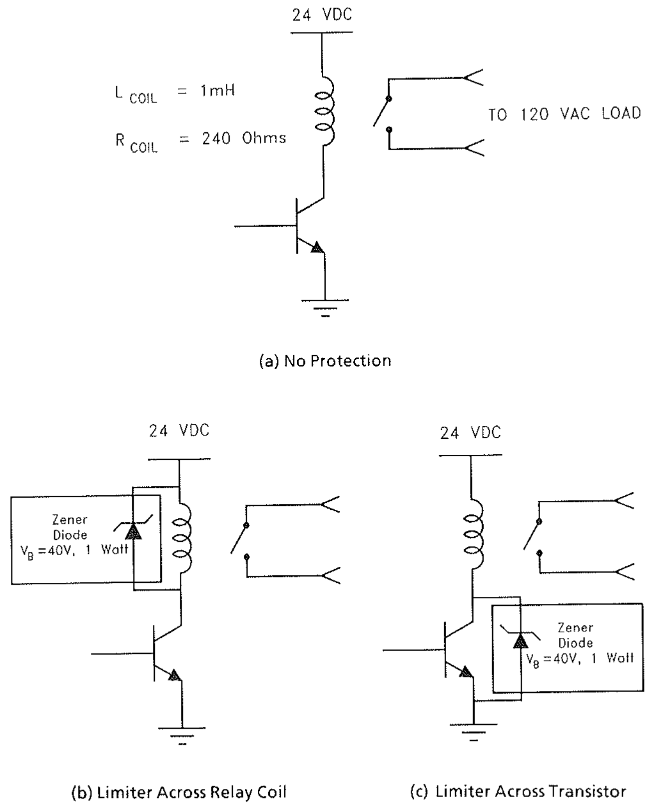


Figure 6. Example of relay switching circuit with and without transient limiter.

3.3.1 Characteristics

Lightning is a short duration, high-current electric discharge to equalize charge distributions between clouds or between clouds and the earth. A typical discharge between cloud and ground starts in the cloud and terminates to a point or object on the earth's surface. The total discharge is called a flash and lasts about one-half second. A flash is made up of various charge components, among which are 3 or 4 high-current pulses called strokes. Each stroke lasts about 1 millisecond (msec) and the separation time between strokes is typically 40 to 80 msec (lightning often appears to "flicker" because the human eye can just resolve the individual light pulses associated with each stroke).

The sequence of events in a multiple-stroke flash is illustrated in Figure 7. The initial path for the discharge is established in 50 μsec. Intermediate return stroke currents of about 1 kiloampere (kA) follow the initial return stroke and last for a few milliseconds. Subsequent strokes occur at intervals of 40 to 80 msec. The return stroke interval may include a continuing current of approximately 100 A which flows for several milliseconds or until the start of the next return stroke.

The lightning discharge involves the transfer of large amounts of electric charge between the cloud and the earth. The typical flash transfers 15 to 20 coulombs (C) (1 coulomb equals 6.2 $\times$ 10^{18} electrons) with some flashes involving as much as 400 C of charge. The energy per flash of lightning has been estimated to be as high as 10^8 W-sec. Table 2 summarizes the range of values for selected lightning parameters.

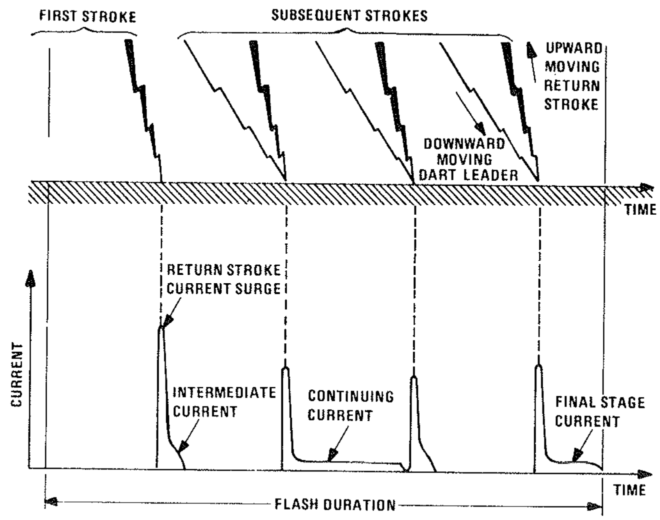


Figure 7. Illustration of events and currents that occur during a lightning flash to ground. (Ref. 3.5)

Table 2. Range of values for lightning parameters. (Ref. 3.6)

Parameter	Minimum	Typical	Maximum
Number of return strokes per flash	1	2 to 4	26
Duration of Flash (s)	0.03	0.2	2
Time between strokes (ms)	3	40 to 60	100
Peak Current per return stroke (kA)	1	10 to 20	250
Charge per flash (C)	1	15 to 20	400
Time to peak current (μs)	0.5	1.5 to 2	30
Rate of rise (ka/μs)	1	20	210
Time to half-value (μs)	10	40 to 50	250
Duration of continuing current (ms)	50	150	500
Peak continuing current (A)	30	150	1600
Charge in continuing current (C)	3	25	330

Note that the peak current per return stroke can be as large as 250 thousand amperes in magnitude. Strokes of this magnitude are somewhat rare, and protection against such extreme currents would be difficult. Protection against the typical level of 20,000 A is more often recommended because such protection can be achieved at reasonable cost in most instances.

A sketch based on actual photographs of a typical lightning flash is shown in Figure 8. In addition to the usual downward

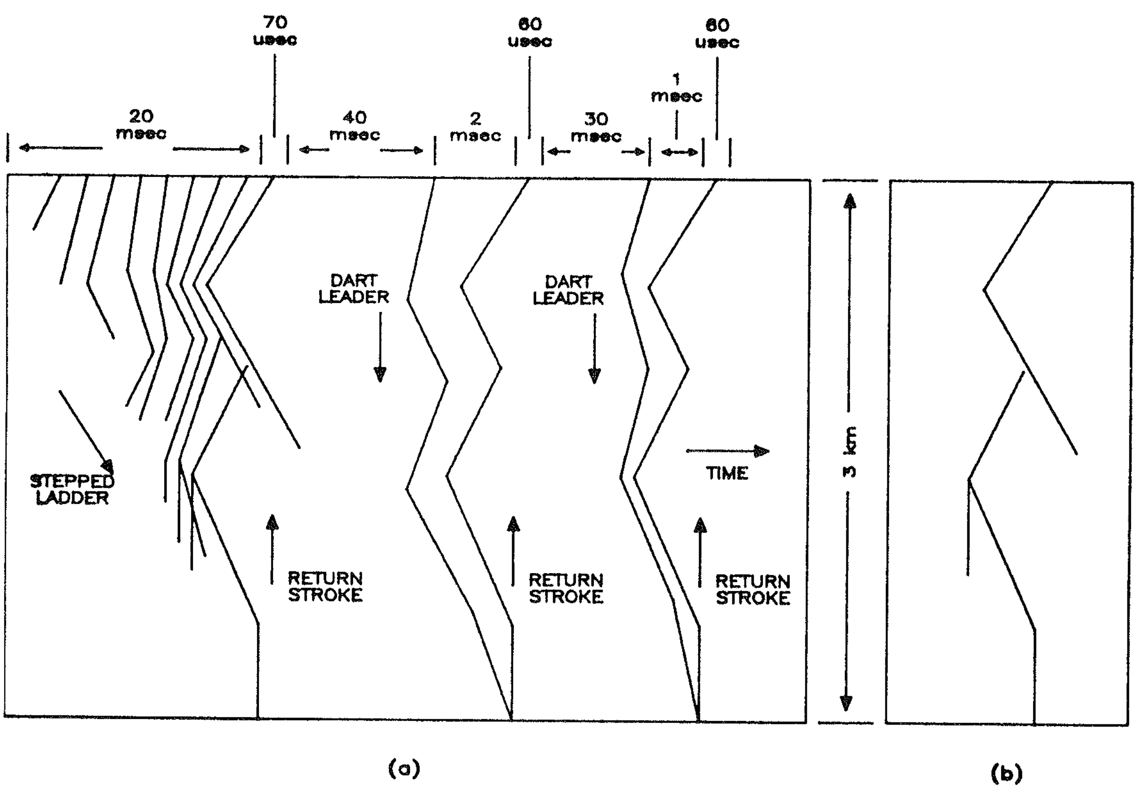


Figure 8. Drawings of lightning strike characteristics from streak camera and ordinary camera photographs: (a) the luminous features of a typical lightning flash as would be recorded by a streak camera; and (b) the same lightning flash as recorded by an ordinary camera.

moving, negatively charged stepped leader, lightning may also be initiated by a positive downward-moving stepped leader. Positive discharges are rather rare, but the peak currents and total charge transfers can be extremely large (*3.8* to *3.15*). Furthermore, lightning can be initiated at the ground, usually from tall structures or mountains, by upward-going stepped leaders that can be either positively or negatively charged (*3.8* to *3.10*). The upward-going leaders branch in an upward direction.

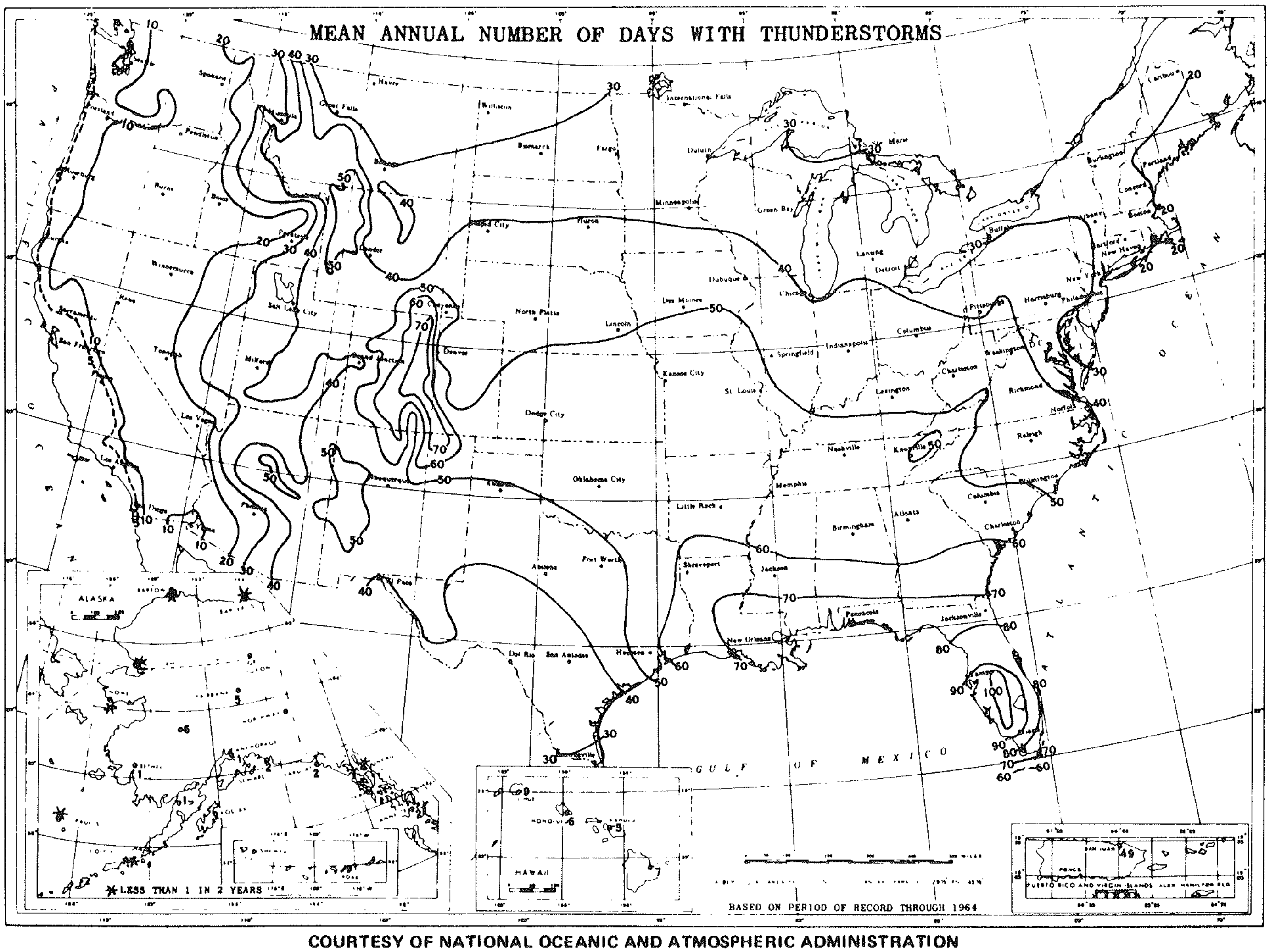
3.3.2 Rate-of-Occurrence

The likelihood of a lightning strike occurring at or near a particular traffic controller is dependent on its geographical location and its proximity to taller structures. If a controller is located near a tall structure, such as a building, it will enjoy a substantial degree of protection against a direct strike because the tall structure serves to attract lightning strikes.

The number of total flashes to which a traffic control system is exposed is related principally to local thunderstorm activity. Local thunderstorm activity can be projected from isokeraunic maps similar to that shown in Figure 9. Isokeraunic maps show the number of thunderstorm days per year for various geographical regions. Maps of worldwide keraunic levels can be obtained (*3.16*).

A thunderstorm day is defined as a local calendar day on which thunder is heard irrespective of whether the lightning flashes are nearby or at some distance away. To an observer at a specific location, the average distance at which lightning may occur and thunder will be heard is about 10 kilometers (km) (*3.6*). Therefore, a thunderstorm day means that at least one lightning discharge has occurred within an area of about 300 sq km surrounding the position of the observer. The actual number of strikes in the immediate vicinity of the observer may be considerably higher or lower than the number of thunderstorm days might indicate, depending on the duration and intensity of a specific storm or series of storms.

In spite of the relative inexactness of a prediction of a lightning strike to a specific object that is based on the keraunic level, the thunderstorm day is the only parameter related to lightning incidence that has been documented extensively over many years. Its primary value lies in the qualitative information which it provides. This information can be used to assist in the determination of whether lightning protection should be provided in



COURTESY OF NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Figure 9. Mean number of thunderstorm days per year for the United States. (Ref. 3.16)

those situations where there is serious doubt as to the relative need for such protection. In an area of frequent thunderstorms, such as the west coast of Florida, the number of outages in areas without protection could be so high as to be unacceptable; in an area of few thunderstorms, for example, Southern California or Alaska, the expected outage from lightning might be once every few years (and could be significantly less than outages from normal failures).

The number of lightning flashes per unit earth surface area increases with the number of thunderstorm days per year, though not linearly. Empirical evidence indicates that the number of flashes per square kilometer, σ_y, can be reasonably predicted from (*3.6*):

$$\sigma_y = 0.007T^2_y \tag{4}$$

where T_y is the number of thunderstorm days per year. Out of the total number of flashes per unit area, the number of discharges to earth increases with increasing geographical latitude (*3.17*). The proportion, *p*, of discharges that go to ground in relation to the geographical latitude, Λ, can be represented as (*3.18*):

$$p = 0.1[1 + (\Lambda/30)^2] \tag{5}$$

Thus in a given location the flash density σ_{yg}, i.e., the number of discharges to earth per square kilometer per year, is:

$$\sigma_{yg} = p\sigma_y \tag{6}$$

To calculate σ_{yg} for a specific location, first determine T_y from the isokeraunic map of Figure 8. The number of thunderstorm days at points between lines may be estimated by interpolation. Using this value of T_y, calculate the total flash density using Eq. 4. Next obtain the geographical latitude of the site from a map of the area and calculate p from Eq. 5. Then determine the number of strokes to earth per year per square kilometer using Eq. 6.

As an example, consider the Atlanta area. From the isokeraunic map, the number of thunderstorm days T_y is between 50 and 60. For convenience, T_y is chosen to be 55, which results in the number of flashes per square kilometer being given by:

$$\sigma_y = 0.007\,(55)^2 = 21.175 \tag{7}$$

Atlanta is located at a latitude of approximately $\lambda = 33°$. This results in

$$p = 0.1[1 + (33/30)^2] = 0.221 \tag{8}$$

The number of discharges to earth per square kilometer per year is thus given by:

$$\sigma_{yg} = (0.221)(21.175) = 4.68 \tag{9}$$

The City of Atlanta traffic control system encompasses an area of approximately 150 sq mi or 388 sq km. The total number of flashes to ground per year then is approximately 1,800. With almost 1,000 traffic controllers located within this area, the probability of a controller being affected by lightning is very high and the cost of protection can be justified.

To aid in the determination of the lightning threat severity, the number of discharges to earth per square kilometer, σ_{yg} for a number of major cities is given in Table 3. To complete the analysis, multiply σ_{yg} by the surface area of concern in square kilometers. This will give the total number of flashes to earth in a particular system.

Table 3. Lightning incidence for various cities.

City	Flashes to Earth per Year per Square Kilometer	Incidence Rating
Los Angeles	0.04	Low
Chicago	3.30	High
New York	2.46	High
Atlanta	4.68	High
Orlando	12.00	Very High

Low	Medium	High	Very High

.1 1 10

In addition to geographic location, another factor influencing the probability of a lightning strike occurring at or near a traffic controller is its proximity to tall objects. The concept of attractive area reflects that an object extending above its surroundings is more likely to be struck by lightning than its actual cross-sectional area might otherwise indicate. For example, thin metallic structures such as flag poles, lighting towers, antennas, and overhead wires offer a very small cross-sectional area; yet, they are frequently struck by lightning.

The ability of tall structures or objects to attract lightning to themselves serves to protect shorter objects and structures. In effect, a taller object establishes a protected zone around it. Within this protected zone, other structures and objects are protected against direct lightning strikes. As the heights of surrounding objects increase, the degree of protection provided to these shorter objects increases. Likewise, as the separation between tall and short structures increases, the protection afforded by the tall structure decreases. The protected space surrounding a lightning conductor is called the zone (or cone) of protection.

The concept of attractive area has a number of consequences to the traffic system. First, if an intersection is in an isolated, flat region with little or no tall objects in the vicinity, it is possible that the traffic signals mounted on posts and utility poles in the vicinity can be struck directly. A direct strike poses a high probability of damage occurring because of energy coupling to power, communication, or sensor leads also in close proximity to the attractive objects. On the other hand, a controller located in a downtown area with many tall buildings in the vicinity is not likely to experience a direct strike because the buildings will serve to attract and shunt the lightning discharges directly to earth.

3.3.3 Effects

Lightning discharges frequently cause damage to electrical and electronic equipment. The voltages developed by the fast rise time, high amplitude current pulse are high enough to break down insulation, and cause component and device failure. These voltages are produced by: (1) potential drop across equipment interfaces resulting from the lightning pulse traveling down power lines or signal lines, through structural members, along down conductors or overhead ground wires, or through the resistance of the earth connection; (2) magnetic induction; and (3) capacitive coupling. Lightning surges in power, signal, and control circuits are generally the result of some combination of these three effects.

Because of the fast risetime (1 to 2 μsec) and high amplitude (20,000 A) characteristics of the current pulse produced by the lightning discharge, the inductance and resistance of even relatively short conductors causes extremely high voltages to be developed on the conductor. The voltages frequently are high enough to exceed the breakdown potential of air and insulation materials and cause flashover to other conductors.

To illustrate the development of voltages on conductors by lightning discharges, consider a 5-m (16 ft, 5 in.) length of No. 6 AWG wire as might be used for power pole grounding. The resistive drop generated by a current level of 20,000 A in 5 m of No. 6 AWG wire (1.30×10^{-3} ohms per meter) will be:

$$V = (2)(10^4)(1.30)(10^{-3})(5) = 130 \text{ volts} \qquad (10)$$

which is insufficient to cause flashover or to pose a serious threat to personnel. Assuming that the conductor is a straight round wire, its inductance can be determined from:

$$L = 0.002\ell(2.303 \log \frac{4\ell}{d} - 0.75) \qquad (11)$$

where L is the total inductance in microhenries, ℓ is the length in centimeters, and d is the diameter in centimeters. The voltage, V, developed across this inductance is given by:

$$V = L\frac{di}{dt} \qquad (12)$$

A 5-m length of No. 6 conductor, which has a diameter of 0.416 cm, will exhibit an inductance of 7.74 μH. From Table 2 the rate of rise of the typical lightning stroke is 20,000 A/μsec which corresponds to a di/dt of 2×10^{10} A/sec. Thus, the voltage developed by the discharge pulse through this 5-m conductor is:

$$V = (7.74)(10^{-6})(2)(10^{10}) = (1.54)(10^5) \text{ volts} \qquad (13)$$

Although the duration of this voltage is typically less than 2 μsec, the voltage generated is high enough to cause flashover to conducting objects as near as 5 in. to this conductor, assuming air breakdown of 30 kV/in.

Circuits not in direct contact with the lightning discharge path can experience damage even in the absence of overt coupling by flashover. Because the high current associated with a discharge exhibits a high time rate of change, voltages are electromagnetically induced on nearby conductors. Extensive evidence (*3.19*) shows that the surges thus induced can easily exceed the tolerance level of many components, particularly solid state devices. Surges can be induced by lightning current flowing in a down conductor or structural member, by a stroke to earth in the vicinity of buried cables, or by cloud-to-cloud discharges occurring parallel to long cable runs, either above ground or buried (*3.20*).

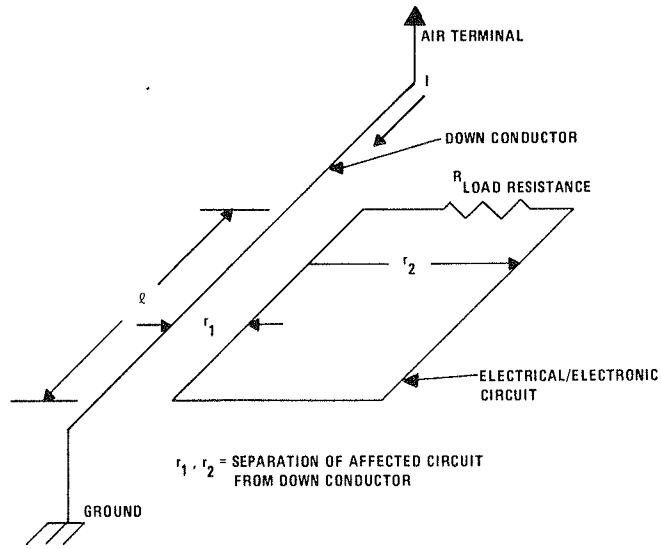


Figure 10. Inductive coupling of lightning energy to nearby circuits. (Ref. 3.5)

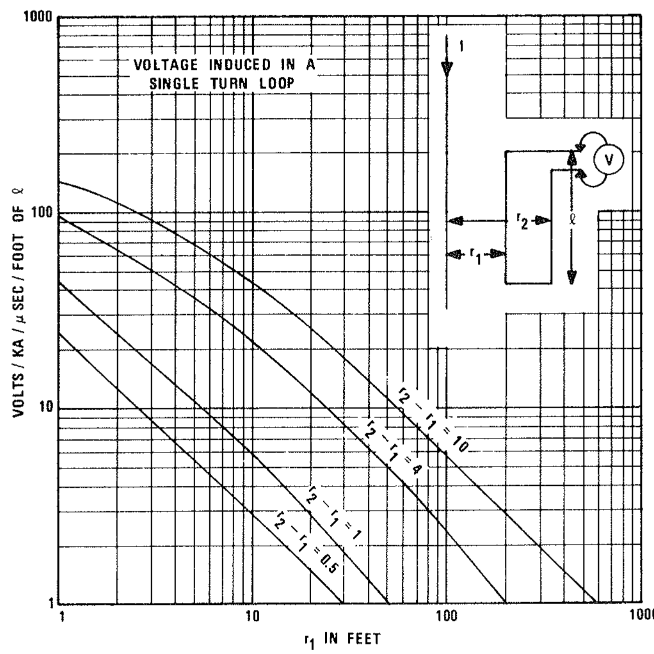


Figure 11. Normalized voltage induced in a single-turn loop parallel to a discharge path. (Ref. 3.5)

Consider a single-turn loop parallel to a lightning down conductor such as the ground wire on a power pole. Figure 10 illustrates this situation. The voltage E magnetically induced in the loop is related to the rate of change of flux produced by the changing current in the down conductor. The voltage induced in the loop is dependent on the dimensions of the loop (ℓ, $r_2 r_1$), its distance from the down conductor (r_1), and the time rate of change of the discharge current (di/dt). Figure 11 is a plot of normalized voltage per unit length that would be developed in a single turn loop of various widths.

These figures suggest the steps that should be taken to minimize the voltage induced in signal, control, and power lines by lightning discharges. First, because no control can be exercised over di/dt because it is determined by the discharge itself, E must be reduced by controlling ℓ, r_1, and r_2. The variable ℓ is a measure of the distance that the loop runs parallel to the discharge path; thus, by restricting ℓ, the induced E can be minimized. Thus, cables terminating in traffic control devices or equipment should not be routed for long distances parallel to conductors subject to lightning discharge currents if at all possible. If parallel runs are unavoidable, Figure 11 also shows that the spacing, r_1, between the loop and the lightning current path should be made as large as possible.

Another observation to be made from Figure 11 is that r_2 minus r_1 should be as close to zero as possible. In other words, the distance between the conductors of the pickup loop should be minimized. One common way of reducing this distance is to twist the two conductors together such that the average distance from each conductor to the discharge conductor is the same.

Another protective measure is to reduce the flux density within the pickup loop by providing electromagnetic shielding. Because the coupling field is primarily magnetic in nature, a shielding material having a high permeability such as iron or nickel should be used. Steel conduit is excellent.

The damage-threshold levels of solid state components used in modern traffic control equipment is substantially lower than that exhibited in older, electromechanical devices. Figure 12 shows the relative damage threshold levels of various solid state and electromechanical devices. Because most solid state logic operates at levels less than 5 V and draws only milliamperes of current, it is not surprising to find the damage threshold only slightly higher than these levels. Note that the damage levels for inductors (relays) are six orders of magnitude greater than those of TTL and CMOS logic devices commonly employed in traffic controllers. Even low level transients from energizing and deenergizing relay coils can cause severe damage to these devices and, therefore, protection may be required even in nonlightning environments.

3.4 SPECIFIC TRAFFIC CONTROLLER THREATS

The lightning and electrostatic discharges, the RF fields, the industrial and power system switching transients, and the in-

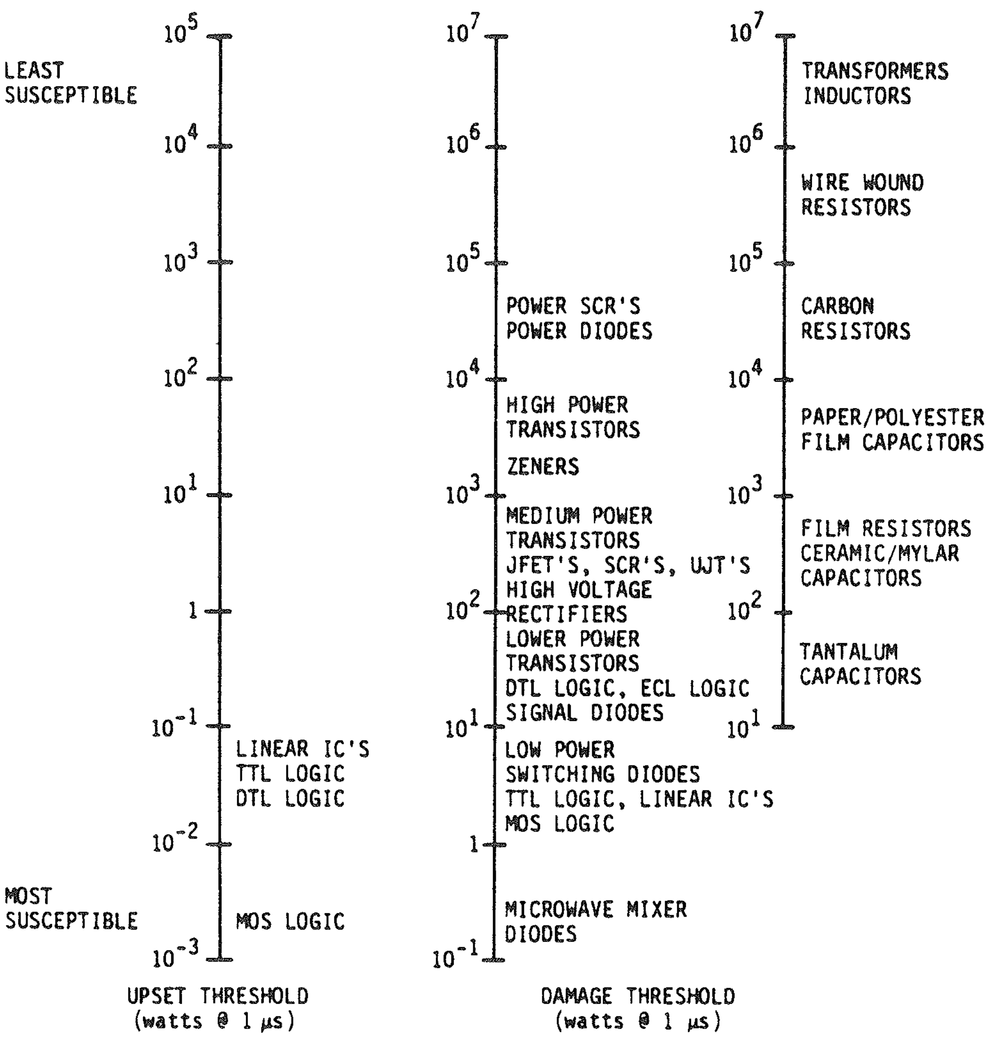


Figure 12. Spectrum of upset and damage thresholds of typical electronic components. (Ref. 3.21)

ternally generated switching spikes pose serious threats of damage to the components used in traffic control equipment. To achieve desired levels of system performance, adequate protection against these threats must be provided. In order to identify the most cost-effective protective measures, the nature of the transient and electromagnetic interference waveforms at the individual controller must be known. Unfortunately, no well-documented studies of the total electromagnetic environment at the various elements of a traffic control system have been identified. But, fortunately, measurements of selected elements of the environment have been made on other systems. For example, several studies have been performed to determine the characteristics of lightning-induced transients on 120 and 240 Vac power lines in residential and commercial installations. The results of these studies have been incorporated into the Institute of Electrical and Electronics Engineers (IEEE 587-1980, "Guide for Surge Voltages in Low-Voltage AC Power Circuits"(*3.22*). This document has become the American National Standards Institute (ANSI) C62.41-1980. Because the traffic controller normally operates on 120 or 240 Vac, the IEEE 587-1980 recommended waveforms and amplitudes are appropriate as a design and measurement requirement for traffic control equipment.

Telephone systems are exposed to frequent lightning surges. Several studies have characterized the nature of lightning transients on both open wire and coaxial lines. Inasmuch as communication and data lines feeding traffic controllers are similar in nature to telephone lines, published lightning data for telephone lines can be used to postulate the transient threat for traffic controller communication ports. The test levels set forth in Part 15, Subpart J of the Code of Federal Regulations, Title 47 (47CFR) can be applied to telephone and communication line inputs (*3.23*).

Lightning threat levels at other inputs such as inductive loop detector and pedestrian crosswalk switch inputs must be estimated because no data specifically measured on these inputs were identified. The levels and waveshapes from IEEE Std C62.31-1984, "IEEE Standard Test Specification for Gas Tube Surge Protective Devices," (*3.24*) are used for non-ac power and non-telephone-type inputs.

Because the NEMA TS 1-1983 (*1.1*) document is intended for assessing the performance of traffic controllers against switching transients, it is used as a guide for defining this particular threat.

Electromagnetic interference from RF emitters and electrostatic discharges are more difficult to specifically characterize. These threats must be addressed on a case-by-case basis.

With this approach, characteristic electromagnetic threat waveforms for traffic control equipment can be defined. These threat waveforms can then be used as the basis for selecting protective measures and for evaluating their effectiveness.

3.4.1 Lightning

The controller circuits most susceptible to lightning are those terminating long input/output lines. The lightning energy that couples to traffic control input/output terminals will depend on the length of the interface cable and its location. For example, overhead ac power and communication lines will be more likely to experience high transient current levels than pedestrian crosswalk switch interface cables. Lightning discharges miles away can produce large transients on power or communication lines at traffic control equipment. Therefore, the two controller terminals of primary concern are ac power and communications inputs.

In most cases, traffic control equipment located at an intersection will be fed by commercial ac power from overhead lines and a secondary arrestor will be provided by the utility company at the distribution transformer. Secondary arrestors on ac power lines with ratings between 10,000 and 20,000 A can reduce the lightning transient voltage amplitude to between 12,000 and 27,000 V, respectively, depending on the secondary arrestor rating (*3.25*). Figure 13 shows the manner in which the surge current is distributed among the various paths from the transformer. An upper limit on the transient voltage is afforded by the clearance sparkover (arcing) of the transformer windings and interconnect wiring breakdown levels. The typical clearance sparkover for most 120 to 240 Vac systems is 6,000 V. Consequently, IEEE 587-1980 (*3.22*), recommends 6,000 V as a typical amplitude limit of transients in 120 to 240 Vac power systems.

IEEE 587-1980 classifies equipment into categories A, B, or C. Category C levels, open-circuit voltages greater than 10,000 V and short circuit current in excess of 10,000 A, apply if (1) the controller cabinet is located in an isolated area, (2) power is supplied from lines not equipped with secondary arrestors rated at 10,000 A or greater, and (3) a utility watt-hour meter is not installed. Based on the guidelines of IEEE 587-1980, most traffic control equipment at intersections can be classified as category B equipment as illustrated in Figure 14. Central control equipment can be considered to be either category A or B, depending on the equipment location inside a building. Category B transient waveforms are given in Figure 15, and include two basic waveshapes, a damped sinusoid or damped exponential. The damped exponential waveform represents the voltages typical at outdoor installations and at locations close to the service entrances of buildings where substantial current is still available in the transient discharge. Further, the lightning transient still

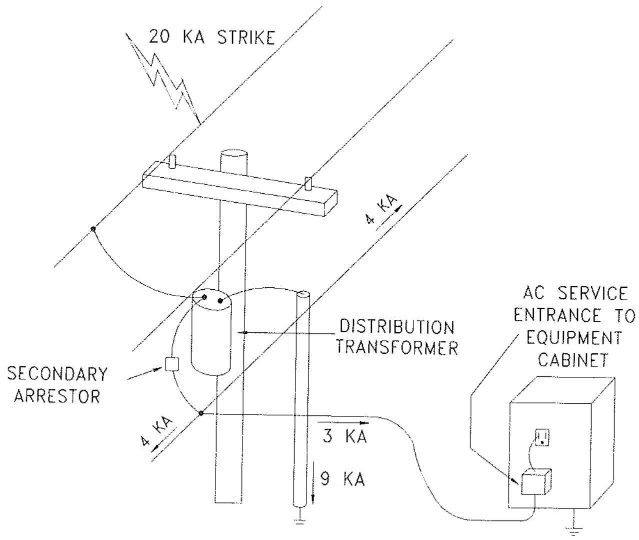


Figure 13. Typical lightning current distribution after coupling to an ac power line. (Scaled from Ref. 3.26)

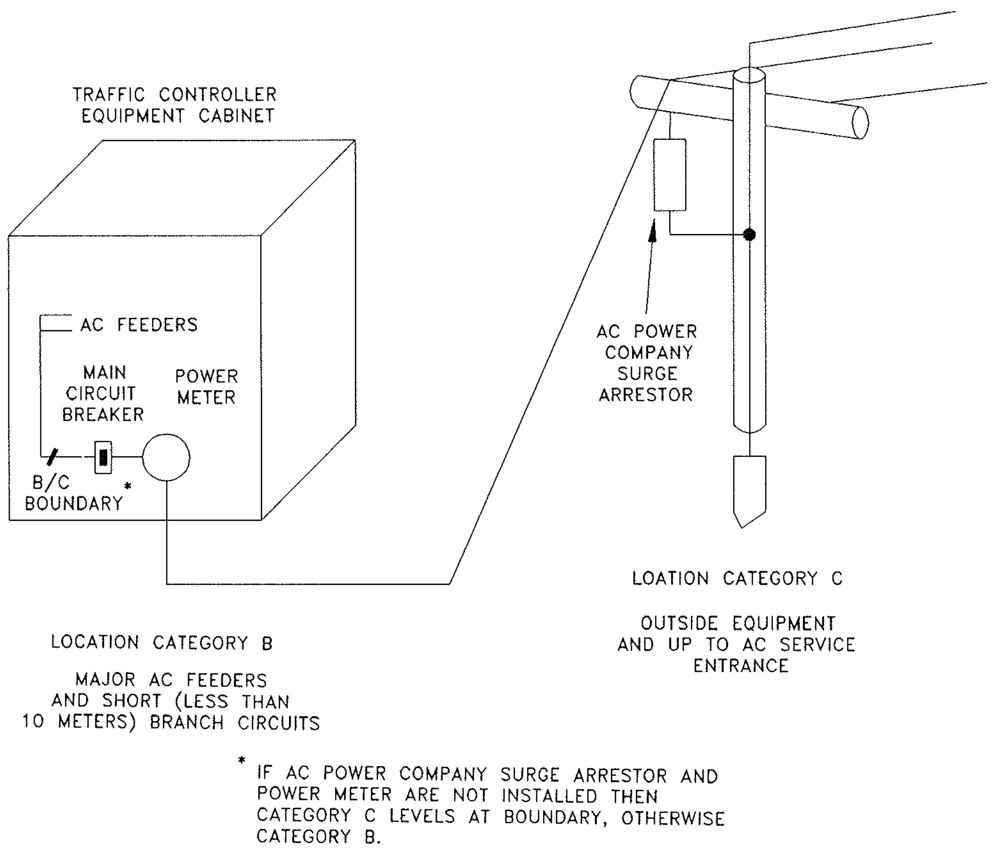


Figure 14. IEEE 587-1980 location categories as applied to a typical traffic controller.

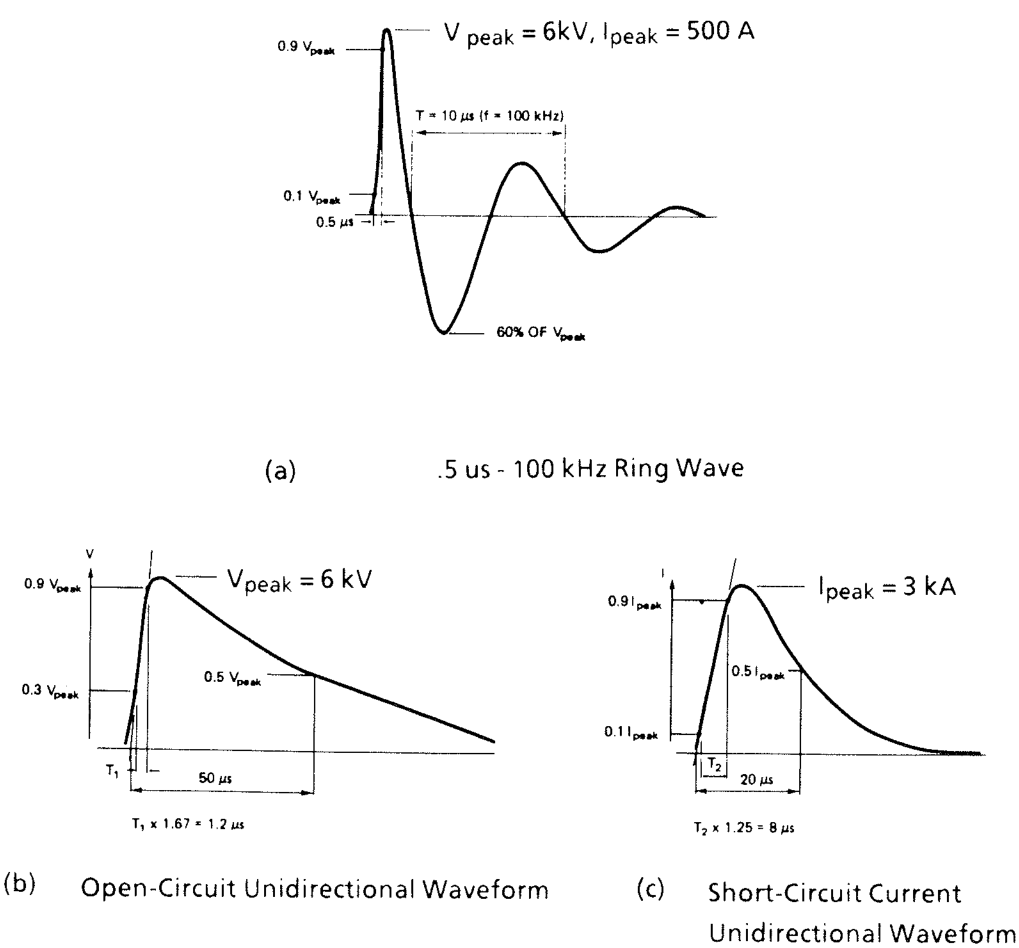


Figure 15. IEEE 587-1980 recommended lightning test waveforms for category B locations. (Ref. 3.22)

resembles the original "pulse" waveshape. Two different rise and fall time specifications are recommended (1) for open-circuit, high impedance device inputs; or (2) low impedance device inputs. The damped sinusoid, or ring-wave, reflects the ringing which occurs between impedance discontinuities, such as at cable terminations and connection points. The relatively fast, 0.5-μsec rise time simulates the characteristics associated with nonlinear voltage distributions in transformer windings and tests the fast rise time susceptibility effects of semiconductors. Faster rise-times exist in lightning and switching transients; however, as the transients propagate through transformers and wiring, the rise-times are slowed because of shunt capacitance effects.

Because many controllers will not have the benefit of a secondary arrestor and a power meter installed before the controller cabinet, the transient threat defined for category C would be appropriate. Inasmuch as this higher energy transient occurs less frequently than the lower energy category B transients, it is recommended that controllers be subjected to fewer repetitions of the category C waveforms than the B conditions (see Appendix). The category C waveforms are identical to the category B, damped exponential waveforms shown in Figure 14 except the amplitude levels are 10,000 V into an open-circuit and 10,000 A into a short-circuit.

Of additional concern are the lightning-induced currents on long communications lines. Most communications lines consist of shielded-twisted pairs (single or multiple pairs) and coaxial cable. The communications cables can be either suspended on poles along with ac power or buried. It is very unlikely that communication cables will receive a direct strike; however, part of the lightning current from discharges to overhead power lines or to the earth can couple indirectly to the cable shields. Though the cable is shielded, protection to signal conductors is not always assured because of the limited effectiveness of the shield. Lightning currents are not usually harmful to the shield itself; however, the high current induces surge voltages on the inner conductors. Such induced surge voltages can be sufficient to damage sensitive communication circuits.

An illustration of the induction of voltages on internal conductors by shield current is shown in Figure 16 (*3.27*). As lightning current flows through the resistance of the shield, an electric field is established along the inside of the shield which capacitively couples to the inner conductors. Because most communication cable shields are very thin, the time required for the lightning current and associated electric field to diffuse to the inside surface of the shield will be short compared to the lightning current rise times of several microseconds. Therefore, the internal electric field will have the same waveshape as the lightning current discharge.

For a typical lightning discharge current of 20,000 A, the induced open- circuit voltage has been computed to be 3,680 V and a short circuit current of 126 A. The short-circuit current for a strike occurring 2.75 mi down the cable will decrease to 71 A (*3.27*). These values of short circuit current and open circuit voltage can be used as typical values and linear extrapolation can be made to higher or lower coupled currents. The risk and fall times are comparable to those of the original lightning pulse. Depending on the depth of burial and soil conductivity, the voltages and currents induced on buried communication cables can be comparable or less than these values. Typically, the voltage induced on buried cables will be less than that on overhead cable.

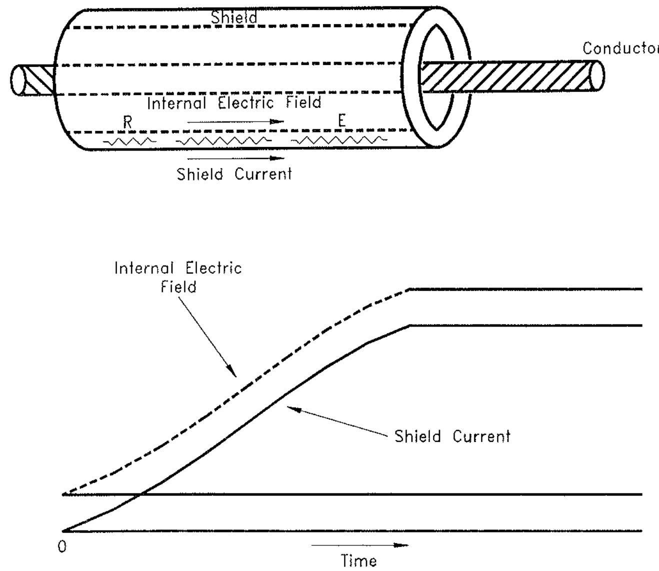


Figure 16. Lightning coupling to coaxial cable. (Ref. 3.27)

Measurements of cable plant surge voltages conducted by Bodle and Gresh (*3.28*) and Bennison (*3.29*) suggest that the voltage surges on paired, shielded overhead conductors typically will not exceed 1 thousand volts for 99 percent of the surges. This indicates that the 3.68 thousand volts prediction given above may be somewhat high. Field experience on exposed rural telephone lines indicates that voltages greater than 1 thousand volts are routinely present, so that the 3.68 thousand volts value is not unreasonable (*3.27*). (It should also be noted that these measurements were made with protectors installed and, thus, it is possible that the protectors themselves limited the peak voltage levels on the lines (*3.27*).)

The FCC in 47 CFR (*3.23*) has adopted a lightning test specification for telephone line inputs and it is recommended that these levels and waveshape parameters be adopted for telephone or long dedicated communication line inputs to traffic control equipment. The waveshape parameters vary, depending on the particular line pairs under investigation. Also, ac-powered telephone equipment have a different ac input test specification than IEEE Std 587-1980 (*3.22*). It is recommended that ac power inputs to the telephone equipment be protected to the levels specified by in 47 CFR. (Table 4 provides the specific levels and waveshape parameters.)

Inductive loop vehicle detectors can serve as very efficient loop antennas because of their large loop areas. The tuned frequency over which the loops are designed to operate (20 KHz to 200 KHz) is also within the peak energy region of the radiated lightning pulse (*3.7*). Because inductive loop detectors are buried just below the roadway surface, very little protection is afforded by the asphalt or concrete covering. By assuming the inductive loop vehicle detector is a loop antenna, the voltage induced at the detector output terminals can be calculated (*3.2*). The worst case radiated coupling condition would occur in a large loop tuned at 200 KHz. A close proximity lightning strike (within 1 km) can produce radiated field strengths of 1,000 V/m (Table 1). Using a 6 ft X 70 ft, 1-turn loop and broadside illumination results in V = 163 volts. For a typical 6 ft $\times$ 6 ft, 3-turn loop, the peak voltage is reduced to 42 V. The voltage of the worst

Table 4. Recommended lightning test waveforms for traffic control equipment.

LOCATION CATEGORY		DAMPED EXPONENTIAL												RING WAVE										
		Risetime (μ sec.) 10%–90%		Falltime (μ sec.) 50%		Open Circuit Voltages* (Volts)	Short Circuit Current* (Amps)	Polarity		Repetition (Each Polarity)	Minimum Time Between Reps (seconds)	Maximum Time Between Reps (seconds)	Risetime (μ sec.) 10%–90%		Frequency (KHz)	Q		Open Circuit Voltages* (Volts)	Short Circuit Current* (Amps)	Repetition	Minimum Time Between Reps (seconds)	Maximum Time Between Reps (seconds)	Reference
		Voltage Waveform	Current Waveform	Voltage Waveform	Current Waveform			+	−				Voltage Waveform	Current Waveform		min	max						
120 Volt AC Power Category C	Phase–to–Neutral	1.25	8	50	20	10,000	10,000	✓	✓	1	–	–											3.22
	Phase–to–Ground	1.25	8	50	20	10,000	10,000	✓	✓	1	–	–											3.22
	Neutral–to–Ground	1.25	8	50	20	10,000	10,000	✓	✓	1	–	–											3.22
120 Volt AC Power Category B	Phase–to–Neutral	1.25	8	50	20	6000	3000	✓	✓	5	30	120	.5	.5	100	5	10	6000	500	5	30	120	3.22
	Phase–to–Ground	1.25	8	50	20	6000	3000	✓	✓	5	30	120	.5	.5	100	5	10	6000	500	5	30	120	3.22
	Neutral–to–Ground	1.25	8	50	20	6000	3000	✓	✓	5	30	120	.5	.5	100	5	10	6000	500	5	30	120	3.22
Telephone	Line–to–Ground	10	10	160	160	1500	200	✓	✓	5	30	120											3.23
	Line–to–Line	10	10	560	560	800	200	✓	✓	5	30	120											3.23
	Phase–to–Neutral (AC powered Eqt. only)	2	2	10	10	6000	3000	✓	✓	3	30	120											3.23
Other (ILD, PEDX)	Line–to–Ground	10	10	1000	1000	3000	100	✓	✓	5	30	120											3.24
	Line–to–Line	10	10	1000	1000	3000	100	✓	✓	5	30	120											3.24

* +/− 5% Tolerance

case condition of a 6 ft × 70 ft loop detector can produce damage to sensitive inductive loop vehicle detector electronics, while for a small loop upset may only occur (i.e., an inadvertent count pulse). Though the radiated transient pick up is less than that on ac power or communication lines, protection of ILD inputs will be necessary because of the low damage and upset levels of solid state detector amplifiers. ILD's may also indirectly couple lightning current that is transferred to ground from nearby overhead line down conductors, ground rods, etc. In the absence of specific measured data, a requirement of 3,000 V and 100 A should be imposed on ILD terminals.

Other inputs which must be considered include the pedestrian crosswalk inputs and interconnect cables between remotely mounted vehicle detector amplifiers and the controller equipment. The pedestrian crosswalk switch interconnect cable is often an unshielded, conductor pair. This wire pair can be over 100 ft long and can serve as a very efficient antenna for lightning and other radiated noise sources. Measurements of coupled transient levels into pedestrian crosswalk inputs or lamp driver cables have not been performed. It is possible that hazardous transients could be induced on these cables from radiated energy or indirect lightning strikes, and thus these terminals must be protected. Recognizing that these exposed inputs will experience transient energy pickup but will be less severely stressed than power or communication lines, a reduced test specification of 3,000 V and 100 A similar to ILD terminals is recommended to be applied to these terminals.

In summary, ac power and communication inputs will be subjected to the most severe lightning threats because of the long cables involved and the resultant increased probability of a lightning discharge coupling to the line. Typically, other inputs, such as vehicle loop detectors and pedestrian crosswalk switches, will be subjected to less serious threats. However, in the case of strikes to nearby objects or to the earth, very high amplitude transients, comparable to those present on ac power or communication lines, can couple to these other inputs causing damage to internal electronics. It is recommended that, in the absence of substantial test and measurement data, the IEEE C62.31-1984 (*3.29*) susceptibility waveforms be adopted for all nonpower input/output pins and that peak levels of at least 3,000 V and 100 A for ILD, pedestrian crosswalk switch, and all other inputs, be adopted. Though higher level lightning transients can occur, achievement of these levels of protection should result in acceptable performance in most locations. Table 4 summarizes the recommended test levels for the various controller inputs.

3.4.2 Radio Frequency Interference

The radiated levels coupled from nearby TV, radio, radar sites, and mobile communications equipment are generally difficult to estimate. Because very few traffic control installations will be impacted by such electromagnetic interference sources, a generalized definition of the threat levels due to them is not deemed necessary. Instead, if an operational problem is believed to be caused by nearby TV, radio, radar or mobile transmitters, field measurements of the radiated and coupled levels should be performed and corrective measures such as those described in the next chapter should be undertaken. For example, additional shielding and filtering may be required.

3.4.3 Switching Transients

Power line switching transients can arise from relay and flasher coil discharges within the equipment cabinet as well as from industrial equipment sharing the same power distribution lines. As noted earlier, transients due to relay and flasher coil discharges can be significantly greater than the coil dc supply voltages. Conducted power line transients from industrial load switching can exceed several thousand volts (*3.30*).

The transient test levels and waveforms contained in NEMA TS 1-1983 (*1.1*) realistically reflect most switching and conducted power line transients. For example, the high repetition noise transients of ± 300 V, 2,500 W peak power, 1 μsec rise time and 10 μsec pulse width with a repetition rate of 1/30 of a second and a duration of at least 3 sec, adequately represent most relay and flasher coil discharge transients. On the other hand, the low-repetition, high-energy transients of ± 600 V and 600 A represent the severe industrial switching and ground fault transients which can occur. However, the nondestruct test specifications of NEMA TS 1-1983, as now written, represent unrealistic conditions. For example, ac power is not applied during the test and the unit must simply operate properly once the unit is powered up. Further, the nondestruct test amplitudes are not severe enough to represent lightning discharges, and the waveform rise and fall times are not clearly defined.

3.4.4 Electrostatic Discharge

Electrostatic discharge (ESD) threat levels cannot be uniquely specified because of the wide range of amplitudes and waveform parameters which can occur. In general, protection against ESD effects can be achieved through proper maintenance, repair, and installation procedures and through the use of proper grounding, bonding, shielding and transient protection as detailed in the next section. The devices which protect against lightning also provide substantial ESD protection. For serious situations, the reader is referred to Ref. 3.4 for specific ESD protection procedures and practices.

3.5 RECOMMENDED TEST SPECIFICATIONS

The electromagnetic interference threat levels and waveforms described in the previous sections provide a basis for a recommended transient and electromagnetic interference test specification for traffic control equipment. A review of the National Electrical Manufacturers Association (NEMA) TS 1-1983 indicates that transients due to internal and external noise sources are treated adequately with the exception of lightning-induced transients. Recommended modifications to NEMA TS 1-1983 to add lightning test specifications are given in the Appendix. The modifications represent a starting point for establishing a lightning test specification for traffic equipment. NEMA TS 1-1983 was chosen primarily because of its wide use in the traffic control community. It is recognized that NEMA TS 1-1983 may not be the final document ultimately selected to impose lightning test specifications and that a separate document on lightning protection may be required. The recommended changes illustrate a possible form of the lightning test specifications, however, and can serve as the initiating document for further efforts in this area.

REFERENCES

3.1 Espeland, R. H., Layton, D. H., Werner, B. D., Teters, L. R., and Morisson, E. L., Jr., "Electromagnetic Interference Effects on Motor Vehicle Electronic Control and Safety Devices. Volume I. Summary." Contract DOT-HS-5-01097, Final Report, prepared for U.S. Department of Transportation, PB 261-765 (Nov. 1976).

3.2 Jasik, H., ed., *Antenna Engineering Handbook First Edition.* McGraw-Hill: New York (1961).

3.3 Denny, H. W., Daher, J. K., and Rohrbaugh, J. P. "Integrated Circuit Technology Assessment (ICTA) Project." Final Technical Report: Definition Phase, Contract No. F41621-83-C-5015 (April 1984).

3.4 DOD-HDBK-263, "Electrostatic Discharge Control Handbook for Protection of Electrical and Electronic Parts, Assemblies and Equipment (Excluding Electrically Initiated Explosive Devices)." (May 2, 1980).

3.5 Denny, H. W., Holland, L. D., Robinette, S. L., and Woody, J. A., "Grounding, Bonding, and Shielding Practices and Procedures for Electronic Equipment and Facilities. Volume 1: Fundamental Considerations." *Report No. FAA-RD-75-215,* 1 (AD-A022-332) (Dec. 1975).

3.6 Cianos, N., and Pierce, E. T., "A Ground-Lightning Environment for Engineering Usage." Contract L.S. - 2817-A3, Stanford Research Institute, Menlo Park, Calif. (Aug. 1972).

3.7 Uman, M. A., *Lightning.* McGraw Hill: New York (1969).

3.8 Berger, K., "Novel Observations on Lightning Discharges: Results of Research on Mount San Salvatore." *J. Franklin Inst.,* 283 (1967) pp. 478–528.

3.9 "Methoden and resultate der blitzforschung auf dem Monte San Salvatore ei Lugano in den jahre 1963–1971." *Bull. Schweiz. Elektrotech.* Ver., Vol. 63 (1972) pp. 1403–1422.

3.10 Takeuti, T., Nakano, M., Nagatani, M., and Nakada, H., "On Lightning Discharges in Thunderstorms." *J. Met. Soc. Japan,* Vol 51 (1973) pp. 494–496.

3.11 Takeuti, T., Nakano, M., and Yamamoto, Y., "Remarkable Characteristics of Cloud-to-Ground Discharges Observed in Winter Thunderstorms in Hokuriku Area, Japan." *J. Met Soc. Jap.,* Vol 54 (1976) pp. 436–439.

3.12 Takeuti, T., Nakano, M., Brook, M., Raymond, D. J., and Krehbiel, P., "The Anamalous Winter Thunderstorms of the Horuriku Coast." *J. Geophys. Res.*, Vol. 83 (1978) pp. 2385–2390.

3.13 Takeuti, T., Israelsson, S., Nakano, M., Lundquist, D., and Astrom, E., "On Thunderstorms Producing Positive Ground Flakes." *Proc. Res. Inst. of Atmospherics,* Nagoya University, Japan, 27-A (1980) pp. 1–17.

3.14 Brook, M., Nakano, M., Krehbiel, P., and Takeuti, P., "The Electrical Structure of the Hokuriku Winter Thunderstorms." *J. Geophys. Res.*, Vol. 87 (1982) pp. 1201–1215.

3.15 Malan, D. J., *The Physics of Lightning.* English Universities Press: London, England (1963).

3.16 "World Distribution of Thunderstorm Days." SMO/OMN No. 21, World Meterological Association, Geneva, Switzerland (1953).

3.17 Maxwell, E. L., et al., "Development of a VLF Atmospheric Noise Prediction Model." Final Report, Contract N00014-69-C-0150, Westinghouse Georesearch Laboratory, Boulder, Colorado (1970).

3.18 Pierce, E. T., "Latitudinal Variation of Lightning Parameters." *J. Appl. Meterol.,* Vol. 9 (1970) pp. 194–195.

3.19 Comber, G., "A Transistorized Video Line System." *IEEE Conference Publication,* Vol. 46, Pt. 1 (Sept. 1968).

3.20 Crawford, S. R., et al., "Final Report on Investigation of Lightning Hazard and Vulnerability of NHS." WDL-TR5103, Contract No. F04701-72- C-0024, Philco-Ford Corporation, Palo Alto, Calif. 94303 (Mar. 12, 1973).

3.21 *Interference Technology Engineer's Master.* (1984) p. 38.

3.22 "IEEE Guide for Surge Voltages in Low-Voltage AC Power Circuits." IEEE Std 587-1980, ANSI/IEEE C62.41-1980.

3.23 Part 15, Subpart J of the Code of Federal Regulations, Title 47 (47 CFR).

3.24 "IEEE Standard Test Specifications for Gas Tube Surge Protective Devices." IEEE Std C62.31-1984.

3.25 "Distribution Data Book." General Electric, GET-1008M.

3.26 Martzloff, F. D., "Origins of Transient Overvoltages." Lecture, September 7, 1983, University of Wisconsin-Extension, Madison, Wisconsin.

3.27 Crouch, K. E., and Wolff, B. I., "A Study of Lightning Transients in Telephone Cables." Presented at FAA/Georgia Institute of Technology Workshop on Grounding and Lightning Protection (May 1978) pp. 241–256

3.28 Bodle, D. W., and Gresh, P. A., "Lightning Surges in Paired Telephone Cable Facilities." *The Bell System Technical J.* (March 1961) pp. 547–577.

3.29 Bennison, E., et al., "Lightning Surges in Open Wire Coaxial, and Paired Cables." IEEE Transactions on Communications, Com. 21 (1973).

3.30 Smith, M. W., and McCormick, M. D., *Transient Voltage Suppression.* Fifth Edition, General Electric: Auburn, N.Y. (1986).

CHAPTER FOUR

EQUIPMENT PROTECTION TECHNIQUES

4.0 INTRODUCTION

To enhance the reliability of the traffic control system and to reduce maintenance costs, the energy levels of transient and interference signals must be reduced to values that can be safely handled by circuit components. Establishment of the necessary protection involves both circumvention and limiting.

Circumvention, or the routing of threatening energy away from susceptible devices, requires integrated grounding, bonding and shielding of enclosures, cable shields, and electrical wiring. Grounding establishes fault clearance and lightning or static discharge paths and interconnects conducting objects to minimize voltage differences during the faults and discharges. Bonding is the process by which the conducting objects are electrically joined with reliable, low impedance connections. Shields enclose sensitive components and conductors inside a conductive covering to prevent the electromagnetic coupling of transient energy and electromagnetic interference via radiated and conducted paths. These three circumvention techniques are described in Sections 4.1, 4.2, and 4.3, respectively.

Limiters, discussed in Section 4.4, restrict to safe levels the magnitude of transient and electromagnetic interference currents and voltages on conductors entering the controller. Commonly used current limiters include resistors, fuses, and voltage dependent resistors. Voltage limiters usually have faster response times than current limiters and also do not load down the protected circuit. Common voltage limiters include spark gaps, zener diodes, silicon avalanche suppressors (SAS), and metal-oxide-varistors (MOV). Filters may be required for both current and voltage limiting. Many situations require hybrid combinations of these protectors.

Section 4.5 describes techniques for reducing the coupling of interference and transient energy to penetrating conductors. Topics covered include common-mode rejection through balancing and transformer isolation and the use of optical devices to interrupt the coupling path.

Section 4.6 addresses configuration control methods and procedures to prevent system degradation from improper maintenance and repair.

4.1 GROUNDING

The term "ground" evolved from words meaning bottom, or foundation. Because the earth was generally that which was underneath and provided the ultimate foundation, or bottom, of most man-made structures, one of the meanings of the term "grounding" became "to contact earth."

Historically, electrical grounding requirements arose from the need to protect people, equipment, and buildings from lightning and static electricity. Structures, as well as electrical apparatus, were connected to earth, i.e., grounded, to provide the paths necessary for lightning and static discharge. As electrical utility systems developed, grounding to earth proved to be effective for the protection of the system against electrical faults. All major components of the system such as generating stations, substations, and distribution networks were interconnected with earth through a low resistance connection to provide fault clearance paths back to the generator or substations.

The housings of electrical equipment were connected to earth or other objects (e.g., metal structural members and water pipes) in contact with earth. In this way, if an electrical conductor touched a metal surface subject to human contact, the electrical potential to which the person would be exposed was kept to a safe level. Interconnecting all metal objects associated with the electrical distribution network completed the fault return paths internal to the building or equipment and caused breakers and fuses to trip or blow rapidly. (Rapid clearance of the fault not only limits human exposure to hazardous voltages, it also minimizes heating of the faulted conductors and thus lessens the fire hazard.) This fault return network came to be referred to as the *grounding* network whether it was connected with earth or not, as for instance when installed in airplanes, spacecraft, satellites, ships, or plastic-enclosed equipment.

Grounding in a traffic control system encompasses: (1) the electrical contacts with earth at the central control facility and at the individual traffic controllers; (2) signal circuit referencing internal to equipment and between equipment; and (3) the interconnections inside the controller cabinet between the circuit references, the enclosure, cable shields, terminal protection devices, fault protection paths and the earth electrode.

The electrical contact with earth at the individual intersection controller is important for limiting fault-caused voltage differentials between the enclosure and earth, pavement, or other grounded objects, such as fences, power poles, or buildings. As a fault-clearance path, the earth connection is likely to be inadequate by itself. The amount of real estate necessary to achieve a sufficiently low resistance to reliably clear an electrical fault is not usually available at the typical intersection. Therefore, the earth connection cannot be relied upon to be the only means for clearing power supply faults: fault protection must be established by installing the electrical supply system in accordance with National Electrical Code (*4.1*) requirements. These requirements include tying the ground system to the power system ground, or "green wire" and using short, low inductance interconnect lines. However, contact with earth is necessary to help equalize potential differences between controller elements during lightning strikes either to the system or to nearby objects.

As discussed in the previous section, lightning discharges to earth are common in many areas. The power lines, in particular, have considerable exposure to lightning. The power distribution system, being an extensive grid of wires, exhibits a high likelihood of being struck by lightning and offers many lightning discharge paths to earth via the overhead ground conductors and the many pole grounds. Even if the lightning does not strike the power line directly, the difference in potential developed between parts of the power distribution network by strokes to nearby objects induces transients into the network. Thus, in a typical thunderstorm, the power conductors serving the traffic control system are likely to experience numerous lightning-induced transients. Because traffic controllers are served by these power conductors, the lightning transients will appear at the signal and power terminals of the controllers. The voltage transients will be produced between conductors of the power line, between conductors of communication and control cables, between cable conductors and the controller cabinets, and between the controller cabinets and the earth. Inasmuch as the charge equalization process of the lightning discharge occurs relative to earth, an earth connection at the controller is needed to minimize the voltage differentials between elements of the traffic control system. In addition to the earth connection, other measures to control potential differences between circuits and devices within the controller itself are also required. These additional measures include using low inductance conductors to interconnect all circuit signal grounds, cable shields, and terminal protection devices within the enclosure and with the ground rod (or other ground electrode, as available).

Although correct grounding is an integral part of protecting equipment and personnel from lightning and electrical faults and for the proper operation of terminal protection devices, it must be emphasized that grounding alone will not protect circuits from transient damage nor from electromagnetic interference.

4.1.1 Types of Grounds

Within the restricted boundaries of the traffic controller equipment cabinet, there will be multiple "grounds" present. As shown in Figure 17, these various "grounds" include: safety ground, arrester ground, cabinet ground, shield ground, circuit (or signal/logic/electronic) ground, earth ground, and so on. Confusion often exists as to whether these various "grounds" should be kept separated from one another, whether all types should be interconnected, or whether only like types should be interconnected with the different groupings connected at one single point.

4.1.1.1 Electrical Safety or Fault Protection Ground

For electrical fault protection, it is necessary that the various metal objects subject to becoming energized and accessible for human contact be interconnected with a conductor sized in accordance with Table 250- 94 of the National Electrical Code (*4.1*). This safety ground path can be serial, i.e., daisy chained; laid out like the spokes of a wheel, i.e., a star configuration; or can have multiple possible paths, as in a grid. The configuration is unimportant so long as a path of sufficiently low resistance exists back to the main power breaker or fuse from the controller. The safety ground should tie together the ac supply "green wire," the enclosure, and the ground rod, as a minimum.

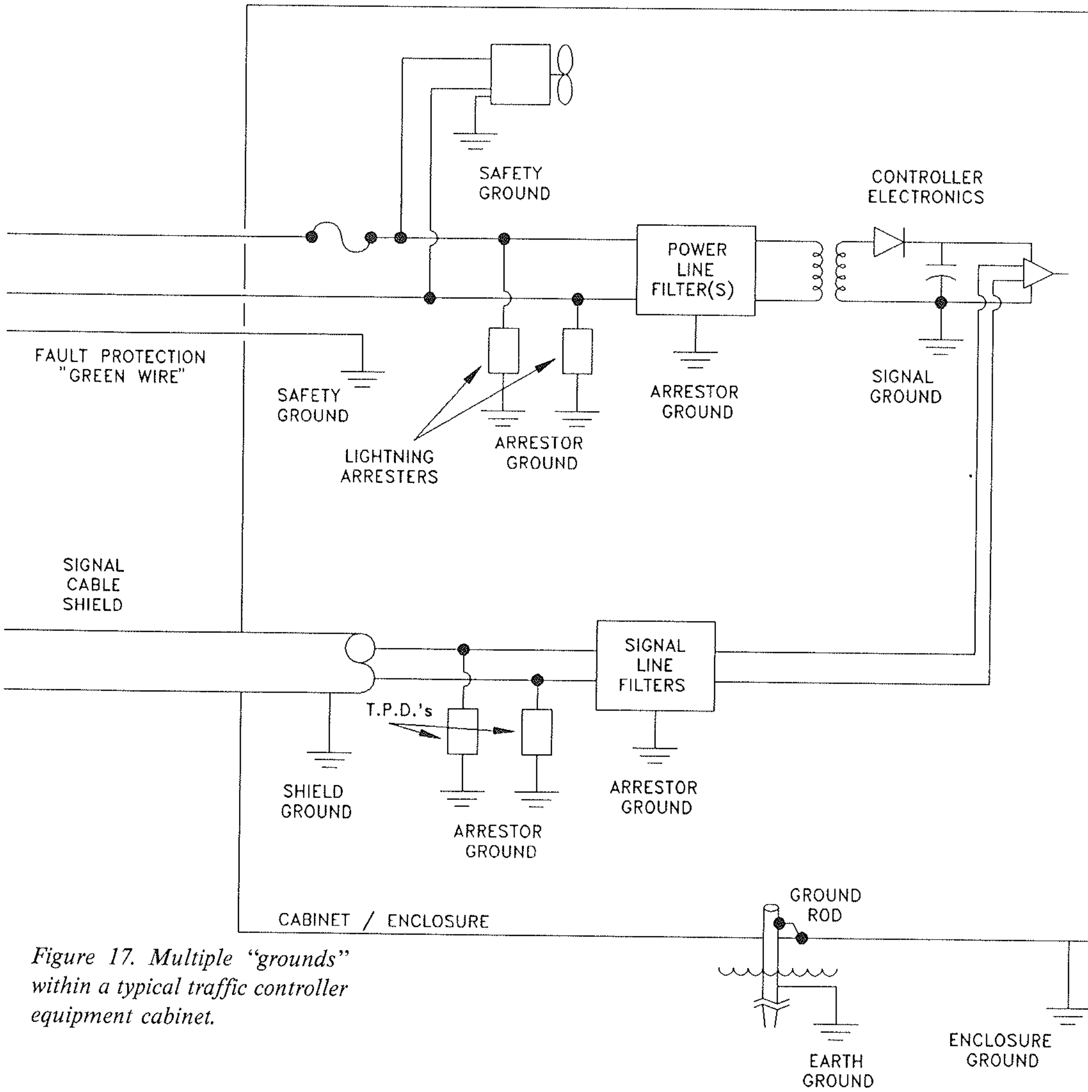


Figure 17. Multiple "grounds" within a typical traffic controller equipment cabinet.

4.1.1.2 Signal or Circuit Ground

If an electronic circuit performs a stand alone task as, for example, monitor some parameter and activate an indicator, its signal (or logic or circuit) reference (usually in the form of power supply common) can often be isolated to the board or subassembly on which it is located. Typically, however, the circuit sends or receives signals to or from other circuits either internal or, in particular, outside the enclosure. The on-board signal ground must be interconnected with the cable shield or with the low side signal conductor of the incoming/outgoing lines unless appropriate signal isolation devices are used. If the cable shield is not bonded to the cabinet, then lightning-induced transients or EMI signals can exist between the circuit/shield ground point and the incoming ac power conductors because of the power safety ground connection to the cabinet. (Special high voltage isolation transformers can be constructed which would permit the circuit/shield ground reference to be isolated from the enclosure/safety ground. However, such transformers are of special design, are not readily available for large volume use, and are much more expensive than standard power supply transformers.) If the cable shield is bonded only to the enclosure, the voltage transients will be developed between the signal conductors themselves and the circuit reference as extended back to the enclosure through the power supply. Therefore, individual circuit/subassembly signal reference points need to be connected to cabinet ground, or, if floated, need to have appropriate surge suppressors installed between the circuit reference and the enclosure. The suppressors need to be fast response types sufficient to protect the most sensitive components exposed to the transient. In addition, fast response suppressors are also needed across signal, data, and power supply buses. (Design guidance on the selection of appropriate suppressors is contained in later sections of this chapter.)

Two examples are given of incorrect signal grounding. In the first example, the pedestrian crosswalk pushbutton ground wire is tied directly to logic ground at a printed circuit card edge connector. Logic and earth ground are then tied together at the printed circuit card edge connector. When the pedestrian cross-

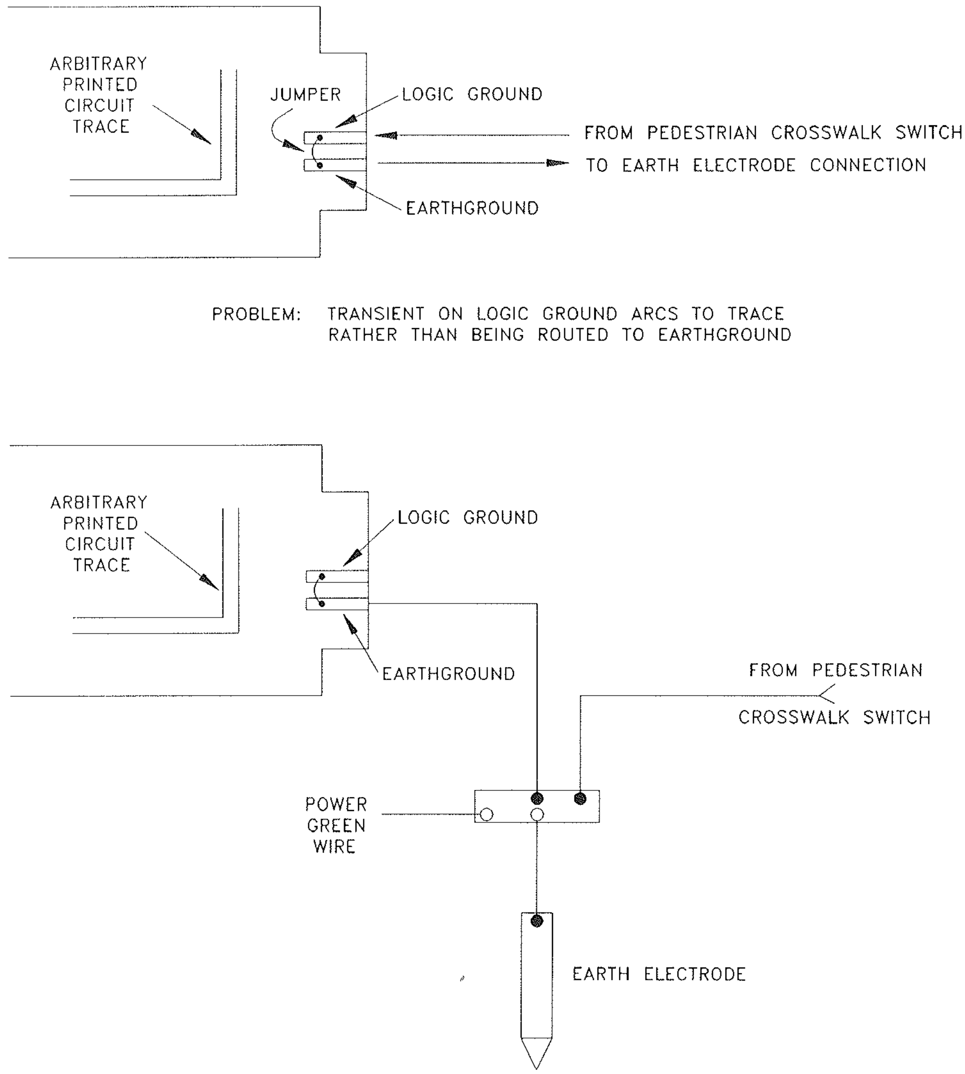


Figure 18. Proper grounding of logic ground to earth ground when logic ground must leave the equipment cabinet.

walk pushbutton wiring is exposed to a high level transient, a significant voltage differential develops between the logic ground and true earth ground because of line inductance associated with the long path from the pushbutton and the typical 2 to 4 ft of wire that ties the "earth ground" pin on the printed circuit card and the earth ground bus or ground rod. The spacing between an arbitrary printed circuit trace and the edge connection point is often less than a tenth of an inch. The transient voltage level that is developed can exceed the dielectric breakdown strength of the printed circuit board material and arc over to the arbitrary trace causing upset or damage to components on the card. The solution to this problem is to tie the pedestrian crosswalk pushbutton logic ground wire to the earth ground bus bar or ground rod and then run a single wire to the printed circuit card as shown in Figure 18.

The second problem is illustrated in Figure 19 where a long shielded communications line is grounded at only one end to prevent 60-Hz power frequency hum. A problem can occur if the cable shield is struck by lightning, a fault occurs, etc., near the ungrounded end of the shield. Because of cable shield inductance, a very high amplitude voltage transient can exist between the cable shield and the inner conductors resulting in damage or upset. To prevent damaging voltage levels from occurring, a limiter should be tied between the cable shield and earth ground. This will provide a path for transient current while allowing normal operation.

4.1.1.3 Enclosure or Cabinet Ground

Because the enclosure is the part of the controller to which human contact is possible, it must be interconnected with the earth ground, i.e., the ground rod, and with the electrical safety grounding conductor. Because the typical controller enclosure consists of solid metal panels welded to steel frame members, it offers the lowest electrical impedance between any two points within the controller. In addition to offering the lowest impedance path for transient and fault currents, the extensive metal

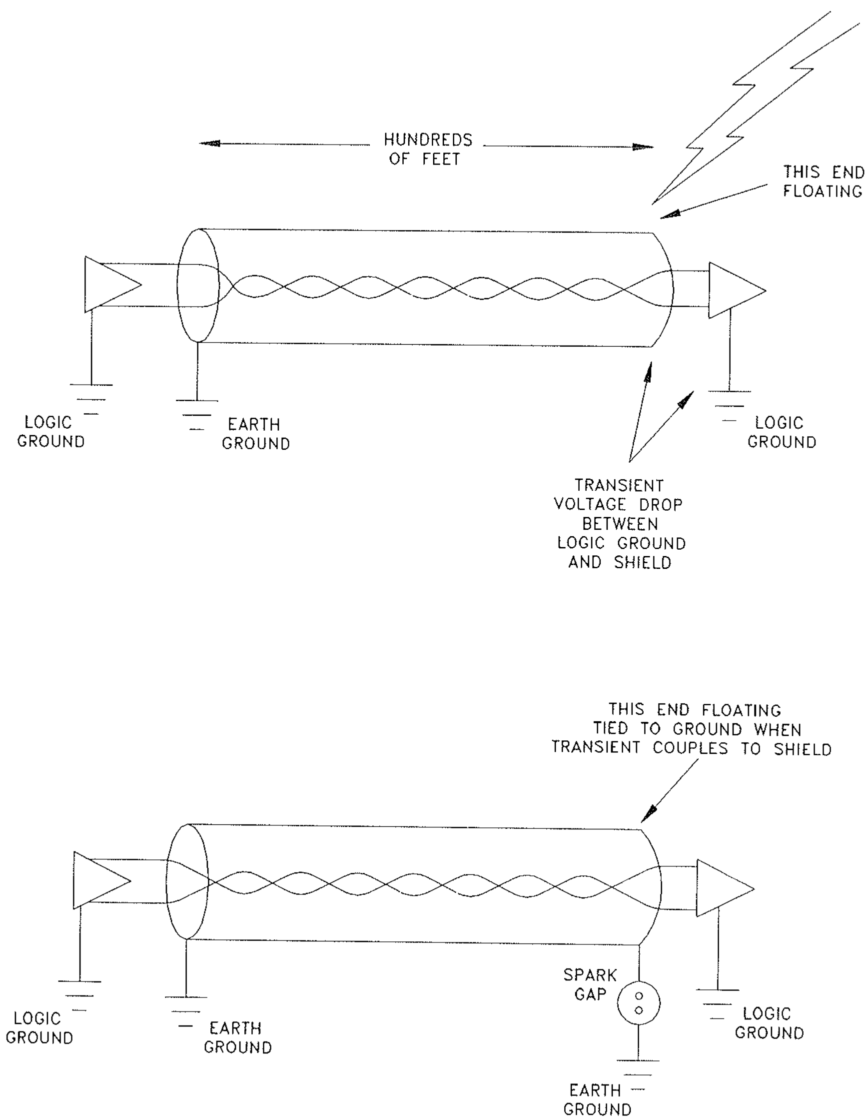


Figure 19. Use of transient suppressor to reduce transient level at ungrounded-end of single point cable ground.

of the enclosure offers the highest current carrying capacity of any conductor within the enclosure. Therefore, the cabinet should be used to advantage to minimize voltage differentials between controller elements during transient events. For example, rather than running separate grounding conductors between cable shields, circuit assembly commons, surge suppressors, and the ground rod, these various grounded elements should be interconnected with the enclosure with short, wide conductors. The enclosure serves as the primary common path between the various "grounds." In turn, the enclosure bond to the ground rod should be as short as possible and should consist of large gauge wire, such as No. 6 AWG, or wide (1/2 in. or more) strips of 20 mils thick, or greater, copper, galvanized steel, or aluminum as appropriate for electrochemical compatibility with the enclosure base metal and with the ground rod itself. Figure 20 shows examples of appropriate connections to the cabinet.

4.1.1.4 Surge Suppressor Grounds

The performance of surge suppressors, or terminal protection devices (TPD's), is critically dependent on the impedance of the current path to ground. The devices themselves exhibit some nominal characteristic impedance which is generally low relative to that associated with the inductance of the leads of the devices. To take maximum advantage of the protection properties of the devices, the total electrical path between the protected device and the ground reference point should be as short as possible. Not only should the device leads (both) be kept as short as possible, the conducting path to their ground reference point should be as short as possible also. Frequently, installers will interconnect the low sides of several protectors with a common bus wire of 10 to 12 gauge and extend this wire several inches, perhaps a foot or two, before connecting to the cabinet or other ground point. Such practices significantly reduce the effectiveness of the protectors. The suppressor common should be constructed of wide metal strips and bonded to the cabinet at the nearest feasible location. The suppressors themselves should be as close as possible to the devices or circuits being protected and should be attached with minimum length conductors.

4.1.2 The Earth Electrode

In most locations, the controller will sit on a concrete pad with direct access to the soil underneath the pad. A ground rod driven in this soil provides a connection with earth. Depending on the soil conditions in the immediate vicinity of the site, the effectiveness of this connection can vary greatly.

The basic measure of effectiveness of an earth electrode is the value in ohms of its resistance to earth. Because of the distributed nature of the earth volume into which electric energy flows, the resistance to earth is defined as the resistance between the point of connection and a very distant point on the earth. Ideally, the earth electrode system provides a zero resistance path between true earth and the point of connection. Any physically realizable configuration, however, will exhibit a finite resistance to earth.

The National Electric Code (NEC) specifies in Article 250 that a made electrode, which is defined as "... a driven pipe, driven rod, buried plate or other device approved for the purpose....", shall where practicable have a resistance to ground not to exceed 25 ohms. Although the language of the NEC clearly implies that electrodes with resistances as high as 25 ohms are to be used only as a last resort, this 25-ohm limit has tended to set the norm for grounding resistance regardless of the specific system needs.

Twenty-five ohms is not low enough for reliable fault protection. For example, 25 ohms offers only marginal personnel protection on 125 Vac systems where device fuses are rated for currents greater than 5 A. With a total grounding resistance of 25 ohms, the maximum fault current would be only 4.8 A from a 120-V line and 8.8 A from a 220-V line. Neither value of current is sufficient to clear a standard 15-A breaker or fuse. It is thus obvious that a total fault path resistance of considerably less than 25 ohms is necessary for reliable protection of personnel in the event of a fault to an object grounded only to the earth. Thus, clearly a hard-wire connection back to the main disconnect for the controller must be supplied in order to assure effective fault protection.

For lightning protection, it is difficult to establish a definite grounding resistance necessary to protect personnel. The current which flows in a direct lightning stroke is typically 20,000 A. Such currents through even 1 ohm of resistance can easily produce hazardous potentials. It is impractical to attempt to reduce the resistance from a traffic controller to earth to a value low enough to absolutely prevent the development of these potentials. Techniques other than simply achieving an extremely low resistance to ground must be employed to protect the traffic control system elements from the hazards produced by a direct stroke. Experience has shown that a grounding resistance of 5 to 10 ohms gives fairly reliable lightning protection. At some sites, resistances as low as 1 ohm or less may be achievable. The lower the resistance, the greater the protection, and therefore attempts should be made to obtain the lowest economical value of resistance.

Earth electrodes can be divided into two general types. The first type includes incidental metal objects such as water pipes,

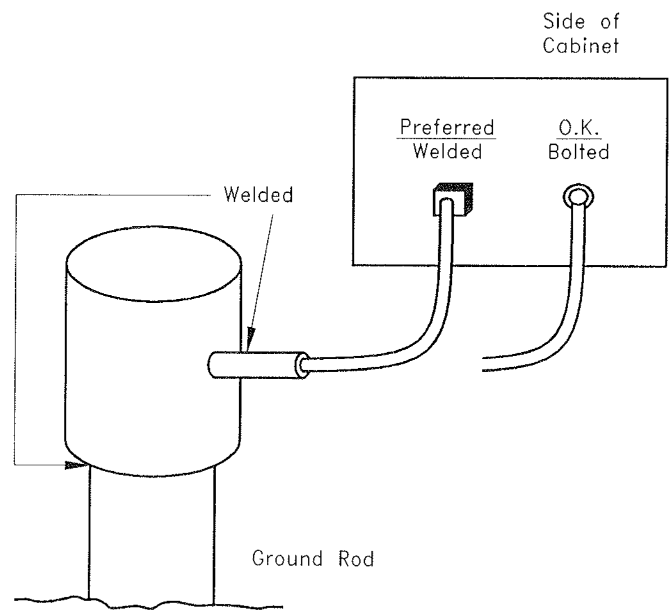


Figure 20. Illustrations of acceptable connections of the ground rod to the equipment cabinet.

water well casings, metal frameworks of buildings, and other metals imbedded in and in contact with the earth. Electrodes in this category can provide a convenient low resistance ground for the traffic control facility. (Before any of them are used, however, their resistance to earth must be carefully measured (see Section 4.1.3) to assure that effective contact with earth is made.)

The second type of earth electrode is defined by the NEC as a "made electrode" and consists of buried and interconnected bare metal rods, plates, strips, grids, and wires. Such alternatives are likely to be the primary electrodes for individual controllers.

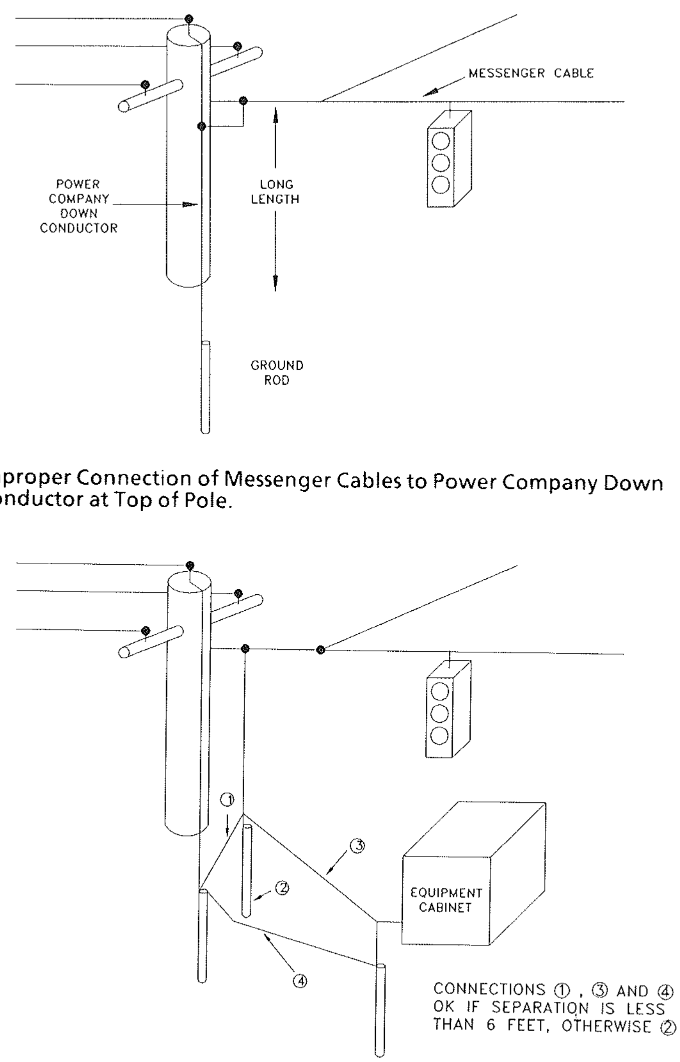
Vertically driven ground rods or pipes are the most common type of made electrode. Rods or pipes are generally used where bedrock is beyond a depth of 10 ft. Ground rods are commercially manufactured in 1/2-, 5/8-, 3/4-, and 1-in. diameters and in lengths from 5 to 40 ft. For most applications, ground rods of 1/2-, 5/8-, and 3/4-in. diameters in lengths of 6, 8, 10, 12, and 16 ft are used. Rods of iron or steel should be at least 5/8-in. in diameter and rods of nonferrous materials should not be less than 1/2-in. in diameter. Although galvanized steel rods are often used because of their low cost, copper-clad steel is preferred for most installations because the steel core provides the strength to withstand driving forces and the copper provides corrosion protection and is compatible with copper or copper-clad grounding cables. It has been found that when galvanized rods are used in close proximity to power company substations, the galanized rods will serve as sacrificial anodes and will erode because of the presence of the large copper ground system under the substation (see Section 4.1.4 on corrosion prevention).

Where bedrock is near the surface of the earth, horizontal strips of metal, solid wires, or stranded cables buried 18 to 36 in. deep may be used effectively. With long strips, reactance increases as a factor of the length with a consequent increase in impedance. A low impedance is desirable for minimizing lightning surge voltages. Therefore, several wires, strips, or cables arranged in a star pattern is preferable to one long length of conductor.

Grids and buried plates can also be used as earth electrodes; however, they are not likely to be practical at traffic control intersections. Grids are likely to be required in power substations and large power consuming facilities where large fault currents may be encountered.

There may be a number of incidental, buried, metallic objects in the vicinity of the earth electrode system. These objects should be connected to the system to reduce the danger of potential differences during lightning or fault protection; their connection will also reduce the resistance to earth of the electrode system. Such additions to the earth electrode system should include the rebar in concrete footings, buried tanks, and pipes.

Careful consideration must be given to where the connection to incidental metal objects should be made. One of the most common mistakes encountered is to tie overhead messenger cables to the power company down conductor at the top of a pole instead of at (1) the power company ground rod, (2) the controller cabinet ground rod, or (3) a ground rod specifically installed for purposes of grounding the messenger cables. The messenger cables are then tied to the signal and pedestrian crosswalk pushbutton grounds. The connection to the power company down conductor and the power company ground rod is often done, as illustrated in Figure 21, to minimize the amount of cable that must be installed. This poses two problems. First, the down conductor will have significant inductance and any transients coupled to this line will develop high transient voltage levels along the down conductor. These transients then enter the traffic control ground system causing upset or damage. Second, because the power company down conductor interconnects a huge grid, the likelihood of a transient coupling to this down conductor, and thus the controller ground system, is magnified proportionately. The solutions are to (1) tie to the power company ground system only at the power company ground rod or (2) do not tie to the power company ground system if the connection path between the controller ground rod and the power company ground rod exceeds 6 ft.



(a) Improper Connection of Messenger Cables to Power Company Down Conductor at Top of Pole.

(b) Proper Connections of Messenger Cable to Ground

Figure 21. Examples of proper and improper messenger cable grounding.

4.1.3 Measurement of Resistance-to-Earth of Earth Electrodes

The calculated resistance-to-earth of a given electrode system is based on a variety of assumptions and approximations that may or may not be met in the final installation. Because of unexpected and uncontrolled conditions that arise during installation or develop afterward, the resistance-to-earth of the installed electrode must be measured. Two commonly used methods for measuring the resistance-to-earth of an electrode are the triangulation method and the fall-of-potential method.

In the triangulation method, illustrated in Figure 22, the resistances of the electrode under test, R_x, and auxiliary electrodes, R_a, R_b, are measured two at a time. The unknown resistance is then computed from the formula:

$$R_x = \frac{(R_x + R_a) + (R_x + R_b) - (R_a + R_b)}{2} \qquad (14)$$

where the terms in the parentheses are the following measured resistances:

$$R_x + R_{a,b} = \frac{V_x^{a,b}}{I_x} \qquad (15)$$

= voltage drop from test electrode, X, to auxiliary electrode A or B divided by current entering test electrode.

For best accuracy, it is important to use auxiliary electrodes with resistances of the same order of magnitude as the unknown. The series resistances may be measured either with a bridge or with a voltmeter and ammeter. Either alternating or direct current may be used as the source of test current. For the three-point measurements, the electrodes must be at reasonable distances from each other; otherwise absurdities such as zero or even negative resistances may arise in the calculations. In measuring a single 10-ft (3-m) driven ground rod, the distance between the three separate ground electrodes should be at least 15 ft (5 m), with a preferable spacing of 25 ft (8 m) or more. For larger area grounds, which are presumably of lower resist-

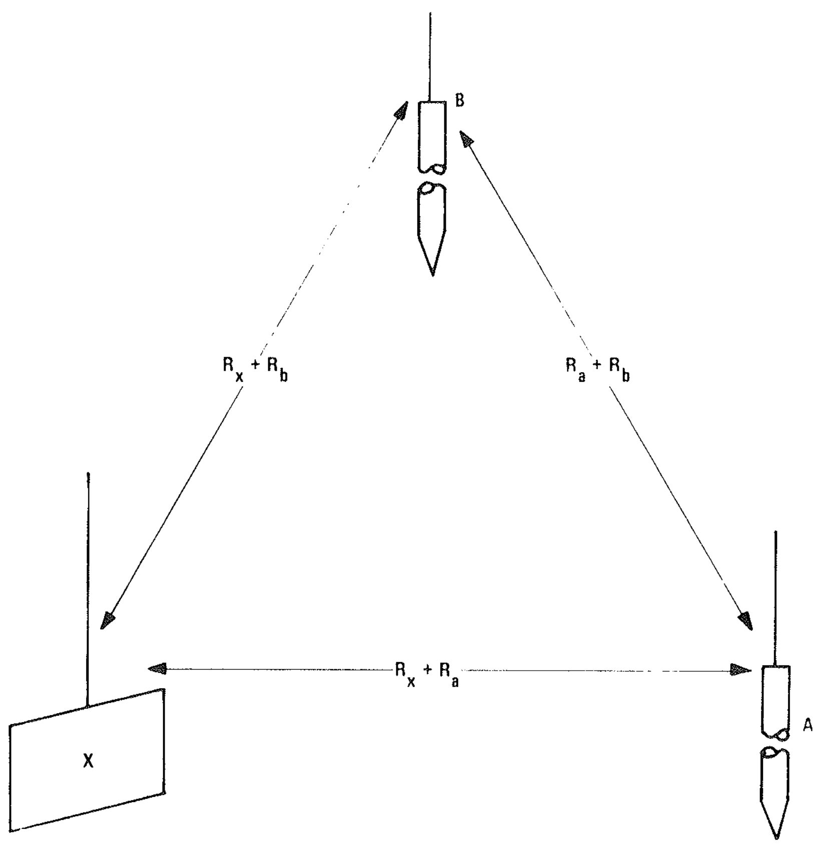


Figure 22. Triangulation method of measuring the resistance of an earth electrode. (Ref. 4.2)

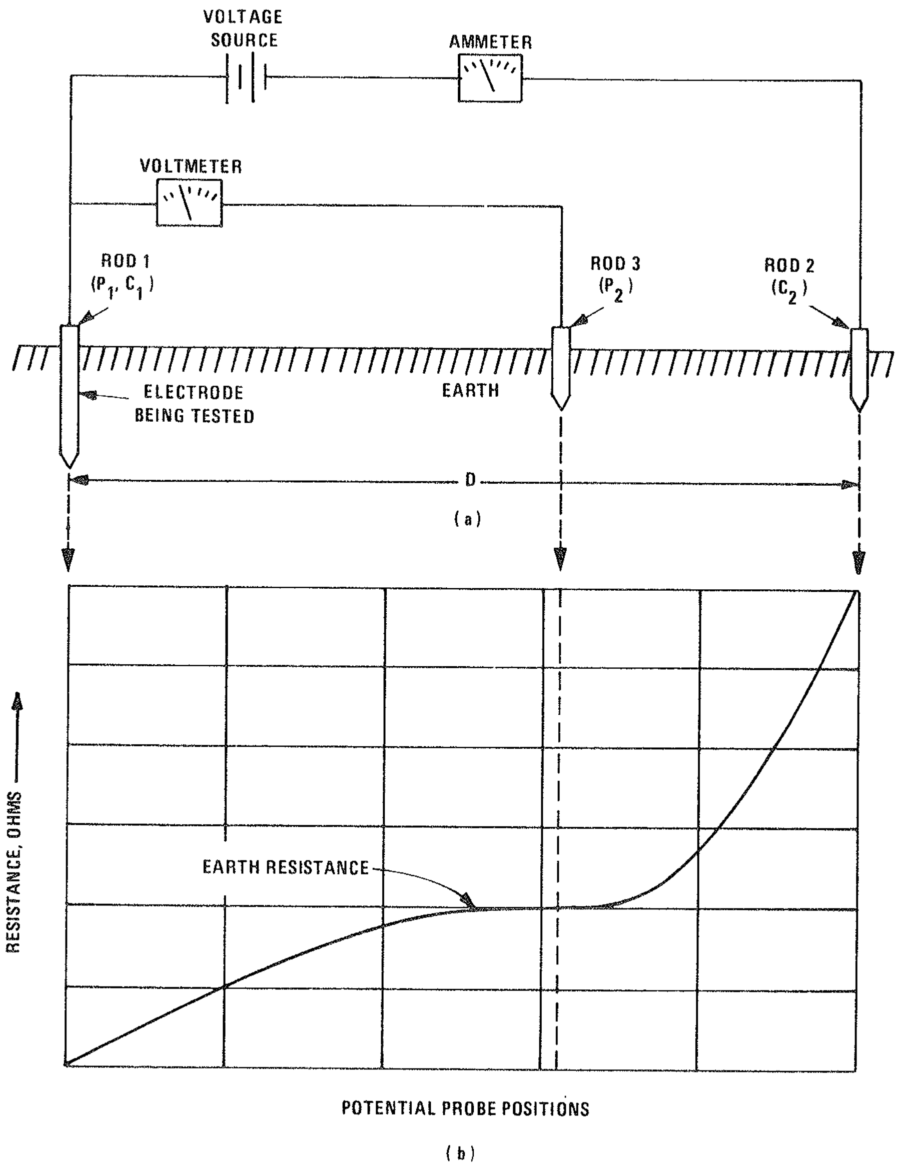


Figure 23. Fall-of-potential method for measuring the resistance of earth electrodes. (Ref. 4.3)

ance, spacing on the order of the dimensions of the ground field should be used as a minimum.

The fall-of-potential method can also be used to measure the earth electrode resistance. The fall-of-potential method involves passing a known current between the electrode under test and a current probe, C_2, as shown in Figure 23(a). The drop in voltage between the earth electrode and the potential electrode, P_2, located between the current electrodes is then measured; the ratio of the voltage drop to the known current gives a measure of the resistance. (By using a voltage measuring device—a null instrument or one having a high impedance—the contact resistance of the potential electrode will have no appreciable effect on the accuracy of the measurement.) Several resistance measurements are taken by moving the potential probe, P_2, from the position of the earth electrode along a straight line to the current probe, C_2, which is left in position. The data obtained is then plotted as resistance versus distance from the earth electrode as illustrated in Figure 23(b).

Current flow into the earth surrounding an electrode produces shells of equipotential around the electrode. A family of equipotential shells exists around both the electrode under test and the current reference probe, C_2. The sphere of influence of these shells is proportional to the size of each respective electrode. The potential probe, P_2, in Figure 23 provides an indication of the net voltage developed at the earth's surface by the combined effect of these two families of shells. If the electrode under test and the current reference probe are so close that their equipotential shells appreciably overlap, the surface voltage variation as measured by P_2 will vary as shown in Figure 24(a). Because the current flowing between the electrodes is constant for each voltage measurement, the resistance curve will have the same shape as the voltage curve. For close electrode spacings, the continuously varying resistance curve does not permit an accurate determination of resistance to be made.

By locating the current reference probe, C_2, far enough away from the electrode under test to ensure that the families of equipotential shells do not appreciably overlap, a voltage curve like that shown in Figure 24(b) will be obtained to produce the type of resistance curve shown in Figure 23. It has been shown (*4.2*) that the true value of resistance to earth corresponds to the ratio of the measured current to the potential when X is 62 percent of the distance, D, from the electrode under test to the current probe, C_2. It is important to remember that D is measured from the center of the electrode under test to the center of the current probe and that D should be large relative to the radius of the electrode under test.

Figure 25 shows an example of data taken with the fall-of-potential method. The correct resistance of 13 ohms corresponds to the potential probe location of 90 ft (27.4 m) which is 62 percent of the distance to the current probe.

Under certain soil conditions and in some locations, a well-defined resistance curve, such as Figure 25, will not be obtained. For these situations, resistance curves should be measured for several C_2 probe distances. On each earth resistance curve, mark the 0.62 C_k resistance values. The true value of the earth-electrode resistance for the site is the asymptote of the curve drawn through the 0.62 C_k values as shown in Figure 26.

The foregoing techniques for measuring earth electrode resistance are applicable, provided metal objects are not in the vicinity to alter the measurements. For typical urban intersections, access to earth may not even be possible. Close by are likely to be concrete sidewalks and roadways, bridges with metal rebar, water boxes and pipes, sign posts, building footings, building ground networks, and sewer lines. Access to earth may be

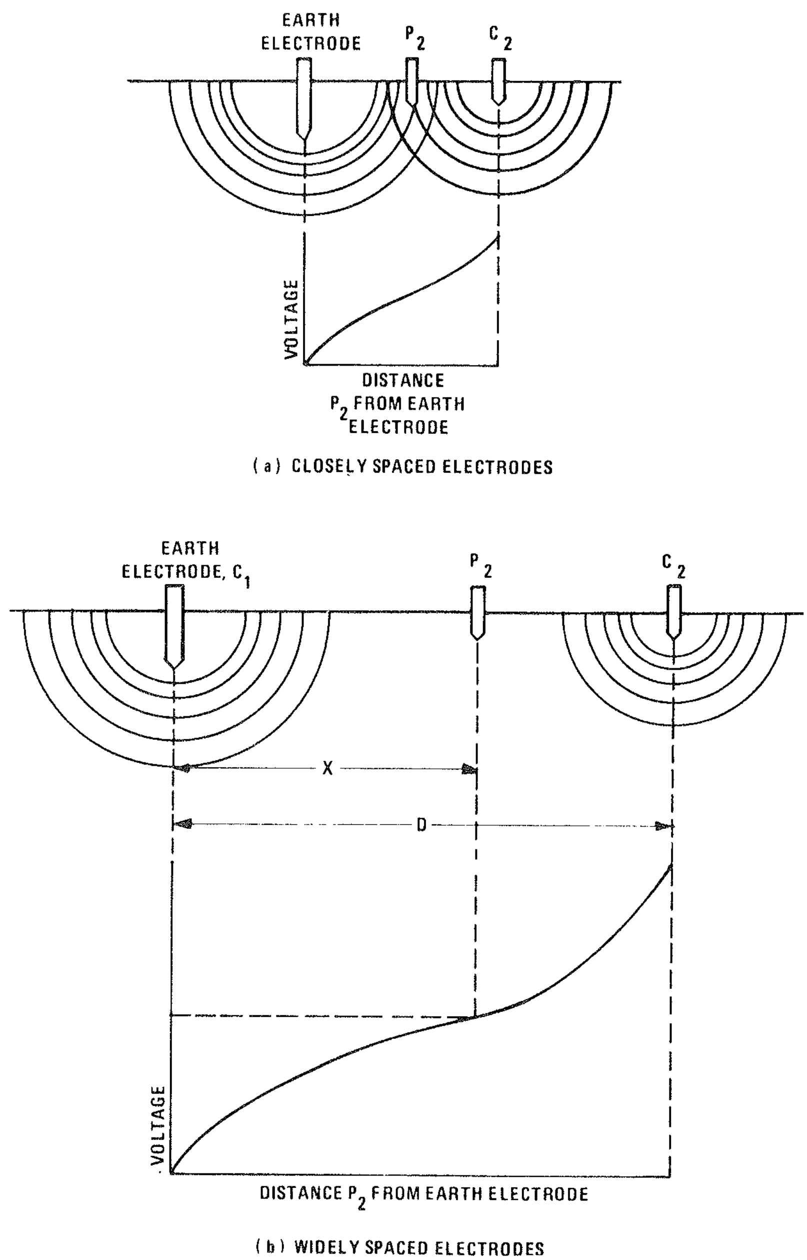


Figure 24. Effect of electrode spacing on voltage measurements. (Ref. 4.2)

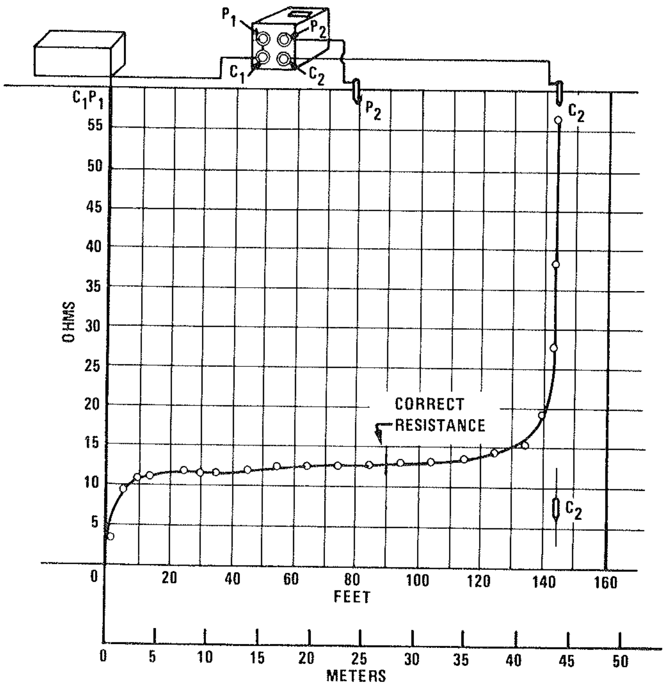


Figure 25. Resistance variations as a function of potential probe position in fall-of-potential methods. (Ref. 4.3)

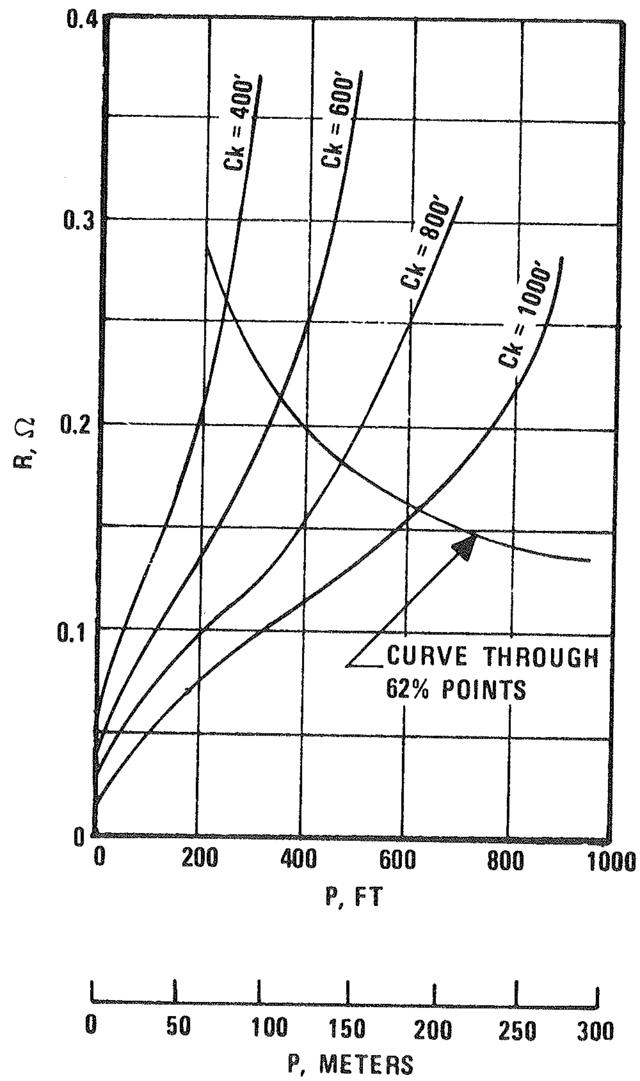


Figure 26. Earth resistance curve for a large electrode system. (Ref. 4.4)

restricted by asphalt and concrete. Although contact with soil can be made by drilling through the concrete or asphalt, this approach may be expensive. A simple alternative under difficult situations is to connect a fuse or circuit breaker to the rod under test and connect to a 120 Vac source. The fuse should be chosen such that the fuse blows or the breaker trips if the electrode resistance to earth is less than the voltage divided by the current rating of the fuse or breaker. For example, a 25-A fuse or breaker can be used if the electrode resistance to earth should be less than 5 ohms. This technique should only be performed if other methods are not available and extreme care must be used to prevent accidental shock hazards to test personnel.

4.1.4 Electrode Enhancement and Corrosion Control

Sites will be encountered where acceptable and practical numbers of driven rods, buried cables, and other available materials will not achieve the required low resistance to earth. In such situations, enhancement of the resistivity of the soil around the electrodes can be made to lower the resistance.

The resistance to earth of an electrode is directly proportional to soil resistivity and inversely proportional to the total area of contact established with the soil. For fixed land areas, additional vertical rods or horizontal cables produce diminishing returns because of increased mutual coupling effects. A straightforward enhancement method is to reduce soil resistivity. The parameters that strongly affect soil resistivity are moisture content, ionizable salt content, and porosity—the latter determining the moisture retention properties of the soil. Thus, two recommended techniques for reducing earth resistivity are increased water retention and chemical salting.

Draining of soils leaches away salts that are necessary for high conductivity and dries out the deeper layers of soil increasing resistivity. Planting of appropriate ground covers to retard runoff and to enhance the natural production of ions in the soil is useful. Surface drainage may be channeled so as to keep the electrode system moist. Maintaining moist earth over the extent of the earth electrode system will keep soil salt in solution as conductive ions. Pavement drainage water which is high in salt content can be useful for continuous salting of the earth electrode.

Reduction of the resistance of an electrode may be accomplished by the addition of ion-producing chemicals to the soil immediately surrounding the electrode. The better known chemicals in the order of preference are:

1. Magnesium sulphate ($MgSO_4$)—epsom salt.
2. Copper sulphate ($CuSO_4$)—blue vitriol.
3. Calcium chloride ($CaCl_2$).
4. Sodium chloride ($NaCl$)—common salt.
5. Potassium nitrate (KNO_3)—saltpeter.

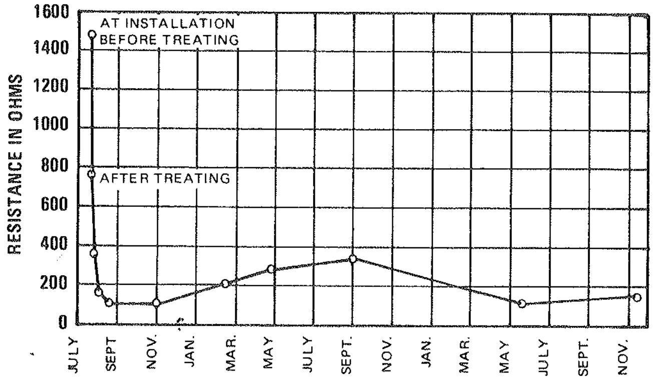


Figure 27. Effect of chemical treatment on resistance of ground rod. (Ref. 4.2)

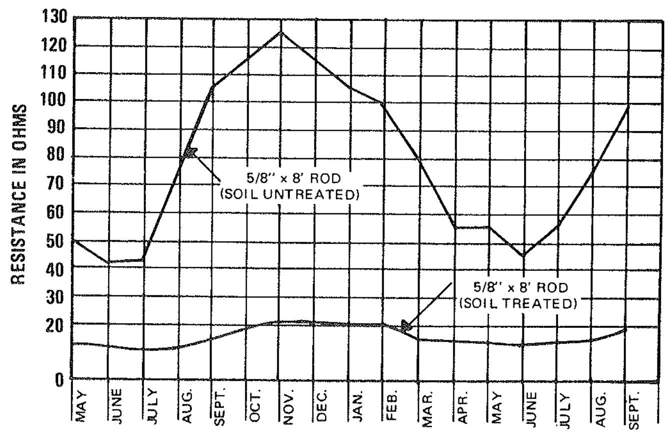


Figure 28. Seasonal resistance variations of treated and untreated ground rods. (Ref. 4.2)

Magnesium sulphate, which is the most common material used, combines low cost with high electrical conductivity and low corrosive effects on the ground electrode. The use of common salt or saltpeter is not recommended as either will require that greater care be given to the protection against corrosion. Additionally, metal objects nearby but not related to grounding will also have to be treated to prevent damage by corrosion.

Large reductions in the resistance to earth of the individual ground electrodes may be expected after chemical treatment of the earth where low resistances are difficult to obtain without chemical treatment. The initial effectiveness of chemical treatment is greatest where the soil is somewhat porous because the solution permeates a considerable volume of earth and increases the effective size of the electrode. In compact soils, the chemical treatment is not as immediately effective because the material tends to remain in its original location for a longer period of time.

The effectiveness of chemical treatment in lowering the resistance of a ground rod is illustrated by Figures 27 and 28. Chemical treatment achieves a significant initial reduction of resistance and further stabilizes the resistance variations. It also limits the seasonal variation of resistance and, additionally, lowers the freezing point of the surrounding soil.

The formulas for the resistance of earth electrodes invariably assume zero contact resistance between the electrode elements and the earth. In reality, however, the interface between the surface of the rod and the earth is far from uniform except when the earth is tamped clay or its equivalent. Granular earth (gravel, sand) makes very poor contact. Reduction of this contact resistance should have a strong effect on reducing the electrode resistance, because it is close to the electrode where current densty is high. Encasing the electrode in concrete is one approach which will improve the contact between the electrode and the earth. Effects of local variations of moisture content will also be reduced and stabilized, as the encasement material absorbs and holds moisture.

The trench method for treating the earth around a driven electrode is shown in Figure 29. A circular trench is dug about one foot deep around the electrode. This trench is filled with the soil treating material and then covered with the earth. The material should not actually touch the rod in order to provide

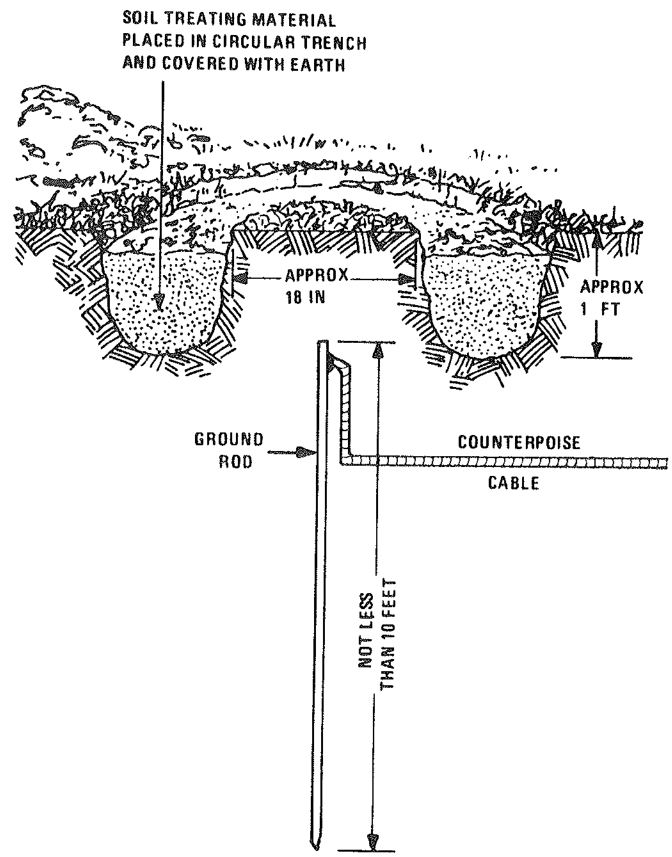


Figure 29. Trench method of soil treatment. (Ref. 4.2)

the best distribution of the treating material with the least corrosive effect.

Another method for treating the earth around a driven electrode, using magnesium sulphate and water, is shown in Figure 30. A 2-ft length (approximately) of 8-in. diameter tile pipe is buried in the ground surrounding the ground electrode filled to within 1 ft of grade level with the magnesium sulphate and watered thoroughly after installation. The 8-in. tile pipe should have a cover with holes and should be located at ground level.

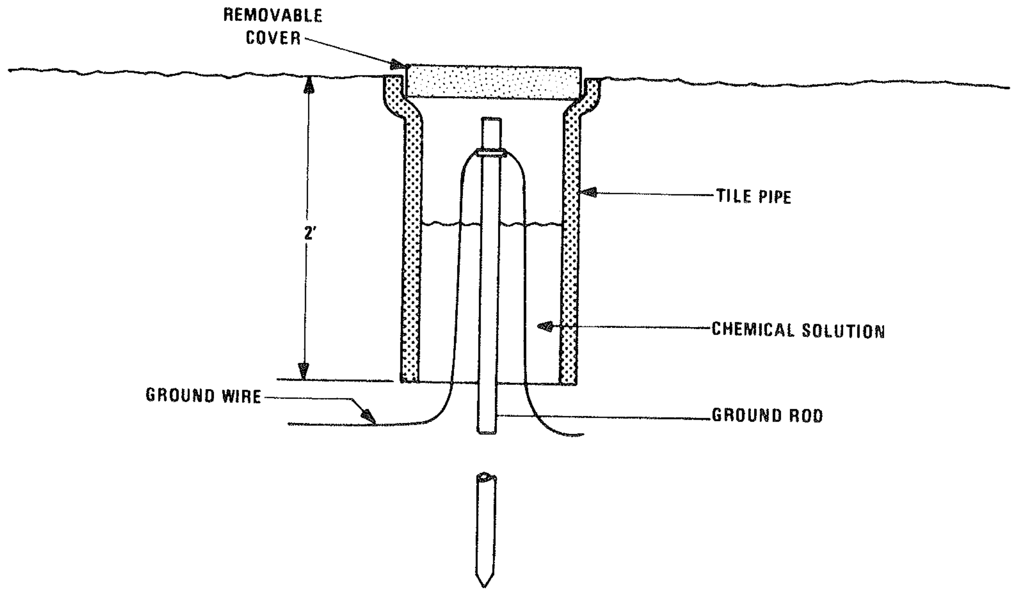


Figure 30. Alternate method of chemical treatment of ground rod. (Ref. 4.2)

Chemical treatment does not permanently alter the earth electrode resistance. The chemicals are gradually washed away by rainfall and through natural drainage. Depending on the porosity of the soil and the amount of rainfall, the period for replacement varies. Forty to ninety pounds of chemical will initially be required to maintain effectiveness for 2 or 3 years. Each replenishment of chemicals will extend the effectiveness for a longer period so that the future treatments have to be done less and less frequently.

When two metals of different types are immersed in wet or damp soil, an electrolytic cell is formed. A voltage equal to the difference of the oxidation potentials of the metals will be developed between the two electrodes of the cell. If these electrodes are connected together through a low resistance path, current will flow through the electrolyte with resultant erosion of the anodic member of the pair. Unfortunately, those factors that aid in the establishment of a low resistance to earth also foster corrosion. Low resistance soils with a high moisture level and a high mineral salt content provide an efficient electrolytic cell with low internal resistance. Relatively large currents can flow between short-circuited electrodes (such as copper ground rods connected to steel footings or reinforcing rods in buildings) and quickly erode away the more active metal of the cell. In high-resistance cells, the current that flows is less and the corrosion is less severe than in low-resistance cells.

Three basic techniques can be used to lessen the corrosion rate of buried metals. The obvious method is to insulate the metals from the soil. Insulation interrupts the current path through the electrolyte and stops the erosion of the anode. Insulation is not an acceptable corrosion prevention technique for earth electrodes. The second choice is to use cathodic protection in which sacrificial anodes or an external current supply are used to counteract the voltage developed by oxidation. Sacrificial anodes containing active metals, such as magnesium, aluminum, manganese, and others, can be buried in the earth nearby or connected directly to iron, steel or lead rods, conduit or shields. The active metals oxidize more readily than the other metals and will supply the ions required for current flow in the oxidation process. If the sacrificial anodes are replenished or replaced regularly, the life of the protected (cathodic) elements is significantly prolonged. Long buried cable runs can be protected by using active cathodic protection where the cable or cable shield is biased to approximately -0.7 to -1.2 V relative to the surrounding soil. The external dc source supplies the ionization current that would normally be provided by the oxidation of the cable shield. A layer of insulation generally covers the cable shield to prevent direct contact with the soil; however, perforations inevitably occur. Active cathodic protection is very appropriate for supplying the leakage current that would normally enter the soil through breaks in insulation caused by careless installation, settling, and jacket perforation by lightning. The third technique for reducing galvanic corrosion is avoiding the use of dissimilar metals at a site. For example, if all metals in contact with the soil are of one type (such as iron or lead or copper), galvanic corrosion is minimized. However, each of these materials has unique properties, such as weight, cost, conductivity, ductility, and strength, that makes its use desirable and, thus, none can be summarily dismissed from consideration for underground applications. Copper is a desirable material for the earth electrode system; besides its high conductivity, the oxidation potential of copper is such that it is relatively corrosion resistant. Because copper is cathodic relative to the more common structural metals, its corrosion resistance is at the expense of other metals. Galvanized iron ground rods are perhaps the best choice for traffic controllers. They will be maximally compatible with other buried metals, are probably the least costly, and their expected lifetimes are sufficient for the typical intersection. The exception is when a large copper ground system, such as a power substation ground grid is within 100 ft. In this case a copper clad rod is preferred because the galvanized rod will serve as a sacrificial anode to the copper ground system. Aluminum is likely to be a poor choice because it corrodes rapidly when in contact with concrete in the presence of moisture.

4.2 SHIELDING

Electromagnetic shielding of traffic control equipment and associated cables may be required to prevent radiated transient energy from causing upset or damage. To provide absolute protection against incident radiated radio frequency (RF) energy, traffic control equipment cabinets would need to be completely enclosed metal boxes without gaps, holes, seams or cable penetrations. Such absolute shielding can never be achieved, however, because every cabinet or enclosure must have entrance points for signaling and power, for access, and for ventilation. By constructing a completely enclosed metal box, continuously welding all enclosure joints and seams, peripherally bonding signal cable shields to the enclosure, routing power and control cables into the enclosure through entrance vaults containing filters and terminal protection devices, applying RF gaskets around covers and doors, and using "honeycomb" RF barriers over air flow ports, very high degrees of protection against radiated RF fields could be obtained. Such comprehensive measures, however, would dramatically increase the cost of the controller cabinet and, thus, must be reserved for those sites exposed to very high radiated RF environments.

As noted in the previous chapter, the RF field levels to which traffic controllers are likely to be exposed are not typically of sufficient intensity to justify the general use of completely shielded cabinets. In some locations, as for example close to airport or military radar installations or very close to broadcast towers, sufficient RF interference may be experienced in a particular controller to require enhancement of the shielding provided by the cabinet. These particular cases, however, can be dealt with on an individual basis without incurring the very large costs associated with having every traffic controller installed in an RF shielded cabinet. Numerous excellent design guides are available for technical assistance in correcting these troublesome cases (*4.4, 4.5*). This section emphasizes those straightforward steps that can be taken to utilize the features of standard cabinets, with some suggestions for enhancing their RF shielding effectiveness.

4.2.1 Cabinet Shielding

The typical traffic control equipment cabinet is made of heavy gauge steel or aluminum with all seams welded. The cabinet generally has five enclosed sides with an open bottom; it is mounted on a concrete pad and all power, communication, sensor and signal output lines enter and leave through the bottom. One side of the cabinet has an access door with a nonconductive weather strip gasket around the edge. Ventilation slots plus a ventilation fan for forced air cooling during summer months are usually located near the top of the cabinet. These various openings provide potential penetration ports for electromagnetic energy to reach susceptible circuits and devices.

As constructed, the traffic controller cabinet will provide some protection against radiated RF energy. However, it can not be assumed that the enclosure will protect internal circuits against a particular RF emitter because there will be certain frequency regions over which the enclosure can be essentially transparent to RF energy. The various openings will exhibit resonant frequencies at which energy, if present, can couple into the cabinet almost as easily as though no enclosure were present.

The lowest frequency in megahertz of minimal attenuation (or shielding) of an opening can be estimated by dividing the largest dimension, as measured in meters, into 225. To perform the estimation, first measure the largest dimension of the opening and convert to meters by multiplying by 0.0254, if in inches, or by 0.305, if in feet. Next, divide 225 by this distance. The answer is the frequency region at which significant levels of RF energy are likely to be coupled directly through the openings in the cabinet. (Coupling via cable shields can be experienced at much lower frequencies and is not predictable by this simple rule.) As an example, consider a controller cabinet with a door that is 40 in. high by 24 in. wide. The larger dimension is thus $40 \times 0.0254 = 1.02$ meters. The frequency of initial concern is thus $225/1.02 = 220$ MHz. High intensity radiated RF fields within 10 percent of this frequency should be particularly examined. For example, Channel 13 occupies the frequency band between 210 and 216 MHz. Thus, this controller may experience radiated interference if located in the vicinity of a Channel 13 broadcast tower. Where the nearby sources are at higher frequencies, as, for example, UHF TV stations, openings of smaller dimensions could allow incident energy to enter the enclosure with little or no attenuation and should be examined.

Where radiated interference conditions are encountered or are suspected to exist, certain steps, such as installing screening materials over the openings or adding RF gaskets to the mating surfaces of doors or covers, may be necessary to eliminate the problem. For example, the bottom can be closed by installing wire screening, wire mesh, or even a solid metal plate over the opening. (This bottom shield should be bonded directly to the ground rod or connected with a minimum length conductor to any ground rods present.) Other openings, such as ventilation ports, may similarly be covered with wire mesh screening to reduce coupling of RF energy. Common galvanized steel or brass screen wire can be very effective. Of the commonly available materials, 1/4-in. mesh hardware cloth with soldered crossovers is perhaps the most effective for covering the bottom. Aluminum screen wire should not be used because of the lack of solid electrical contact between the wire strands. In addition, aluminum is not electrochemically compatible with steel and serious corrosion may result, particularly if contact with concrete occurs. Any such covers must be carefully bonded to the cabinet around all sides of the opening.

If RF gaskets are added around doors or covers, the mating surfaces must be cleaned to establish intimate electrical contact between the gasket and the door and the enclosure. All nonconductive materials, such as paint, must be removed. The gaskets must be completely protected from weather, otherwise their effectiveness will be short lived. (The bonding procedures described in Section 4.3 should be followed when installing supplemental shielding.)

The most likely paths for RF energy to penetrate the controller cabinet are unshielded cables or improperly terminated shields on shielded cables. Shields of cables and conduit must be bonded to the enclosure at the point of penetration. Ideally, these bonds will establish direct contact between the enclosure and the circumference of the shield itself. If direct bonding is not possible, the added bonding conductors should be as short as possible. For nonshielded cables, metal conduit should be

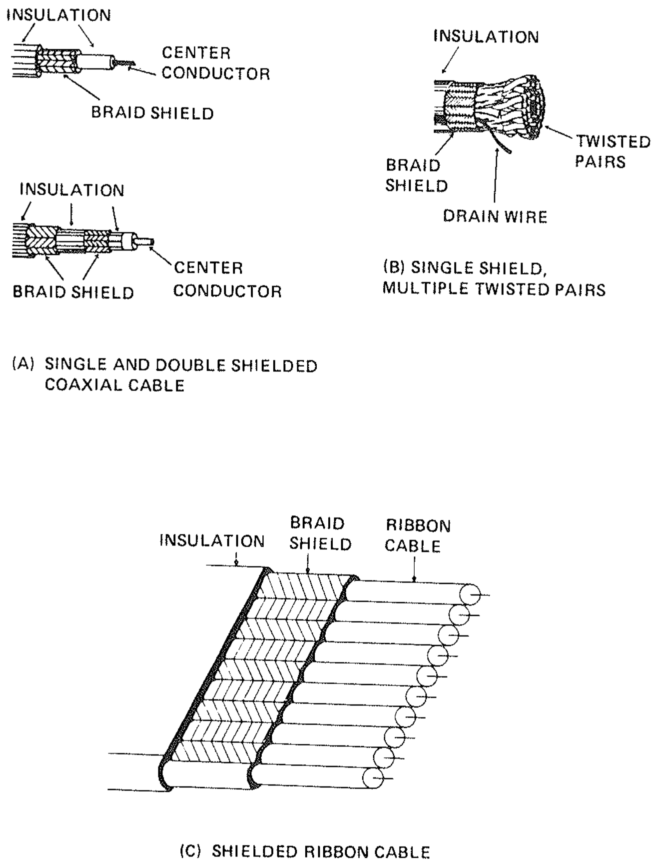


Figure 31. Illustration of braided shield cables. (Ref. 4.9)

added so that once inside the enclosure the cables remain in conduit up to the point where filters and terminal protection devices are located.

If installing supplemental conduit over unshielded cables is impractical, some reduction in cable-radiated pickup can be achieved by enclosing troublesome cables in conductive heat shrinkable tubing (*4.6*) or zippered shields (*4.7*). The user should be aware that these after-the-fact shielding measures are not as effective as using manufactured cable or installing metal conduit at original construction. They should thus be implemented only as a last resort and not routinely relied upon.

4.2.2 Cable Shielding

The principal methods of shielding cables include the use of: (1) braid, (2) flexible conduit, (3) spiral-wound shields of high permeability materials, and (4) rigid conduit. The primary types of shielded cables that are available include shielded single conductor, shielded multiconductor (bundle and ribbon), shielded-twisted pair, and coaxial. Cables are also available with single and multiple shields in many different forms and with a variety of physical characteristics.

Braid, consisting of woven or perforated material, is used for cable shielding in applications where the shield cannot be made of solid material. Several examples of cables which use braided cable shields are illustrated in Figure 31. The advantages of braided shields are flexibility, light weight, and ease of handling. However, it is to be noted that the shielding effectiveness of woven or braided materials decreases with increasing frequency because of coupling through the braid apertures, and increases with the density of the weave or number of insulated shield layers. Thus, it is important that the percent shield coverage (ratio of metal to total possible shield surface) be adequate to maintain an effective shield, particularly under conditions of cable flexing. The percent braid coverages of typical well-shielded cables range from approximately 80 to 95 percent. The higher coverage values maximize cable shielding effectiveness. Additional protection may also be provided by using cables with more than one shield.

For protection against low frequency (power frequency related) magnetic fields, an adequate shield can often be obtained by wrapping one or more layers of high permeability metal tape around the cable. Multiple layers of tape wound shields formed from silicon iron alloys, low carbon steel, or other high permeability materials can provide an effective shield against magnetically coupled transients. High permeability tape is usually available with or without adhesive backing. Also, tapes are available which incorporate both high permeability and highly conductive materials to provide shielding against both electric and magnetic fields.

Tape-wound shields find application where shield flexibility, low cost and low level RF field strengths are expected. However, the shielding effectiveness of tape wound shields is very poor, particularly when single layer wraps are used. Also, the durability of tape wound shields is questionable, particularly if frequent flexing of the cable is necessary.

Metal conduit, either solid or flexible, may be used to shield cabling and wiring from the electromagnetic environment. Solid conduit provides the highest shielding effectiveness of any cable shield because there are no apertures. Shielding effectiveness of conduit is maximized by using thick-walled tubing to reduce the diffusion of energy through the wall (*4.4, 4.10*).

For solid conduit to be effective as a shield it must be assembled properly. First, only metal conduit should be used. Second, all threaded sections should be thoroughly cleaned using emery cloth or steel wool immediately before assembly. No lubricating oil or teflon pipe sealing tape should be used on conduit threads. Third, all junction box lids must be firmly attached, preferably with a recessed lid.

Flexible conduit may provide adequate shielding at lower frequencies where the openings between links are small compared to a wavelength, but at higher frequencies these openings will seriously degrade the shielding effectiveness of the conduit. Flexible conduit is usually provided for physical protection rather than for shielding. When using flexible conduit, internal wiring should be shielded if significant levels of shielding effectiveness need to be assured.

A comparison of the characteristics of solid and braided cable shields is given in Table 5. Note that both solid shields (conduit) and multilayer braid shields will provide very high values of shielding effectiveness, whereas the protection afforded by single layer braid shields is somewhat limited. The choice of a particular type of cable shield will depend on both the electromagnetic field protection and application requirements. If both shielding and physical protection of cabling are required, solid conduit is recommended. If physical protection is not required, or if handling or installation requirements dictate the use of a flexible cable, single or multilayer braided cables will likely be the best choice.

Table 5. Comparison of solid and braided cable shields. (Ref. 4.5)

	Probable Shielding Effectiveness	Probable Durability In Vibration	Probable Corrosion Resistance	Relative Weight	Probable Contact Resistance	Tensile Strength	Relative Cost	Other Comments
SOLID SHIELDS	> 100 dB	--	--	--	--	--	--	
Ferromagnetic								
Permalloy,	Excellent	Questionable	Excellent	Thin/Light	High	High	High	
Hypernom	Excellent	Questionable	Poor	Thin/Light	Moderate	High	Low	
Steel								
Non-Magnetic								
Aluminum	Excellent	Fair	Poor	Light	High	Low	Low	
Copper	Excellent	Good	Fair	Heavy	Low	Low	Moderate	
Brass	Excellent	Good	Fair	Heavy	Moderate	Moderate	Moderate	
BRAID SHIELDS (Single Layer)	20-50 dB	--	--	--	--	--	--	See Notes 1&2
Tinned Copper	Excellent	Excellent	Excellent	Moderate	Low	Low	Low	
Nickel Plated Copper	Excellent	Excellent	Excellent	Moderate	Low	Low	Low	
Monel	Good	Questionable	Excellent	Moderate	Low	High	Moderate	
Nickel	Good	Good	Excellent	Moderate	Low	High	Moderate	
Aluminum	Excellent	Poor	Poor	Light	High	Low	Low	
Stainless Steel	Good	Questionable	Excellent	Moderate	High	High	Moderate	
MULTILAYER BRAID SHIELDS								
Double-Braid	70-100 dB	--	--	Heavy	--	--	Moderate	See Notes 1&2
Triple-Braid	90-120 dB	--	--	Very High	--	--	High	See Notes 1&2

Note: 1. Optimum braid weave angles are in the range of 30-45 degrees.
2. Braid optical coverage should be 85 percent or better.

A number of special cable shields are available which can be used in "quick fix" applications. These special shields include zipper tubing and heat shrinkable conductive materials (*4.6, 4.7*). The shielding effectiveness of these types of cable shields is low to moderate, and is primarily determined by the shielding effectiveness of the cable/connector junction. These types of cable shields should only be considered for applications where undesired effects are identified after the installation, where shielding requirements are minimal, and a low cost alternative to redesign is required.

In order for the effectiveness of a cable shield to be maintained, the shield must be properly terminated at the enclosure interface. To obtain a cable shield termination which does not degrade the effectiveness of the shield, three conditions must be satisfied: (1) the cable shield must be correctly attached to the cable connector; (2) the shielding effectiveness of the connector must be high (preferably equal to or greater than the cable shielding effectiveness); and (3) the mating connector must be correctly attached to the enclosure. A violation of any of these three conditions will permit shield "leakage" at the cable/enclosure interface.

To properly terminate a cable shield, the entire periphery of the shield should be bonded to the connector shell to minimize the penetration of RF energy through the cable shield-connector junction. Soldering to terminate shields should be avoided because of the danger of damaging conductor insulation.

A frequently used method of shield termination is shown in Figure 32. In this arrangement, the cable shield is flared so that it extends over the rear portion of the sleeve, and the crimp ring is slid into place over the sleeve. A crimping tool is then used to crimp the crimping ring onto the sleeve.

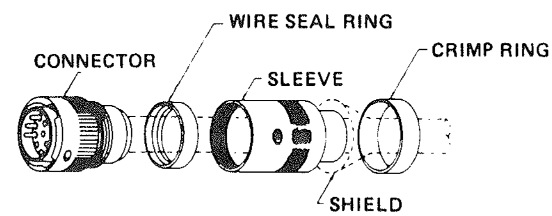


Figure 32. Shield termination using crimping. (Ref. 4.6)

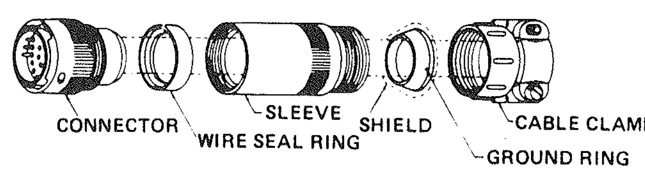
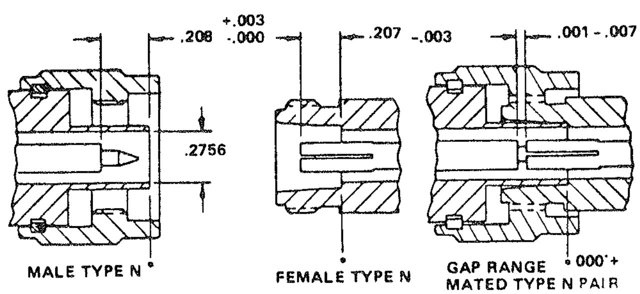


Figure 33. Shield termination using threaded assembly. (Ref. 4.6)

An alternative to crimping is shown in Figure 33. The shield is placed through the cable clamp and ground ring and then flared back over and around the ground ring. The shield may be secured to the ring with a spot tie. The ground ring is then slid into the rear of the sleeve, which has a tapered base. Tightening the cable clamp onto the end of the sleeve assures positive 360-deg bonding of the shield, and provides a strain relief for the cable.

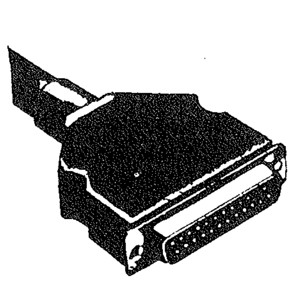
The use of silver epoxy or other synthetic conducting material is generally not recommended for shield bonding because of lack of mechanical strength. Anodized connector shells should never be used because anodizing produces an insulating layer on the metal outer surface and thus prevents the electrical contact needed for shielding.

Three basic types of connectors are commonly employed to interconnect circuit enclosures: (1) threaded connectors (single and multiconductor); (2) bayonet (single and multiconductor); and (3) friction fit (subminiature shell) and edge connectors. Figure 34 provides an illustration of each of these types of connectors. For shielding, the preferred type of connector is threaded. Threaded connectors have several advantages, including low transfer impedance (high shielding effectiveness), high environmental tolerances (e.g., tolerance to vibration), and excellent electrical characteristics. Also, threaded connectors make a continuous 360-deg bond to the mating connector. Shielding effectiveness is achieved by tightening beyond hand tight but not to the point of damage.



(a) Threaded Type N Coaxial Connector Pair. [4.11]

(b) BNC Bayonet Connector Pair. [4.12]



(c) Multiconductor Shielded Junction Shell Connector. [4.13]

Figure 34. Illustration of typical shielded connectors.

In general, bayonet and friction type connectors should be avoided for outdoor applications because they do not provide sufficient protection against moisture and other contaminants. Bayonet connectors have the advantage of quick connect/disconnect; however, their overall performance characteristics are lower than threaded connectors because of the poor bond to the mating connector.

Friction fit connectors are the least desirable type of connector because of the highly unreliable bond to the mating connectors. Friction fit connectors, however, are widely used in commercial applications because of low cost and ease of use. If friction fit connectors are employed, a positive locking mechanism, such as a screw fastener, should be added.

When interfacing to an equipment enclosure, bulkhead connectors are typically used. When mounting bulkhead connectors, the bond to the equipment enclosure should be uniform with no cracks or seams and should provide a low impedance electrical connection to the equipment shield. The area to be bonded should be clean and bare of any nonconductive finish materials and the metals to be joined, as well as that of any screws or bolts to be used, must be electrochemically compatible (Section 4.3). After installation, the joined area should be refinished with a sealant to prevent surface oxidation and to prevent water from seeping into the bonded area.

4.3 BONDING *(4.2)*

Within traffic control equipment, numerous interconnections are required to provide electric power, minimize electric shock hazards, provide lightning protection, and establish references for electronic signals. Ideally, each of these interconnections should be made so that the mechanical and electrical properties of the path are determined by the connected members and not by the connection itself. Further, the joint must maintain its properties over an extended period of time in order to prevent progressive degradation of electrical performance. Bonding is concerned with those techniques and procedures necessary to achieve a mechanically strong, low impedance electrical interconnection between metal objects and to prevent the path thus established from subsequent deterioration through corrosion or mechanical loosening.

Bonding is necessary to: (1) protect equipment and personnel from the hazards of lightning discharge; (2) establish fault current return paths; (3) establish homogeneous and stable paths for signal currents; (4) protect personnel from shock hazards arising from accidental power grounds; and (5) prevent static charge accumulation.

With proper design and implementation, bonds minimize differences in potential between points within the fault protection, signal, static discharge, and lightning protection paths of the traffic control system. Poor bonds, however, lead to a variety of hazardous and interference-producing situations. For example, loose connections in ac power lines can produce unacceptable voltage drops at the controller and the heat generated by the load current through the increased resistance of the poor joint can be sufficient to damage the insulation of the wires and produce a power line fault, or develop a fire hazard, or both. Loose or high impedance joints in signal and control lines are particularly annoying because of intermittent signal behavior such as decreases in signal amplitude, increases in noise level, or both. Poor joints in lightning protection paths can be particularly dangerous. The high current of a lightning discharge may generate several thousand volts across a poor joint. Arcs produced by the lightning discharge present both a fire and explosion hazard and may possibly be a source of upset or damage to signal and control equipment. The additional voltage developed across the joint also increases the likelihood of flashover occurring to other equipment or components.

Bonding is also important to the performance of transient and other interference control measures. For example, adequate bonding of connector shells to controller cabinets is essential to the maintenance of the integrity of cable shields and to the signal transmission properties of the cables. Interference reduction components and devices, such as filters and amplitude limiters, also must be well bonded for optimum performance. Filters, lightning arresters and other terminal protection devices must be properly bonded in order to work as intended.

Bonds can be classified as either direct or indirect. Direct bonding is the establishment of the desired electrical path between the interconnected members without the use of an auxiliary conductor. Specific portions of the surface areas of the members are placed in direct contact. Electrical continuity is obtained by establishing a fused metal bridge across the junction by welding, brazing, or soldering or by maintaining a high pressure contact between the mating surfaces with bolts, rivets, or clamps. Examples of direct bonds are the connections between lightning down conductors and the earth electrode, the mounting of an equipment chassis to the connector cabinet, and the mounting of connector shells to equipment panels or cabinets.

Properly constructed direct bonds exhibit a very low dc resistance and provide an RF impedance as low as the geometry of the bond members will permit. Direct bonding is always preferred; however, it can be used only when the two members can be connected together and can remain so without relative movement. The establishment of electrical continuity across joints, seams, hinges, or fixed objects that must be physically separated requires indirect bonding with straps, jumpers, or other auxiliary conductors.

For reasons of economy, future accessibility, or functional requirements, welding, brazing or soldering can not always be used. Bonds must then be formed by holding the mating surfaces together under high pressure. Auxiliary fasteners such as bolts, screws, rivets, or clamps are employed to apply and maintain the pressure on the surfaces. The resistance of these bonds is determined by the kinds of metals involved, the surface conditions within the bond area, the contact pressure at the surfaces, and the cross-sectional area of the mating surfaces.

Surface films will be present on practically every bond surface. The commonly used metals such as iron and aluminum readily oxidize to form surface films while copper, tin and nickel are less affected by oxide films.

If the surface films are much softer than the contact material, pressure can be applied to establish a quasimetallic contact. Harder films, however, may support all or part of the applied load, thus reducing or eliminating the conductive contact area. If such films are present on the bond surfaces, they must be removed before joining the bond members. Even when metal flow processes are used in bonding, these surface films must be removed or penetrated to permit a homogeneous metal path to be established.

Foreign particulate matter on the bond surface will further impair bonding. Dirt and other solid matter such as high resistance metal particles or residue from abrasives can act as

Table 6. Resistance of direct bonds between selected metals.

Bond Composition	Resistance μΩ)
Brass-Brass	6
Aluminum-Aluminum	25
Brass-Aluminum	50
Brass-Steel	150
Aluminum-Steel	300
Steel-Steel	1500

Notes: Apparent Bond Area: 1 in2 (6.45 cm2)
Fastener Torque: 100 Inch-pounds
Adapted from Reference 4.14.

stops to prevent metallic contact. Therefore, all such materials must be thoroughly removed from the surfaces prior to joining the bond members.

The hardness of the bond surfaces also affects the contact resistance. Under a given load, the softer metals will undergo greater plastic deformation and establish greater metallic contact. Likewise, at a junction between a soft and a hard material, the softer material will tend to conform to the surface contours of the harder material and will provide a lower resistance contact than would be afforded by two hard materials. Table 6 shows how the resistance of 1 sq in. (6.45 sq cm) bonds varies with the type of metals being joined.

Both mating surface areas should be as large as practical for several reasons. Large surface areas maximize the cross-sectional area of the path for current and, correspondingly, maximize the total number of true metallic contacts between the surfaces. In addition to the obvious advantage of decreased bond resistance, the current crowding which can occur during power fault conditions or under a severe lightning discharge is lessened. Such current crowding produces a higher effective bond resistance than is present during low current flow. The increased bond resistance raises the voltage drop across the junction to even higher values and adds to the heat generated at the junction by the heavy current flow. Large bond areas not only lessen the factors that contribute to heat generation, they also distribute the heat over a larger metallic area which facilitates its removal. Further advantages of a large area bond are that it likely provides greater mechanical strength and will be less susceptible to corrosion.

Direct bonds may be either permanent or semipermanent in nature. Permanent bonds may be defined as those intended to remain in place for the expected life of the installation and are not required to be disassembled for inspection, maintenance, or system modifications. Joints that are inaccessible by virtue of their location should be permanently bonded and appropriate steps taken to protect the bond against deterioration.

In terms of electrical performance, welding is the ideal method of permanent bonding. The intense heat (in excess of 4,000°F) involved is sufficient to boil away contaminating films and foreign substances. A continuous metallic bridge is formed across the joint; the conductivity of this bridge typically approximates that of the bond members. The net resistance of the bond is

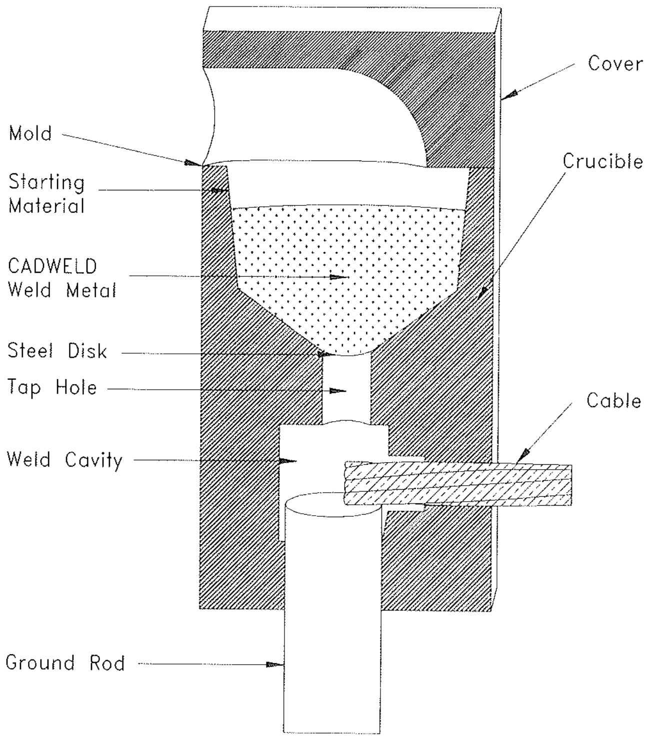


Figure 35. Illustration of Cadweld exothermic welding technique. (Ref. 4.8)

Table 7. Additional material that Cadweld process is applicable. (Ref. 4.8)

Common Steel
Stainless Steel
Steel Rail
Copper-Clad Steel
Galvanized and Bethanized Steel
Wrought Iron
Commercially Pure Iron
Cast Iron
Brass
Bronze
Monel
Nichrome
Chromax
Silicon Bronze
Columbium
Niobium

essentially zero because the bridge is very short relative to the length of the bond members. The mechanical strength of the bond is high; the strength of a welded bond can approach or exceed the strength of the bond members themselves. Because no moisture or contaminants can penetrate the weld, bond corrosion is minimized. The erosion rate of the metallic bridge should be comparable to that of the base members; therefore, the lifetime of the bond should be as great as that of the bond members.

Welding should be used whenever practical for permanently joined bonds. Although welding may be a more expensive method of bonding, the reliability of the joint makes it very attractive for bonds which will be inaccessible once assembly and installation are completed. Most metals encountered in normal construction can be welded with one of the standard welding techniques such as gas, electric arc, Heliarc, and exothermic.

An excellent example of an exothermic welding technique is the Cadweld process (*4.8*) illustrated in Figure 35. The Cadweld process is a method of making electrical connections of copper-to-copper or copper-to-steel with no outside source of heat required. Premeasured amounts of powdered metals (copper oxide and aluminum) are placed into an especially molded graphite crucible and ignited using a flint igniter. The reduction of the copper oxide by the aluminum (exothermic reaction) produces molten copper and aluminum oxide slag. Besides copper, the Cadweld process is applicable to the other materials given in Table 7. Exothermic welding techniques are preferred for making connections between ground rods and metal controller cabinets because bolts have a tendency to work loose. When using exothermic welding techniques, never mix materials from different manufacturers, and use molds and crucibles designed for the specific wire and ground rod sizes and materials to be connected.

Brazing to include silver soldering is another metal flow process for permanent bonding. In brazing, the bond surfaces are heated to a temperature above 800°F but below the melting point of the bond members. A filler metal with an appropriate flux is applied to the heated members which wets the bond surfaces to provide intimate contact between the brazing solder and the bond surfaces. As with higher temperature welds, the resistance of the brazed joint is essentially zero. However, because brazing frequently involves the use of a metal different from the primary bond members, particular care must be taken to protect the bond from deterioration through corrosion.

Soft soldering is an attractive metal flow bonding process because of the ease with which it can be applied. Relatively low temperatures are involved and it can be readily employed with several of the high conductivity metals such as copper and tin. With appropriate fluxes, aluminum and other metals can be soldered. Properly applied to compatible materials, the bond provided by solder is nearly as low in resistance as one formed by welding or brazing. Because of its low melting point, however, soft solder should not be used as the primary bonding material where higher currents may be present. For this reason, soldered connections are not permitted by the National Electrical Code in grounding circuits for fault protection. Similarly, soft solder is not permitted for interconnections between elements of lightning discharge paths (*4.2*). In addition to its temperature limitation, soft solder exhibits low mechanical strength and tends to crystallize if the bond members move while the solder is cooling. Therefore, soft solder should not be used if the joint must support mechanical loading, and the tendency toward crystallization must be recognized and proper precautions observed when applying soft solder.

Soft solder can be used effectively in a number of other ways, however. For example, it can be used to "tin" surfaces prior to assembly to assist in corrosion control. Soft solder can be used effectively for the bonding of seams in shields and for the joining of circuit components together and to the signal reference plane associated with the circuit. Soft solder can be combined with mechanical fasteners. By heating the joint enough to melt the solder, a low resistance filler metal is provided which augments the path established by the fasteners; in addition, the solder provides a barrier to keep moisture and contaminants from reaching the mating surfaces.

In many applications, permanent bonds can not be used. For example, if equipment must be removed from enclosures or moved to other locations, ground leads and other connections must be broken. Often, equipment covers must be removable to facilitate adjustments and repairs. Under such circumstances, a permanently joined connection could be highly inconvenient to break and would limit the operational flexibility of the system. Besides offering greater flexibility, less permanent bonds may be easier to implement, require less operator training, and require fewer specialized tools.

The most common semipermanent bond is the bolted connection because it provides flexibility and accessibility. The bolt (or screw) should serve only as a fastener to provide the necessary force to maintain the 1,200 to 1,500 lb/sq in. pressure required between the contact surfaces for satisfactory bonding (*4.2*). Except for the fact that metals are generally necessary to provide the required tensile strength, the fastener does not have to be conductive. Although the bolt or screw threads may provide an auxiliary current path through the bond, the primary current path should be established across the metallic interface and not through the fastener itself. Because of the poor reliability of screw thread bonds, self-tapping screws should never be used as the sole bond. Likewise, Tinnerman nuts, because of their tendency to vibrate loose, should not be used for securing screws or bolts.

The size, number, and spacing of the fasteners should be sufficient to establish the required bonding pressure over the entire joint area. The pressure exerted by a bolt will be concentrated in the immediate vicinity of the bolt head. However, large, stiff washers can be placed under the bolt head to increase the effective contact area. Because the load is distributed over a larger area, the tensile load on the bolt should be raised by increasing the torque. The nomograph of Figure 36 may be used to calculate the necessary torque for the size bolts to be used. Where the area of the mating surfaces is so large that unreasonably high bolt torques are required, more than one bolt should be used. For very large mating areas, rigid backing plates should be used to distribute the force of the bolts over the entire bond area.

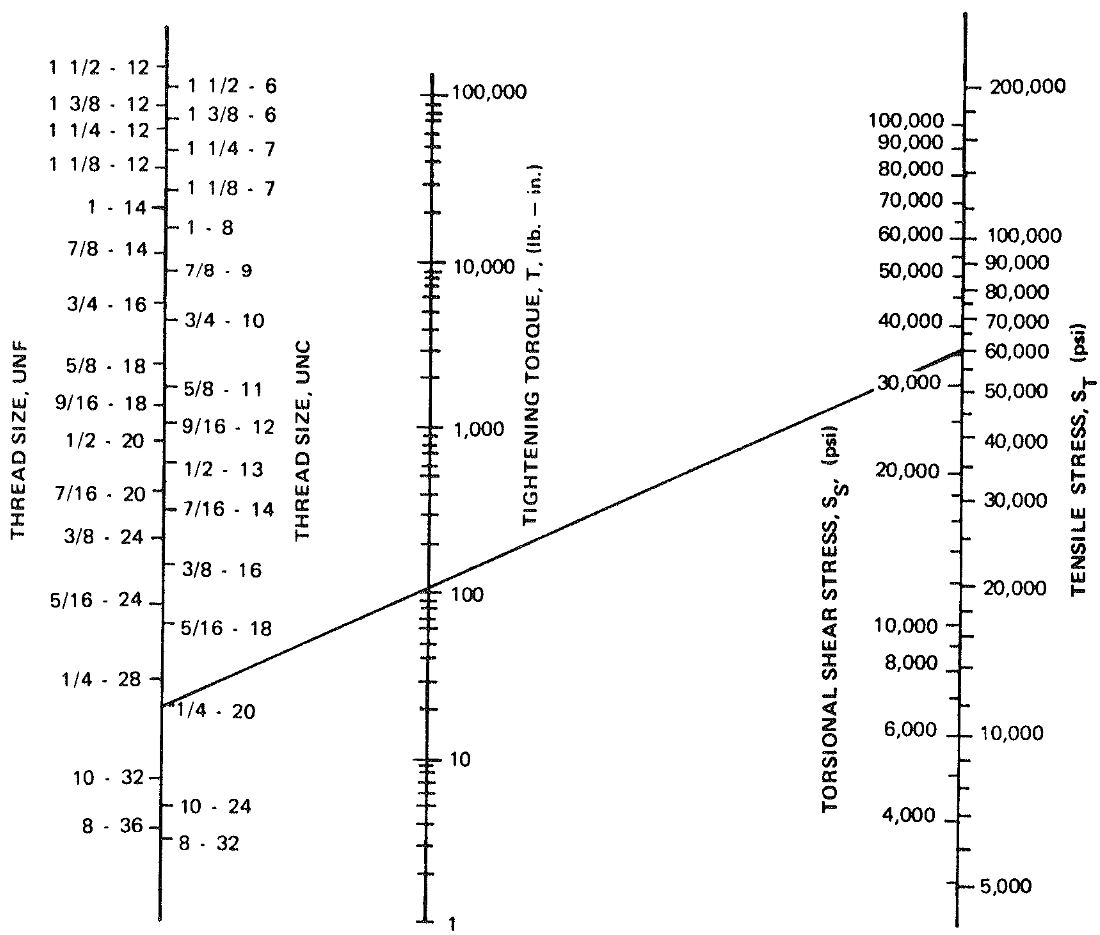


Figure 36. Nomograph for torque on bolts. (Ref. 4.15)

Riveted bonds are less desirable than either bolted connections or joints bridged by metal flow processes. Rivets lack the flexibility of bolts without offering the degree of protection against corrosion of the bond surface that is achieved by welding, brazing, or soldering. The chief advantage of rivets is that they can be rapidly and uniformly installed with manual or automatic tools.

Table 8 shows comparative ratings of the most commonly used bonding methods. In this table a rating from zero to 10 is assigned to each method for each performance parameter. A rating of 10 means that the method is suitable from the standpoint of the specific parameter listed in the extreme left-hand column of the table. Lower ratings mean that the method is less suitable. A zero rating implies the method is a poor choice, while a dash means that it does not apply.

A 100 percent consistency in ratings is impossible because any given method may vary widely in workmanship. A low-rated method, expertly performed, will work better than a high-rated, poorly performed method. When using the table assume that all methods are equally well implemented. Operational requirements or equipment construction may preclude direct bonding. When physical separation is necessary between the element of the equipment, auxiliary conductors must be incorporated such as bonding straps or jumpers. Such straps are commonly used for the interconnection of circuit board signal references to the controller enclosure and for bonding the enclosure to the ground rod. Bond straps or cables are also used to prevent static charge buildup and to connect metal objects to lightning down conductors to prevent flashover.

In many applications, braided straps must be used instead of solid straps because they offer needed flexibility. It has been shown that the impedance of a braided copper strap and a solid copper strap are virtually the same (*4.17*). However, because the strands are exposed, braided straps are more susceptible to corrosion; thus, braided straps may be undesirable for use in traffic control equipment because of weather exposure or because of condensation.

To achieve an effective and reliable bond, the mating surfaces must be free of any foreign materials, such as dirt, filings, and preservatives, and nonconducting films, such as paint, anodizing, oxides and other metallic films. Various mechanical and chemical means can be used to remove the different substances that may be present on the bond surfaces. After cleaning, the bond should be assembled or joined as soon as possible to minimize recontamination of the surfaces. After completion of the joining process, the bond region should be sealed with appropriate protective agents to prevent bond deterioration through corrosion of the mating surfaces.

Solid materials such as dust, dirt, filings, lint, sawdust, and packing materials impede metallic contact by providing mechanical stops between the surfaces. They can affect the reliability of the connection by fostering corrosion. Dust, dirt, and lint will absorb moisture and will tend to retain it on the surface. They may even promote the growth of molds, fungi, and bacteriological organisms which give off corrosive products. Filings of foreign metals can establish tiny electrolytic cells which will greatly accelerate the deterioration of the surfaces.

The bond surface should be cleaned of all such solid materials. Mechanical means such as brushing or wiping are generally sufficient. Care should be exercised to see that all materials in grooves or crevices are removed. If a source of compressed air is available, air blasting is an effective technique for removing solid particles if they are dry enough to be dislodged.

Paints, varnishes, lacquers, and other protective compounds along with oils, greases and other lubricants are nonconductive and, in general, should be removed from the bond region. Commercial paint removers can be used effectively. Lacquer thinner works well with oil-based paints, varnishes, and lacquer. If chemical solvents can not be used effectively, mechanical removal with scrapers, wire brushes, power sanders, sandpaper, or sand blasters should be employed. When using mechanical techniques, care should be exercised to avoid removing excess material from the surfaces. Final cleaning should be done with a fine sandpaper, such as 400-grit, or steel wool. After all of the organic material is removed, abrasive grit or steel wool filaments should be brushed or blown away. A final wipe down with denatured alcohol, dry cleaning fluid, or lacquer thinner should be done to remove any remaining oil or moisture films.

CAUTION

Many paint solvents such as lacquer thinner and acetone are highly flammable and toxic in nature. They should never be used around open flames and adequate ventilation must be present. Inhalation of the fumes must be prevented.

Many metals are plated or coated with other metals or are treated to produce surface films to achieve improved wearability or provide corrosion resistance. Metal platings such as gold, silver, nickel, cadmium, tin, and rhodium should have all foreign solid materials removed by brushing or scraping and all organic materials removed with an appropriate solvent. Because such platings are usually very thin, acids and other strong etchants should not be used. Once the foreign substances are removed, the bond surfaces should be burnished to a bright, shiny condition with fine steel wool or fine grit sandpaper. Care must be exercised to see that excessive metal is not removed. Finally, the surfaces should be wiped with a cloth dampened in denatured alcohol or dry cleaning solvent and allowed to dry before completing the bond.

Chromate coatings such as iridite 14, iridite 18P, oakite 36, and alodine 1000 offer low resistance as well as provide corrosion resistance. These coatings do not need to be removed. Many aluminum products are anodized for appearance and corrosion resistance. Because these anodic films are excellent insulators, they must be removed prior to bonding. Those aluminum parts to be electrically bonded either should not be anodized or the anodic coating must be removed from the bond area.

Oxides, sulfides, sulfates, and other corrosion by-products must be removed because they restrict or prevent metallic contact. Soft products such as iron oxide and copper sulfate can be removed with a stiff wire brush, steel wool, or other abrasives. Removal down to a bright metal finish is generally adequate. When pitting has occurred, refinishing of the surface by grinding or milling may be necessary to achieve a smooth, even contact surface. Some sulfides are difficult to remove mechanically and chemical cleaning and polishing may be necessary. Oxides of aluminum are clear and thus the appearance of the surface can not be relied upon as an indication of the need for cleaning. Although the oxides are hard, they are brittle and roughening of the surface with a file or coarse abrasive is an effective way to prepare aluminum surfaces for bonding.

Table 8. Ratings of selected bonding techniques. (Ref. 4.16)

		Thermal					Chemical	Mechanical							
												Screws			
		Solder	Braze	Gas or Arc Weld	Exothermic Weld	Spot Weld	Conductive Adhesive	Bolts	Crimp	Rivets	Clamps	Wire	Terminal	Twisted Wires	Wire Nuts
Electrical Properties	Low Resistance	9	10	10	10	10	3	9	9	9	8	9	9	9	9
	Resistance Stability	10	10	10	10	10	7	8	9	9	5	7	9	5	8
	Voltage Drop	9	10	10	10	10	5	9	9	10	8	8	9	5	8
	Current Capacity	5	10	10	10	9	1	9	9	9	8	9	9	8	9
Mechanical Properties	Pulloff Force	8	10	10	10	10	1	9	9	9	9	3	10	2	8
	Low Creep	9	10	10	10	10	5	9	9	9	8	3	8	2	8
	Strength	6	10	10	10	7	4	9	9	10	8	5	9	4	8
Conductor Applica- bility	Solid Wire	10	10	10	10	10	10	10	10	5	9	10	-	9	10
	Stranded Wire	9	9	8	9	0	9	9	10	2	9	2	-	9	10
	Aluminum Wire	5	2	1	8	0	2	9	8	4	9	4	-	1	6
	Bus Bars and Structures	8	8	8	9	9	6	9	7	10	7	-	10	-	-
Environ- mental	High Tempera- ture	3	9	10	10	10	1	8	9	4	5	7	8	5	7
	Low Temperature	9	10	10	10	10	5	8	9	5	5	8	8	7	7
	Thermal Shock	8	9	10	10	10	7	9	8	4	5	2	8	2	8
	Vibration	6	7	10	10	9	1	7	9	5	4	2	9	1	7
	Corrosive Atmosphere	9	10	10	10	10	5	6	9	8	3	7	9	4	8
	Aging	9	10	10	10	10	5	8	8	8	7	7	8	7	8
Cost Economy	Tooling	7	4	3	4	4	9	8	8	7	10	9	10	10	10
	Process	6	5	5	5	5	8	5	9	8	10	10	10	10	10
Accessi- bility in Assembly	Method Needs Little Space	8	5	4	5	8	8	8	9	8	9	9	9	10	8
	Ease of Repair	8	6	5	5	9	9	9	9	7	9	10	10	10	9

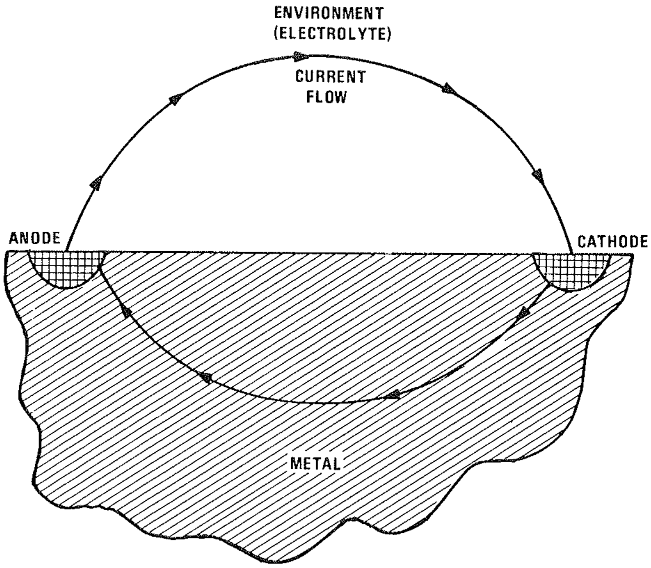


Figure 37. Basic diagram of the corrosion process. (Ref. 4.2)

Table 9. Standard electromotive series. (Ref. 4.18)

Metal	Electrode Potential* (Volts)
Magnesium	2.37
Aluminum	1.66
Zinc	0.763
Iron	0.440
Cadmium	0.403
Nickel	0.250
Tin	0.136
Lead	0.126
Copper	-0.337
Silver	-0.799
Palladium	-0.987
Gold	-1.50

NOTE: *Signs of potential are those employed by the Amer. Chem. Soc.

After cleaning of the mating surfaces, the bond members should be assembled or attached as soon as possible. Assembly should be completed within 30 min if at all possible. If more than 2 hours is required between cleaning and assembly, a temporary protective coating must be applied. Of course, this coating must also be removed before completing the bond.

The bond surface must be kept free of moisture before assembly and the completed bond must be sealed against the entrance of moisture into the mating region. Acceptable sealants are paint, silicone rubber, grease, and polysulfates. Where paint has been removed prior to bonding, the completed bond should be repainted to match the original finish. Excessively thinned paint should be avoided; otherwise, the paint may seep under the edges of the bonded components and impair the quality of the connection.

Corrosion is the deterioration of a substance (usually a metal) because of a reaction with its environment. Most environments are corrosive to some degree. Those containing salt sprays and industrial contaminants are particularly destructive. Bonds exposed to these and other environments must be protected to prevent deterioration of bonding surfaces to the point where the required low resistance connection is destroyed.

The basic diagram of the corrosion process for metal is shown in Figure 37. The requirements for this process to take place are that (1) an anode and a cathode must be present to form an electrochemical cell and (2) a complete path for the flow of direct current must exist. These conditions occur readily in many environments. On the surface of a single piece of metal, anodic and cathodic regions can be present because of impurities, rain boundaries and grain orientations, or localized stresses. These anodic and cathodic regions are in electrical contact through the body of metal. The presence of an electrolyte or conducting fluid completes the circuit and allows the current to flow from the anode to the cathode of the cell.

Anything that prevents the existence of either of these conditions will prevent corrosion. For example, in pure water, hydrogen gas will accumulate on the cathode to provide an insulating blanket to stop current flow. Most water, however, contains dissolved oxygen which combines with the hydrogen and permits corrosion to proceed. This principle of insulation is employed in the use of paint as a corrosion preventive. Paint prevents moisture from reaching the metal and thus prevents the necessary electrolytic path from being established.

The oxidation of metal involves the transfer of electrons from the metal to the oxidizing agent. In this process of oxidation, an electromotive force (EMF) is established between the metal and the solution containing the oxidizing agent. A metal in contact with an oxidizing solution containing its own metal ions establishes a fixed potential difference with respect to every other metal in the same condition. The set of potentials determined under a standardized set of conditions, including temperature and ion concentration in the solution, is known as the EMF (or electrochemical) series. The EMF series (with hydrogen as the reference potential of 0 volts) for the more common metals is given in Table 9. The importance of the EMF series is that it shows the relative tendencies of metals to corrode. Metals high in the series react more readily and are thus more prone to corrosion. The series also indicates the magnitude of the potential established when two metals are coupled to form a cell. The farther apart the metals are in the series, the higher the voltage between them. The metal higher in the series will act as the anode and the one lower will act as the cathode. When the two metals are in contact, loss of metal at the anode will occur through oxidation to supply the electrons to support current flow. This type of corrosion is defined as galvanic corrosion. The greater the potential difference of the cell, i.e., the greater the dissimilarity of the metals, the greater the rate of corrosion of the anode.

The EMF series is based on metals in their pure state—free of oxides and other films—in contact with a standardized solution. Of greater interest in practice, however, is the relative ranking of metals in a typical environment with the effects of surface films included. This ranking is referred to as the galvanic series. The most commonly referenced galvanic series is given in Table 10. This series is based on tests performed in seawater and should be used only as an indicator where other environments are of concern.

Galvanic corrosion in the atmosphere is dependent largely on the type and amount of moisture present. For example, corrosion will be more severe near the seashore and in polluted industrial environments than in dry rural settings. Condensate near the seashore or in industrial environments is more conductive even under equal humidity and temperature conditions because of increased concentrations of sulfur and chlorine compounds. The higher conductivity means that the rate of corrosion is increased.

When joints between dissimilar metals are unavoidable, the anodic member of the pair should be the largest of the two. For a given current flow in a galvanic cell, the current density is greater for a small electrode than for a larger one. The greater the current density of the current leaving an anode, the greater is the rate of corrosion as illustrated by Figure 38. As an example, if a copper strap or cable is bonded to a steel column, the rate of corrosion of the steel will be low because of the large anodic area. On the other hand, a steel strap or bolt fastener in contact with a copper plate will corrode rapidly because of the relatively small anode area of the cell.

Paint or metallic platings used for the purpose of excluding moisture or to provide a third metal compatible with both bond members should be applied with caution. When they are used, both members must be covered as illustrated in Figure 39. Covering the anode alone must be avoided. If only the anode is covered, at imperfections and breaks in the coating, corrosion will be severe because of the relatively small anode area. All such coatings must be maintained in good condition.

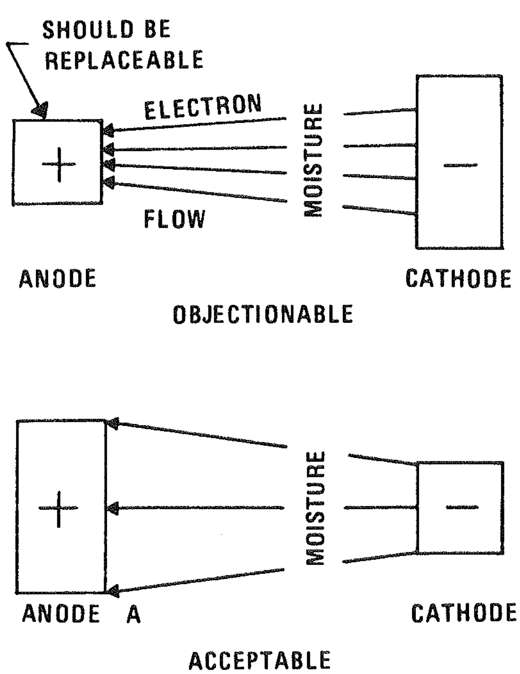


Figure 38. Anode-to-cathode size at dissimilar junctions. (Ref. 4.2)

Table 10. Galvanic series of common metals and alloys in seawater. (Ref. 4.19)

(ANODIC OR ACTIVE END)
Magnesium
Magnesium Alloys
Zinc
Galvanized Steel or Iron
1100 Aluminum
Cadmium
2024 Aluminum
Mid Steel or Wrought Iron
Cast Iron
Chromium Steel (active)
Ni-Resist (high-Ni cast iron)
18-8 Stainless Steel (active)
18-8 Mo Stainless Steel (active)
Lead-tin Solders
Lead
Tin
Nickel (active)
Inconel (active)
Hastelloy B
Manganese Bronze
Brasses
Aluminum Bronze
Copper
Silicon Bronze
Monel
Silver Solder
Nickel
Inconel
Chromium Steel
18-8 Mo Stainless Steel
Hastelloy C
Chlorimet 3
Silver
Titanium
Graphite
Gold
Plantinum
(CATHODIC OR MOST NOBLE END)

Those personnel involved with making bonds must be thoroughly familiar with the techniques and procedures required. Where bonds are to be welded, for example, work should be performed only by qualified welders. No additional training should be necessary because standard welding techniques appropriate for construction purposes are generally sufficient for establishing electrical bonds. Qualified welders should be used where brazed connections are to be made.

Whichever bonding method is determined to be the best for a given situation, the mating surfaces must be cleaned of all foreign material and substances which would preclude the establishment of a low resistance connection. Next, the bond members must be carefully joined employing techniques appropriate to the specific method of bonding. Finally, the joint must be finished with a protective coating to ensure continued integrity

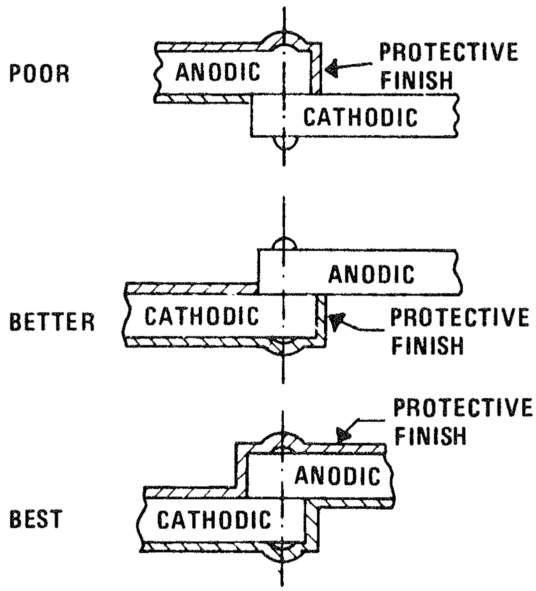


Figure 39. Techniques for protecting bonds between dissimilar metals. (Ref. 4.2)

of the bond. The quality of the junction depends on the thoroughness and care with which these three steps are performed. In other words, the effectiveness of the bond is influenced greatly by the skill and conscientiousness of the individual making the connection. Therefore, this individual must be aware of the importance of electrical bonds and must have the necessary expertise to correctly implement the method of bonding chosen for the job.

4.4 TERMINAL PROTECTION DEVICES

Because of the severity of lightning-induced transients, the ac power, communications, and signal input/output terminals will require the installation of terminal protection devices (TPD's) to divert the high energy transients safely to ground rather than to the input/output terminals of sensitive circuitry. A number of devices exist for the protection of traffic control equipment input, output, and power supply terminals. Terminal protection devices include amplitude limiting devices, such as spark gaps, varistors, and semiconductor diodes, and frequency selective devices, such as low-pass and high-pass filters. Terminal protection device selection depends on the sensitivity, frequency response, and criticality of the terminal to be protected, the expected transient threat levels, and cost.

A single amplitude limiter is generally insufficient to provide protection needed against the wide range of threat conditions facing traffic control equipment. In the remainder of the subsections, information is given on amplitude limiters and filters. Then, in Section 4.4.3, hybrid suppressors which combine multiple amplitude limiters with filters to provide protection over a broad threat range are discussed.

4.4.1 Amplitude Limiters

Amplitude limiters operate by clamping, or limiting, the voltage across a device or by limiting the current through a device.

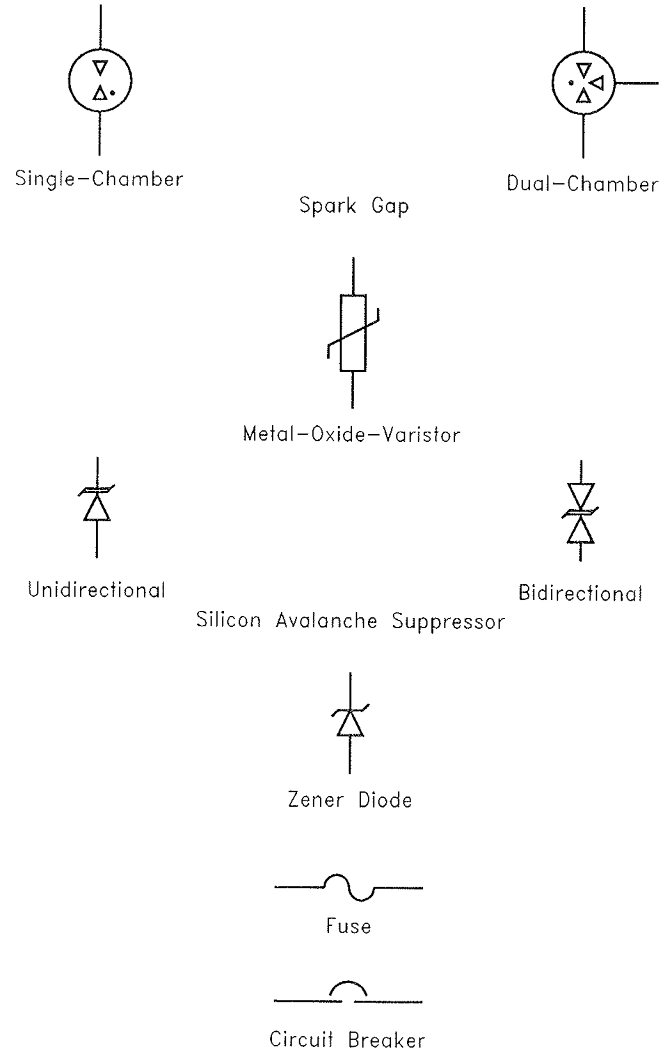


Figure 40. Common symbols for amplitude limiters.

Symbols for commonly used amplitude limiters are given in Figure 40. Examples of voltage limiters are spark gaps, varistors, silicon avalanche suppressors, and zener diodes. Examples of current limiting devices are fuses and circuit breakers. Voltage limiters are necessary to protect circuits against fast rising, high energy lightning transients because fuses and circuit breakers do not operate fast enough to suppress the fast rising leading edge of the transient. Fuses and circuit breakers are required to clear slow surges or ground faults where fast response is not needed. Fuses and circuit breakers are also necessary to prevent high energy, slow surges from causing damage to the high speed, low energy amplitude limiters.

4.4.1.1 Spark Gaps

Spark gaps for circuit level lightning protection are usually gas-filled spark gaps rather than carbon-block-type devices. Gas-filled tube spark gaps consist of metal electrodes that are hermetically sealed to a glass or ceramic body and are filled with gas having a high insulation resistance and low dielectric loss. Generally, the gas is doped with a trace amount of a radioactive

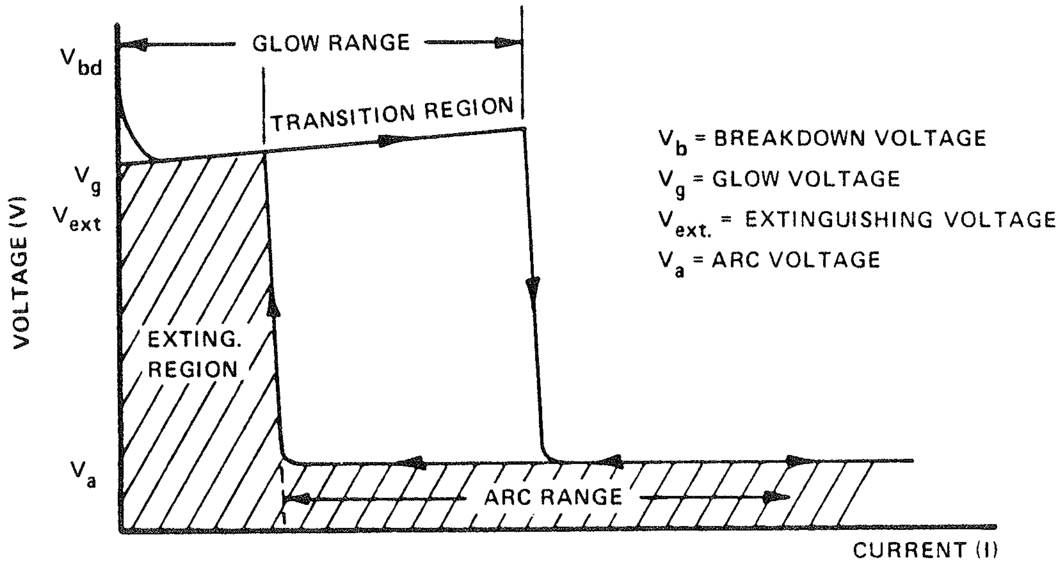


Figure 41. DC holdover curve for spark gap. (Ref. 4.20)

element, such as Krypton, to speed arc formation and to stabilize the gap dc breakdown voltage. As the voltage across the gap increases, a point is reached where the gas ionizes and the gap conducts, with the voltage across the gap dropping to its arc voltage. As the current through the gap decreases, a point is reached where the gap extinguishes and returns to its normally off condition. Figure 41 illustrates the dc holdover curve for a gas-filled tube spark gap and shows how the gap fires and extinguishes with applied voltage and current.

For rapidly rising transients, the point at which the spark gap fires is different from the dc breakdown voltage. Figure 42 presents the firing voltage with varying transient rate-of-rise for a typical spark gap.

Spark gaps have the following general advantages over other types of suppressors: (1) high insulation resistance—typically greater than 10^{12} ohms in the offstate; (2) low-to-high power and energy dissipation capabilities; (3) high durability; (4) insensitivity to environmental changes because of hermetically sealed gas-filled electrodes; and (5) no potential fire hazard presented as with carbon block devices.

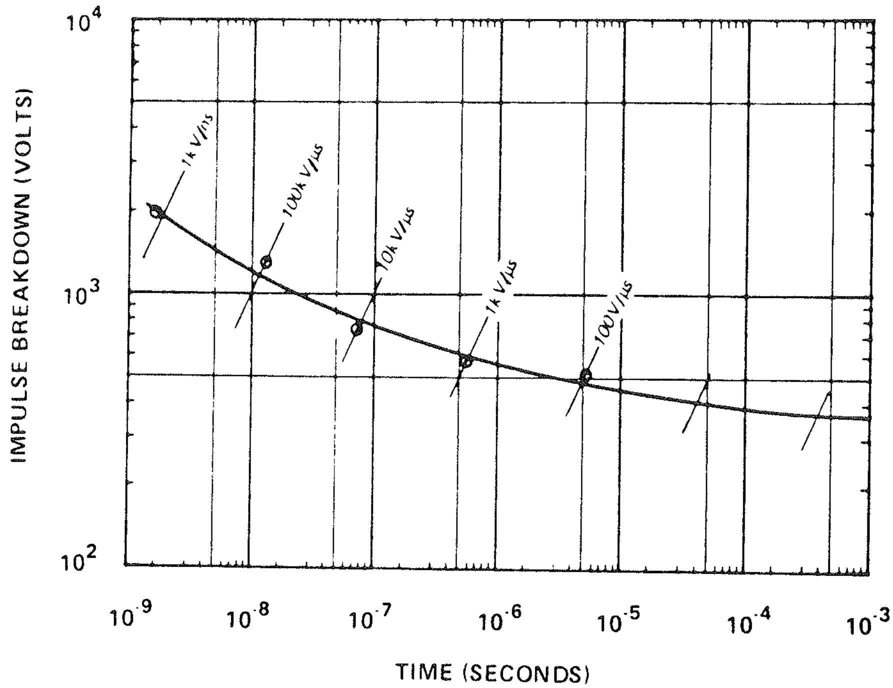
The primary disadvantages of spark gaps are: (1) slow turn on times (the firing voltage of spark gaps is typically four to five times the dc breakdown voltage for transient rates of rise on the order of an expected fast rising lightning pulse; (2) high dc breakdown voltages—typically greater than 100 volts; and (3) firing and turn-off characteristics, particularly ac follow current effects when protecting low frequency (60 cycle) power lines.

To illustrate ac follow current in low frequency power circuits, consider the example shown in Figure 43. In this example a transient occurs near the beginning of a positive half cycle. The spark gap fires and continues to conduct until the voltage across the gap and the current through the gap fall to the extinguishing region. The gap must be capable of dissipating the entire ac follow current. The energy dissipation requirements in this case can be much more severe than the transient energy dissipation requirements.

Multiple-electrode spark gaps can be used to protect balanced lines or paired circuits. The advantage of the multiple-electrode, common-chamber unit over individual two electrode units is that the common-mode voltage difference, which occurs when one gap fires after another, is substantially reduced. Figure 44(a) illustrates the use of two separate two-electrode spark gaps and Figure 44(b) shows a three-electrode common-chamber gap. The development of common-mode voltage in a three-electrode common-chamber gap versus a pair of two-electrode gaps is shown in Figure 44(c) and 44(d). In the three electrode common-chamber gap, when an arc discharge begins from the first electrode to ground, the resultant gas ionization immediately causes an arc discharge to begin from the second electrode to ground. The time between the two arc formations is much shorter with the three electrode, common-chamber gap than with the pair of two-electrode devices and, thus, the common-mode voltage is of much shorter duration.

In summary, when using or selecting spark gaps the following considerations are important:

1. *Impact of Transient Rise Time.* For slow rates of rise, the device will break down at or near the dc breakdown rating. For fast rising transients, the inherent breakdown delay of the gap can result in a significant increase in breakdown potential (overshoot). The resulting overshoot pulse will generally be of large amplitude, short time duration, and low energy content relative to that of the incoming transient pulse. Therefore, the overshoot pulse may be attenuated by following the spark gap with either a low-pass filter or a fast response amplitude limiter (zener or silicon avalanche suppressor) which has been isolated from the gap by a series impedance or a length of transmission line. An additional benefit can be derived from capacitive input low-pass filters, which can limit the rise time and therefore decrease the amount of spark gap overshoot. Overshoot can be reduced by using high speed (radioactively ionized) spark gaps with minimum lead lengths, although the superior performance comes at a higher cost.



RATE OF RISE	RANGE OF BREAKDOWN	AVERAGE BREAKDOWN
DC	333-421	369
100V/µs	420-680	515
1.4k V/µs	510-690	585
10k V/µs	640-850	739
100k V/µs	2kV @ s.2kV/ns	1033
1.1k V/ns	1.2 @ 1.1	1900

Figure 42. Typical volt-time curves for spark gap. (Ref. 4.20)

2. *Impact of Lead Inductance.* Appreciable inductance in the leads used to connect a spark gap to the circuit terminals to be protected will increase the amount of overshoot and, in some extreme cases, may even inhibit the gap from firing. Ideally, leadless spark gaps should be purchased and mounted in special holders. In no instance should the total lead length exceed 2 in. (1 in. per lead) and the use of low inductance leads, such as braided straps, is advisable.

3. *Extinguishing and Follow Current Considerations.* When using a spark gap on dc or ac power lines, it must be capable of extinguishing conduction after arcing and must be capable of handling the follow current delivered by the line before extinction (*4.20*). In a dc power line application, a spark gap whose current is limited to the glow region by an impedance in series with the gap (for instance a high dc system source impedance) and across whose terminals the dc system voltage is less than the glow voltage will extinguish following initiation of an arc by an electrical surge. If the dc system voltage is greater than the glow voltage, even though the gap current is in the glow region, the spark gap will fail to extinguish and will continue to draw glow current from the system source. It may overheat and eventually destroy itself. If the gap current is not limited to the glow region, the dc system voltage must be less than the arc voltage for the gap to extinguish following initiation of an arc. If the gap does not extinguish, it will continue to draw arc current from the system source and will destroy itself. Thus, in dc power applications, the current through the gap must be limited by a series resistance to allow the gap to extinguish.

In an ac power circuit, this extinguishing problem usually does not exist because the gap voltage and current return to zero after each half cycle. The gap voltage is brought to a point below both the glow and arc voltages and the gap extinguishes. However, an ac power circuit presents the alternate problem of follow current. In ac applications, the fired spark gap will conduct during the remainder of the half cycle or until the voltage across the gap and the current through the gap brings it into the region which permits extinction. The extinguishing behavior of a protector can be affected by overheated electrodes, caused either by high surge currents above the gap ratings or excess follow current which may prevent extinguishing and cause repeated firing in following half cycles. The follow current, because of its possible long duration, can also cause deterioration of the spark gap electrodes resulting in erratic breakdown performance. Deposition of the sputtered electrode material on the interior walls of the insulator of the device also causes some decrease of insulation resistance and a rise in electrode-to-electrode capacitance. In ac circuit applications where voltage transients routinely fire a protective gap, the degradations caused by follow current can alter or destroy the device after a period of time.

4. *Noise Generation Considerations.* The large voltage drop, which occurs during the quick breakdown transition of a spark gap, can cause a significant amount of broadband noise to be generated. To prevent potential circuit upset from this broadband noise source, spark gaps followed by filters on the output leads should be used.

Spark gaps are not recommended for use on ac power lines if the 60-Hz power line frequency is used for system timing purposes. Spark gap firing can significantly distort the ac line voltage waveform which can not be easily corrected. High energy metal oxide varistors should be used in place of spark gaps in these situations.

5. *Device Failure Considerations.* There are two primary failure modes for spark gaps. The first mode of failure is a loss of gas pressure resulting from a leak in the gas chamber seal. Loss of pressure usually results in an increase in the breakdown voltage of the gap. The second failure mode is a deterioration of the gap electrodes resulting either from large follow current or an excessive number of gap firings. The typical results of this failure mode are erratic gap breakdown characteristics. Neither of the two primary failure modes results in a significant change in the device's impedance and normal signal transfer is usually unaffected. Consequently, there will be no clear indication of failure, which implies the need for periodic testing of spark gaps to detect subtle deteriorations of their performance characteristics.

A list of current spark gap manufacturers is given in Table 11.

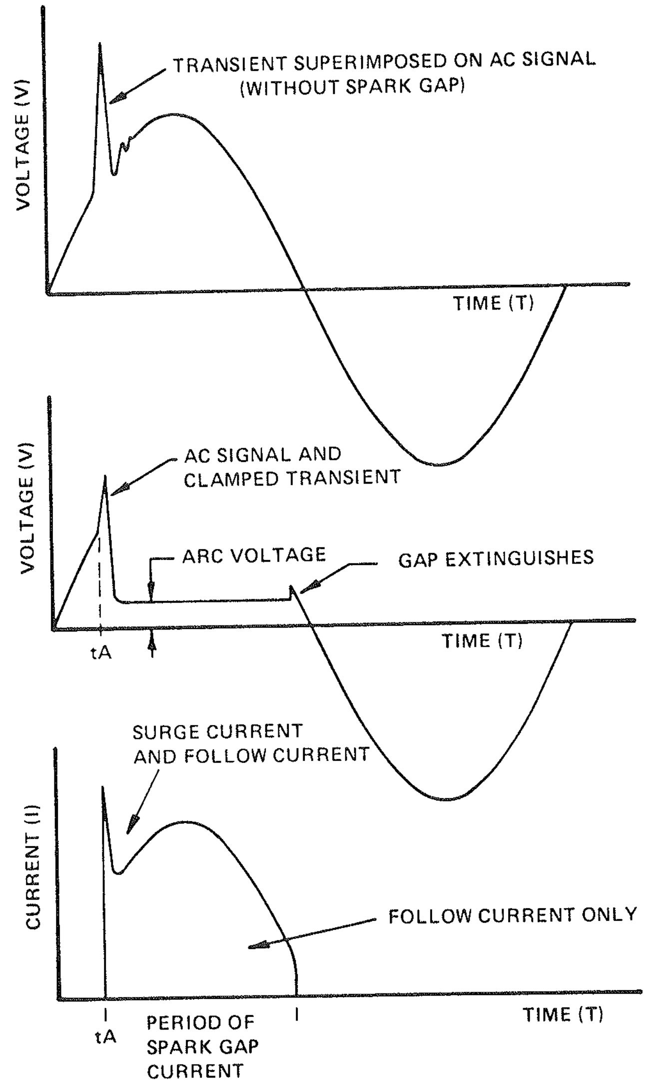


Figure 43. AC follow current for spark gap. (Ref. 4.20)

4.4.1.2 Varistors

Varistors are variable resistance devices whose resistance decreases as the voltage across the device increases. The resistance generally decreases in an exponential manner, and varistors are often classified by their degree of nonlinearity, given by the term α. The current-voltage relation of the device determines the value of α and this relation is given by:

$$I = KV^{\alpha} \qquad (16)$$

where: I = current through the device, V = voltage across the device, K = arbitrary constant of proportionality, and α = degree of nonlinearity.

Ordinary resistors have an $\alpha = 1$. The higher the value of α the better the clamping capability of the device. Silicon rectifiers and diodes generally have the largest values, followed by metal oxide varistors, selenium rectifiers, and silicon carbide varistors. In general, most transient suppressors, except spark gaps, can be characterized by an α value. The current-voltage curves of various suppressors, illustrating the various α values of typical devices, are given in Figure 45. Silicon carbide varistors and selenium rectifiers find little application in transient protection circuitry because of their low α values in comparison with MOV's and semiconductor diodes. A low α value results in excessive leakage current when placed across a line at normal operating voltages and high clamping voltage levels. These low α devices find primary application when used as current limiting resistors with spark gaps to assist in mitigating ac follow current effects.

Metal oxide varistors (MOV's) are composed primarily of zinc oxide with small amounts of bismuth, cobalt, manganese and other metal oxides. The structure of the body consists of a matrix of conductive zinc oxide grains separated by insulating grain boundaries providing PN junction (diode) characteristics. At low voltages the boundaries do not conduct. As the voltage across the MOV increases, the resistance decreases in an exponential manner. A typical varistor voltage versus current (V-I) characteristic curve is illustrated in Figure 46. Note the uniform bidirectional operation of the device and the sharp turn on characteristics.

MOV's have the following advantages:

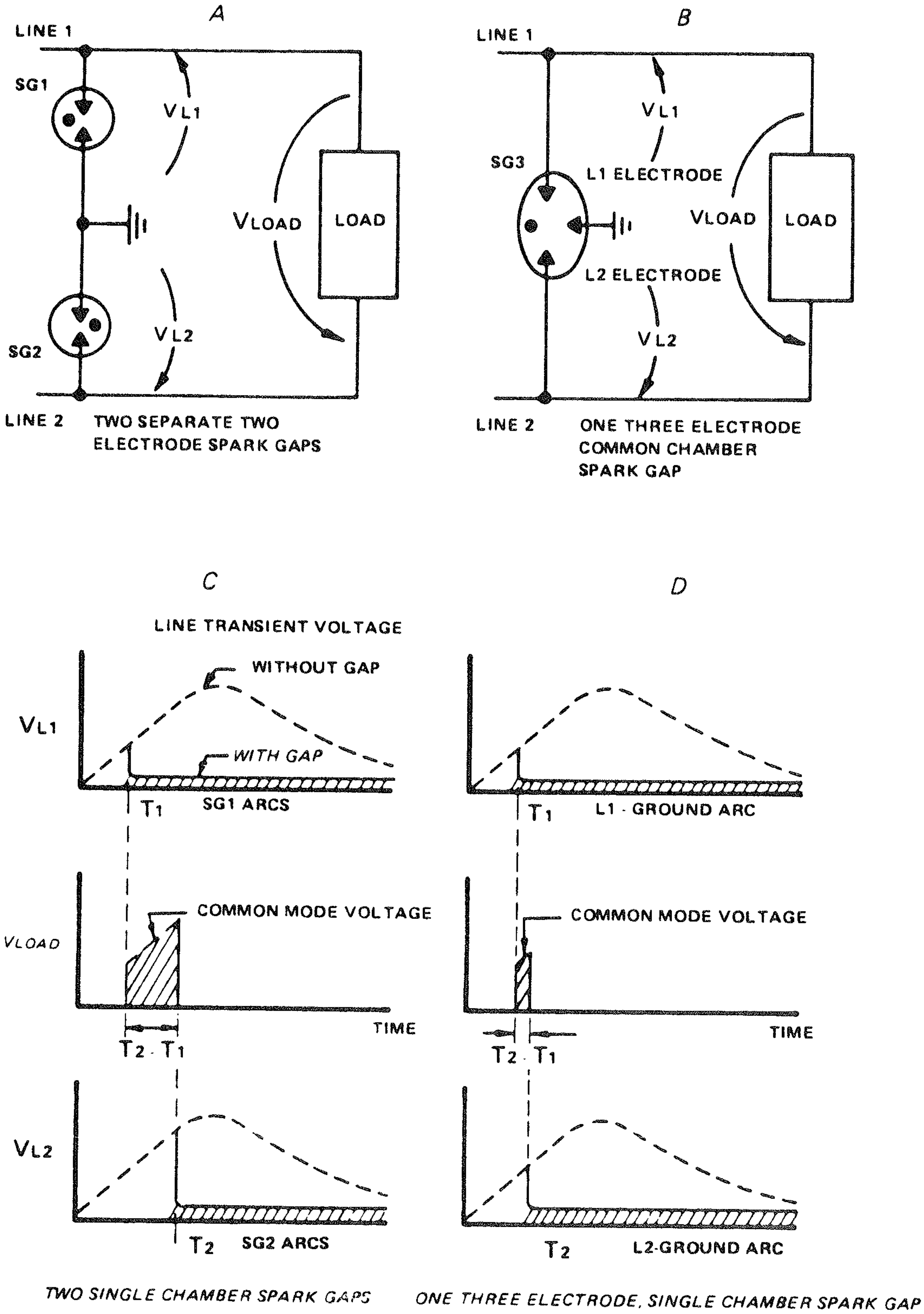


Figure 44. Comparison of two separate two-electrode gaps with one three-electrode, common-chamber gap. (Ref. 4.20)

1. Relatively constant clamp voltage with increasing current through the device. Figure 47 compares the clamp voltage versus peak current for an MOV and a silicon avalanche suppressor (SAS). Note that the MOV voltage gradually increases, while the SAS voltage stays virtually constant until approximately 200 A peak current. Above 2,000 A peak current the MOV would have a lower clamp voltage than the SAS.
2. Clamp voltages from 5 V to hundreds of volts are available.
3. Low to high energy dissipation capabilities.
4. Naturally bidirectional operating characteristics.
5. Rapid turn-on times, typically between 1 and 10 nsec.

Disadvantages of metal oxide varistors are:

1. Relatively low input impedances.
2. High input capacitance with capacitance inversely proportional to clamp voltage.
3. Lower pulse life characteristics than would be expected from extrapolations of vendor curves. To be conservative, the vendor curve should be flatlined below the 20 μsec single pulse current value (*4.22*).
4. Clamp voltage changes each time suppressor activates. This implies nonconstant device characteristics over the life of the device. MOV suppressors show a decrease in clamp voltage at 1-mA leakage current when repetitively pulsed and also exhibit a "softening" of the knee of the V-I curve.
5. Sensitive to environmental stress.

MOV's find primary application in protecting low frequency circuitry due to the low input impedance and high input capacitance of a typical MOV device. MOV's can be effectively used to protect low amplitude signal and control lines and dc power lines. MOV's have higher surge energy handling capabilities than comparably sized bypass capacitors, silicon avalanche suppressors, or zener diodes.

In summary, the following considerations are important when using or selecting MOV's:

Table 11. Current manufacturers of spark gaps. (**Notice:** The Transportation Research Board, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.)

Company Name	Address
Amperex Electronic Corp.	6024 N. Keystone Avenue Chicago, IL 60646 (312) 539-3108
Clare Division, General Instrument Corp	3101 W. Pratt Boulevard Chicago, IL 60645 (312) 262-7700
EG & BG, Inc.	35 Congress Street Salem, MA 01970 (617) 745-3200
Joslyn Electronic Systems	P.O. Box 817 Goleta, CA 93116 (805) 968-3551
Lightning Protection Corp.	Box 6086 Santa Barbara, CA 93160 (805) 967-5089 / 4577
Maxwell Labs.	8835 Balboa Avenue San Diego, CA 92123 (619) 279-5100
PolyPhase or Corp.	1425 Industrial Way P. O. Box 1237 Gardnerville, NY 89410 (702) 762-2511 / (800) 325-7170
Pulsar Products Div.	2700 Merced Street San Leandro, CA 94577 (415) 577-7236
Siemens Corp.	Special Components Dept. Components Division 186 Wood Avenue South Iselin, NJ 09830
TII Industries, Inc.	1375 Akron Street Copiaque, NY 11726 (516) 789-5020

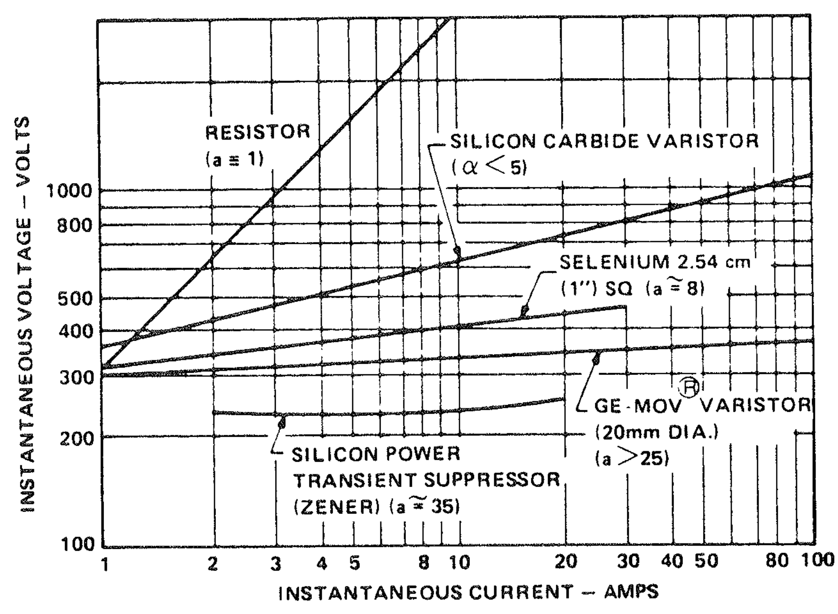


Figure 45. V-I characteristics of four transient suppressor devices. (Ref. 4.21)

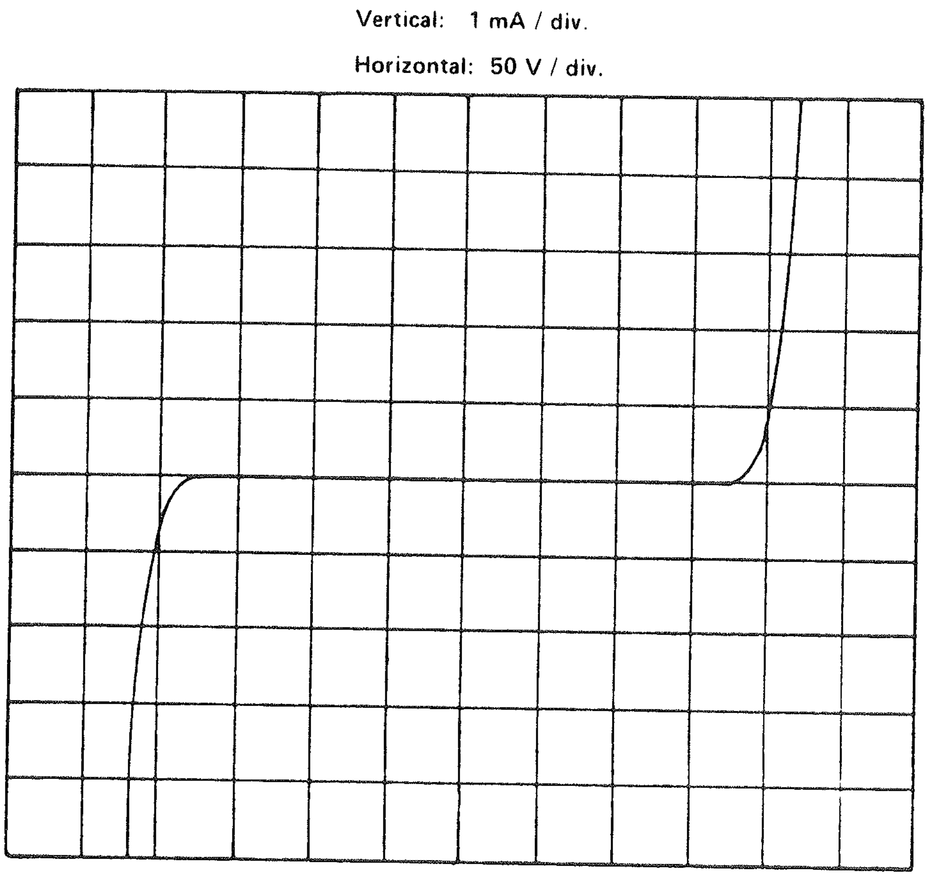


Figure 46. Typical varistor V-I characteristics. (Ref. 4.21)

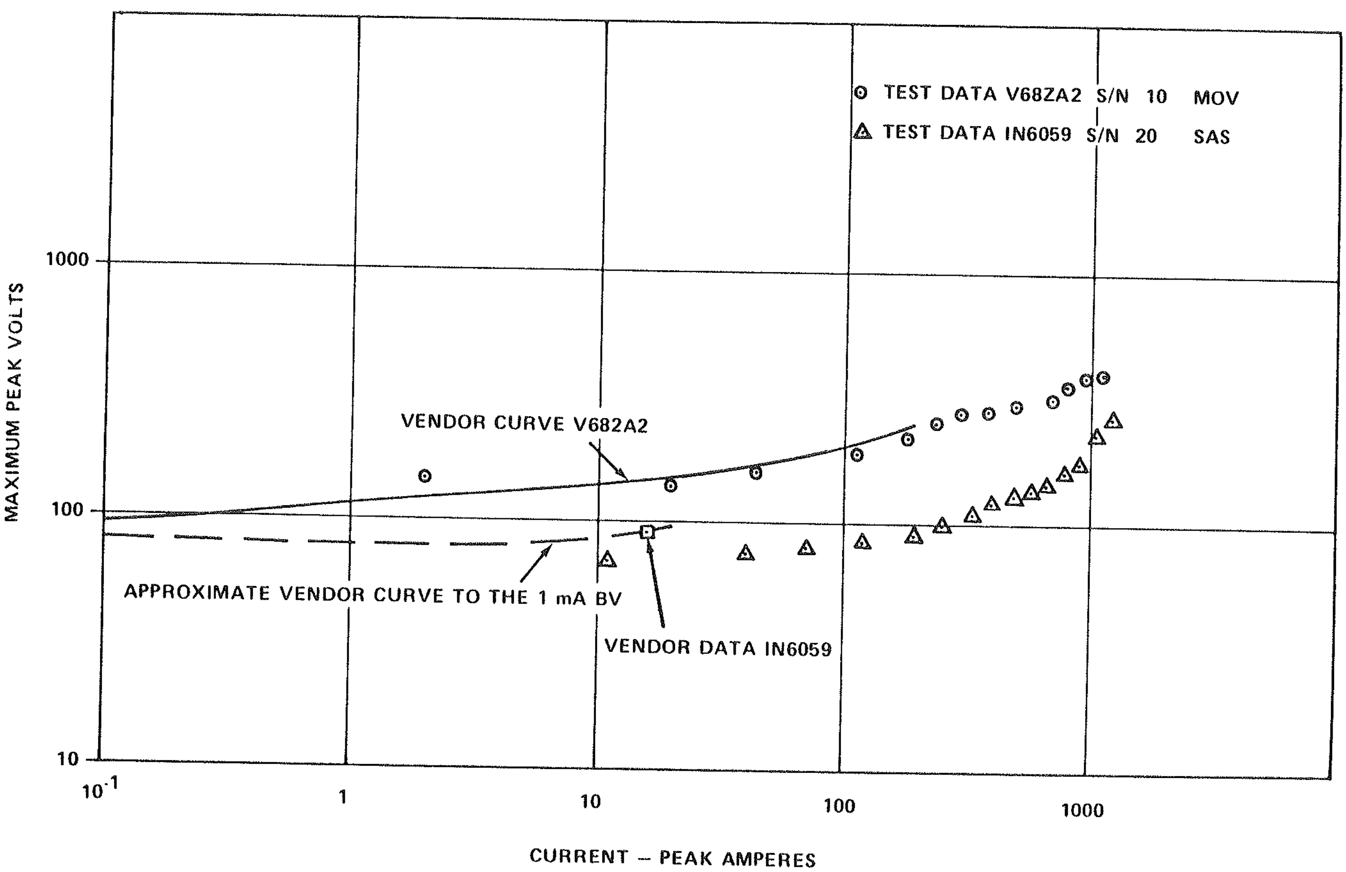


Figure 47. Comparison of MOV and SAS V-I characteristics. (Ref. 4.22)

1. *Impact of Transient Rise Time.* The overshoot characteristics of MOV's are superior to those of ordinary spark gaps. However, lead inductance must be minimized to take advantage of the inherently fast response of the device (on the order of a nanosecond).

2. *Impact of Lead Inductance.* The response time of MOV's can be significantly degraded by appreciable lead inductance in combination with the relatively high internal capacitance of the device. Short length, low inductance leads should therefore be used.

3. *Noise Generation Considerations.* The fast clamping characteristics of MOV's tend to generate broadband noise, although this problem is not as severe as when using spark gaps.

4. *Device Failure Considerations.* When subjected to surges above their peak current/energy ratings or to steady state voltages well beyond their voltage ratings, MOV's may fail in a short-circuit mode, may open circuit because of melting of the lead solder joint, or may even explode. More subtle changes, such as an increase in clamping voltage, are also possible. The circuit should be designed so as not to be damaged under the condition that the MOV fails in a short-circuit. Periodic testing should be performed on MOV's to verify not only proper impedance levels, but proper clamping voltages as well.

A list of current MOV manufacturers is given in Table 12.

4.4.1.3 Silicon Avalanche Suppressors

Silicon avalanche suppressors (SAS) are specially designed high power semiconductor diodes. They are designed such that the PN junction to heat sink distance is minimized, thus resulting in high power handling capabilities.

An SAS has the following advantages:

1. Rapid turn-on times. Theoretically, only a picosecond of turn-on time is required, but in practice between 1 and 10 nsec are experienced because of packaging inductance.
2. Constant clamp voltage up to peak surge currents of approximately 200 A.
3. Available in wide ranges of package styles from DIP packages to RF coaxial connector mount packages.
4. Clamp voltages from 10 to hundreds of volts.
5. Excellent repetitive pulse characteristics. Test data indicate that devices can safely survive 50 pulses at twice the vendor-rated power levels (*4.22*).

Disadvantages of the SAS are:

1. High input capacitance—comparable to an MOV.
2. Low insulation resistance—comparable to an MOV.
3. Lower energy handling capabilities than spark gaps or MOV's.
4. Unidirectional device.

The input capacitance of an SAS can be reduced by placing low capacitance switching diodes in series with the SAS. However, this approach results in slower device turn-on times because of added packaging inductance and a reduction of current-carrying capabilities to those of the switching diode. Prepackaged devices are commercially available.

Table 12. Current manufacturers of metal oxide varistors. (Notice: The Transportation Research Board, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturer's names appear herein solely because they are considered essential to the object of this report.)

Company Name	Address
Colber Corp.	26E Buffington Street Irvington, NJ 07111 (201) 371-9500
Electrostatic Consulting Assoc.	556 Lowell Road Groton, MA 01450 (617) 448-5485
General Electric Corp.	Power Electronics Semi, Dept. W. Genesee Street Auburn, NY 13021
GTE Supply, GTE Communications Systems	5225 Wiley Post Way Salt Lake City, UT 84116 (801) 537-5237
Maida Development Co.	20 Libby Street Hampton, VA 23663 (804) 723-0785
Marcon America Corp.	310 Era Drive Northbrook, IL 60062 (312) 564-2820
Mepco/Electra, Inc. North American Philips Corp.	Columbia Road Morristown, NJ 07960 (407) 881-3200
Panasonic	Industrial Electronic Comps. P.O. Box 1503 Secaucus, NY 07094 (201) 348-7000
RCD Components, Inc.	330 Bedford Street Manchester, NH 03101 (603) 669-0054
Sohio Engineered Mat. Co.	P.O. Box 156 Niagria Falls, NY 14302 (716) 278-2000
Sylvania Electronic Comps. Philip ECG, Inc.	100 First Avenue Waltham, MA 02254 (617) 890-6107
Thomson-CSF Comps. Corp.	Passive Comp. Div. 5850 Canoga Avenue Suite 300 Woodland Hills, CA 81367
Victory Engineering Corp.	Victory Road Springfield, NJ 07081 (201) 379-5900
Workman Electronic Products	P.O. Box 3828 Sarasota, FL 33578 (419) 923-7525

An SAS is primarily used in conjunction with other higher energy handling devices, such as spark gaps or MOV's, or is installed at the circuit level. Because of their low clamp voltages, SAS's are primarily used to protect low frequency or dc signal and power lines unless they are specially configured using low capacitance diodes. They can be used to protect low amplitude signal lines.

The following considerations are important when using or selecting SAS's:

1. *Impact of Transient Rise Time.* The overshoot of SAS devices is negligible when low-inductance packaging and installation are used and response times on the order of one nanosecond may be achieved. The inherent speed of the device will be lost, however, if standard (DO-13) packaging and/or significant lead lengths are employed.

2. *Impact of Lead Inductance.* Appreciable lead or package inductance can generate overshoot spikes capable of damaging sensitive electronic components. Therefore, minimum lead length and low-inductance packages should be employed whenever possible.

Table 13. Current manufacturers of silicon avalanche suppressors. (Notice: The Transportation Research Board, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.)

Company Name	Address
General Semiconductor	2001 West Tenth Place TEmpe, AR 85281 (602) 968-3101
Ledex/Lucas, Inc.	801 Scholz Drive Vandalia, OH 45377 (513) 898-3621

3. *Device Failure Considerations.* SAS's usually develop a short circuit through the semiconductor when subjected to transients beyond their peak current/energy ratings. As was the case with MOV's the circuit should be designed to prevent damage in the event of an SAS short. In power supply circuits, the SAS should be located after the fuse.

Current manufacturers of SAS's are given in Table 13.

4.4.1.4 Semiconductor Diodes

Diodes are not recommended for use in high or medium energy transient environments. Zener diodes do not have sufficient high energy handling capabilities to handle narrow, short rise time pulses. Zener diodes should only be used in conjunction with other protection devices such as spark gaps, MOV's or an SAS, or where the energy to be dissipated is less than 10 joules (watt-seconds). The primary advantages in using semiconductor diodes are the lower input capacitance of switching diodes and lower cost of zeners in comparison to MOV's or an SAS.

The disadvantages of semiconductor diodes are:

1. Slow turn-on times, particularly for zeners, rectifiers, or silicon-controlled rectifiers (SCR's).
2. High input capacitance of zeners, rectifiers, or SCR's.
3. Low energy handling capabilities.

4.4.1.5 General Selection Guidelines

The important parameters of transient suppressor selection are summarized as follows:

1. *DC Breakdown Voltage.* The dc breakdown voltage corresponds to the suppressor firing voltage when the transient has a very slow rate of rise. A suppressor can not be employed in a circuit where the steady state ac or dc operating voltage exceeds the dc breakdown voltage of the protection device.
2. *Transient Breakdown Voltage.* The transient breakdown voltage is dependent on the transient rate of rise and on inductive lead effects. Devices such as spark gaps have firing voltages significantly higher than the dc transient breakdown voltage because of the time required to cause ionization of the gas and subsequent arcing. Devices such as MOV's and SAS's have transient breakdown voltages comparable to the dc breakdown voltage with overshoot determined primarily by inductive lead effects.
3. *Clamp Voltage.* The clamp voltage is the voltage level that is reached after the suppressor device fires. In the case of spark gaps, it is the arc voltage, and for SAS's and MOV's it is often the dc breakdown voltage, although it may be higher, depending on the current dissipated through the suppressor.
4. *Maximum Current-Carrying Capability.* The suppressor should be specified to withstand the maximum surge current. In the case of a spark gap surge arrestor, consideration must also be given to the steady state ac follow current in addition to the transient surge current. If a spark gap is installed on an ac power line, and if the gap fires at the beginning of the ac positive half cycle, the gap will have current flowing through it until the end of the positive half cycle. In many cases the follow current through the suppressor can exceed the surge current.
5. *Maximum Energy Dissipation.* The energy dissipation is the amount of power a device can dissipate over a certain period of time. For lightning protection, the device must be able to handle a large amount of power for a short period of time. To determine the energy absorbed by an amplitude limiter, the following equation applies:

$$E = KV_c IT \tag{17}$$

where I is the peak current applied, V_c is the clamp voltage which results, T is the impulse duration, and K is a constant. Values of K for different transient waveshapes are given in Figure 48. For a complex waveform, divide the waveform into segments that can be treated separately. For example, consider the damped exponential waveform shown in Figure 49 which is applied across an MOV. The waveform is divided into two parts: the triangular rise-time section and the damped exponential fall-time section. As an example, for a GE V130LA1 MOV, the maximum voltage across the MOV is 470 V at a peak current of 100 A based on the V-I characteristics of the MOV. The total energy absorbed by the MOV is given by,

$$E_{\text{SECTION1}} = KV_c IT = (0.5)(470)(100)(5\times10^{-6}) = 0.12 \text{ J} \tag{18}$$

$$E_{\text{SECTION2}} = KV_c IT = (1.4)(470)(100)(50-5)(10^{-6}) = 2.96 \text{ J} \tag{19}$$

$$E_{\text{TOTAL}} = 0.12 + 2.96 = 3.08 \text{ J} \tag{20}$$

The peak energy dissipation rating of the selected MOV, from its specification sheet, should be at least two to three times the computed energy dissipation in order to provide a reasonable safety factor. For example, the V130LA1 has a peak energy dissipation rating of 11J (safety factor of 3.6), which is adequate for this application.

6. *Input Impedance in Off State.* The input impedance is comprised of a resistive and capacitive term along with a lead inductance term. Because suppressors are placed in parallel to the circuits to be protected, it is desirable to maximize the resistance of the suppressor in the off state, while minimizing input capacitance and lead inductance.
7. *Leakage Current in Off State.* The leakage current of a

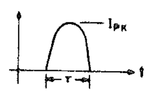
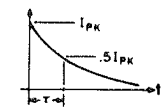
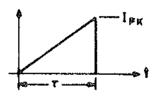
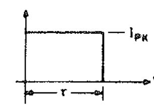
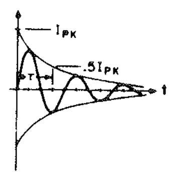
WAVESHAPE	EQUATION	K	WAVESHAPE	EQUATION	K
	$I_{PK} \sin\left(\frac{\pi}{T} t\right)$	0.637		$I_{PK}\, e^{-t/1.44T}$	1.4
	$I_{PK} \left(\frac{t}{T}\right)$	0.5		I_{PK}	1.0
	$I_{PK} \sin(\pi t) e^{-t/T}$	0.86			

Figure 48. Energy form factor constants. (Ref. 4.21)

transient suppressor is the current measured when less than rated voltage is applied across the suppressor. The leakage current is very low for spark gaps and in general is highest for MOV's. Insulation resistance is often stated instead of leakage current.

8. *Extinguishing Characteristics.* Suppressors such as spark gaps have unique extinguishing characteristics. When specifying spark gaps, a thorough consideration of the extinguishing characteristics such as extinguishing voltage and current are necessary.

9. *Environmental Sensitivity.* Many devices, such as MOV's, degrade when subjected to environmental extremes. Degradation is often indicated by changes in dc operating values and leakage current. Environmental effects which influence suppressor operation include temperature, humidity, vibration, and atmospheric pressure.

10. *Repetitive Pulse Effects.* All suppressors are susceptible to damage from repeated pulsing. A rapid succession of pulses can cause damage to the suppressor because of the inability to dissipate the applied energy. The firing characteristics of some devices, such as MOV's, also permanently change with the application of each pulse, regardless of the time interval between the next applied pulse.

11. *Packaging.* Low inductance packages such as RF-coaxial devices, as illustrated in Figure 50 are available. By minimizing the inductance of the suppressor the firing time is reduced and the input impedance is improved.

General installation criteria for transient suppressors are:

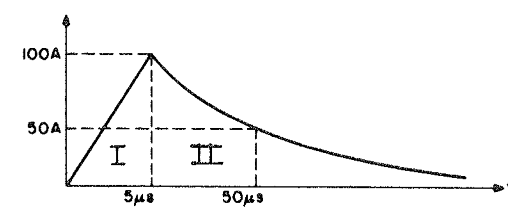


Figure 49. Waveform for MOV-energy dissipation computation. (Ref. 4.21)

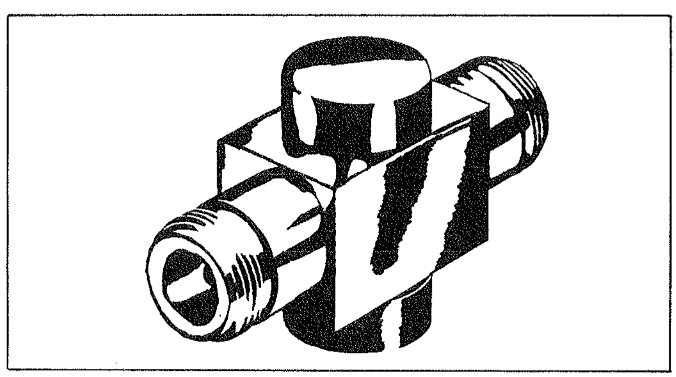


Figure 50. A 50-ohm low inductance TPD for coaxial applications. (Ref. 4.23)

1. Minimize packaging and lead inductance by minimizing the interconnecting lead lengths.
2. Allow sufficient spacing between successive suppressors or circuitry to allow the initial suppressor to fire properly. The necessary time delay can often be accomplished by using a short length of wire or cable. The amount of delay necessary is dependent on the firing time of the initial suppressor and on the response time of the successive suppressors, filters, and circuitry to be protected.
3. The installation wire size must be capable of withstanding the surge current without being destroyed. A larger size wire also provides a lower inductance than a smaller wire of the same length. The wire should also be stranded rather than solid core and should be as short a length as possible. The wire should be installed such that bends and kinks are eliminated or minimized.

4.4.2 Filters

An electrical filter is a network of lumped or distributed constant elements (capacitors, inductors, and resistors, or their equivalent) that permits the transmission of signals at some frequencies and impedes the transmission of signals at other frequencies. The passband of a filter is the frequency range in which there is little or no attenuation. The stopband is the frequency range in which attenuation is desired.

The selection criteria for filters include determination of: (1) the class of filter, i.e., low-pass, high-pass, band-pass, or band-reject; (2) the filter design method, i.e., iterative, Butterworth, Chebyshev, elliptic, or Bessel; and (3) whether to use reactive or lossy elements.

Filters find wide application at power supply inputs, data line inputs, and following limiters to suppress the high frequency leading edge of transients or for general electromagnetic interference rejection.

4.4.2.1 Classes of Filters

Filters are divided into four classes according to the relative positions of the passbands and stopbands in the frequency spectrum. The four classes of filters are low-pass, high-pass, band-pass, and band-reject. The attenuation as a function of frequency for each of the classes is shown in Figure 51.

A low-pass filter (shown in Figure 51(a)) passes all frequencies below its cutoff frequency, f_c, and theoretically attenuates all frequencies above the cutoff frequency. This type of filter is used extensively in electromagnetic interference control applications. Power line filters are low-pass-type filters, which pass dc or ac power frequencies without significant power loss, while attenuating signals above these frequencies. In addition, low-pass filters are used on control and signal lines where all undesired frequencies are above the desired signal frequencies.

A high-pass filter (Figure 51(b)) passes all frequencies above its cutoff frequency and attenuates all frequencies below the cutoff frequency. High-pass filters are used on lines where all of the undesired frequencies are lower than the desired signal frequencies. In particular, such filters are used to remove ac power line frequencies from signal channels.

A band-pass filter (Figure 51(c)) passes all frequencies between a lower cutoff frequency, f_{c1}, and an upper cutoff frequency, f_{c2}, and attenuates all frequencies below f_{c1} and above f_{c2}. This type of filter is used in cases where undesired frequencies are both lower and higher than the desired signal frequencies.

A band-reject filter (Figure 51(d)) attenuates all frequencies between a lower cutoff frequency, f_{c1}, and an upper cutoff frequency, f_{c2}, and passes all frequencies below f_{c1} and above f_{c2}. This type of filter is used where the undesired signals are within a restricted frequency range and the desired signal frequencies may be located over a considerable frequency range both above and below the undesired signal band.

4.4.2.2 Filter Design Methods

Filter design generally entails the approximation of the passband and stopband attenuation specifications through either iterative or classical approximation methods. Iterative procedures, which require implementation on a computer, can result in optimum designs for specifications requiring differing amounts of attenuation in two or more stopband regions. If a computer and/or the design methods are inaccessible, or if the stopband specifications are simple, classical approximation methods are used. Four commonly used classical approximations will be briefly described below: Butterworth, Chebyshev, elliptic, and Bessel filter approximations. The design parameters for each filter type have been extensively tabulated in the literature (e.g., Ref. 4.25) and therefore will not be included here.

Butterworth filters provide a maximally flat passband and monotonically increasing attenuation in the stopband as shown in Figure 52. Butterworth filters have a moderate attenuation slope in the transition region (between passband and stopband) and have acceptable transient characteristics (i.e., overshoot and damping characteristics in the step and impulse responses). Butterworth filter designs usually result in more practical and less sensitive element values than other classical designs and are commonly employed because of their versatility and generally favorable performance characteristics.

Chebyshev filters provide an equiripple passband and a monotonically increasing attenuation in the stopband as shown in Figure 52. Chebyshev filters are more efficient than Butterworth filters in the sense that for the same order (number of componenets) and for an equal amount of passband attenuation, the Chebyshev filter has a steeper attenuation slope in the transition region (i.e., is a better approximation to the ideal filter with a rectangular frequency response characteristic). Consequently, for a specified minimum stopband attenuation, Chevyshev filters have a narrower transition region between the passband and stopband regions. As the passband ripple and filter order are allowed to increase, the rate of rolloff increases.

As shown in Figure 52, elliptic filters have an equiripple passband and an equiripple stopband attenuation. The elliptic filter is more efficient than either the Butterworth or Chebyshev filters in the sense that a given passband and stopband attenuation specification can be met with the lowest order filter. Because a lower order corresponds to less components, elliptic filters often are less expensive to realize than other filter types.

Bessel filters provide a maximally flat delay characteristic. Consequently, the stop response has essentially no overshoot or ringing. However, the frequency response (Figure 52) is much less selective than the other filter types. Consequently, Bessel filter applications are restricted to situations in which the transient properties are a major consideration, such as digital pulse filtering applications.

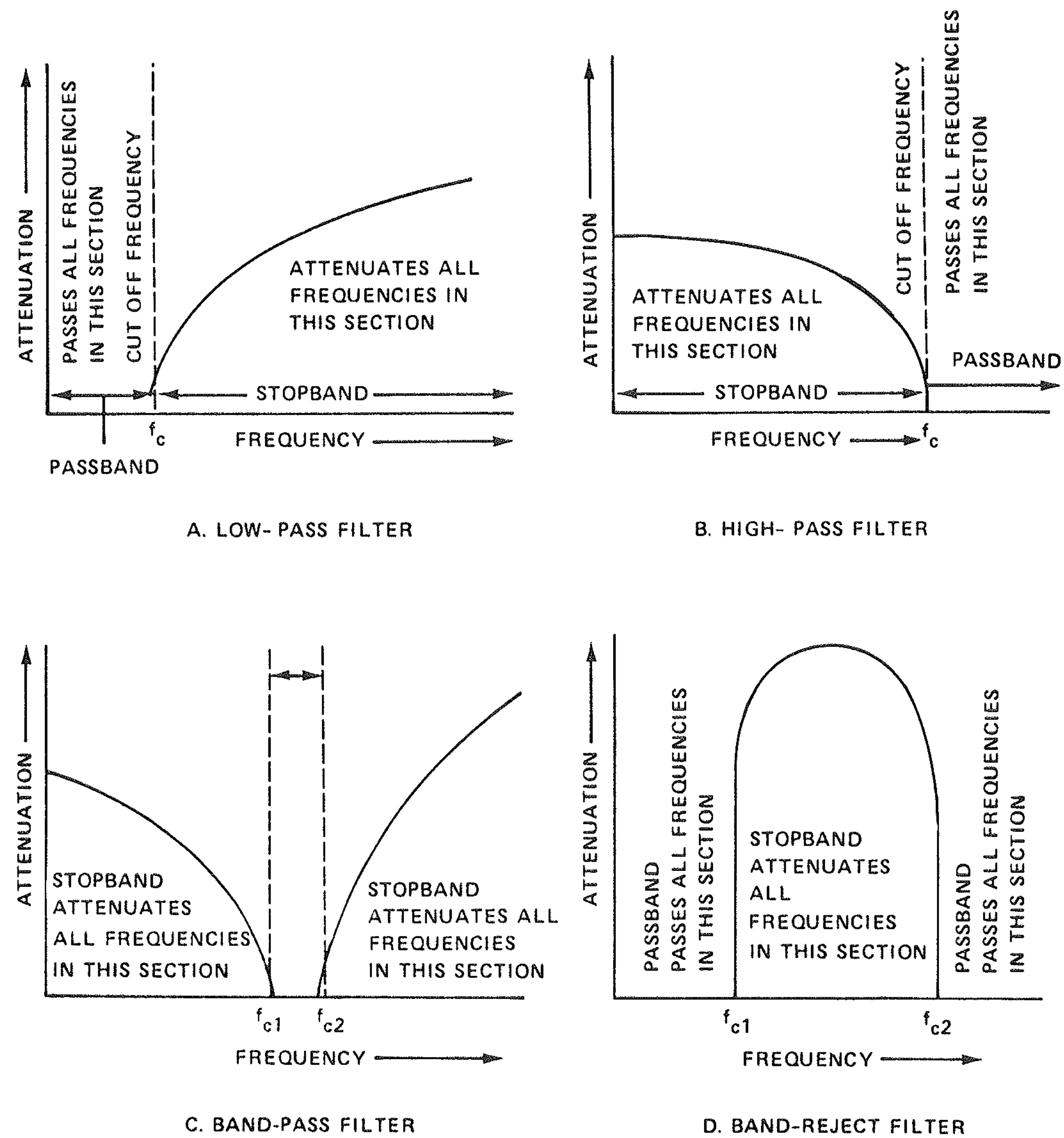


Figure 51. The four basic classes of filters. (Ref. 4.24)

Low-pass filters are often used after slow response amplitude limiters, such as spark gaps, to (1) eliminate or slow the rate of rise of a transient leading edge which travels past the spark gap, or (2) to provide delay between a spark gap and a lower energy, high speed suppressor such as an MOV or SAS. Delay between limiters is necessary to prevent the high speed limiter from operating before the spark gap. When used to provide delay between limiters, the filter design method greatly affects the amount of delay obtained. Of importance is the filter's step response which is determined by the design method, filter order, and cutoff frequency. Normalized design figures illustrating how filter order and design method affect step response can be found in Ref. 4.26.

4.4.2.3 Reactive Versus Lossy Filters

Filters are also classified according to the manner by which attenuation is achieved. Reactive, or lossless, filters provide attenuation of unwanted signals by reflecting energy back to the source. Absorptive, or lossy, filters attenuate unwanted signals by converting them to heat in a lossy dielectric or in a thin layer of resistive material in addition to reflecting energy back to the source.

There are two factors that significantly affect the effectiveness of reactive, or reflective, type filters. These factors become extremely important in applications where the filters are required to exhibit either passband or stopband characteristics over extremely wide frequency ranges (for example, a low-pass filter which is required to attenuate frequencies over the frequency range from 1 MHz to 100 MHz). In order for a reflective-type filter to exhibit the specified bandpass and stopband characteristics, both the input and output terminals of the filter must be terminated in the characteristic impedance of the filter. These matched impedance conditions must be satisfied over the entire stopband region as well as the passband region if the specified attenuation is to be realized. In cases where the desired stopband (or passband in the case of a high-pass or band-reject filter) covers several octaves or decades of frequency range, it is extremely difficult (if not impossible) to maintain the matched

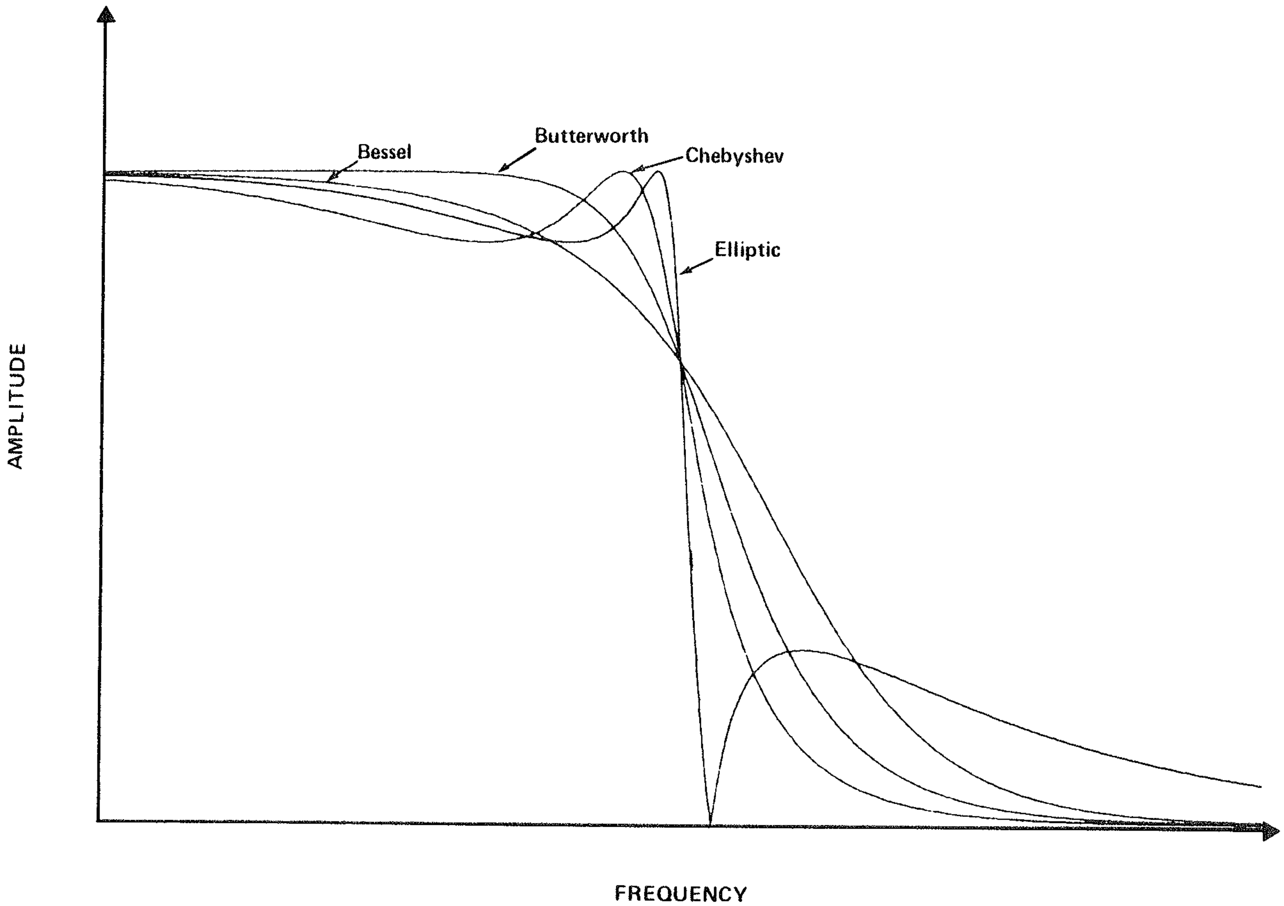


Figure 52. Generalized frequency response for classical filter types. (Ref. 4.25)

impedance conditions (even if they are known). In addition, for some applications such as power line filtering, the source, or input, impedance is probably unknown and may vary drastically with frequency. Under these conditions, the performance of the filter will likely differ from the design specifications. A second factor to be considered with reflective-type filters is the fact that they will exhibit spurious resonances, that is, frequency bands where no signal attenuation takes place, which will degrade the stopband or passband characteristics where the bands extend over frequency ranges of several octaves. The spurious resonances result from the stray, or parasitic, reactance associated with lumped element filters and from the inherent periodicity in transmission line filters. The effects of the spurious responses on the attenuation characteristics of a lumped element and a transmission line filter are shown in Figures 53 and 54, respectively.

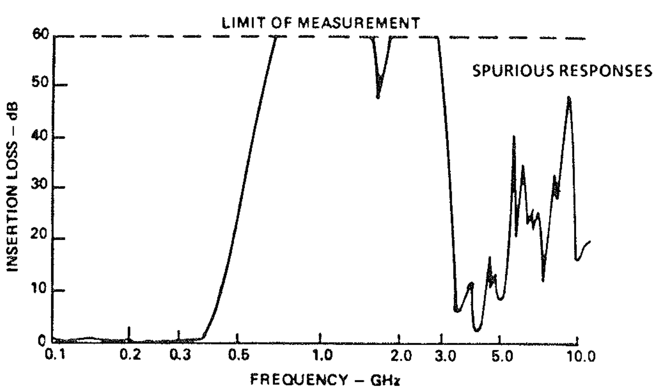


Figure 53. Typical low-pass attenuation characteristic of a lumped element filter. (Ref. 4.24)

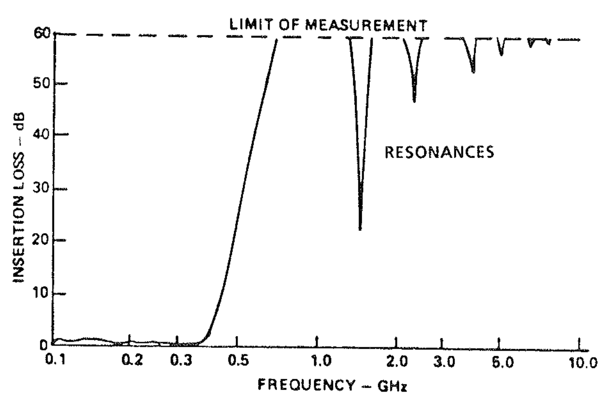


Figure 54. Typical low-pass attenuation characteristic of a transmission line filter. (Ref. 4.24)

The deficiencies of reflective-type filters lead to the development of lossy, or dissipative, filters that take advantage of the loss-versus-frequency characteristics of materials such as ferrite compounds and carbonyl iron mixes. These materials have the unique characteristic of low dc attenuation and good high frequency attenuation over broad continuous frequency ranges. The attenuation of the lossy filter is directly proportional to the distance that the signal travels through the lossy material and is specified in terms of decibels per megahertz per unit length. A significant feature of dissipative filters is that they do not exhibit spurious resonances in the stopband region. In addition, because the undesired energy is absorbed in the lossy material of the filter, an impedance mismatch at the input and/or the output terminals of the filter has no significant effect on the attenuation characteristics of the filter. The filter becomes extremely lossy in the frequency range where either electric or magnetic losses, or both, become large and increase rapidly with frequency. Dissipative filters of this type are necessarily low-pass and a major application is general purpose power line filtering. Typical attenuation characteristics of a lossy filter are shown in Figure 55.

In cases where more rapid attenuation slopes are required, a hybrid dissipative-reflective filter can be used. With proper design, the sharp cutoff characteristics of the reflective filter can be realized, while the dissipative features of the filter will eliminate the spurious passbands in the stopband region and reduce the impedance matching requirements for the filter. Typical attenuation characteristics of a hybrid dissipative-reflective filter are shown in Figure 56.

Ferrite material is an often used dissipative filter material which finds a wide variety of uses. Ferrite materials can be molded (ceramic-type of material) into tubular shapes (beads) that can be slid over wires or used for choke cores. A ferrite bead has the equivalent circuit of an inductor and resistor as shown in Figure 57. The magnitude of the bead impedance is given by:

$$Z = \sqrt{R^2 + (2\pi fL)^2} \tag{21}$$

where R and L are the equivalent resistance and inductance, respectively, of the bead. Most manufacturers provide plots of the magnitude of the bead impedance versus frequency. Figure 58 shows representative data for two beads, one which is primarily resistive and one which is primarily inductive. As seen in the figure, the bead impedance is fairly low (less than 100 ohms at frequencies less than approximately 100 MHz.) This characteristic limits the application of beads to low impedance circuits.

The advantages of ferrite beads are that they are available in a wide variety of shapes and sizes, are low cost, and are dissipative rather than reflective. Disadvantages are that they are restricted to low-pass filter designs, are useful only in low impedance circuitry (less than a few hundred ohms), and saturate at fairly low current levels. Ferrite beads suppress frequencies above 1 MHz, whereas ferrite chokes may be used at frequencies as low as 20 kHz with special design. One disadvantage of these devices is that with dc currents present they saturate quite easily. Saturation can occur in particular types for dc currents as low as 10 mA.

Still another type of lossy filtering is available in filter-pin connectors. In these type connectors, the filter is built into the cable-pin assembly. Each filter-pin is configured as a PI-type connector through the use of lossy material surrounding the pin, and shunt capacitors between the pin and the connector shell. Filter-pins have been miniaturized to such small sizes that filter-pin connectors are now available with as many as 128 pins. However, because the shunt capacitance and series inductance that can be constructed in the pin are limited, filters of this small type offer little attenuation below about 1 MHz. In a 50-

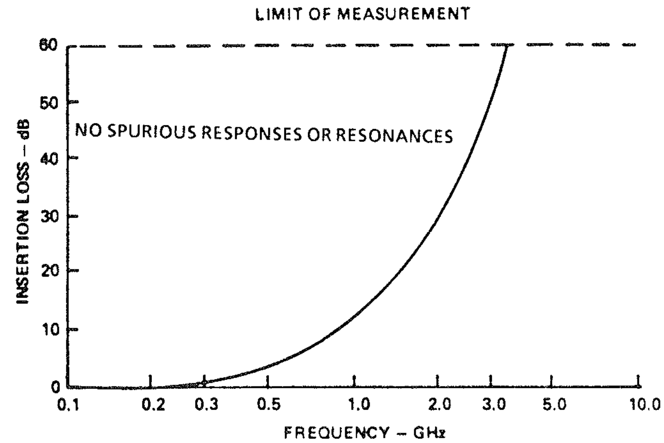


Figure 55. Attenuation characteristic of a dissipative filter. (Ref. 4.24)

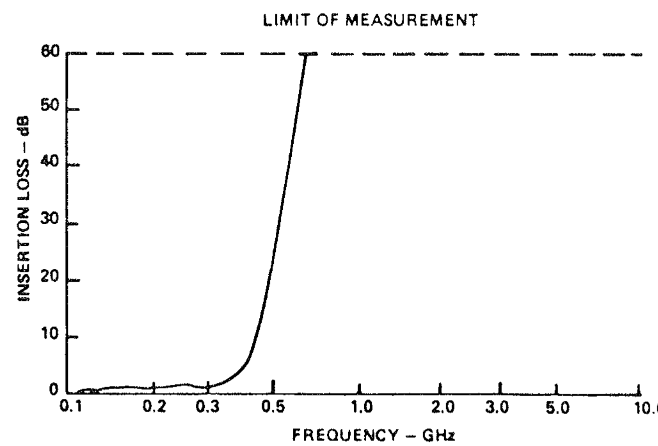


Figure 56. Attenuation characteristic of a hybrid dissipative-reflective filter. (Ref. 4.24)

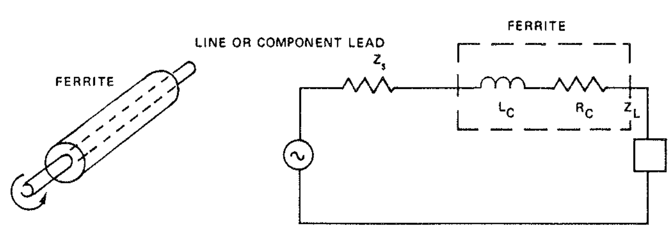


Figure 57. Ferrite bead on wire and its equivalent circuit. (Ref. 4.27)

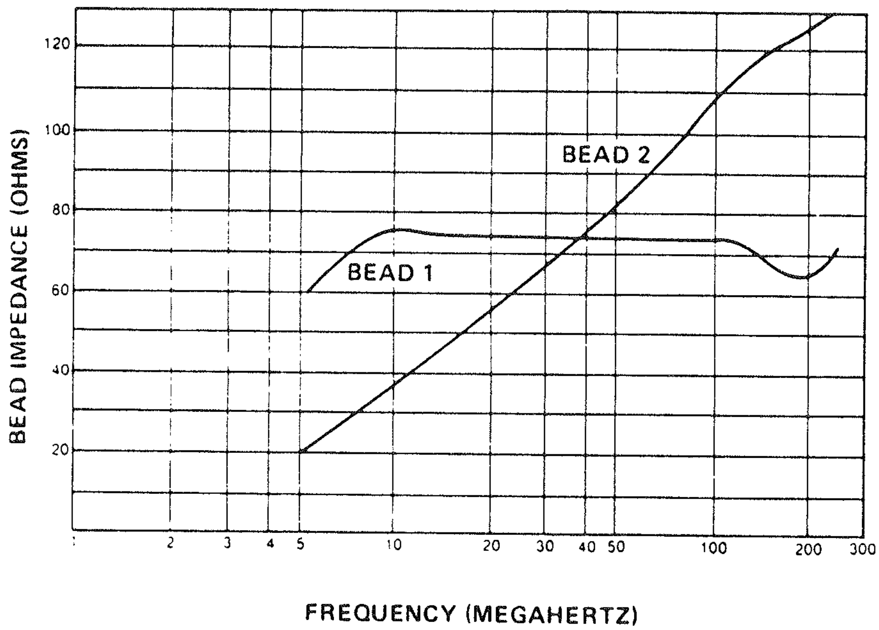


Figure 58. Insertion loss data for two types of ferrite beads: bead 1—resistive bead; bead 2—inductive bead.

ohm system, the typical attenuation offered by filter pins is approximately 20 dB at 10 MHz and up to 80 dB at 100 MHz.

4.4.2.4 Filter Installation and Mounting

In order to achieve the desired results with filters, it is absolutely necessary to adhere to certain guidelines with respect to the installation and mounting of filters. The impedance between the filter case and ground must be made as low as possible. Otherwise, the filter insertion loss may be seriously degraded at the higher frequencies. The preferred contact between the filter case and ground is a direct metal-to-metal bond between the filter case and the shielded enclosure wall or equipment chassis. In addition, effective separation (isolation) between the input and output wiring of the filter is mandatory to prevent radiation from the input wiring to the output wiring from circumventing or degrading the effects of the filter. If complete isolation is achieved between input and output, a filter insertion loss approaching the design specification can be realized.

Where possible, the use of bulkhead mounted feed-through filters are recommended because this configuration is optimum for establishing a good high frequency bond between the filter case and ground and provides good isolation between the input and output terminals of the filter. In cases where feed-through filters are not used, it will probably be necessary to provide additional compartmental shielding to isolate the input and output terminals of the filters.

4.4.2.5 Specifying Filters

In the design of a shielded enclosure which is to protect circuits from a transient or other electromagnetic interference environment, it is important that any wire or cable that is exposed to this environment and penetrates the shielded enclosure be filtered to maintain the integrity of the shielding effectiveness of the enclosure. In addition, filters may be necessary on interconnecting wiring to prevent interference signals from being conducted to circuits internal to the enclosure. To prevent the voltage/current limits of a filter from being exceeded, transient suppressors may be required on the input terminals. On the other hand, filters may be used to eliminate or reduce the high frequency leading edge of a transient that does not get clamped by a surge arrestor.

The general selection and installation guidelines of filters are specified as follows:

1. *Impedance.* The input and output impedances must be specified to match the impedance of the line into which the filter will be inserted. The impedance matching is particularly critical for signal transmission lines, so that the filter does not impair the normal operation of the equipment on both ends of the line. In addition, care must be taken that the filters to be used do not degrade the desired performance of circuits within the system. This includes waveform distortion as well as required impedance levels.
2. *Voltage Rating.* The peak voltage rating of the filters must be specified to assure that each filter is adequate for its particular application. The filter voltage ratings must be sufficient to provide reliable operation under the extreme transient and environmental conditions expected. However, specifying a rating higher than required will result in penalties in size, weight, and additional cost.
3. *Current Rating.* The peak current rating of the filter should be specified for the maximum transient current in addition to the maximum allowable continuous operation of the circuit in which it is installed (consistent with the current rating of the wire, components, circuit breakers and fuses with which it will be used). A current rating higher than required will add size, weight, and cost penalties.
4. *Voltage Drop.* The maximum allowable voltage drop through the filter should be specified for power filters. With the maximum current specified, the voltage drop requirement specifies the maximum passband insertion loss of the filter.

5. *Filter Type.* The type of filter (e.g., Butterworth, Chebyshev) should be specified based on the overall filter requirements such as amplitude, phase, and pulse response characteristics. For most power line filter applications, Butterworth filters are sufficient, while communications lines will require careful engineering analysis to prevent signal distortion and line loss.

6. *Insertion Loss.* The maximum allowable insertion loss in the filter passband should be specified.

7. *Frequency Response Characteristic.* The relative frequencies and magnitudes of the desired and undesired signals must be considered when specifying the frequency characteristics of a filter. In general, the size, weight, and cost of a filter rise rapidly as the attenuation slope increases.

8. *Temperature.* Filters must be able to withstand the environmental operating ranges of the equipment in which they are used. The specified temperature range for the filters must include both the extreme low and extreme high temperatures in which the equipment will be required to operate.

9. *Size and Weight.* In most cases, size and weight will be important considerations in the selection of filters. Filter manufacturers are fairly flexible in being able to provide a wide choice in the shape of a filter case, the method of mounting, and the types of terminals and connectors.

10. *Bonding.* The high frequency impedance between the filter case and ground must be made as low as possible. Otherwise, the filter insertion loss may be seriously degraded at the higher frequencies. The preferred contact between filter case and ground is a direct metal-to-metal bond between the filter case and the shielded enclosure wall or the equipment chassis.

11. *Isolation.* To prevent coupling between the input wiring and the output wiring from degrading the filter performance, the input and output wiring should be isolated.

4.4.3 Hybrid Suppressors

Hybrid suppressors combine more than one amplitude limiter or filter to provide protection against a wide range of transient and other electromagnetic interference threats. The best choice for components within a hybrid suppressor will vary widely depending on the range of threats, severity of the threats, weight and volume restrictions, cost, and type of input/output terminals to be protected. Even though a variety of limiters and filters are incorporated in a hybrid suppressor, the hybrid suppressor may be completely ineffective and may cause improper circuit operation if installed, fabricated, or designed improperly.

A hybrid suppressor can be assembled by traffic control personnel using individual limiters and filters or manufactured hybrid suppressors can be purchased for use on ac power and communication lines. Many manufactured hybrids for ac power and communication line applications are designed and tested to meet IEEE 587-1980 class A, B, or C limits (*3.22*). Further, many of the hybrids designed for ac power line protection are incorporated into multiple outlet ac power strip packages that are adequate for indoor use but may not be appropriate for installation in traffic control cabinets. Table 14 gives the names and addresses of a number of hybrid suppressor manufacturers.

When specifying a hybrid suppressor, the suppressor manufacturer should be required to provide a circuit diagram, list of replacable parts (if any), and test results. (There have been reports of bogus hybrids containing nothing more than sand and gravel being purchased and installed to the considerable embarrassment of the engineer involved.) In the following subsections, hybrid suppressor design examples are given for ac power and communication line applications.

Table 14. Current manufacturers of hybrid suppressors. (Notice: The Transportation Research Board, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.)

Company Name	Address
Atlantic Scientific Corp.	2711 South Harbor City Blvd. Melbourne, FL 32901 (305) 725-8000
Brooks Power Systems	3569 Bristol Pike Suite 102 Bensalem, PA 19020 (215) 244-0264
Computer Accessories Corp.	6610 Nancy Ridge Drive San Diego, VA 92121 (61(695-3773
Dynatech Computer Power, Inc.	4744 Scotts Valley Drive Scotts Valley, CA 95066 (408) 438-5760
EDCO, Inc.	P.O. Box 1778 Ocala, FL 32678 (904) 732-3029
General Semiconductor	2001 West Tenth Place Tempe, AR 85281 (602) 968-3101
LEA Dynatech, Inc.	12516 Lakeland Road Santa Fe Springs, CA 90670 (213) 944-0916
MCG Electronics, Inc.	12 Burt Drive Deer Park, NY 11729 (516) 586-5125
Panamax	150 Mitchell Boulevard San Rafael, CA 94903 (415) 472-5547
Perma Power Electronics, Inc.	5615 West Howard Avenue Niles, IL 60648 (312) 647-9414
Poly Phaser Corp.	1425 Industrial Way P.O. Box 1237 Garderville, NY 80410 (702) 782-2511 / (800) 325-7170
Power Integrity Corp.	1840 Pembroke Road P.O. Box 9682 Plaza Station Greensboro, NC 27429 (919) 379-9773
PTI Industries	320 River Street Santa Cruz, CA 95060 (408) 429-6881

4.4.3.1 AC Power Line Applications

Figure 59 shows typical combinations of limiters and filters that can be used to form a hybrid suppressor for ac power input protection. A fuse or circuit breaker is used to clear direct shorts or faults and for service disconnect during repair, maintenance, or equipment installation. A typical hybrid suppressor can consist of four basic elements: (1) a spark gap or high clamping voltage MOV, (2) a low-pass filter or delay line element, (3) a low voltage, fast response MOV or SAS, and (4) a lossy filter or ferrite bead(s).

To protect an ac power line input against a lightning discharge such as the class B short circuit current waveform specified in

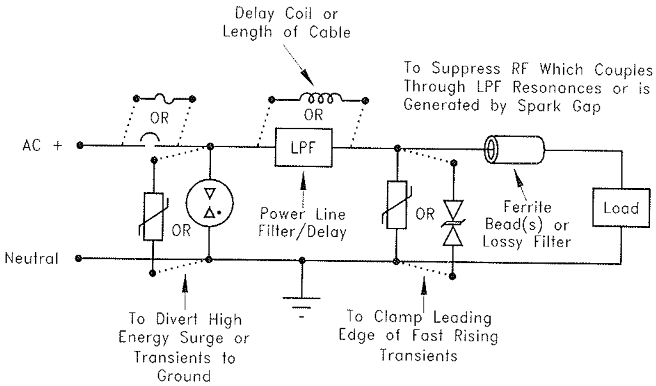


Figure 59. Typical combinations of limiters and filters to form a hybrid suppressor for ac power input protection.

IEEE 587-1980, the energy dissipation rating of the first protection device must be computed. Suppose a MOV is to be used as the first input protection device and the damped exponential waveform shown in Figure 15(c) is incident on the MOV. A GE model V130LA10A varistor will be considered for use first based on its peak current rating of 4,500 A—just adequate for an incident peak current of 3,000 A. From the MOV voltage versus current curves, the MOV will clamp at 600 V for an incident peak current of 3,000 A. The energy dissipated by the MOV can be calculated to be 37.4 J using the procedures given in Section 4.4.1.5. The energy rating of the V130LA10 is 38 J which is just equal to the calculated energy dissipation with no safety factor. The highest rated MOV in the V130LA series will also be inadequate because the maximum energy dissipation rating is only 70 J, less than twice the calculated dissipation energy. To obtain adequate protection under this threat condition, A GE V130HE150 series MOV, rated at 220 J and 20,000 A would have to be used. This unit is bulkier and more costly than the LA series radial lead MOV's ($30 for V130HE versus less that $2 for all V130LA series). The V130HE150 series MOV is more difficult to install and much more costly than a comparably rated gas tube spark gap (radial lead, Joslyn MSP2031-35-B at less than $3). It is because of the size and cost versus energy dissipation rating that miniature gas tube spark gaps are often used to dissipate the bulk of the high energy lightning discharge, while MOV's and SAS's are used to limit the high-speed leading edge of the transient which propagates past the spark gap. If the threat environment is not as severe as that shown in Figure 15(c) or if a MOV is preferred over a spark gap because of the spark gap firing characteristics, a high clamping voltage MOV can be used instead of a spark gap.

A delay element must be used following the spark gap or high clamp voltage MOV suppressor and before the fast response MOV or SAS to prevent the high-speed limiter from operating before the spark gap or high clamp voltage MOV. If a Joslyn MSP 2031-35-B gas tube spark gap is used, the gap will fire at 650 V (implies peak current of 325 A with 2-ohm source resistance) in 0.75 μsec for a transient rate-of-rise of 1,000 V/μsec. If the fast response MOV limits the output voltage to 300 V the minimum inductance value required to provide 0.75 μsec of delay plus the required voltage drop is:

$$L = V\frac{dt}{dI} = \frac{(650 - 300)(0.75)(10^{-6})}{325} = 0.8\ \mu\text{H} \qquad (22)$$

For faster rising transients, the voltage drop across the inductor will be sufficient to allow the gap to break down prior to the MOV or SAS operating. For slower rising transients, particulary surges caused by ground faults, a larger inductor may be necessary. Typically, the inductance should be 10 to 100 microhenries (μH) for suitable results. A low-pass filter (LPF) can be used as an alternative to a single inductor as a delay element. The LPF must provide approximately 1 μsec delay which can be computed from the filter's step response as discussed in Section 4.4.2.2.

The inductor or LPF should be capable of withstanding, without arcing or damage, at least 500 V/350 A peak (1 μsec rise time) and must also be capable of carrying the normal power current (15 to 30 A, depending on fuse/breaker rating).

Finally, a lossy filter, or one or more ferrite beads may be necessary to: (1) dissipate high frequency emissions that can couple through the LPF due to resonances or spurious responses, or (2) eliminate high-frequency noise generated by the spark gap or fast response MOV/SAS operation. Most ac power line filters will have spurious responses or resonances at high frequencies because the filter is not terminated in a fixed load impedance and the source impedance can also vary. More than one ferrite bead may be required, depending upon the ac line current and load resistance. In some cases, lossy pin filters or ferrite beads may be unusable because high ac power currents can cause the magnetic material within the filter to saturate, making them ineffective as filters.

4.4.3.2 Communication Line Applications

Figure 60 shows typical combinations of limiters that can be used to form a hybrid suppressor for communication or sensor line applications. Different circuits are shown, depending on the communication data rate and whether unbalanced or balanced (see Section 4.5.1) communication lines are used. There are a number of differences between hybrid suppressors designed for communication line applications and those designed for use on ac power lines. First, the threat levels are typically not as severe, particularly the peak current, so that components having lower energy ratings can be used. Second, inductors can not be used as delay elements because line inductance can introduce significant signal distortion. Resistors are used in place of inductors to allow sufficient voltage to develop across the initial limiter so that the second limiter does not operate before the first.

In addition, the shunt capacitance of the limiters, in combination with the added series resistance will act as a low pass filter, thus reducing the communication link bandwidth. For high data rate lines, the added series resistance and shunt capacitance must be minimized. The total series resistance should be close to the characteristic impedance of the line, typically 50 to 150 ohms, depending on the line chosen, in order to minimize signal reflections. Spark gaps introduce negligible added shunt capacitance, less than 2 picofarads (pF) and are therefore preferred over MOV's or SAS's as the initial limiter. For high data rates, low capacitance diodes can be placed in series with the higher capacitance MOV's or SAS's. The total shunt capacitance of the series combination is determined by the lower capacitance diode. Care must be taken in selecting and packaging the combination diodes and MOV's or SAS's so that the clamping speed and energy rating of the combination are maximized. Prepackaged units are available from a number of manufacturers.

In balanced line applications, a dual-chamber spark gap should be used instead of two single-chamber units to prevent common-mode to differential-mode signal conversion as discussed earlier in Section 4.4.1.1 on spark gaps.

4.5 CABLE INTERFACES

A significant reduction in transient and electromagnetic susceptibility levels can often be achieved through different communication interface designs. By using shielded twisted pairs in balanced communication circuits, significant reductions in the levels of radiated interference coupling to data lines can be achieved. Coupling of interference to some parts can be eliminated completely by using fiber optic cable links between controllers and remotely located sensors. Section 4.5.1 discusses methods of reducting transient and electromagnetic interference susceptibility levels through the use of common-mode rejection techniques, and Section 4.5.2 discusses fiber optic link applications.

4.5.1 Common-Mode Rejection Techniques

Lightning-induced transients and other sources of electromagnetic interference are generally coupled to cable pairs in a common-mode (i.e., transients induced on conductors are of equal amplitude and in-phase), whereas desired signals are transmitted in a differential-mode (i.e., signals impressed on conductors are of equal amplitude but 180 deg out-of-phase). Common-mode rejection (CMR) techniques can be used to decouple common-mode interference from sensitive electronics by employing circuits that pass only the differential-mode signal and reject the common-mode interference. If single-ended lines are used, as shown in Figure 61, common-mode rejection is not possible because the desired signal and the interfering signal are both common-mode. Common-mode rejection refers to a device or circuit's ability to prevent common-mode signals at the input from being converted to differential-mode signals at the output. The common-mode rejection ratio (CMRR) of a device is defined to be the ratio of the differential-mode gain to the common-mode gain and is a parameter commonly used to quantify the effectiveness of the device in suppressing common-mode interference. For example, if a device has a CMRR of 60 dB, a 1-V common-mode input signal produces an output level equivalent to that produced by a 1-mV differential-mode input signal.

The immunity of circuits that interface to external signal cables can be significantly improved in many cases by using high common-mode rejection techniques in conjunction with balanced cabling (shielded-twisted pairs are recommended for most applications). Note that both balanced cabling and balanced interface circuitry are required to achieve the desired result. An improvement of about 20 dB in the coupling of signals between 1 and 10 MHz can be expected for a design configuration incorporating balanced differential signaling, as opposed to a similar unbalanced configuration. Up to 60 dB may be possible at lower frequencies; common-mode rejection is most efficient at low frequencies where stray capacitance and inductive imbalance are insignificant. As with other decoupling techniques, the benefits provided by CMR may require a trade-off of bandwidth, weight, additional circuit complexity, or cost.

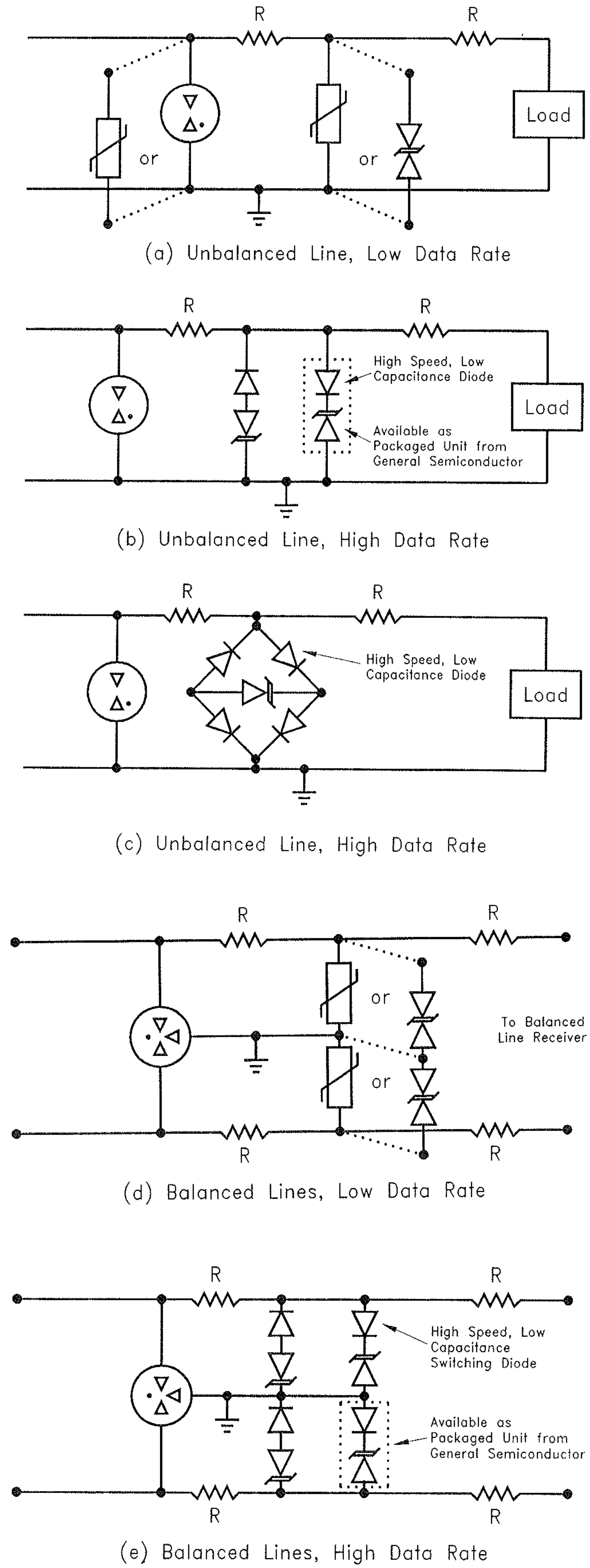


Figure 60. Examples of hybrid suppressor designs for communication line applications.

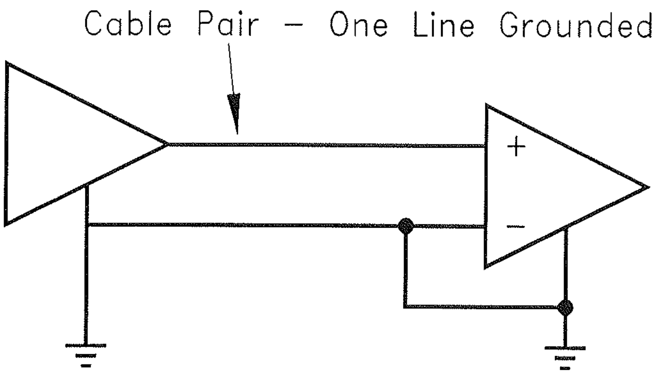


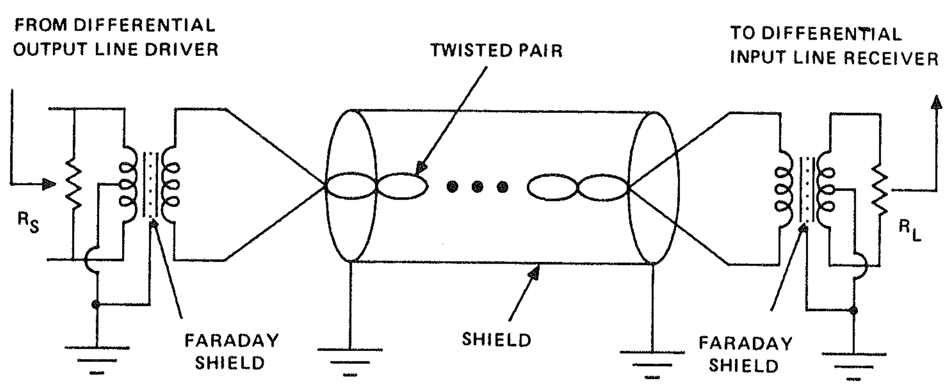
Figure 61. Example of single-ended line.

The most widely used common-mode rejection techniques involve the use of: (1) shunt-connected transformers, (2) series-connected transformers, (3) differential amplifiers, and (4) balanced opto-isolators. The basic method for terminating a shielded twisted pair using shunt-connected transformers is shown in Figure 62. Though not necessary for lightning protection, many transformers include a Faraday shield for electrostatic protection. If a shunt-connected transformer with a Faraday shield is used to interface with balanced circuits, the Faraday shield and the center taps on the balanced sides of the circuit should be grounded, keeping ground leads as short as possible. A shunt-connected transformer may also be used to convert an unbalanced line to a balanced line and vice versa by using the configuration shown in Figure 63.

The primary disadvantages of using shunt-connected transformers in the signal transmission paths are poor transmission characteristics at low frequencies and poor common-mode rejection characteristics at high frequencies (typically rolling off at 40 dB per decade) (*4.29*). Many electronic techniques are available to circumvent or improve the poor low frequency transmission characteristics of shunt-connected transformers. For example, a digital signal may be chopped into narrow pulse signals that are more efficiently coupled by the transformers. Low frequency analog signals can be transmitted more efficiently by using one of a wide variety of signal modulation schemes such as amplitude, frequency, or pulse-code modulation.

Series-connected transformers can also be used to terminate a balanced transmission line and yield significant common-mode rejection. The basic configuration for series-connected transformers is shown in Figure 64. A complete transmission link for a series transformer connection is shown in Figure 65. Both the driver and receiver circuits consist of a TTL gate and emitter follower. This arrangement is useful from dc to 10 MHz in rejecting common-mode interference. The primary advantage of the series connection over the shunt connection is improved low frequency transmission characteristics. In fact, there is no lower frequency limit using series-connected transformers. However, though the series connection ideally offers the same common-mode rejection as shunt connection, such is not the case in practice. Figure 66 shows that the common-mode rejection of the shunt transformers increases monotonically with decreasing frequency, whereas the series transformers common-mode rejection decreases at both very low and very high frequencies. Another advantage of a shunt-connected transformer over a series-connected transformer is that shunt connection provides ground isolation and does not require a ground return for satisfactory operation.

Another technique for providing common-mode rejection and balanced signaling is to employ differential amplifiers or comparators at the interface points. The external connections for a differential amplifier are shown in Figure 67. When using differential amplifiers, it is important to specify the common-mode rejection ratio (CMRR), the bandwidth, and the maximum common-mode voltage. This latter parameter is related to the damage threshold of the active device. Unless some protection is employed, integrated circuit differential amplifiers are usually



NOTE 1. IF THE TRANSFORMER HAS A FARADAY SHIELD THEN THE CENTER TAP ON BOTH SIDES SHOULD BE TIED TO GROUND ALONG THE FARADAY SHIELD.

Figure 62. Methods of terminating a shielded-twisted pair using shunt-connected transformers. (Ref. 4.9)

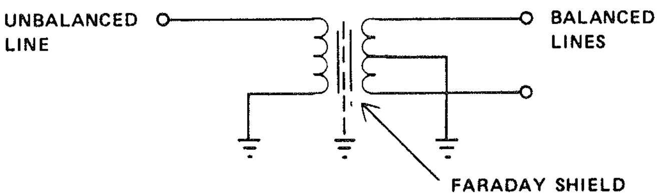


Figure 63. Balancing transformer. (Ref. 4.9)

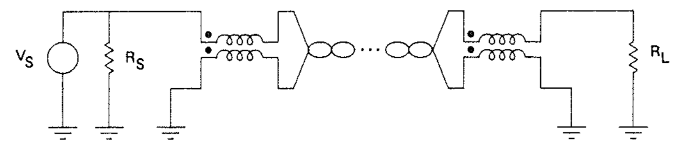


Figure 64. Series-connected transformer configuration. (Ref. 4.9)

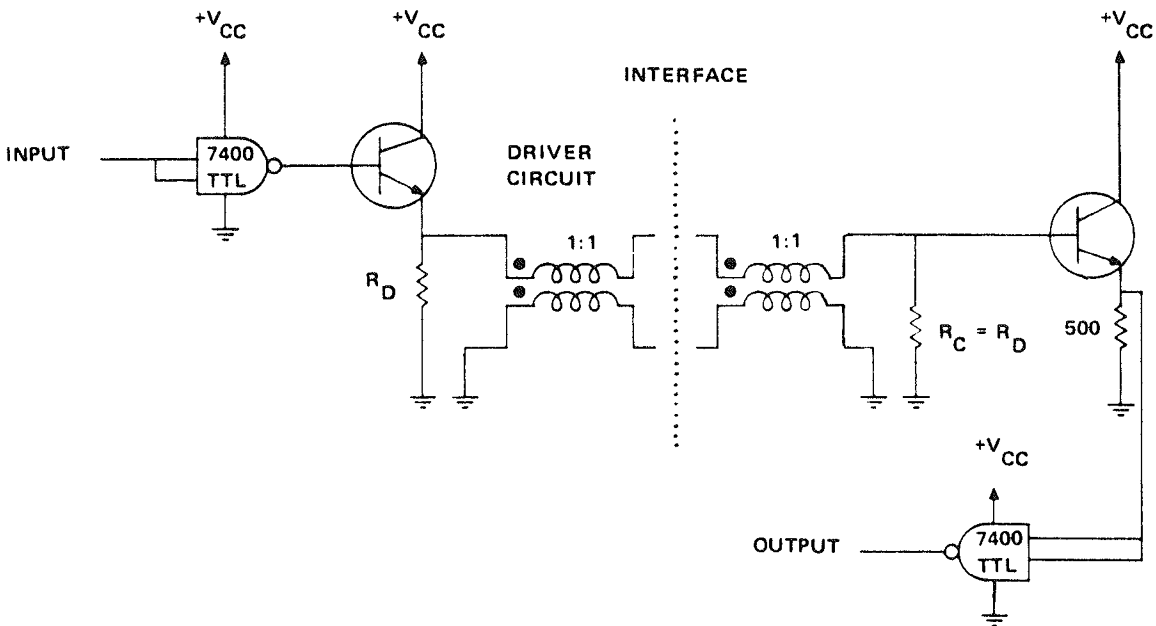


Figure 65. Series transformer line driver and receiver interface circuits connecting two electronic systems. (Ref. 4.9)

limited to common-mode voltages of 5 to 20 V. An example of a wide-bandwidth integrated circuit differential amplifier is the Fairchild μ A733 having a CMRR of 40 dB at 100 MHz and a maximum common-mode voltage of ± 6 V. A schematic of a differential amplifier design which has a ± 100-V common-mode input range is shown in Figure 68. For long cable runs exposed to large transient fields, limiting and filtering are necessary to protect active interface circuits from damage caused by large common-mode surges. Care must be exercised to ensure that the line remains balanced after installation of the suppressors and filters.

Differential amplifiers offer advantages over transformers in decreased weight and size requirements and improved low frequency characteristics, but they also have high input impedances, are susceptible to oscillation at high frquencies, and may be damaged or fail when exposed to large common-mode overvoltages. On the other hand, transformers have limited bandwidth and possibly high insertion loss. In addition, transformers may require protection against burnout and arcing.

Protection of receiving interface circuits may also be accomplished by using optically coupled isolators (opto-isolators) in balanced-mode circuit designs. An opto-isolator is constructed by mounting a light source (for example a light emitting diode) close to a light sensor (for example, a phototransistor) which will transmit electrical signals while maintaining a high degree of electrical isolation between the two elements. Opto-couplers commonly have insulation voltages (input-to-output) on the order of 1,000 to 15,000 V, input-to-output capacitance values of 0.5 to 30 pF, and a high CMRR. Figure 69 illustrates some typical opto-isolator packages.

Most opto-isolator applications are found in digital circuits. They are usually not recommended for analog applications because the isolator's transfer characteristics vary nonlinearly with temperature and input current changes. A common opto-isolator combines a gallium arsenide or infrared light-emitting-diode (LED) as the light source with a silicon phototransistor as the sensor, as shown in Figure 70. A major disadvantage of the phototransistor isolator is its typical 100-kHz bandwidth, which restricts its use to low-data-rate applications.

Improvements in device technology have produced the diode/transistor isolator and the diode/integrated circuit logic gate isolator (shown in Figure 71), which utilize gallium-arsenide-phosphide light-emitting diodes as the light source and have data rate capabilities greater than 1 MHz. The data-handling rates of various types of opto-isolators are compared in Figure 72. Diode/IC logic gate units that have a data-rate capacity of

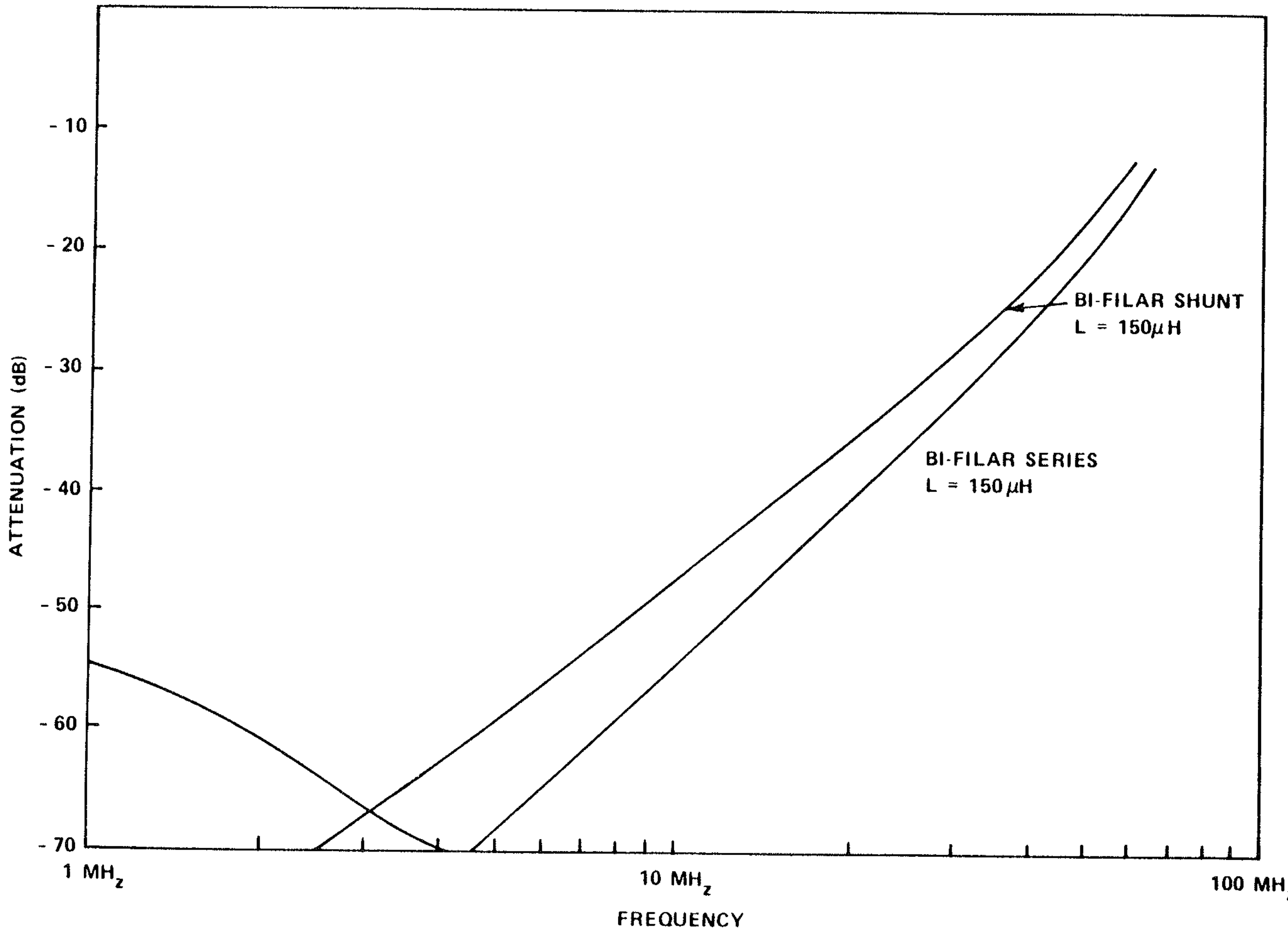


Figure 66. Common-mode rejection test curves. (Ref. 4.29)

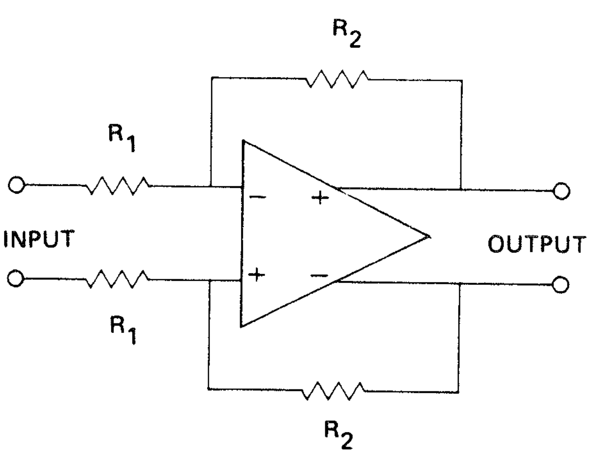


Figure 67. Differential amplifier circuit used in a balanced interface scheme. (Ref. 4.30)

20 MHz and a 20-dB CMRR at 10 MHz are commercially available.

As a balanced line receiver, either the diode/transistor coupler or the diode integrated circuit (IC) logic gate coupler can be used, althought the IC logic gate couplers are better suited to this application because of their lower input current requirements. Figure 73 shows how a line receiver using a coupler should be connected. The resistor values are chosen to match the line driver to the isolator line reciever. The line driver should be designed to supply more current than the isolator input diode requires; this permits the use of a shunt resistor at the receiving end for better impedance-matching and improved noise immunity. Series resistors are then added to bring the line-to-line voltage up to what it would be with only a line-to-line terminating resistor—in other words, without the isolator and its resistor termination.

To maintain a reasonable impedance match during the negative excursion when the isolator input diode is reverse-biased, a diode matching the characteristics of the input diode should be connected in reverse polarity across the input diode as shown in Figure 73. The isolator input diode can be matched either by selecting an LED with the same forward conduction voltage or, preferably, by using the additional LED input diode on a dual isolator package. The additional capacitance resulting from this parallel configuration may be unsuitable for very high speed

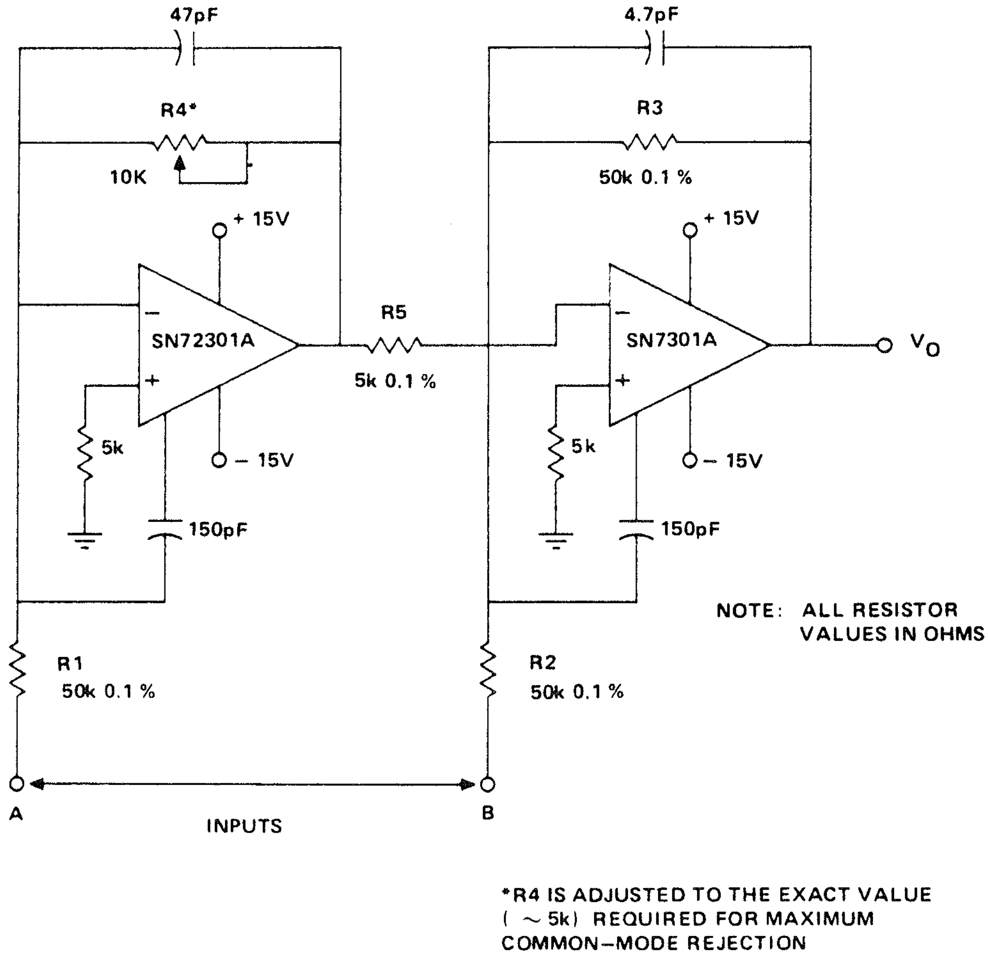


Figure 68. Differential amplifier circuit with ± 100-volt input, common-mode range. (Ref. 4.31)

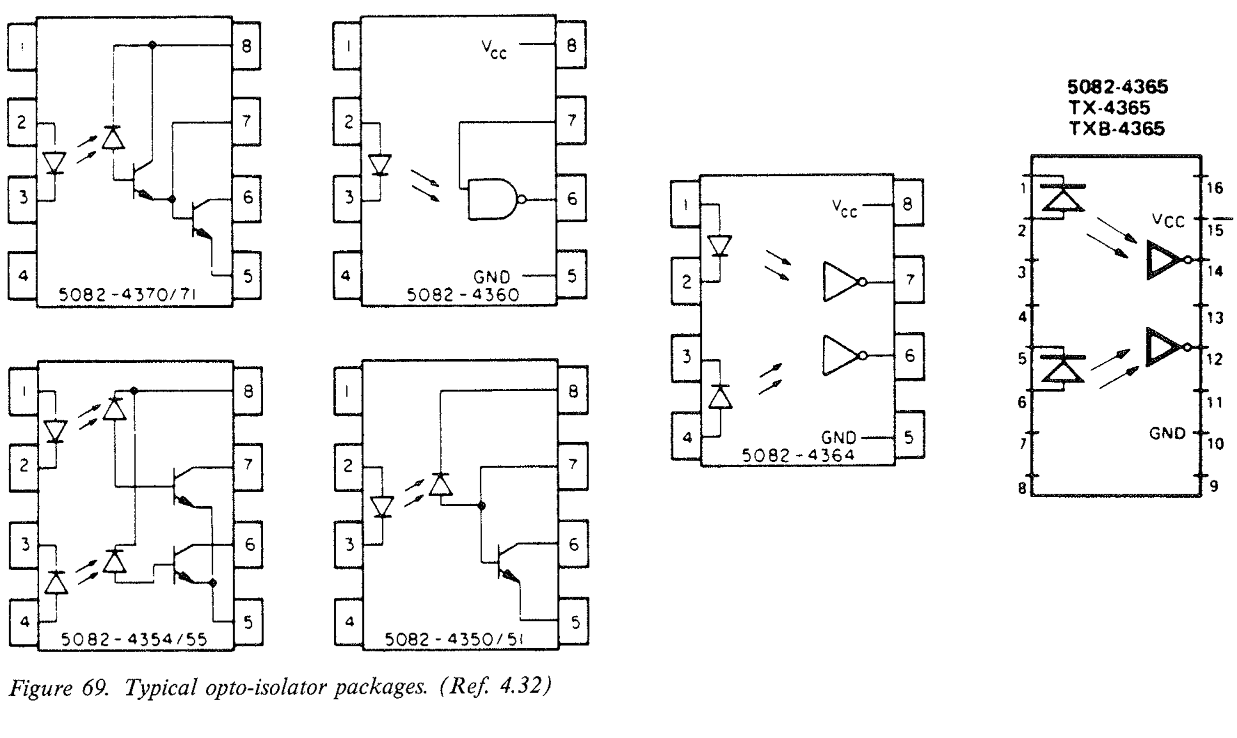


Figure 69. Typical opto-isolator packages. (Ref. 4.32)

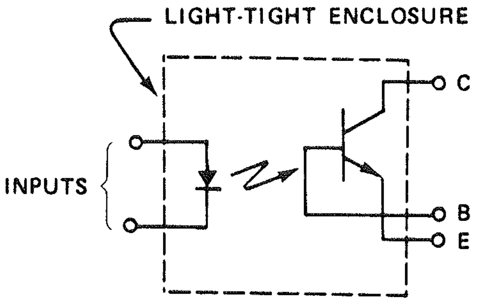


Figure 70. LED-phototransistor opto-isolator circuit symbol.

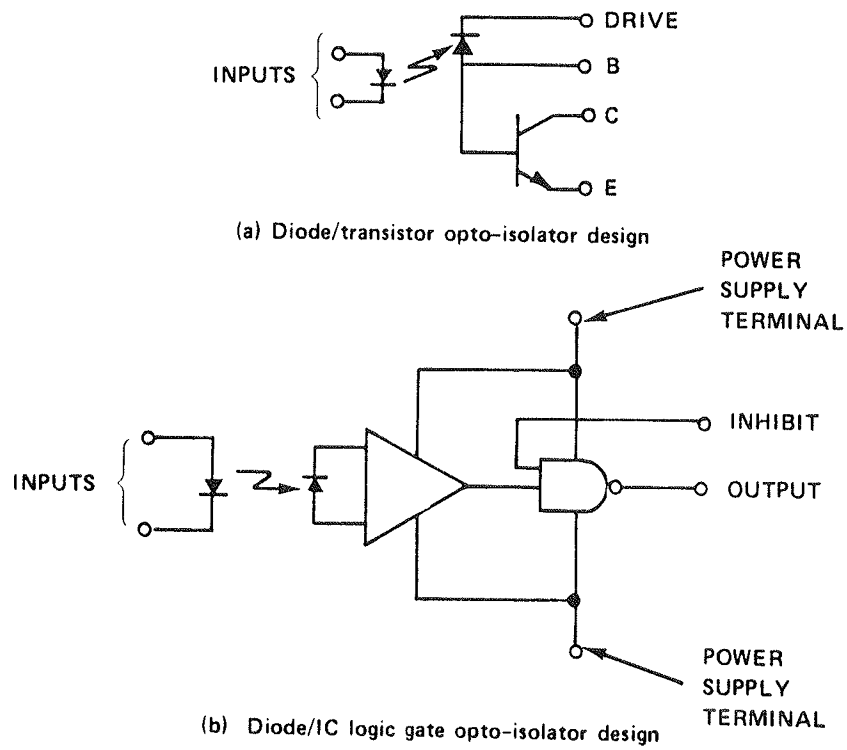


Figure 71. High-speed opto-isolator. (Ref. 4.33)

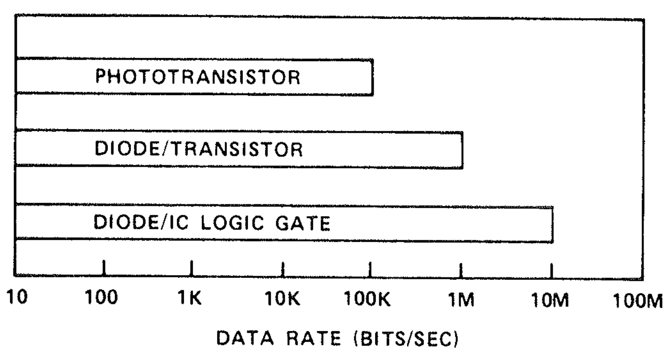


Figure 72. Data-handling rates of various types of optical couplers. (Ref. 4.33)

applications. A preferred configuration under these conditions would be the series combination of two low capacitance silicon switching diodes connected across the LED input.

There exists a wide variety of opto-isolators and possible interconnection techniques. Reference 4.32 should be consulted for further information.

It should be noted that opto-isolators are semiconductor devices and the LED itself must be protected from damage due to large transients. Typical protection schemes for opto-isolators are shown in Figure 74. The type of suppression technique used is dependent on the expected threat characteristics, the signal frequency and amplitude, and the damage threshold of the opto-isolator LED.

4.5.2 Fiber Optics

In recent years, there has been a significant increase in the use of fiber optics (optical waveguides) as a replacement for metallic conductor cables in communication systems. Fiber optic systems offer several performance advantages over conventional cables. Some of these advantages are small size and weight, wide bandwidths, and freedom from conventional transmission line problems such as standing waves and dependence of transmission loss on frequency.

Fiber optic links also offer several significant advantages over conventional cables in terms of electromagnetic interference protection. A primary advantage is that when exposed to a radiated electromagnetic environment, a fiber optic cable will be transparent to signals in the environment. Hence, the coupling of electromagnetic interference to the cable (which might occur with conventional cables, even if well shielded) will not be a problem.

Another advantage is the large bandwidth capability of fiber optic cables. Many signals can be multiplexed onto one fiber, thus permitting several metallic signal cables to be replaced by a single fiber optic link. By reducing the number of electrical penetrations into a circuit enclosure, the overall shielding effectiveness of the enclosure can be improved.

Although fiber optic penetrations will not couple electromagnetic interference into the circuitry, fiber optic circuitry (transmitters and receivers) internal to a circuit enclosure can be affected by electromagnetic interference which couples into the enclosure via other electrical penetrations or through enclosure apertures. Note that ac and dc power must be supplied

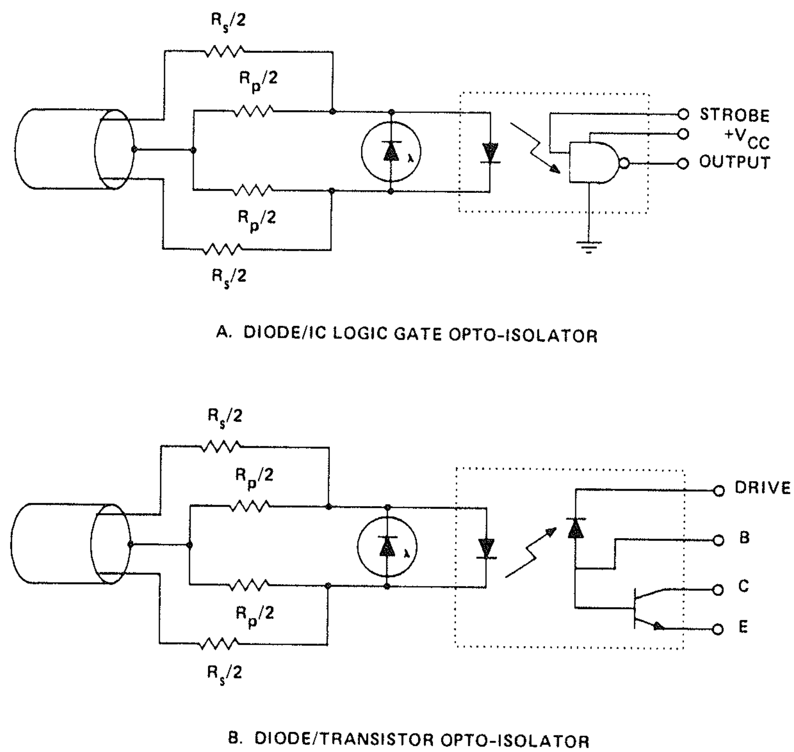


Figure 73. Line receiver circuit designs using optically coupled isolators. (Ref. 4.33)

using conventional metallic lines. Thus, it is important to ensure that the advantages of fiber optic systems for electromagnetic interference protection are not negated by inadequate treatment of other enclosure penetrations and apertures or by inadequate protection of internal circuitry and wiring.

Because the received optical power in fiber optic receivers is typically in the microwatt range, it may be necessary to shield and filter the first stage optical amplifier to prevent radiated or power lead conducted interference from causing upset or damage. Fiber optic transmitter circuitry may also require protection against interference, particularly those drive circuits which interface with external sensors.

Because an optical fiber cable is a dielectric, fiber optic cables are transparent to radiated electromagnetic fields. Hence, a fiber optic cable will not pick up or couple electromagnetic energy into a circuit enclosure. However, if the cable is not specified properly, it can inadvertently present an electromagnetic interference coupling problem. For instance, a fiber optic cable bundle is often used which contains more than one optical fiber. Such cables often have a central strength member and an outer protective layer made of metal as shown in Figure 75. These strength and protection members serve no electrical function but are included for physical and environmental protection of the optical fibers. Unfortunately, when exposed to a radiated environment, these metallic members can serve as effective antennas or can receive a direct lightning strike, thus conducing potentially damaging interference energy into sensitive electronics.

If physical protection requirements dictate the need for metal reinforced cable bundles, the metallic inner strength member should not be carried into the enclosure. The metallic protective covering should be bonded to the cable connector or enclosure wall as necessary to satisfy physical protection/mechanical strength requirements. Here, the establishment of a good electrical bond is not critical because the protective covering is not intended to function as a shield.

When possible, the fiber optic cable bundle should be specified to have an inner strength member made of nonconductive fiber, such as Kevlar or ARAMID fiber, rather than metal. If an outer protective jacket is required it should be a nonconductive material. Examples of two and four fiber cables designed for field use are shown in Figure 76.

Methods of treating fiber optic penetrations into an equipment enclosure generally involve some form of waveguide-below-cutoff aperture treatment. If it is necessary to run a fiber optic cable through an enclosure wall without breaking the optic link, a waveguide-below-cutoff tube should be used. An illustration of a waveguide-below-cutoff tube is given in Figure 77(a). The cutoff frequency and attenuation provided by circular waveguide-below-cutoff tubes can be determined from the information presented in Ref. 4.2. For most lightning protection applications, attenuation values exceeding 100 dB are relatively easy to achieve. Thus, the primary concern in using waveguide-below-cutoff tubes is to ensure that the tube is properly bonded to the enclosure wall such that no cracks or seams are present.

Because the attenuation of a waveguide-below-cutoff tube is dependent on the ratio of the tube length to tube diameter, caution must be exercised when running large numbers of optical

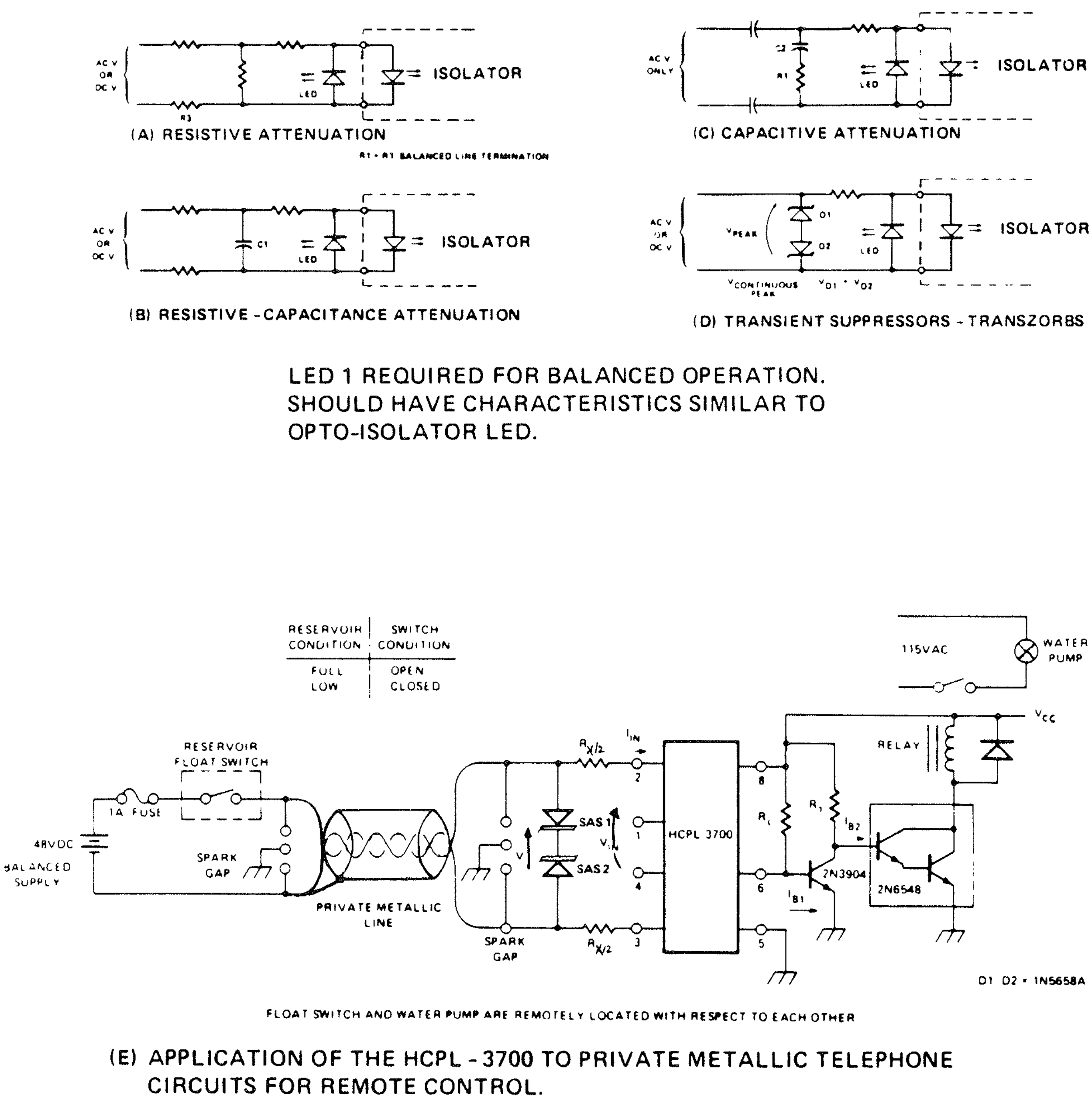


Figure 74. Typical opto-isolator protection techniques. (Ref. 4.32)

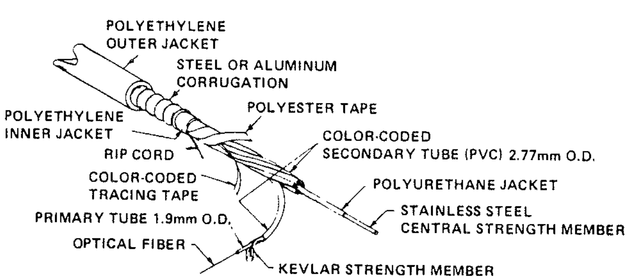


Figure 75. Fiber-optic cable bundle with inner strength member and outer shield made from stainless steel. (Ref. 4.34)

fibers through a single tube. As the tube diameter is increased to accommodate a large number of fibers, the length must also be increased to maintain the desired attenuation. Long tubes may present physical or mechanical layout problems.

Figure 77 illustrates a bulkhead mounted fiber optic connector. A typical bulkhead connector can be modeled as a waveguide-below-cutoff tube and computed attenuation values are on the order of 400 dB at 100 MHz (*4.36*). Actual attenuation will be less because of skin effects and finite metal conductivity; however, the attenuation will generally be much greater than the overall shielding effectiveness of the circuit enclosure. As with the waveguide-below-cutoff tube of Figure 77(a), proper bonding techniques must be followed to prevent leakage around the connector/bulkhead interface.

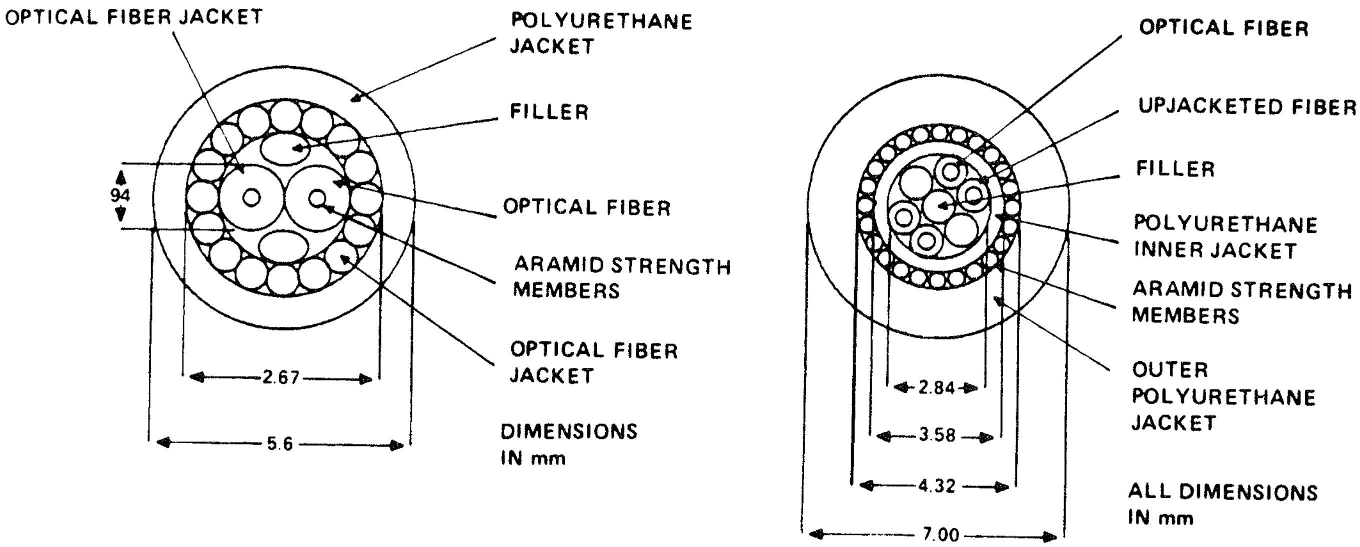


Figure 76. Construction of two and four fiber cables for field use. (Ref. 4.35)

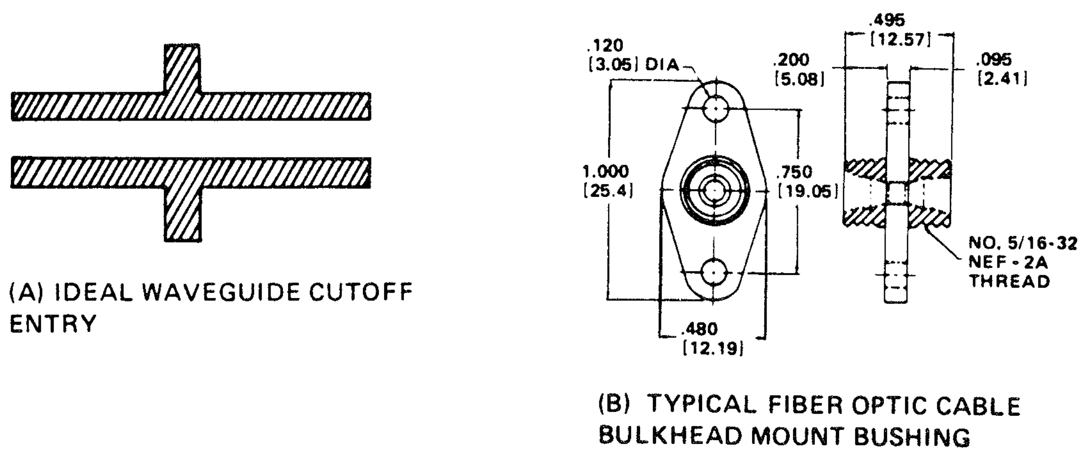


Figure 77. Fiber optic cable connectors. (Ref. 4.12)

In a traffic control system, fiber-optic cable could be used in a number of applications. Obviously, telephone or communication cables between master, local, and slave controllers could be replaced by fiber optic links. Further, pedestrian crosswalk switches and interfaces between traffic signal lights and traffic sensors could be made using inexpensive plastic or wide-diameter glass fiber. Though more expensive than metallic cable, the use of fiber optic communication links may be less expensive than incorporating transient limiters and filters, and long-term maintenance and repair costs may decrease as a result of reduced coupled transient threat levels.

4.6 CONFIGURATION CONTROL AND RETROFIT

When implementing electromagnetic interference and transient protection practices in either new or existing installations, care must be taken to maintain proper cable and equipment configuration in order to: (1) assure normal equipment operation, (2) ensure proper operation of existing or added protection devices, (3) avoid introducing additional operational problems through improper installation procedures. Configuration control is very important when maintenance and repair are performed on an equipment installation. If equipment is removed and then reinstalled in the equipment cabinet during maintenance or repair, care must be taken to preserve the original cable and equipment installation.

In particular, the following items should be considered:

1. Ground connections should be as short as possible.
2. Lines exposed to high transient or electromagnetic interference signal levels should be physically separated from more sensitive input/output lines in order to minimize coupling. Separation can be achieved by routing in separate cable bundles, cable trays, conduit, etc. Lengths of sensitive, unshielded cables should not be run parallel with noisy lines.
3. Cable shields should be peripherally terminated using shielded cable connectors. Protection devices should be installed

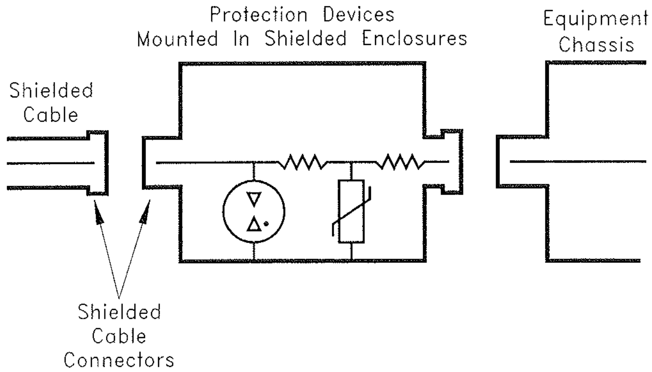


Figure 78. Shielded suppressor.

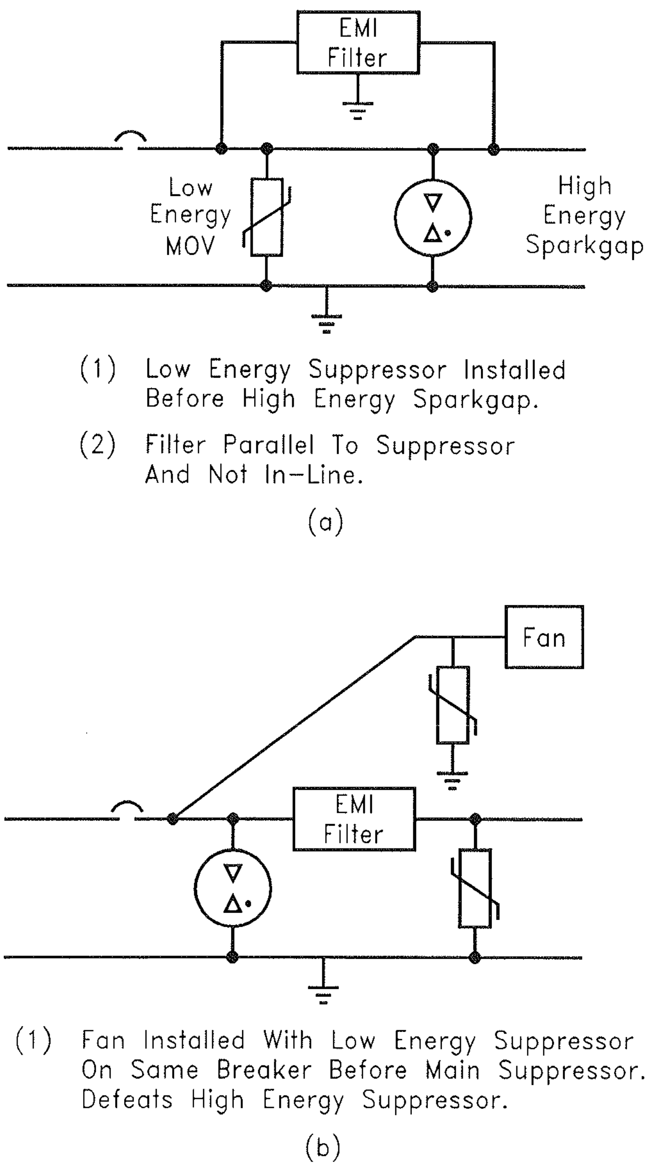


Figure 79. Examples of improperly installed EMI and transient protection devices.

in-line in a shielded enclosure to maintain shielding effectiveness as shown in Figure 78.

When installing protection devices the following cautions should be observed:

1. Minimize lead lengths in order to minimize transient overshoot due to lead inductance.
2. Install devices in proper order. It is not unusual to find protection devices installed in reverse order or otherwise incorrectly, as illustrated in Figure 79.
3. Minimize sharp bends and kinks in leads in order to minimize charge buildup at these points. Arcing and higher radiated emission levels will occur because of the higher electric field levels at bends and kinks.

All permanent and semipermanent bonds, particularly threaded connections, should be regularly inspected to assure good electrical connection. Threaded connections can work loose because of thermal cycling and vibration. Loose connections can render terminal protection devices useless.

In addition, the following general guidelines should be followed (*4.37*):

1. All terminal protection devices should be mounted on the front side of any cabinet panel or piece of equipment so that they may be readily inspected, tested, or removed if necessary.
2. All components should be used in accordance with accepted practice as indicated in applicable Institute of Electrical and Electronics Engineers (IEEE) and National Electrical Manufacturers Association (NEMA) performance specifications.
3. All terminal protection devices should be clearly identified and marked as to manufacturer, part number, and pin identification.
4. All manufacturers of terminal protection devices should indicate conformance with imposed test specifications and should provide supporting documentation and test data, including test procedures and equipment used.
5. Epoxy encapsultated terminal protection devices must be made from or enclosed in flame-retardant material.

■ REFERENCES ■

4.1 *National Electrical Code.* 1984 Edition, NFPA No. 70-1984, ANSI C1-1984, National Fire Protection Association, 60 Batterymarch St., Boston, Mass. (1971).

4.2 Denny, H.W., Holland, L.W., Robinette, S.L., Woody, J.A., "Grounding, Bonding, and Shielding Practices and Procedures for Electronic Equipment and Facilities, Volume 1: Fundamental Considerations." FAA–RD–75–215,1,AD–A022–332 (Dec. 1975).

4.3 "Theory, Principles, and Practices of Grounding Procedures and Lightning Protection for C-E Equipment, Facilities, and Systems." T. O. 31–10–24, U. S. Air Force Ground Electronics Engineering Installation Agency Standard (Dec. 20, 1969).

4.4 Morgan, G.E., et al, "Design Guidelines for EMP Hardening of Aeronautical Systems." *Autonetics Report No. C72–451/201* (Aug. 1972).

4.5 "Electromagnetic Compatibility Design Guide for Avionics and Related Ground Support Equipment." Department of the Navy, Naval Air Systems, Command, Washington, D.C., AD 1115 (Dec. 1975).

4.6 *Technical Bulletins 24 and 33.* Chomerics, Woburn, Massachusetts.

4.7 The Zipper Tubing Company, Los Angeles, California.

4.8 Cadweld Welded Electrical Connections, ERICO Products Inc. 34600 Solon Rd., Solon, Ohio, 44139 (12–1–86).

4.9 Donaldson, E.E., Denny, H.W., Daher, J.K., and Rohrbaugh, J.P., "Design Guidelines for the Mitigation of EMP Effects in Electronic Circuits." Final Draft, Contract No. DNA 001–82–C-0347 (Oct. 1984).

4.10 Nielsen, P., "EMP/EMI Hardening of Electrical Conduit Systems." U.S. Army Corps of Engineers, Construction Engineering Research Laboratory, Champaign, Illinois, *Technical Report M–292* (Sept. 1981).

4.11 Butler, C.M., et al., "Selected Topics in EMP Interaction." U.S. Air Force, Air Force Weapons Laboratory, Kirtland AFB, New Mexico, EMP Interaction, Note 339 (Aug. 1976).

4.12 AMP Special Industries Standard Products Catalog No. 2005–8 (Feb. 1981).

4.13 Belden Electronic Wire and Cable Catalog. Belden Corporation, Richmond, Indiana 47374 (1982).

4.14 Denny, H.W., and Warren, W.B., "RF Bonding Impedance Study." RADC–TR–67–106, Contract AF30(602)–3282, Engineering Experiment Station, Georgia Institute of Technology, Atlanta, Georgia (Mar. 1967).

4.15 "Nomogram for Torque on Bolts." *Design News* (May 22, 1972).

4.16 Whitley, J.H., "Which Permanent Electrical Connection Should You Use?". *Electronics* (Jan. 25, 1963) pp. 50–51.

4.17 Evans, R.W. "Metal-to-Metal Bonding for Transfer of Radio Frequency Energy." IN–R–ASTR–64–15, NASA Marshall Space Flight Center, Huntsville, AL (June 25, 1964).

4.18 *American Institute of Physics Handbook.* Second Edition (1963).

4.19 Rossler, G.D., "Corrosion and the EMI/RFI Knitted Wire Mesh Gasket." *Frequency Technology,* Vol. 7, No. 3 (Mar. 1969) pp. 15–24.

4.20 Hart, W.D., and Higgins, D.F., *A Guide to the Use of Spark Gaps for Electromagnetic Pulse Protection.* Joslyn Electronic Systems, Federal Products Department, Goleta, Calif. (1973).

4.21 *Transient Voltage Suppression Manual.* Fifth Edition, General Electric Company (1986).

4.22 "Transient Suppression Device Characterization Test Report." Boeing Aerospace Company, Contract No. DNA001-82-C-0085 (Dec. 1982).

4.23 Clark, O.M., *EMP Transient Suppression.* Protection Engineering and Management Note Number 31, Lawrence Livermore Laboratories, Livermore, Calif. (Aug. 1974).

4.24 "Management and Design Guidance—Electromagnetic Radiation Hardness for Air Launched Ordnance Systems." MIL–HDBK–335 (Jan. 15, 1981).

4.25 Zverev, A.I., *Handbook of Filter Synthesis.* Wiley: New York (1967).

4.26 Williams, A.B., *Electronic Filter Design Handbook.* McGraw-Hill: New York (1981).

4.27 Roffman, G.L., "Application of Filters for High-Altitude Electromagnetic Pulse Protection." Harry Diamond Laboratories, *HDL-TM-81-0* (April 1981).

4.28 Ott, H.W., *Noise Reduction Techniques in Electronic Systems.* Wiley: New York (1976).

4.29 Hampel, D., et al., "EMP Hardened Circuits, Phase II Final Report." AD 911349 (June 1973).

4.30 Rogers, S.R., et al., "Engineering Design Guidelines for Electromagnetic Pulse Hardening of Naval Equipment, Final Report." Electromagnetic Applications, Inc., Denver, Colorado, under Contract No. N670921-80-C-01, Naval Surface Weapons Center, White Oak, Silver Spring, Maryland (July 15, 1981).

4.31 Pippenger, D.E., and McCollum, C.L., "Linear and Interface Circuits, Applications." Texas Instruments (1974).

4.32 *Hewlett-Packard Optoelectronics/Fiber-Optics Applications Manual.* Second Edition, McGraw-Hill: New York (1981).

4.33 Bloom, G.E., and Duncan, L.W., "Survey of Circuit Elements Used for Reduction of and Protection from Systems Generated Electromagnetic Pulse Effects." Air Force Weapons Laboratory. *AFWL-TR-74-309,* Intelcom Rad Tech, San Diego, Calif. (July 1975).

4.34 VALTEC Fiber Optic Telecommunication Cable, 4-6 Channel, Cable Part No. 40110, Data Sheet, VALTEC Communications Fiber Optics, West Boylston, Massachusetts 01583.

4.35 Smith, J.C., "Using Fiber in Military Tactical Cables." *Lightwave, The Journal of Fiber Optics* (June 1986) p. 34.

4.36 Greenwell, R.A., and Hansen, C.R., "EMP Hardening of the Ground Launched Cruise Missile Signal Transfer System: Design Considerations and Trade Off Factors." Final Report: March 1980–December 1980, Naval Ocean Systems Center, *NOSCTR 667* (Mar. 2, 1981).

4.37 Cunagin, W.D., and Ayoub, N.A., "Handbook of Guidelines for the Lightning Protection of Electronic Traffic Control Equipment, Final Report." Contract No. DTF H61-85-C-00067, submitted to the Federal Highway Administration (Feb. 1986).

CHAPTER FIVE

CONCLUSION

Electronic traffic control equipment is subjected to a wide range of transient and other electromagnetic threats including lightning, electrostatic discharge, internally and externally generated inductive switching transients, and radiated electromagnetic interference from radio, TV, radar, and mobile communication transmitters. The most severe of these threats is lightning. Definitions are given of the general and specific lightning threat levels to traffic control equipment. Typical threat levels are used since protection against the worst case condition is likely to be too costly. In addition, methods for predicting the likelihood of a lightning-induced transient occurring within a traffic control system based on geographic location and local thunderstorm activity are described.

Many protection practices and techniques are presented, including: (1) grounding, (2) shielding of equipment and interface cables, (3) bonding and corrosion control, (4) terminal protection techniques using amplitude limiters and filters, (5) interface designs using balanced line inputs and fiber optics, and (6) guidelines on configuration control and retrofitting. For the protection techniques to be effective, they must be properly selected, installed, and coordinated.

There is a need for a general lightning test specification for traffic control equipment. Equipment installed in high lightning incidence areas should be designed to meet a general, realistic lightning test specification. By standardizing the threat conditions, controller manufacturers can provide a protected unit at a lower cost than if individual municipalities impose varying specifications and requirements. By designing the controller initially with transient protection, overall system costs should be significantly reduced, because the cost to repair and retrofit a controller is significantly higher than the cost to design it properly in the first place. A candidate general test specification in the form of a modification of the National Electrical Manufacturers Association (NEMA) TS 1-1983 to include lightning test requirements is contained in the Appendix.

APPENDIX

SUGGESTED MODIFICATIONS TO NEMA TS 1-1983 TO INCLUDE LIGHTNING TRANSIENT TESTING

A. ANALYSIS OF NEMA TS 1-1983 REQUIREMENTS

In Chapter 3 of this report a specific transient threat to traffic control equipment is defined based on expected threat levels. One of the most widely used specifications for traffic control equipment is the National Electrical Manufacturers Association (NEMA) TS 1-1983 [A-1]. Due to its wide use, a comparison of the NEMA transient requirements and the lightning threat levels given in Chapter 3 was performed to determine the adequacy of the NEMA specification for evaluating lightning protection.

The comparison results were then used to determine changes that would be appropriate to allow NEMA TS 1-1983 compliant equipment to meet a nominal lightning protection requirement. It should be noted that modification of NEMA TS 1-1983 may not be the most appropriate action since many municipalities do not have the lightning problems that others, say in South Florida, do. Imposing a stringent transient requirement on NEMA equipment would create added expense for many that may be unjustified. The material which follows should be viewed only as a starting point for future specifications, whether as a modified NEMA TS 1-1983 specification, or another.

The NEMA specification discusses ac power (Section 2.1.6), input/output (Section 2.1.7), loop detector signal inputs (Section 7.2.6.7 or 11.2.6.7), and loop detector power (Sections 7.2.6.5, 7.2.6.6 or 11.2.6.5, 11.2.6.6). Four classes of transient tests are also defined: (1) high repetition noise transients (2.1.6.1); (2) low-repetition high energy transients (2.1.6.2); (3) non-destruct transient immunity (2.1.8); and (4) transients, input-output terminals (2.1.7). The high-repetition noise, the low-repetition high energy transients, and the input/output transient tests require that the unit be powered up and that no upset occur during the tests. They therefore represent non-damaging transients, such as conducted or radiated powerline switching transients, or low level radiatively coupled lightning transients. The non-destruct transient immunity tests are performed at the ac power input without power applied and the unit must simply not malfunction after power is connected. Unfortunately, most controllers will be operating under ac power during thunderstorms so the test conditions are not realistic from an operational standpoint.

The non-destruct test specification further states that the 120 Vac input must survive three applications once every two seconds of a $\pm$ 1000 volt unipolar discharge from an oil filled, 15 microfarad capacitor having a surge impedance of less than 1 ohm. This implies a short circuit current capability of 1 thousand amps. It is difficult to translate this requirement into a rise and fall time specification since the load impedance is not specified. For example, the Institute of Electrical and Electronics Engineers (IEEE) Std 587-1980 [A-2] guidelines specify the waveform into an open or short circuit load. Further, the peak voltage of only 1 thousand volts and peak short- circuit current of 1 thousand amps is significantly less than the 6 thousand volt, 3 thousand amp unipolar specification of IEEE Std 587-1980 for Class B equipment or the 10 thousand volt, 10 thousand amp Class C equipment specification.

The high-repetition noise, low-repetition high energy transients, and the input/output terminal transients do not adequately represent lightning transients and should not be interpreted as such. They represent switching and fault current transients which occur due to internal or external sources. An example would be the inductive switching transients of crosswalk flashers.

The non-destruct transient tests defined for loop detector ac power inputs suffer from the same limitations discussed above for the general ac power specification. The transient defined for dc powered units is a low energy specification and may be adequate in many cases. Typically, ac is converted to dc and protection is afforded by the dc regulation circuitry. The exception would be when dc power is fed to loop detectors from a remote ac/dc converter over aerial or buried cables. In this case the levels given in Table A-1 should be used.

The loop detector input terminal specification of a 200 volt nondestruct limit and the 3000 volt test of Section 7.2.6.7 (or 11.2.6.7) adequately represent amplitude levels of the most severe threats likely to occur at the loop detector inputs either due to radiated or conducted lightning discharges. A rise and fall time specification of 10 X 1000 microseconds into a short circuit should be added based on IEEE Std C62.31-1984 requirements [A-3].

In summary, the NEMA TS 1-1983 specification as presently written does not adequately test for lightning threat immunity. It is recommended that all ac power inputs be tested in conformance with IEEE Std 587-1980 guidelines for Class B and C equipment. Power should be applied to the units under test. While upset may occur, damage should not. Consult Reference A-4 for appropriate filter designs to prevent damage to the ac power supply. Input/output terminals should be tested to the levels listed in Table A-1 using the damped exponential waveform specifications given in IEEE Std C62.31-1984 [A-3] and Part 15, Subpart J of the Code of Federal Regulations, Title 47(47CER) [A-5]. The high repetition noise transients (2.1.6.1) and low-repetition, high-energy transients (2.1.6.2) should continue to be performed as specified since they represent lower level, high probability of occurrence events such as switching transients within the controller itself. The units should continue to operate properly in the presence of these transients. The non-destruct transient immunity tests (2.1.8), however, should be modified to more adequately represent lightning threat conditions.

B. RECOMMENDED NEMA TS 1-1983 MODIFICATIONS

In the following paragraphs, the existing transient test requirements of NEMA TS 1-1983 are presented first. Recommended additions to NEMA TS 1-1983 are indented and in bold print. Recommended deletions are italized and single spaced.

2.1.6 Transients, Power Service

The controller assembly and the major units of the controller assembly shall maintain all of their defined functions when the independent test pulse levels specified in 2.1.6.1 and 2.1.6.2 occur on the alternating-current power service:

2.1.6.1 High-Repetition Noise Transients

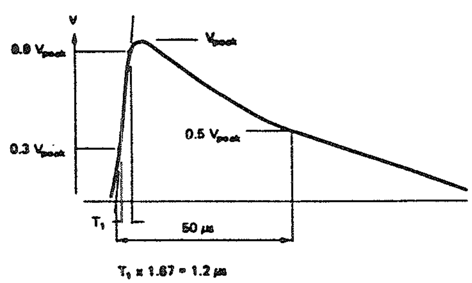
The test pulses shall not exceed the following conditions:

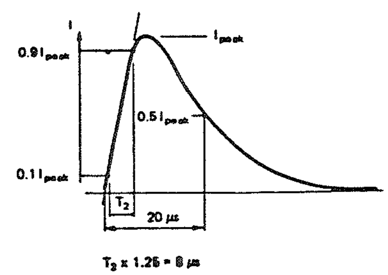
1. Amplitude - 300 volts, both positive and negative polarity.
2. Peak Power - 2500 watts.
3. Repetition - 1 pulse approximately every other cycle moving uniformly over the full wave in order to sweep across 360 degrees of the line cycle once every 3 seconds.

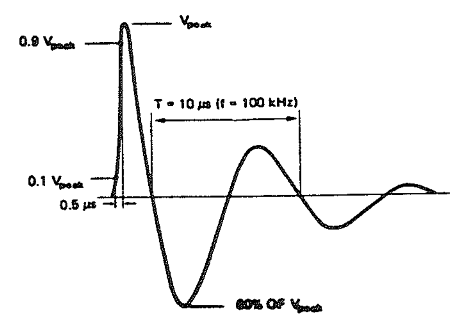
TABLE A-1. RECOMMENDED LIGHTNING TEST WAVEFORMS FOR TRAFFIC CONTROL EQUIPMENT.

LOCATION CATEGORY		DAMPED EXPONENTIAL											RING WAVE										
		Risetime (µ sec.) 10%–90%		Falltime (µ sec.) 50%									Risetime (µ sec.) 10%–90%										
		Voltage Waveform	Current Waveform	Voltage Waveform	Current Waveform	Open Circuit Voltages* (Volts)	Short Circuit Current* (Amps)	Polarity +	Polarity –	Repetition (Each Polarity)	Minimum Time Between Reps (seconds)	Maximum Time Between Reps (seconds)	Voltage Waveform	Current Waveform	Frequency (KHz)	Q min	Q max	Open Circuit Voltages* (Volts)	Short Circuit Current* (Amps)	Repetition	Minimum Time Between Reps (seconds)	Maximum Time Between Reps (seconds)	Reference
120 Volt AC Power Category C	Phase–to–Neutral	1.25	8	50	20	10,000	10,000	✓	✓	1	–	–											A–2
	Phase–to–Ground	1.25	8	50	20	10,000	10,000	✓	✓	1	–	–											A–2
	Neutral–to–Ground	1.25	8	50	20	10,000	10,000	✓	✓	1	–	–											A–2
120 Volt AC Power Category B	Phase–to–Neutral	1.25	8	50	20	6000	3000	✓	✓	5	30	120	.5	.5	100	5	10	6000	500	5	30	120	A–2
	Phase–to–Ground	1.25	8	50	20	6000	3000	✓	✓	5	30	120	.5	.5	100	5	10	6000	500	5	30	120	A–2
	Neutral–to–Ground	1.25	8	50	20	6000	3000	✓	✓	5	30	120	.5	.5	100	5	10	6000	500	5	30	120	A–2
Telephone	Line–to–Ground	10	10	160	160	1500	200	✓	✓	5	30	120											A–5
	Line–to–Line	10	10	560	560	800	200	✓	✓	5	30	120											A–5
	Phase–to–Neutral (AC powered Eqt. only)	2	2	10	10	6000	3000	✓	✓	3	30	120											A–5
Other (ILD, PEDX)	Line–to–Ground	10	10	1000	1000	3000	100	✓	✓	5	30	120											A–3
	Line–to–Line	10	10	1000	1000	3000	100	✓	✓	5	30	120											A–3

* +/– 5% Tolerance







4. Pulse Rise Time - 1 microsecond.

5. Pulse Width - 10 microseconds.

2.1.6.2 Low-Repetition High Energy Transients

The test pulses shall not exceed the following conditions:

1. Amplitude - 600 volts, $\pm$ 5 percent, both positive and negative polarity.
2. Energy Source - Capacitor, oil filled, 10 microfarads $\pm$ 10 percent, internal surge impedance less than 1 ohm.
3. Repetition - 1 discharge every 10 seconds.
4. Pulse Position - Random across 360 degrees of the line cycle.

2.1.7 Transients, Input-output Terminals

The controller assembly and the major units of the controller assembly shall maintain all of their defined functions when the test pulse occurs on the input-output terminals.

1. Amplitude - 300 volts, both positive and negative polarity.
2. Pulse Source - 1000 ohms nominal impedance.
3. Repetition - 1 pulse per second, for a minimum of five pulses per selected terminal.
4. Pulse Rise Time - 1 microseconds.
5. Pulse Width - 10 microseconds.

2.1.7.1 Non-Destruct Lightning Transients, Input-Output Terminals

The controller assembly and the major units of the controller assembly shall be capable of withstanding the non-destruct transient pulses given in Table A-1 applied to the input-output terminals with transient protection devices installed and with ac power applied.

2.1.8 Nondestruct Transient Immunity

The controller assembly and the major units of the controller assembly shall be capable of withstanding a high-energy transient having the following characteristics repeatedly applied to the alternating-current input terminals (no other power connected to terminals) without failure of the test specimen:

1. Amplitude - 1000 volts $\pm$ 5 percent, both positive and negative polarity.
2. Energy Source - Capacitor, oil filled 15 microfarads $\pm$ 10 percent, internal surge impedance less than 1 ohm.
3. Repetition - Applied to the controller assembly once every 2 seconds for a maximum of three applications for each polarity.

After the foregoing, the controller assembly and the major units of the controller assembly shall perform all of their defined functions upon the application of nominal alternating-current power.

2.1.8.1 Nondestruct Lightning Transient Immunity

The controller assembly and the major units of the controller assembly shall be capable of withstanding the high- energy lightning transients having the characteristics specified in Table A-1 applied to the alternating current input terminals (with alternating-current power applied at nominal levels with transient protection devices installed), phase-to-neutral, phase-to-ground and neutral to-ground without failure of the specimen. Two classes of tests shall be performed, a damped exponential discharge test and a ring wave discharge test. The two classes of tests are defined below.

2.1.8.1.1 Damped Exponential, Category B

1. **Amplitude - peak of 6000 volts, +/- 5 percent, both positive and negative polarity into an open-circuit.**
2. **Short-Circuit Current - peak of 3000 amps +/- percent.**

3. Wave Shape - 8 microsecond risetime, 20 microsecond 50 percent decay time into a short-circuit. 1.25 microsecond risetime, 50 microsecond 50 percent decay time into an open-circuit.

4. Repetition - Applied phase-to-ground, phase-to-neutral and neutral-to-ground five times for both polarities.

5. Time Between Discharges - random, 120 seconds, maximum; 30 seconds, minimum.

2.1.8.1.2 Ring Wave, Category B

1. Amplitude - peak of 6000 volts +/- 5 percent into an open-circuit

2. Short-Circuit Current - peak of 500 amps +/- 5 percent

3. Wave Shape - 0.5 microsecond risetime, 100 kilohertz oscillation frequency, Q between 5 and 10.

4. Repetition - Applied phase-to-ground, phase-to-neutral and phase-to-ground five times.

5. Time Between Discharges - random, 120 second, maximum; 30 seconds, minimum.

2.1.8.1.3 Damped Exponential, Category C

1. Amplitude - peak of 10,000 volts, +/- 5 percent, both positive and negative polarity into an open-circuit

2. Short-Circuit Current - peak of 10,000 amps, +/- 5 percent.

3. Wave Shape - 8 microsecond risetime, 20 microsecond 50 percent decay time into a short-circuit. 1.25 microsecond risetime, 50 microsecond 50 percent decay time into an open-circuit.

4. Repetition - Applied phase-to-ground, phase-to-neutral and neutral-to-ground one time for both polarities.

5. Time Between Discharges - Random, 120 minutes maximum; 30 seconds, minimum.

2.2.2 Test Unit

The test unit shall be the complete controller assembly, in the weatherproof equipment cabinet with provisions for ventilation, as specified by the equipment manufacturer, including:

1. Terminal facilities.
2. Surge protection.
3. Line filters.
4. Controller unit.
5. Load switches.
6. Signal conflict monitor.
7. Auxiliary control devices (as required).
8. Flashers.

The test equipment shall be set up in accordance with Figure 2-1.

2.2.3.2 Test B-Transient Tests (Power Service)

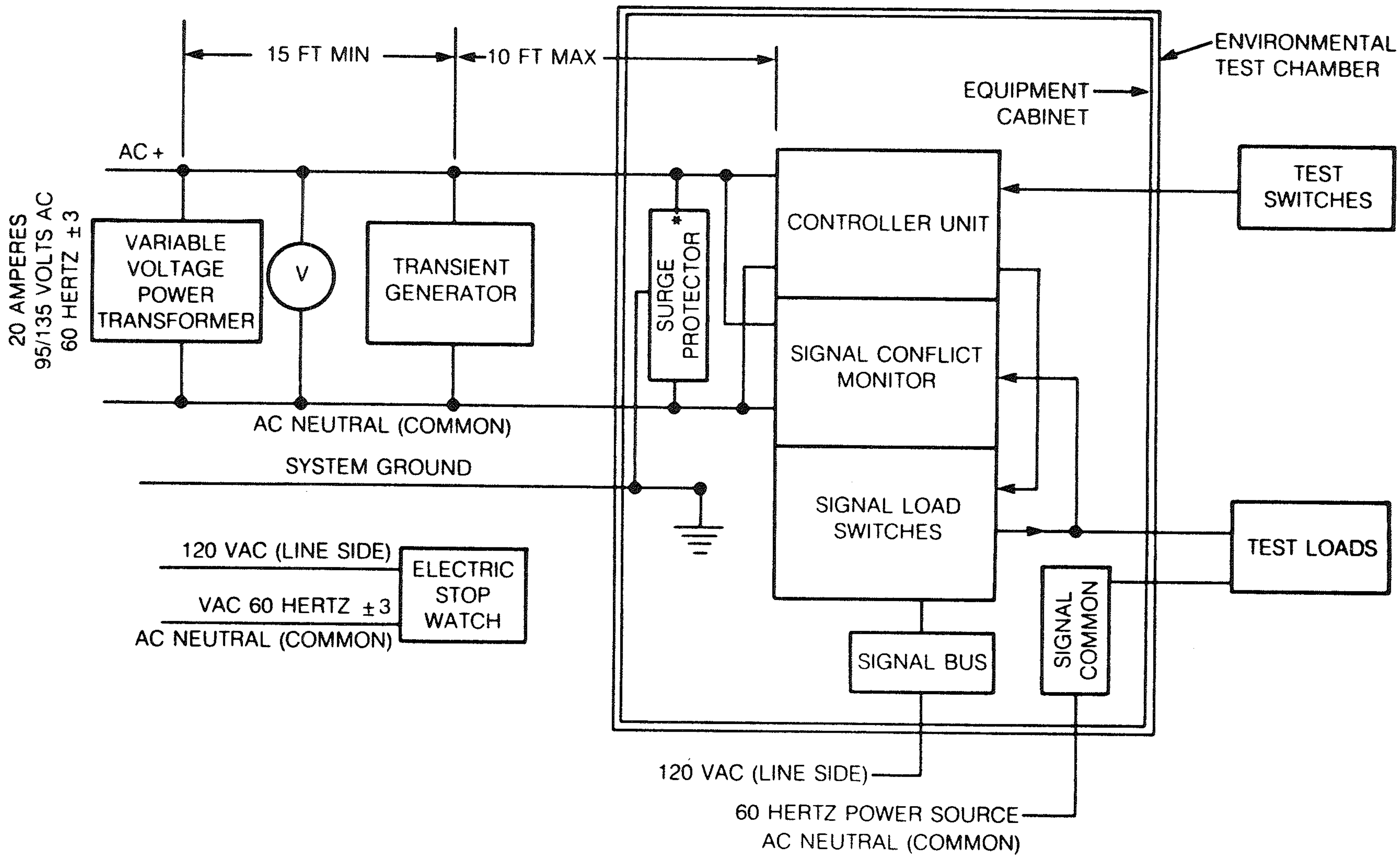
The surge protector and line filters shall be removed from the alternating-current power source circuit of the equipment cabinet for the following transient tests:

1. Program the contoller unit so it will dwell in a selected phase-120 volts alternating-current input from the variable- voltage power transformer.

2. Set a transient generator to provide high-repetition noise transients as follows:

   a. Amplitude - 300 volts $\pm$ 5 percent, both positive and negative polarity.

   b. Peak-power - 2500 watts.



*The surge protector and line filtering in the equipment cabinet shall be removed during the transient probe; 2.2.3.2, 1 through 13.

The surge protector and line filtering in the equipment cabinet shall not be removed during the transient probe specified in 2.2.3.2, 14 and 15.

Figure 2-1
6A TYPICAL TEST DIAGRAM

c. Repetition rate - one pulse every other cycle moving uniformly over the full wave in order to sweep once every 3 seconds across 360 degrees of line cycle.

d. Pulse rise time - 1 microsecond.

e. Pulse width - 10 microseconds.

3. Apply the transient generator output to the alternating- current voltage input as indicated in Figure 2-1 for at least 5 minutes. Repeat this test for the condition of dwell for each phase of the controller unit. The controller unit must continue to dwell in the selected phase without incidence of false calls or indications.

4. Program the controller unit to cycle on minimum recall. Turn on the transient generator (output in accordance with item 2) for 10 minutes, during which time the controller unit shall continue to cycle without malfunction.

5. Set a transient generator to provide high-repetition noise transients as follows:

   a. Amplitude - 300 volts $\pm$ 5 percent, both positive and negative polarity.

   b. Peak power - 2500 watts.

   c. Repetition - one pulse per second for a minimum of five pulses per selected terminal.

   d. Pulse rise time - 1 microsecond.

   e. Pulse width - 10 microseconds.

Progam the controller unit so it will dwell in a selected phase-120 volts alternating-current input.

6. Apply the transient generator (output in accordance with item 5) between logic ground and the connecting cable termination of selected input/output terminals of the controller unit. (Certain auxiliary equipment may not comply with the requirements of this test at this time. Special test procedures should be used for auxiliary equipment).

A representative sampling of selected input/output terminations shall be tested. The controller unit shall continue to dwell in the selected phase without incidence of false calls or indications.

7. Program the controller unit to cycle on minimum recall. Turn on the transient generator (output in accordance with item 5) apply its output to the selected input/output terminations. The controller unit shall continue to cycle without malfunction.

8. Set a transient generator to provide low-repetition high- energy transients as follows:

   a. Amplitude - 600 volts $\pm$ 5 percent, both positive and negative polarity.

   b. Energy discharge source - capacitor, oil-filled 10 microfarads.

   c. Repetition rate - one discharge each 10 seconds.

   d. Pulse position - random across 360 degrees of line cycle.

9. Program the controller unit so it will dwell in a selected phase-120 volts alternating-current input from the variable- voltage power transformer.

10. Discharge the oil-filled 10 microfarad capacitor ten times for each polarity across the alternating-current voltage input. Repeat this test for the condition of dwell for each phase of the controller unit. The controller unit shall continue to dwell in the selected phase without incidence of false calls or indications.

11. Program the controller unit to cycle on minimum recall. Discharge the capacitor ten times for each polarity while the controller is cycling on minimum recall, during which time the controller unit shall continue to cycle without malfunction.

12. During the preceding transient tests (items 3 through 11) the controller must continue its programmed functions. The controller shall not skip intervals or phases when cycling; place false calls or produce false indications while in dwell; disrupt normal sequences in any manner; or change timings.

13. Non-destruct Transient Immunity:

   a. Turn off the alternating-current power input to the test unit from the variable-voltage power source.

   b. Apply the following high-energy transient to the alternating-current voltage input terminals of the controller unit (no other power connected to terminals):

      1. Amplitude - 1000 volts, both positive and negative polarity.

      2. Peak power discharge-capacitor, oil-filled, 15 microfarads.

3. Repetition rate - applied to the controller assembly once every 2 seconds for a maximum of three applications for each polarity.

c. Upon completion of the foregoing, apply 120 volts alternating-current to the controller assembly and verify that the controller unit goes through its prescribed start-up sequence and cycles properly in accordance with the programmed functions. The first operation of the over-current protective device during this test shall not be considered a failure of the controller assembly.

Upon satisfactory completion of this test, reconnect the surge protector and line filters and proceed to Test C.

14. <u>Non-destruct Lightning Transient Immunity:</u>

a. **Install transient surge protectors and line filters to alternating-current power inputs.**

b. **Turn on the alternating-current power input to the test unit from the variable - voltage power source.**

c. **Apply the high-energy lightning transient as specified in 2.1.8.1 to the alternating-current voltage input terminals of the controller unit.**

d. **Upon completion of the foregoing, the unit shall not suffer damage with the exception of input fuses. Circuit breakers can operate but not be damaged.**

15. <u>Non-destruct Lightning Transient Immunity for Input-Output.</u>

a. **Install transient surge protectors and line filters to input-outputs.**

b. **Turn on the alternating current power input to the test unit from the variable-voltage power source.**

c. **Apply the high-energy non-destruct lightning transient as specified in 2.1.7.1 to the input-output pins. Adjust the open circuit voltage and short circuit current as appropriate for the input-output pin under test.**

d. **Upon completion of the forgoing, the unit shall not suffer damage with the exception of input fuses (if utilized). Circuit breakers (if utilized) can operate but not be damaged.**

3.2.2 Transient Immunity

The operation of the controller unit shall not be affected during operation by the application to any input or output terminal of pulses having a duration of 10 microseconds, a positive or negative amplitude of 300 volts, and a maximum repetition rate of 1 pulse per second, using a pulse source having an output impedance of not less than 1000 ohms and not greater than 10,000 ohms.

<u>3.2.2.1 Non-Destruct Lightning Transients</u>

The controller unit shall not be damaged with the application of the transients specified in 2.1.7.1 to the input-output terminals of the controller unit.

7.2.6.5 Transients, AC-Powered Units

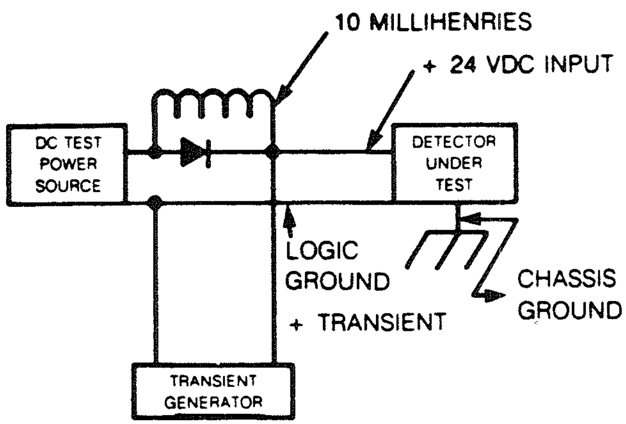
Loop detector units using 120 volts ac 60-Hertz input power shall meet the following requirements:

1. The detector unit shall withstand the high-repetition noise transients as described in 2.1.6.1.
2. The detector unit shall withstand the low-repetition, high-energy transients as described in 2.1.6.2.
3. The detector unit shall withstand the nondestructive transient described in 2.1.8.
4. **The detector unit ac power inputs shall withstand the non-destruct lightning withstand tests of 2.1.8.1.**

7.2.6.6 Transients, DC-Powered Units

Loop detector units using 24-volt dc input power shall operate normally when the test impulse described in 2.1.7 is applied as follows:

1. Between LOGIC GROUND and the +24-volt dc power input. The test set- up shown in Figure 7.3 shall be used for this test.
2. Across the output terminals of each channel while in both the detect and nondetect condition.



TEST CONDITIONS:

1. Transient generator is described in 2.1.7.
2. The input voltage shall be 24 ± 2.5 volts dc measured at the input terminal to the loop detector under test.
3. The dc power source must be capable of supplying at least 100 milliamperes per channel.
4. When testing for the reverse polarity transient, the diode shown shall be reversed.

Figure 7-3
TEST CONFIGURATION

3. **The detector units shall withstand the non- destruct lightning withstand tests of 2.1.8.1 if dc power is supplied from a remote power source located 100 feet or greater from the control unit cabinet.**

Detector loop inputs are specifically excluded from this test.

7.2.6.7 Transients, Loop Detector Input Terminals

The detector shall be capable of withstanding the following nondestructive transient test:

1. The detector loop input terminals, with loop not connected, shall be subjected to the nondestruct transient immunity test described in 2.1.8, except that the amplitude shall be 200 volts ± 5 percent.

2. Each detector loop input terminal shall be subjected to one transient pulse of each polarity between the loop terminal and chassis ground with the other loop terminal ungrounded and repeated with the other terminal connected to chassis ground as shown in Figure 7.4. The test shall be performed with the detector operating from its normal power source and with a 100 microhenry 10 percent coil connected across the loop terminals of each channel.

Delete the following sentences:

The energy source shall be a capacitor of 0.05 microfarads +/- 5 percent.
The pushbutton shall be activated for at least 1 second for each of the eight conditions.

11.2.6.5 Transients, AC Powered Units

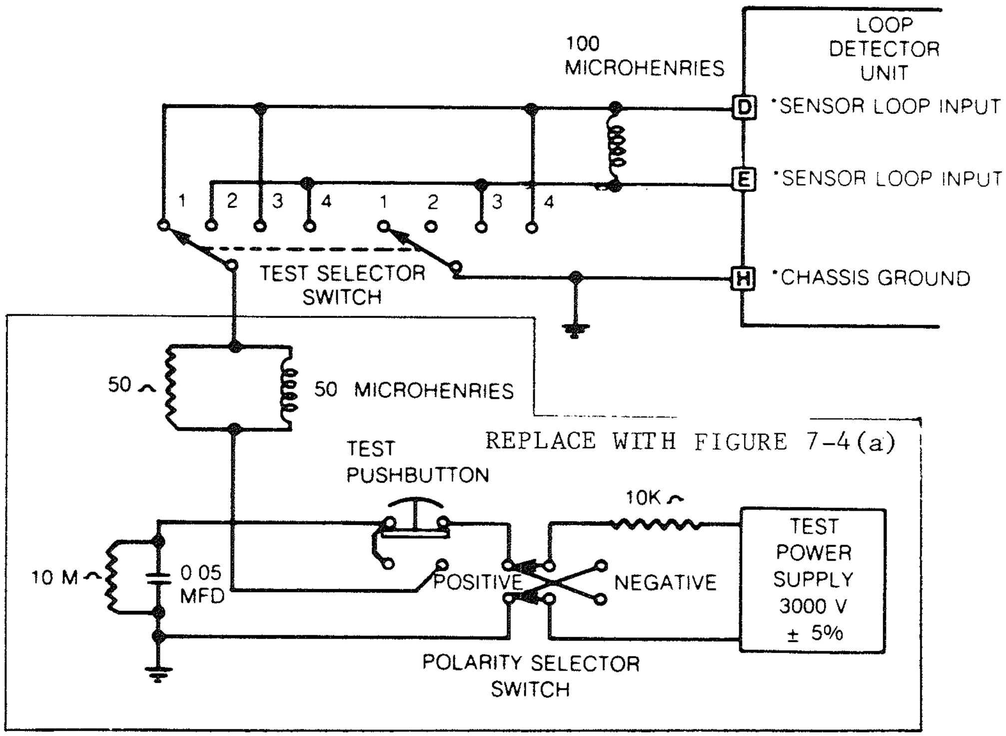
Loop detector units using 120 Vac 60 Hz input power shall meet the following requirements:

1. The detector unit shall withstand the high-repetition noise transients as described in 2.1.6.1.

2. The detector unit shall withstand the low-repetition high-energy transients as described in 2.1.6.2.

3. The detector unit shall withstand the non-destructive transient as described in 2.1.8.

4. **The detector unit ac power inputs shall withstand the non-destruct lightning withstand tests of 2.1.8.1.**



TRANSIENT TEST CONFIGURATIONS

TEST NUMBER	TEST SELECTOR POSITION	POLARITY SELECTOR	TESTED INPUTS*
1	1	POSITIVE	D TO H
2	2	POSITIVE	E TO H
3	3	POSITIVE	D TO E
4	4	POSITIVE	E TO D
5	1	NEGATIVE	D TO H
6	2	NEGATIVE	E TO H
7	3	NEGATIVE	D TO E
8	4	NEGATIVE	E TO D

Figure 7-4
LOOP INPUT TERMINAL TRANSIENT TESTS

*The pin designations shown are for a single channel detector. Similar tests shall be performed on all channels of a multichannel detector.

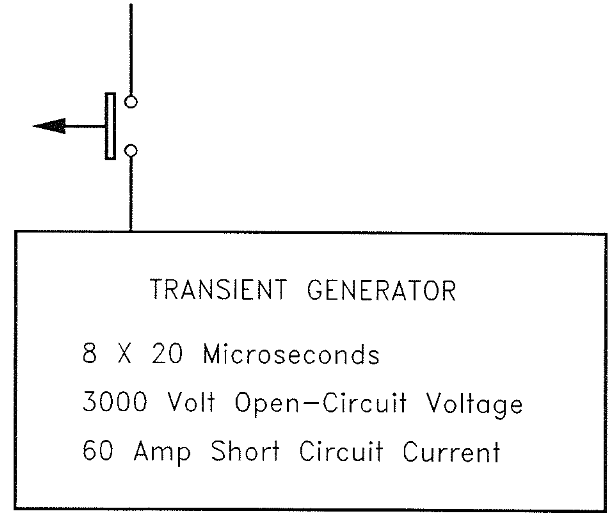


Figure 7-4(a). Modification to Loop Input Terminal Transients Tests.

11.2.6.6 Transients, DC Powered Unit

Loop detector units using 24 Vdc input power shall operate normally when the test impulse described in 2.1.7 is applied as follows:

1. Between LOGIC GROUND and the + 24 Vdc power input. The test set-up shown in Figure 11-3 shall be used for this test.
2. Across the output terminals of each channel while in both the detect and non-detect condition.
3. Between LOGIC GROUND and the control inputs.
4. **The detector units shall withstand the non- destruct lightning withstand tests of 2.1.8.1 if dc power is supplied from a remote power source located 100 feet or greater from the control unit cabinet.**

Detector loop inputs are specifically excluded from this test.

11.2.6.7 Transients,Loop Detector Input Terminals

The detector shall be capable of withstanding the following non-destructive transient test:

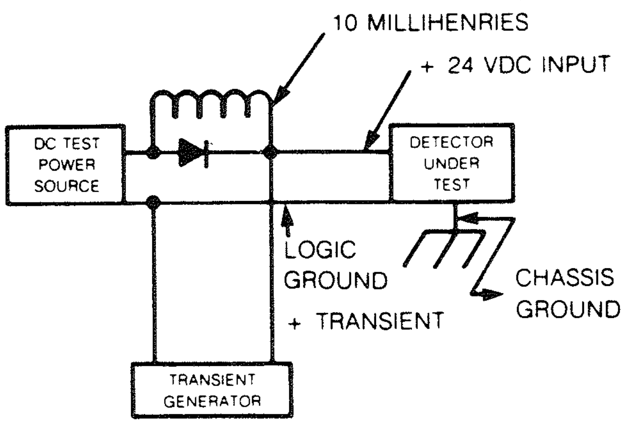
1. The detector loop input terminals, with loop not connected shall be subjected to the non-destruct transient immunity test described in 2.1.8, except that the amplitude shall be 200 volts $\pm$ 5%.
2. Each detector loop input terminal shall be subjected to one transient pulse of each polarity between the loop terminal and chassis ground with the other loop terminal ungrounded and repeated with the other terminal connected to chassis ground as shown in Figure 11-4.

Delete the following sentences:

The test shall be performed with the detector operating from its normal power source and with a 100 microhenry +/- 20% coil connected across the loop terminals of each channel

The energy source shall be a capacitor of 0.05 microfarads +/- 5% connected in accordance with Figure 11-4.

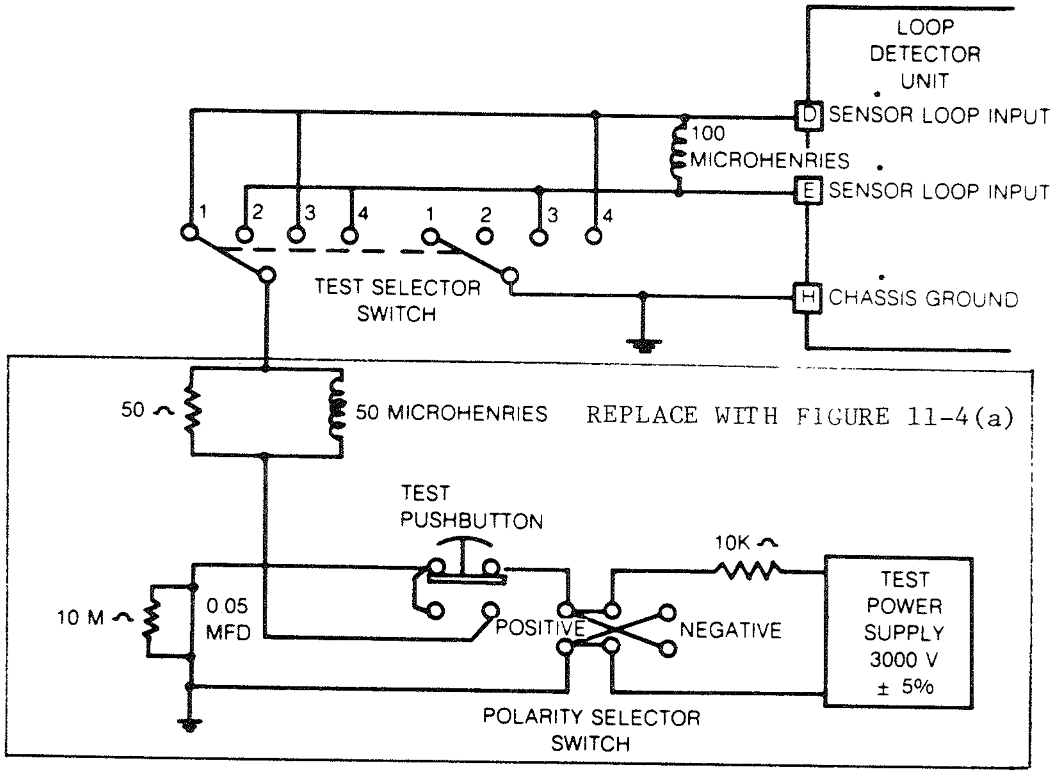
The voltage on the capacitor shall be adjusted to 3000 volts +/- 5%.
The pushbutton shall be activated for at least one second for each of the eight conditions.



TEST CONDITIONS:

1. Transient generator is described in 2.1.7.
2. The input voltage shall be 24 $\pm$ 2.5 volts dc measured at the input terminal to the loop detector under test.
3. The dc power source must be capable of supplying at least 100 milliamperes per channel.
4. When testing for the reverse polarity transient, the diode shown shall be reversed.

Figure 11-3
TEST CONFIGURATION



TRANSIENT TEST CONFIGURATIONS

TEST NUMBER	TEST SELECTOR POSITION	POLARITY SELECTOR	TESTED INPUTS*
1	1	POSITIVE	D TO H
2	2	POSITIVE	E TO H
3	3	POSITIVE	D TO E
4	4	POSITIVE	E TO D
5	1	NEGATIVE	D TO H
6	2	NEGATIVE	E TO H
7	3	NEGATIVE	D TO E
8	4	NEGATIVE	E TO D

*The pin designations shown are for a single channel detector. Similar tests shall be performed on all channels of a multichannel detector.

Figure 11-4
LOOP INPUT TERMINAL TRANSIENT TESTS

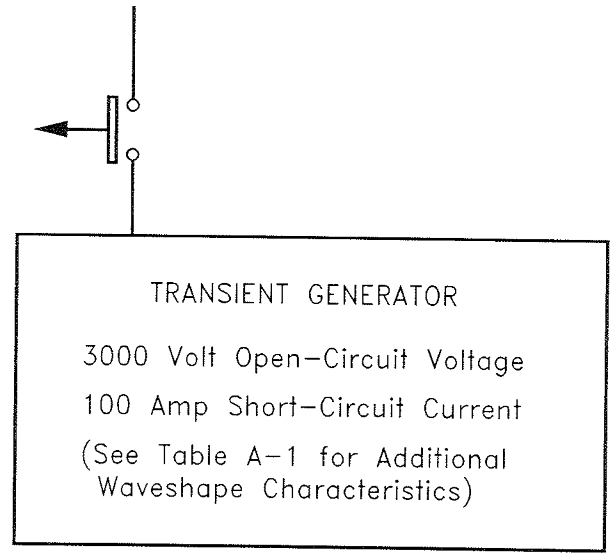


Figure 11-4(a). Modification to Loop Input Terminal Transient Tests.

13.2.2 Transient Immunity

The operation of the controller unit shall not be affected during operation by the application to any input or output terminal of pulses of 10 microseconds duration, 300-volt positive or negative amplitude, and with a maximum repetition rate of 1 pulse per second. For purposes of this requirement, a pulse source having an output impedance of not less than 1000 ohms, nor greater than 10,000 ohms, shall be used.

13.2.2.1 Non-destruct Lightning Transients

The controller unit shall not be damaged with the application of the transients specified in 2.1.7.1 to the input-output terminals of the controller unit.

REFERENCES

A-1 "Traffic Control Systems," NEMA TS 1-1983, Revision No. 2 - October 1985, National Electrical Manufacturers Association, Washington, D.C.

A-2 "IEEE Guide for Surge Voltages in Low-Voltage AC Power Circuits," IEEE Std 587-1980.

A-3 "IEEE Standard Test Specifications for Gas-Tube Surge-Protective Devices," IEEE Std C62.31.1984.

A-4 "Surge Protection Test Handbook: A Practical Guide for Designers, Builders and Users of Modern Electronic Equipment," KeyTek Instruments Corp., Burlington, MA, 1982.

A-5 Part 15, Subpart J, of the Code of Federal Regulations, Title 47 (47 CFR).