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Design Recommendations for Grounding
and Bonding in C³I Facilities

Integrated Grounding and Bonding Practices in Command, Control, Communications, and Intelligence Facilities

by
Hugh W. Denny
Timothy G. Shands
Jimmy A. Woody
Ray G. McCormack

Command, control, communications, and intelligence (C^3I) facilities are essential to the nation's defense system. These facilities must operate reliably while maintaining electrical safety, surviving lightning, controlling electromagnetic interference, maintaining signal security, and retaining immunity against an electromagnetic pulse event. Proper grounding and bonding are essential to highly reliable operation.

This research defined the C^3I facility in terms of its necessary elements, identified the grounding and bonding requirements imposed by various electrical/electromagnetic environments, and developed a set of grounding and bonding practices for generic facilities.

Existing C^3I facilities were visited and analyzed to determine the degree of conformance with the practices recommended in this report. Procedures appropriate to the particular sites are presented; however, the procedures are applicable to other sites as well.

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FOREWORD

This work was performed for the Directorate of Engineering and Construction, Headquarters, U.S. Army Corps of Engineers (HQUSACE), under project 4A162781AT45, "Energy and Energy Conservation"; Technical Area D, Work Unit 009, "Design Recommendations for Grounding and Bonding in C^3I Facilities." The HQUSACE Technical Monitor was Mr. Rodney Wells, CEEC-EE.

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1 INTRODUCTION

Background

Effective control and deployment of the nation's defense resources require a worldwide command, control, communications, and intelligence (C^3I) network. This network contains an extensive variety of equipment and facilities. For example, fixed land-based C^3I facilities range from small structures performing dedicated missions with few pieces of equipment to large complexes performing varied jobs involving many different kinds of signal and data processing equipment.

Regardless of the specific mission, land-based C^3I facilities have certain characteristics that make them unique relative to administrative and support facilities. For example, in addition to commercial power, they commonly contain extensive onsite power generation capabilities for both emergency backup and power conditioning.[1]* Effective protection against electrical faults within this combined power system must be established. Also, because much of the information processed by the facilities is classified, TEMPEST** measures must be taken to protect against unauthorized interception. In many locations, lightning presents a serious threat of damage to the sensitive equipment and protection must be provided. Hardness against disruption and damage from electromagnetic pulses (EMP) produced by nuclear blasts is also required in many facilities, or will be in the future. Further, because of the amount of electronic data processing, transmission, and reception equipment in the facilities, there are many opportunities for electromagnetic interference (EMI) to occur. Integral to reliable operation of the C^3I facility in this electromagnetic "environment" is the establishment of electrical fault protection networks and lightning discharge paths, the installation of interference control and surge suppression devices, and the implementation of electromagnetic shields between sensitive receptors and troublesome EM sources. Grounding and bonding are essential elements of these protective measures.

Typically, existing C^3I facilities have been built to a variety of building codes that either directly dictated specific grounding and bonding practices or indirectly restricted what could be done. Generally, these codes were concerned only with a specific portion of the total electromagnetic environment and, hence, their grounding and bonding practices did not take into account the rest of the operating environment. Consequently, the practices may vary or be incomplete with respect to other environmental

*References are listed numerically at the end of the report (p 49).

**TEMPEST refers to investigations and studies of compromising emanations. TEMPEST includes the collective measures taken to prevent unauthorized interception of electrically generated and transmitted classified information.

grounding and bonding practices. For example, the practices set forth in the National Electrical Code 1984 (NFPA 70)[2] issued by the National Fire Protection Association (NFPA) control only the configuration and installation of the electrical fault protection ground network. The Lightning Protection Code 1983[3] defines lightning grounds and bonds. The grounding and bonding networks prescribed by these two codes are inadequate, however, for suppressing potentially compromising emanations from facilities processing classified data. For these facilities, either NACSIM 5203[4] or Military Handbook (MIL-HDBK)-232[5] define the necessary TEMPEST practices.

As the number, complexity, criticality, and sensitivity of signal processing, data processing, and power conditioning equipment increase, the necessity to provide additional hardening against undesired electromagnetic upset or damage from internal and external sources, and from EMP threats also increases. Grounding, bonding, and shielding in new electronics facilities are discussed in Military Standard (MIL-STD)-188/124A[6] and MIL-HDBK-419A.[7] These two documents encompass grounding and bonding for fault protection, lightning protection, TEMPEST, and EMI/EMP.

The practices and procedures of MIL-STD-188/124A and MIL-HDBK-419A are oriented toward new construction and may not be easy to apply in existing facilities. Many facilities were designed and built before some of the requirements contained in these documents were defined or imposed. Consequently, the physical layouts of electrical grounding conductors are not likely to conform to the recommended practices.

In a new facility, the builder has considerable opportunity to place conductors and perform bonding in locations that will be inaccessible once construction is finished. Grounding conductors can be placed in the earth, under floors, and in walls with relative ease. Joints in structural members can be properly bonded during construction with only a minimal increase in the total cost of the facility. Before the equipment and fixtures are installed, signal referencing networks such as the Equipotential Plane required by MIL-STD-188/124A can be installed with little trouble. The grounding networks can be appropriately configured to accommodate EMI/EMP shields and TEMPEST requirements while retaining the required shielding effectiveness. During original construction, grounding networks and bonds can be inspected, tested, and redone if standards of performance are not met.

In an existing operational facility, however, installing grounding networks that are fully compatible with MIL-STD-188/124A and MIL-HDBK-419A may be difficult, expensive, and disruptive to operations. For example, structural members are likely to be inaccessible for bonding or for measuring bond resistance. Earth electrode subsystem members are likely to be buried or underneath the floor or foundation, making them inaccessible for modification or for testing. In some installations, a dedicated earth electrode subsystem may not even exist. If a dedicated subsystem does not exist, installing one at an existing facility can be impractical or very expensive because of nearby buildings, parking lots, streets, and other obstructions. Power and communication cables are likely to enter an existing facility at many locations, with little concern having been paid to routing and treatment of penetration points to minimize coupling of EMP and other transient energy. Utility pipes may also enter the facility at random locations and have little penetration treatment.

Equipment which must remain in continuous operation may be difficult to move or to work around when installing the Equipotential Plane signal reference subsystem required by the Standard and Handbook. Most C^3I facilities cannot be shut down to retrofit grounding and bonding systems. Consequently, major modifications to the grounding system may need to be done in phases or may need to wait until a major equipment upgrade is being performed so that the new grounding measures can be implemented as a part of the equipment changeover.

Adding to the challenge is the overall complexity of C^3I facilities and the interconnections between the various system elements. Further, documentation on the grounding and bonding networks actually in place is typically not kept current. Consequently, a need exists for a unified set of grounding and bonding practices specifically formulated for standard C^3I facilities.

Objective

The objective of this research was to develop an integrated set of grounding and bonding practices for design and installation that are applicable to both new and existing C^3I facilities.

Approach

To formulate the practices recommended in this report, the following approach was used:

1. The state-of-the-art and commonly accepted practices for grounding and bonding were determined for EMI/EMP, TEMPEST, lightning, alternating current (ac) power systems, direct current (dc) power systems, internal mission equipment, and internal and external cabling and conduit systems.

2. The state-of-the-art and commonly accepted practices were identified for bonding between interconnecting facilities' systems and components for system-imposed ground loops for both underground and above-ground facilities.

3. Standard C^3I facility configurations applicable to grounding and bonding were defined.

These first three steps were accomplished through reviews and analyses of current standards, handbooks, and technical reports pertaining to grounding and bonding; surveys of typical C^3I facilities; and discussions with experienced personnel within the Government and industrial community.

4. After gathering the information, the rationale was developed and backup analyses were performed for grounding and bonding designs for simultaneously obtaining protection against EMP, EMI, TEMPEST, and lightning environments.

5. Recommended design principles and practices for the standard facility and for specific sites were developed (Appendix B).

Scope

Although this document presents an integrated set of grounding and bonding practices for design and installation in C^3I facilities, it must be emphasized that GROUNDING AND BONDING ALONE WILL NOT AND CANNOT GUARANTEE ABSOLUTE PROTECTION AGAINST EM ENVIRONMENTAL THREATS. Improper practices, however, can negate the effectiveness of other protective measures, such as shielding and surge suppression. Therefore, the practices are to: (1) accomplish adequate fault and lightning protection, (2) allow effective TEMPEST protection to be implemented, (3) support reliable signal and data transmission without introducing noise coupling via safety grounds, and (4) maintain the integrity of EMI control and EMP hardness measures.

The basis and rationale for the recommended practices are provided in the following chapters. The practices themselves are contained in Appendix A.

Mode of Technology Transfer

It is recommended that a summary of the integrated grounding and bonding practices discussed in this report be included in a revision to TM 5-855-5.[8]

2 GENERIC C^3I FACILITY ELEMENTS

To support its mission of gathering, processing, and transmitting information, the generic C^3I facility contains the following 10 distinguishable elements:

1. The structure or housing
2. Electrical power generation and distribution (both ac and dc)
3. Nonelectrical utilities
4. Heating, ventilation, and air-conditioning (HVAC)
5. An earth connection
7. Communications
8. Data processing
9. Control and security
10. Personnel support.

Several of these elements are found in commercial and administrative facilities as well as in C^3I facilities. For example, all facilities have structural, utility, HVAC, and personnel support elements. Other facilities may contain a number of the remaining elements.

In general, C^3I facility elements must conform to the requirements commonly encountered in commercial construction. However, because of their unique mission, the C^3I facility elements must also accomodate several specialized requirements not found in commercial buildings or in military administration and support buildings. These specialized requirements impose restrictions on the configuration and installation of grounding networks and on bonding practices which are not common in routine construction.

The structure provides physical support, security, and weather protection for equipment and personnel. The structure is an element common to all facilities, yet it is the most varied. The size, configuration, material, and construction are rarely the same in any two C^3I facilities. Wood, stone, glass, or concrete, which are essentially transparent to EM energy, provide little shielding to EMI and EMP threats. Structures containing steel reinforcing bars or steel superstructures offer some degree of EM protection. Other structures that have walls containing wire mesh, corrugated metal panels, aluminum siding, or solid metal foils or sheets offer still more protection against the transmission of EM energy into or out of the facility. Generally, as the metal content of the structure increases, so does the available EM protection. However, this protection depends heavily upon the electrical continuity (bonding) and topology of the structure. For example, structures which are completely enclosed by well-bonded steel sheets or plates with adequately treated apertures may provide over 100 decibels (dB) of protection from a few kilohertz to several gigahertz. On the other hand, open metallic construction may actually enhance coupling at frequencies where the members exhibit resonant lengths.

Where TEMPEST or EMP protection is required, the structure of the C^3I facility typically incorporates continuously bonded metal sheets in exterior walls or around rooms or clusters of rooms to provide a zonal barrier[9] to prevent disruptive or compromising coupling of electromagnetic energy between internal equipment and the external environment. To maintain the shielding integrity of these EM barriers, all seams must be made electrically tight and all penetrations must be constructed and maintained to prevent unintended coupling of energy through the barrier. These penetrations include those required for personnel access, HVAC support, and signal and power transmission.

For underground facilities, the housing typcially consists of large interconnected metal rooms. The rock and earth overburden provides some degree of attenuation to EM energy; however, for complete EMP and TEMPEST protection, the added metal enclosures are necessary.

The C^3I facilities associated with the generation and transmission of high power radio frequency (RF) signals (e.g., long range radar installations or those providing high satellite linkages) commonly incorporate continuous RF shielding to control EMI to internal equipment. Similar requirements also exist in those facilities near commercial broadcast facilities or other RF-generating sources.

Steel structural members offer many parallel conducting paths between various points within the facility and between these points and earth. These structural support members are frequently in direct contact with soil and can provide a low impedance path to earth. Because of the large cross-sectional areas of steel superstructural members, the net impedance between points is frequently less than that provided by lightning down conductors and electrical grounding conductors. For this reason, crossbonding between lightning down conductors and structural members is required to control flashover.

Throughout the typical existing C^3I facility, structural members are in frequent electrical contact with other facility elements either through intentional grounding or inadvertent grounding as a result of normal construction and installation practices. In general, structural members do not provide either adequate electromagnetic shielding or reliable power safety grounding. On the other hand, with proper bonding of structural members and with proper control of stray power return currents, the structure can be used to effectively augment grounding networks within the facility.

Power System

The power system is a network of electrical equipment, conductors, and distribution panels located throughout the C^3I facility. The purposes of this network are to:

- Transform, as necessary, and route commercially supplied power into the facility;

- Generate appropriate online electrical power as required, especially during the absence of commercial power;

- Switch between these two sources of electrical power;

- Condition the electrical power for the critical loads being served;

- Provide uninterrupted electrical power for critical equipment in all situations; and

- Distribute appropriate electrical power to the various equipment loads throughout the facility.

The overall facility power system includes both ac and dc subsystems. A generic ac system is illustrated by the single-line diagram in Figure 1. It consists of a substation/transformer bank, a number of engine/generators (E/Gs), various switchgear, intermediate transformers, an uninterruptable power supply (UPS), transfer switches, and a network of conductors, disconnects, and distribution panels.

The substation/transformer bank, which can range in size from a single pad-mounted transformer to a complete power substation, converts the incoming commercial power to the proper voltages for use at the facility. Commercial power is a primary ac power source for C^3I installations wherever such sources are available and where operational and economic considerations permit. Independent, redundant sources are desirable. Thus, onsite electrical generators driven by diesel engines are commonly used to produce ac power as needed. The main facility switchgear is used to select one of the commercial power feeds or the E/Gs as the primary source of facility power, to synchronize these sources, and to switch between them. In addition to having redundant feeds, this switchgear is configured with multiple buses so as to provide redundant paths to technical operational loads.

C^3I facilities contain four types of electrical/electronic equipment to which power must be supplied: critical technical, noncritical technical, nontechnical operational loads, and nonoperational loads. Critical technical loads are those which must remain operational (100 percent continuity) in order for the facility to carry out its assigned mission. Noncritical technical loads are those which are supportive of the assigned mission but are not required to have 100 percent continuity. Nontechnical operational loads indirectly support the C^3I mission. Nonoperational loads are ancillary to the primary mission.

The configuration of the ac power subsystem following the main switchgear depends on the type of facility load being served. The critical and noncritical technical operational equipment loads are supplied through multiple bus switchgear and double feeds to provide redundant distribution paths. The nonoperational loads are supplied through a single feed and single bus switchgear either from one bus in the main facility switchgear or directly from commercial power. In addition to the redundant distribution paths, the critical technical equipment loads are supplied through a redundant UPS. The UPS provides continuous, high quality, uninterruptable power, in all operational situations, to the critical technical equipment within the facility. It consists of a rectifier bank driving a group of inverters which generate the required ac power. Uninterruptable ac power results from paralleling the dc output of the rectifiers with a battery bank capable of carrying the critical facility load until the E/Gs are started, brought up

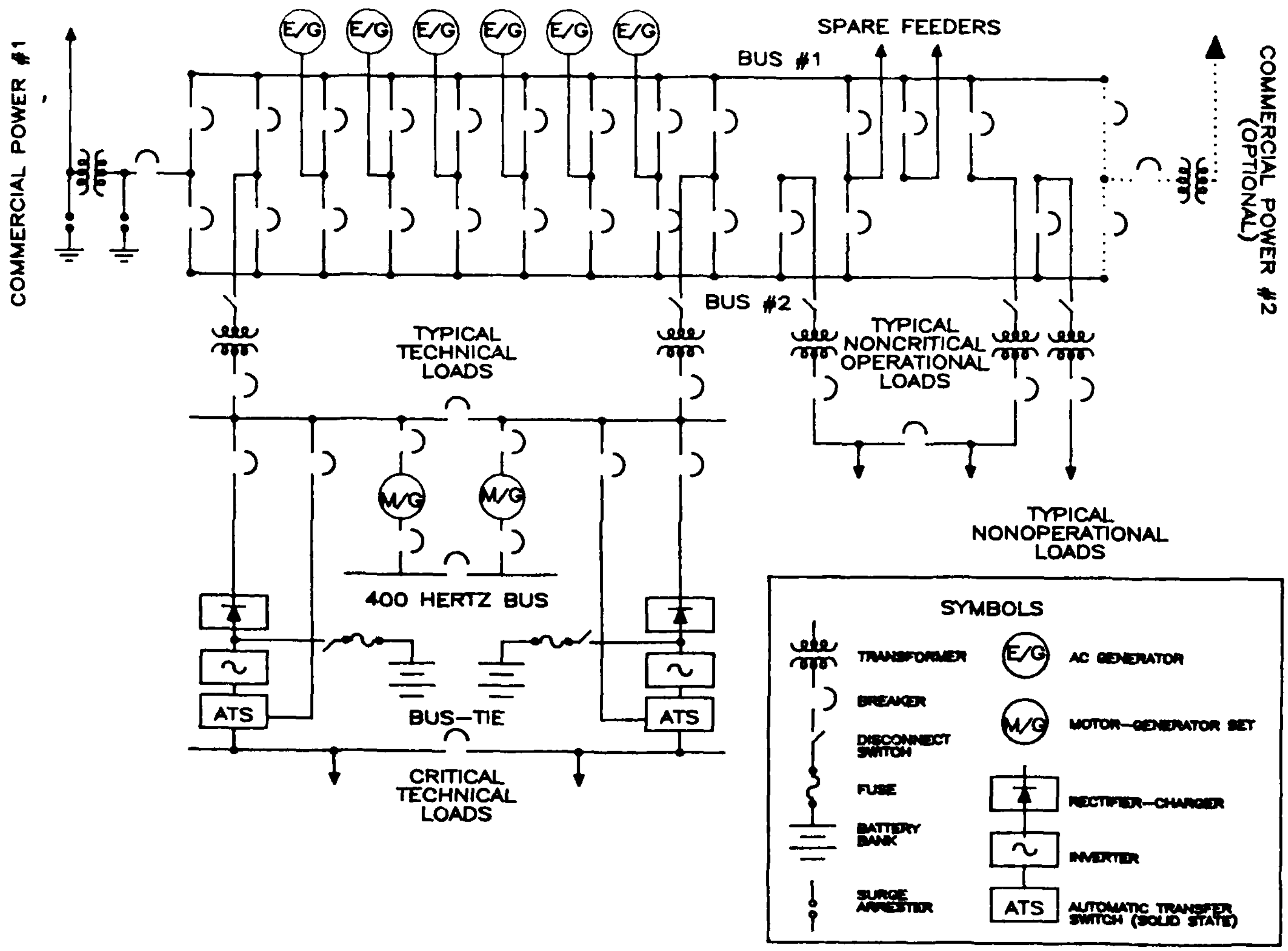

Figure 1. Single-Line Diagram of Generic AC Power Susbystem.

to speed, and switched online. In addition, all incoming commercial and E/G power to critical loads is conditioned by the rectifier/battery/inverter process in normal operational situations.

The output of the UPS is routed via multiple buses and redundant feeds through breakers in the critical bus switchgear to branch distribution panels. These branch panels are located throughout the facility at critical equipment locations. The critical power is then routed through circuit breakers in each of these panels to specific pieces of equipment.

At appropriate locations in the power distribution paths for critical operational, noncritical operational, and nonoperational loads, transformers and intermediate switchgear (indoor unit substations) and transfer switches may be employed. The transformers convert the ac power to the appropriate voltages and configuration (i.e., three-phase, delta or wye, or single phase) for the loads being served. The transfer switches, which are typically automatic, switch between two sources of power to provide continuous operation in the event of failure of one of the sources.

A typical configuration for the ac power system showing the neutral and grounding conductor is illustrated in Figure 2. (To simplify this figure, the redundant buses in the switchgear and the redundant feeds are not shown.) Typically, every transformer between the ac power source and the load is a delta-primary/wye-secondary configuration, thus establishing a separately-derived source at each transformer. Furthermore, the neutral is usually not run between intermediate switchgear. For example, although the neutral is usually present in the intermediate switchgear, it is usually not continued to the next successive transformer/switchgear assembly. It commonly begins at the last transformer prior to a single-phase load and is then routed with the phase conductors through the remaining switchgear and distribution panels to the loads.

The dc power subsystem usually consists of multiple battery racks located at various places in the facility and includes dc switchgear, battery chargers, and distribution conductors. In some C^3I facilities, individual battery racks are located near the dc loads they serve; in others, a large battery rack called the Station Battery serves the function of, and replaces, several individual battery racks. The dc power system supplies appropriate power for switchgear circuit breaker controls, protective and auxiliary relays, and pilot lights; for other instrumentation and control signaling and switching; and for the UPS equipment. Since the major functions of the dc loads are associated with generation, monitoring, and control of the ac power, a significant portion of the dc power system is located near the ac power switchgear.

In many facilities, there will be power conditioning centers dedicated to supplying highly filtered and protected power to data processing and other equipment demonstrated to be highly susceptible to power line transients and ground system noise. These centers commonly contain filters, terminal protection devices (TPDs) , isolation transformers, voltage regulators, and overload protection. Depending upon the criticality of the equipment being served, a secondary UPS may also be provided by the power conditioning center.

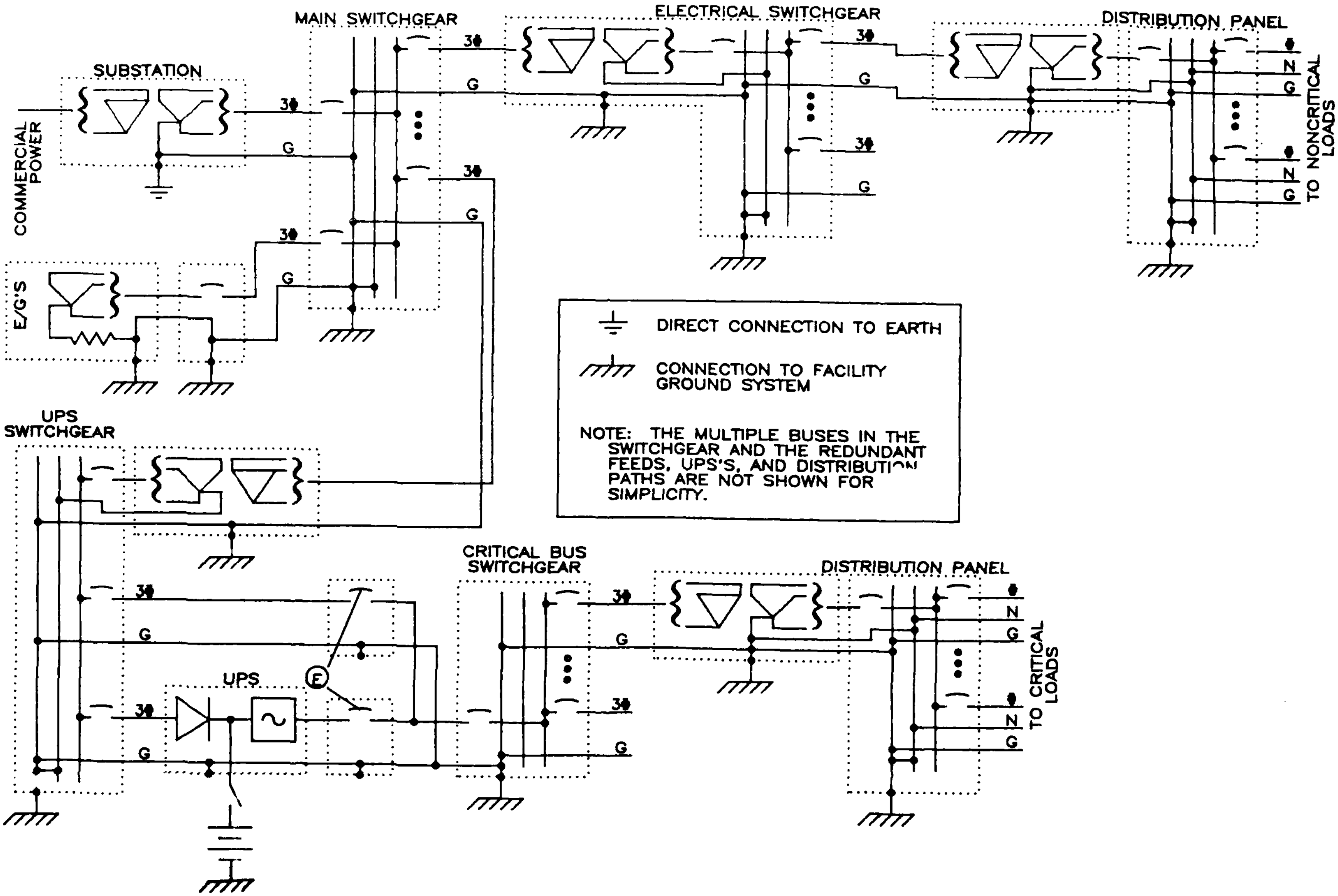

Figure 2. Typical AC Power Subsystem Configuration.

Utilities

As a facility element, utilities are the nonelectrical piping used for gas, sewer, and water (both for fire fighting and normal use). In addition to these normal services, the facility will likely contain other utilities such as halon fire suppression, chilled water, compressed air, etc. The utility lines providing these services are typically constructed of steel, cast iron, copper, or plastic. Some buried sewer lines may be fired clay.

In older facilities, the lines enter the facility at different points and then branch out to form an interwoven tree network of pipes. Metal pipes are frequently joined electrically. For example, gas and water pipes become interconnected at hot water heaters; water and sewer pipes interconnect at sinks and appliances; all may interconnect with structural elements via mounting brackets. Through chilled water and other coolant systems, the utility piping network can become electrically interconnected with electronic equipment. The internal piping is commonly joined electrically to the external system of pipes. This electrically joined network may provide coupling paths for unwanted energy both between equipment internal to the facility and between internal equipment and the external environment, if adequate measures are not taken to disrupt the coupling path.

HVAC

The heating, ventilation, and air-conditioning subsystem (HVAC) is the network of equipment that regulates the internal physical environment of the facility. This system consists of (1) the furnaces, air-conditioners, heat pumps, and humidifiers that condition the air, and (2) the ducts, vents, and fans that distribute the conditioned air throughout the facility.

The HVAC ducts are routed throughout the facility and are likely to make frequent contact with structural elements. The duct system may or may not be electrically continuous.

Some components of the HVAC system, such as cooling towers and oil tanks, are usually outside the structure. These components can act as pickup conductors for lightning and EMP energy; thus, penetrating conductors such as fuel, water and coolant lines, and the protective conduit of electrical supply lines associated with external elements of the HVAC subsystem must be peripherally bonded. Electrical conductors must have appropriate transient suppressors and filters installed.

Earth Electrode Subsystem

The earth electrode subsystem is a network of conductors buried in soil to establish an electrical connection between the facility and the body of the earth. This connection:

1. Provides a preferential path to the earth for lightning discharge currents in a manner that protects the structure, its occupants, and the equipment inside.

2. Ensures that any faults in the facility substation or transformer-breaker system have a sufficiently low impedance return path between the fault and the generating source to reliably cause breakers (in the substation or in generators) to trip and clear the fault and to minimize voltage hazards until the fault is cleared.

3. Restricts the step-and-touch potential in areas accessible to personnel to levels below the lethal threshold even under lightning discharge and power fault conditions.

The earth electrode subsystem commonly consists of both intentional and incidental metal conductors. Intentional conductors include ground rods (plus an interconnecting cable), grids, horizontal radials, or some combination of these. These conductors are generally placed around the perimeter of the structure, underneath the equipment as in the case of generators and high voltage transformers, or at penetration points of long external conductors. Since the C^3I facility includes auxiliary generators and, typically, a commercial substation as integral elements of the power system, substation ground mats are likely to be a part of the facility earth electrode system either through integral design or by extension through normal interconnections. Further, where auxiliary towers are a part of the complex, their grounds are also part of the earth electrode subsystem of the facility.

Incidental earth electrode conductors are those buried objects which are directly or indirectly interconnected with the intentional earth electrode subsystem. Examples of incidental members of the earth electrode subsystem are underground storage tanks connecting to the facility via metal pipes, structural steel pilings, buried metal utility pipes (usually the cold water main), well casings, and, for underground facilities, conduit for power conductors and signal cables which penetrate the overburden.

Lightning Protection Subsystem

A lightning protection subsystem is frequently installed to protect the structure, personnel, and equipment of the C^3I facility from damage due to lightning discharges.

The subsystem is a network of bonded air terminals and down conductors distributed over the exterior of the structure and multiply connected to the earth electrode subsystem. The lightning protection subsystem also includes properly bonded support towers, to include their interconnections with the earth electrode subsystem. Primary and secondary surge arresters on power lines, along with terminal protection devices on power and signal conductors located at penetration points into EM-protected areas, also are integral parts of the lightning protection subsystem.

Air terminals are vertically mounted conductors placed on roof edges, ridges, corners, and any structural projection likely to receive a lightning stroke. Their purpose is to divert to themselves the lightning energy which would otherwise enter the structure. Air terminals are interconnected with roof conductors routed along the roof edges and ridges.

Lightning down conductors provide preferential paths for the lightning energy to follow from the air terminals and roof conductors to earth. Since analytical tools and measurement methods are not available for determining in advance the path of least resistance for a lightning discharge, down conductors are routed to follow the straightest and shortest path from the air terminals to earth. The down conductors must terminate to the lowest available impedance contact with earth, which should be the earth electrode subsystem for the facility.

Lightning surge arresters are placed on the primary and secondary terminals of transformers supplying commercial power to the facility. These surge arresters are typically the robust spark gap variety used by the power utilities to protect against lightning strokes to the transmission network. Additional arresters are placed at penetration points into the facility and at subsequent stepdown transformers, switchgear, the UPS, and other vulnerable equipment locations. These added arresters include both lightning surge suppressors and the fast-acting semiconductor terminal protection devices (TPDs) necessary for EMI and EMP transient suppression. Complete lightning and EMP protection also requires that TPDs be placed on all exposed signal and control conductors at penetration points into EM-protected volumes.

Communications Subsystem

The communications subsystem is the network of electronic equipment, interfaces, and antennas whose elements are located both in, and around, the C^3I facility. The purpose of the communications subsystem is to transfer information from one point to another. The information transfer may take place between points located within the facility or between different facilities.

The electronic equipment making up the communications subsystem frequently include RF receivers and transmitters; audio, baseband, and RF amplifiers; data terminals and displays; telephones; modems; multiplexers; frequency converters; encryption devices; and other C-E (communication-electronic) equipment. Within the facility, the interfaces between equipment are generally hard-wired signal lines or waveguides. Signal penetrations into the facility include coaxial and waveguide for RF signals and, shielded, multiconductor cables for telephone, data, and control signals. Fiber optic penetrations are being increasingly used for EMP-protected facilities. Between facilities, the information transfer is usually via land lines or RF transmission. The RF antennas are generally located on or near the facility.

The various communication subelements include telephone, radio, local area data transfer, and high speed data. The telephone subelement provides internal communications via hard-wired interfaces and intersite communications via land lines or microwave links. As a minimum, the telephone subsystem consists of the telephone instrument sets, cabling, and distribution frames. Larger facilities generally also have a PBX (Centrex) and/or automatic switching racks, intercom apparatus, and a telephone power plant.

The radio subsystem converts audio and baseband signals to an RF signal, radiates the RF signal to the receiving point, and then converts the RF signal back to the appropriate audio or baseband signal. Since it has both low frequency and RF equipment interconnected within the same network, the operating frequencies of the radio subsystem cover an extremely wide range.

The low frequency signal interfaces to and from the RF equipment may be either single-ended or balanced, twisted-pair lines. Depending on the frequency of operation, the RF signal interfaces may be either coaxial lines or waveguides. These various types of interfaces are commingled within the radio subsystem.

Another subsystem is that associated with high speed data transmission. This subsystem is used to transfer high speed data signals between data processing equipment. The transmission paths employ both shielded twisted pair and coaxial cables.

The equipment of the various communication elements is likely to be distributed throughout the facility and grounded at multiple points. The equipment cases, racks, and frames are grounded to the ac power ground, to raceways and conduit, and to structural members at numerous locations within the facility. In many facilities, a single point configuration for the signal reference ground is said to be implemented for telephone circuits and for data processing circuits. Actually, however, a single point ground configuration does not exist because of internal grounding of signal references to cabinets and enclosures with subsequent interconnections to power conduits and raceways and because of the use of unbalanced interfaces between the various pieces of equipment. Consequently, the effective signal reference ground for the communication subsystem in the typical C^3I facility is a multipoint grounded system with numerous interconnections between signal references, equipment enclosures, raceways, conduit, and structural members.

Computing and Data Processing Subsystem

A distinguishing feature of the C^3I facility is the presence of many digital processors ranging from microcomputers performing dedicated equipment and instrument control to large interconnected mainframes providing complex analyses, signal processing, and image displays. These processors typically interface with numerous I/O (input/output) devices including keyboards, monitors, disk drives, tape drives, remote terminals, data acquisition and control equipment, and other processors.

The data processing subsystems are configured in various ways. These various configurations result in different grounding connections being established. For example, stand-alone desktop computers obtain power from single ac outlets and thus establish only one electrical safety ground connection. Other small computing systems may be configured so that the processor and I/O devices share the same outlet, or perhaps the same branch circuit. In this configuration, the ground connection is effectively a single connection although more than one physical tie is made. Where I/O and other peripherals are separated by large distances from the processor, multiple connections to the facility ground network result.

Larger computing subsystems are generally characterized by having the processor in one place and the peripherals distributed throughout the facility. In this configuration, the peripherals are supplied from different ac outlets, off different branch circuits, or perhaps from different phases of the line. In some installations, remote terminals may even be in separate buildings and supplied from different transformer banks. Each remote device must have a safety ground at its location. Noise in interconnecting paths can be encountered from stray currents in the ground reference network. The most practical approach to solving these noise problems is not to strive to implement a "single point" ground connection for the main processor but rather to minimize the stray current in the ground reference system and use effective common mode suppression techniques and devices in data paths.

Control Subsystems

Typical C^3I facilities have many control and security devices which gather information and then automatically respond to a given situation by alerting personnel or engaging equipment to correct it. These subsystems range in nature from pneumatic and mechanical to electrical, electronic analog or digital, or a combination of these. Numerous current sensors, intrusion detectors, trip relays, sound detectors, remote control locks, remote control doors, and alarms are typically included in the systems.

Many of the control subsystems are self-contained and independent, as, for example, intrusion detectors that sound alarms. Often, however, they interact with other facility elements. For example, the heating, ventilation and air-conditioning subsystem contains an integral network of temperature and humidity sensors along with actuators that control the interior air. For fire protection, smoke detectors sound alarms and temperature sensors start halon purging of the affected area. The power subsystem incorporates electronically operated circuit breakers to close or open circuits and to keep particular breaker combinations from being opened or closed simultaneously.

Control subsystems range from being entirely automated to completely manual. One example of automated controls is that which switches over from commercial power to engine/generator power upon loss of commercial power. The control elements can automatically start the engine/generators, bring them up to proper speed and voltage, and switch the appropriate breakers. On the other hand, the operator has the option of performing each of these functions separately using selected devices of the control system to monitor the progress.

In terms of grounding, the large diversity of the control subsystem results in various grounding paths being established. Small control devices are typically grounded through the ac safety ground provided via the power outlet. The more automated and complex subsystems, however, resemble a computer net or a communication subsystem. For example, sensors communicate information from their locations (which may be very remote) to a central location. In many cases, processors monitor the sensors, determine if an abnormal situation exists, and provide appropriate commands to control the necessary equipment. The processor may be the main facility computer. In such cases, the grounding network resembles that of both data processing and communications.

Many control sensors and actuators are outside EM-protected portions of the facility. Particularly with automated control subsystems, these exposed portions are extremely susceptible to upset or damage from high level EM transients such as produced by lightning and EMP. Clearly, appropriate incorporation of shielding, terminal protection, grounding, and bonding are necessary. Specific attention must be paid to the filtering and terminal protection of control cables penetrating the boundary of the EM-protected volume and to effectively establishing adequate grounding paths for transient energy, and to accomplishing electrically tight bonds around the penetrations into control devices.

Personnel Support Equipment

Typically, C^3I facilities are manned 24 hours per day. This means that in addition to routine office equipment, food, lodging, and recreational facilities are normally required for operating personnel on duty. This personnel support equipment includes those electrical devices which connect directly to the power system and do not interconnect with the communication, computer, or control system under normal operation. Devices such as office typewriters, lighting fixtures, kitchen equipment, cleaning apparatus, and electric tools are examples of personnel support equipment. Even nonelectrical objects like carpeting, which can contribute to static charge build up, need to be considered.

Support equipment are usually electrically self-contained units that have their own internal safety grounds. The connection to the power ground is via the three pronged electrical plug which connects to the "green" wire safety ground or otherwise provides an electrical safety grounding connection.

Certain kinds of furniture and carpet may be responsible for the build up of static charges. When personnel walking across carpet or in contact with furniture touch a piece of electronic equipment, a discharge canoccur causing serious damage to solid state devices. Computer and communication equipment are especially susceptible to damage of this type, particularly if they contain MOS integrated circuits. However, static build up can be eliminated by proper choice of materials and by proper grounding of the offending objects and the affected equipment. Properly designed raised floors in data processing areas can largely fulfill this grounding requirement.

3 GROUNDING AND BONDING REQUIREMENTS

The ten identified elements of the generic C^3I facility may logically be divided into three categories. The first category includes those which must establish contact with earth in order to function correctly. In this category are the earth electrode subsystem and the lightning protection subsystem. The second category includes those elements which do not require grounding in order to perform their primary function, but which must be grounded for safety, for lightning protection, or because they tend to become part of the Facility Grounding System* through convenience or accessibility. In this category are the structure, electrical power generation and distribution subsystem, utilities, HVAC, and personnel support. In the third category are those facility elements which must be grounded for fault protection and whose functioning may be severely impacted by improper grounding and bonding practices. This category includes the communications, data processing, and security and control subsystems. For these subsystems, in particular, the necessary protection against EMI, control of unwanted emissions, and EMP may be compromised unless proper grounding and bonding practices are followed.

The grounding and bonding practices for the C^3I facility must conform to the protection requirements for electrical safety and for lightning protection, must not compromise signal security, and must not degrade EMI control and EMP hardness. The particular requirements and constraints imposed on each of the ten C^3I facility elements by the 5 electrical/environmental areas are summarized in Tables 1 through 10.

<u>Electrical Safety</u>

The two primary goals of the fault protection subsystem are:

1. Protection of personnel from exposure to electrical shock hazards in the event that short circuits or leakage paths occur between electrical conductors and exposed metal surfaces or objects; and

2. Rapid clearance of fault conditions to minimize potential fire hazards.

Effective electrical fault protection is achieved through the establishment of a low resistance contact with earth; the installation of ground mats or grids underneath high voltage transformers, circuit breakers and switchgear; and the installation of dedicated grounding conductors ("green wire") to equipment surfaces likely to become energized in the event of a fault.

A low resistance connection to earth at substations and transformer locations simultaneously aids in clearing primary side line faults while minimizing hazardous potentials. Since commercial power lines are highly exposed to lightning, the lightning surge arresters protecting the transformers, breakers, and switches are likely to be activated regularly.

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*For C^3I facilities, there should be only one Facility Ground System consisting of the earth electrode, fault protection, lightning protection, and signal reference subsystems.

Table 1

Grounding and Bonding Principles for Structures

ELECTRICAL SAFETY	LIGHTNING	EMC	EMP	SIGNAL SECURITY
The structure can not be substituted for the required equipment grounding conductor, i.e., "green wire." Wherever possible and convenient, the structure should be frequently interconnected with the fault protection subsystem. The structure should be frequently interconnected with the earth electrode subsystem.	All exterior metal walls must be bonded to lightning down conductors. No lightning protection subsystem conductors need penetrate the structural boundary of the facility. Bonds for the protection against lightning flashover must be connected to opposite sides of the structural boundary. Large exterior metal objects within 2 meters of down conductors must be cross bonded to the nearest down conductor. Large interior metal objects and shielded rooms positioned within 2 m of exterior steel structural members must be bonded to these members. Resistance of bonds should not exceed 1 milliohms.	To provide the lowest impedance facility ground system, all structural joints should be electrically well bonded.	All structural joints should be electrically well bonded. No untreated grounding conductors may penetrate or cross the structural boundary. External grounding conductors must be bonded to the outside of the structure. Internal grounding conductors must be bonded to the interior surface of the structure or enclosure.	No untreated grounding conductors may penetrate or cross the structural boundary. External grounding conductors must be bonded to the outside of the structure. Internal grounding conductors must be bonded to the interior surface of the structure or enclosure.

Table 2

Grounding and Bonding Principles for Power Distribution

SAFETY	LIGHTNING	EMC	EMP	SIGNAL SECURITY
Ground the neutral of 3-phase wye and 1-phase supply lines at the service disconnect for the facility and/or individual buildings. Electrical supporting structures should be interconnected and connected with facility ground. Neutrals of engine generators should be grounded through a current limiting resistance or with a grounding transformer to the facility ground. The equipment grounding conductors, i.e., "Green wire grounds," must be run with power conductors and connected to equipment frames and housings. Resistance of bonds should not exceed 1 milliohms.	Lightning ground must be interconnected with power ground. Surge suppressors installed on transformers shall be grounded to the transformer housings and their earth electrode connections with minimum length conductors. Suppressors installed on service entrance panels shall be grounded to the common neutral-grounding conductor connection with minimum length connections. TPD's installed on power and control cables interfacing with HVAC elements must be grounded to the enclosure of the protected equipment with minimum length conductors. Resistance of bonds should not exceed 1 milliohms.	The neutral should not be grounded at any point on the load side of the disconnect, other than as required on the secondaries of delta-wye step-down transformers or isolation transformers. (See exception for certain personnel support appliances. For this exception, however, it is essential that the frames or cabinets NOT be interconnected with the structure or fault protection subsystem.) All fuse and breaker panels, switch boxes, junction boxes, power outlets, electronic equipment enclosures, etc., MUST have no inadvertent neutral/grounding wire (white/green) reversal. All power conductors, including neutrals, entering or leaving protected regions of the facility must be equipped with EMI power line filters.	All power conductors entering or leaving protected regions of the facility must be equipped with EMP power line filters and TPD's. Grounding conductors must be bonded to the structure, EM shield, or EMP zonal boundary at the point of penetration of the power conductors. No untreated grounding conductors may penetrate or cross the structural boundary. External grounding conductors must be bonded to the outside of the structure. Internal grounding conductors must be bonded to the interior surface of the structure or enclosure. Multiple entry panels may be used; however, the aggregation of all penetrating conductors-power, signal, data, control lines, and utility conductors-to a single entrance panel or vault should be a goal during upgrades and continuing modifications of the C^3I facility.	All power conductors (including neutrals) entering or leaving Controlled Access Areas (CAA) must be equipped with EMI power line filters. Grounding conductors, i.e., green wires, must be bonded to the outside and the inside surfaces of EM shields surrounding the CAA. A common grounding stud may be used to terminate the external and internal grounding conductors. External grounding conductors must terminate to the exterior part of shielded volume.

Table 3

Grounding and Bonding Principles for Nonelectrical Utilities

POWER SAFETY	LIGHTNING	EMC	EMP	SIGNAL SECURITY
Except for gas lines, exterior pipes are to be bonded to the earth electrode subsystem and to the structure. Exterior gas supply lines shall be isolated from conductors inside the facility, if required by local codes. Metallic piping including gas lines inside the structure should be frequently interconnected with the facility ground.	Buried metal pipes must be bonded together and to the earth electrode subsystem.	All utility pipe penetrations into protected areas must be properly treated.	Utility pipes must be bonded to the structure at the point of penetration. If possible, peripheral bonding to a penetration panel or through a shielded entrance vault is preferred. All utility pipes should be bonded to the earth electrode subsystem at the point of crossing the subsystem. Utility pipes should have an insulating section inserted immediately outside the earth electrode subsytem. All utility pipes outside the Zone 0/1 boundary should be below grade.	All utility pipes entering Controlled Access Areas (CAA) must be peripherally bonded to the CAA shield or utilize waveguide-below-cutoff penetrations.

Table 4

Grounding and Bonding Principles for Heating, Ventilation, and Air-Conditioning

POWER SAFETY	LIGHTNING	EMC	EMP	SIGNAL SECURITY
Green wire grounds must be run with power conductors and connected to equipment frames and housings.	Any external HVAC elements exposed to direct lightning strokes must have air terminals mounted thereon and be interconnected with roof and down conductors. Any other external HVAC equipment located within 2 m of roof and down conductors should be interconnected with the nearest down conductor. TPD's installed on power and control cables interfacing with HVAC elements must be grounded to the enclosure of the protected equipment with minimum length conductors.	Isolation sections must be inserted in air ducts immediately prior to shield penetrations. Filters and TPD's installed for noise suppression and transient protection must be grounded to their mounting enclosures (which presumably is mounted directly on the housing of the HVAC equipment) with direct connections or with minimum length conductors.	Filters and TPD's installed for noise suppression and transient protection must be grounded to their mounting enclosures (which presumably is mounted directly on the housing of the HVAC equipment) with direct connections or with minimum length conductors.	Isolation sections must be inserted in air ducts immediately prior to shield penetrations.

Table 5

Grounding and Bonding Principles for Earth Electrode Subsystem

POWER SAFETY	LIGHTNING	EMC	EMP	SIGNAL SECURITY
A low resistance connection to earth is required, i.e., 10 ohms or less. Ground mats or grids shall be installed as required to limit step-and-touch potentials in generating plants, sub-stations, switching stations, and power conditioning centers. Except for gas lines, all nearby buried metal objects shall be interconnected to the earth electrode subsystem. Local codes may dictate that exterior gas supply lines be isolated from conductors inside the facility.	The earth electrode subsystem shall be configured as a ground rod and counterpoise ring around the facility. Ground connections must be 0.6 m outside the facility wall and must extend a minimum of 3 m into soil. Multiple paths between air terminals and the earth electrode subsystem must be installed. Except for gas lines, all nearby buried metal objects shall be interconnected to the earth electrode subsystem. Gas lines shall have a minimum 1 m insulating section installed outside at the point of penetration inside the facility and before crossing the earth electrode subsystem conductors.	No untreated conductors may penetrate protected areas.	All metal conductors shall be peripherally bonded to the earth electrode subsystem at the point of crossing or shall have insulating sections installed. No untreated conductors may penetrate protected areas.	No untreated conductors may penetrate protected areas.

Table 6

Grounding and Bonding Principles for Lightning Protection

POWER SAFETY	LIGHTNING	EMC	EMP	SIGNAL SECURITY
Any exterior metal objects within 2 m of lightning down conductors must be bonded to the down conductors. The lightning protection subsystem's earth connection must be common with the facility's earth electrode subsystem.	For above ground facilities, an air terminal, roof conductor, and down conductor network is required. At least two paths from each air terminal to earth must exist. Locate air terminals and down conductors so as to assure that all building extensions are effectively protected. Each down conductor shall terminate to a ground rod of the earth electrode subsystem. Lightning down conductors should be bonded to structural steel members at the top of the structure and near ground level. On towers, lightning down conductors should be periodically bonded to the tower structure along their downward paths. Resistance of bonds should not exceed 1 milliohms.	No untreated conductors may penetrate protected areas.	No untreated conductors may penetrate protected areas. No lightning protection subsystem conductors may penetrate the zonal boundary of the facility. Bonds for the protection against lightning flash-over must be connected to opposite sides of the zonal boundary. The ground lugs of terminal protection devices shall be bonded to the distribution frame, junction box, penetration panel, or filter box where mounted. The frame, box or panel must be grounded directly to the nearest point on the structure or on the EMP/EMI shield and, by extension, to the lightning down conductor and earth electrode subsystem.	No untreated conductors may penetrate protected areas.

Table 7

Grounding and Bonding Principles for Communications

POWER SAFETY	LIGHTNING	EMC	EMP	SIGNAL SECURITY
Green wire grounding conductor must be run with power conductors and connected to equipment cases.	The ground terminal of surge arresters and TPD's shall be bonded to the mounting enclosure with minimum length conductors. The enclosure shall be mounted directly to the tower structure or will be bonded with a minimum length, flat conductor. The ground lugs of terminal protection devices shall be bonded to distribution frame or junction box where mounted. The distribution frame or junction box must be grounded to the nearest structural frame member and, by extension, to the lightning down conductor. Penetrating waveguides and the shields of signal lines shall be bonded to the entrance panel, or to the facility ground with a minimum length conductor. Signal cable shields and waveguides shall be bonded to antenna tower structural members at the point of departure from the tower.	A Signal Reference Subsystem shall be established. This ground reference subsystem will consist of multiple interconnections between equipment cabinets, frames, and racks; between conduit, raceway and wireway; between these communication subsystem members and structure; and shall incorporate raised floors into the reference subsystem. Where space and accessibility exist, a wire mesh grid may be installed at floor level or overhead to supplement the above cabling network. Equipment enclosures and racks should be bonded to this wire mesh. The mesh should be bonded to structure at each point where structural members are accessible. Both ends of shielded cable shall be terminated to case or enclosure. Continuous peripheral bonding of the shield is best. Filters and TPD's installed for noise suppression and transient protection must be directly grounded to the enclosures of the protected equipment. TPD's installed in distribution frames and junction boxes must be terminated directly to the ground bus or to the mounting enclosure. The ground bus and the mounting enclosure must be bonded to the fault protection subsystem with minimum length conductors.	A Signal Reference Subsystem shall be established. This ground reference subsystem will consist of multiple interconnections between equipment cabinets, frames and racks; between conduit, raceway and wireway; between these communication subsystem members and structure; and shall incorporate rasied floors into the reference subsystem. Where space and accessibility exist, a wire mesh grid may be installed at floor level or overhead to supplement the above cabling network. Equipment enclosures and racks should be bonded to this wire mesh. The mesh should be bonded to structure at each point where structural are accessible. Filters and TPD's installed for noise suppression and transient protection must be directly grounded to the enclosures of the protected equipment. TPD's installed in distribution frames and junction boxes must be terminated directly to the ground bus or to the mounting enclosure. The ground bus and the mounting enclosure must be bonded to the fault protection subsystem with minimum length conductors. Both ends of shielded cable shall be terminated to case or enclosure. Continuous peripheral bonding of the shield shall be used.	A signal reference subsystem shall be established inside the Controlled Access Area (CAA). This ground reference subsystem will consist of multiple interconnections between equipment cabinets, frames and racks; between conduit, raceway and wireway; between these communication subsystem members and structure; and shall incorporate raised floors into the reference subsystem. Terminate shields of all cables in the CAA to the signal reference subsystem within the CAA's.

Table 8

Grounding and Bonding Principles for Computers and Data Processing

POWER SAFETY	LIGHTNING	EMC	EMP	SIGNAL SECURITY
Green wire grounding conductor must be run with power conductors and connected to equipment cases.	The ground lugs of terminal protection devices shall be bonded to the distribution frame or junction box where mounted. The distribution frame or junction box must be grounded to the nearest structural frame member and, by extension, to the lightning down conductor. The shields of penetrating data lines shall be bonded to the entrance panel, or to the facility ground with a minimum length conductor. Data cable shields shall be bonded to antenna tower structural members at the point of departure from the tower.	A Signal Reference Subsystem shall be established. This ground reference subsystem will consist of multiple interconnections between equipment cabinets, frames and racks; between conduit, raceway and wireway; between these communication subsystem members and structure; and shall incorporate raised floors into the reference subsystem. Where space and accessibility exist, a wire mesh grid may be installed at floor level or overhead to supplement the above cabling network. Equip-ment enclosures and racks should be bonded to this wire mesh. The mesh should be bonded to structure at each point where structural members are accessible. Both ends of shielded cable shall be terminated to case or enclosure. Continuous peripheral bonding of the shield is best. Filters and TPD's installed for noise suppression and transient protection must be directly grounded to the enclosures of the protected equipment. TPD's installed in distribution frames and junction boxes must be terminted directly to the ground bus or to the mounting enclosure. The ground bus and the mounting enclosure must be bonded to the fault protection subsystem with minimum length conductors.	A Signal Reference Subsystem shall be established. This ground reference subsystem will consist of multiple interconnections between equipment cabinets, frames and racks; between conduit, raceway and wireway; between these communication subsystem members and structure; and shall incorporate raised floors into the reference subsystem. Where space and accessibility exist, a wire mesh grid may be installed at floor level or overhead to supplement the above cabling network. Equipment enclosures and racks should be bonded to this wire mesh. The mesh should be bonded to structure at each point where structural members are accessible. Both ends of shielded cable shall be terminated to case or enclosure. Continuous peripheral bonding of the shield is required. Filters and TPD's installed for noise suppression and transient protection must be directly grounded to the enclosures of the protected equipment. TPD's installed in distribution frames and junction boxes must be terminated directly to the ground bus or to the mounting enclosure. The ground bus and the mounting enclosure must be bonded to the fault protection subsystem with minimum length conductors.	A signal reference subsystem shall be established inside the CAA. This ground reference subsystem will consist of multiple interconnections between equipment cabinets, frames and racks; between conduit, raceway and wireway; between these communication subsystem members and structure; and shall incorporate raised floors into the reference subsystem. Both ends of shielded cable shall be terminated to case or enclosure. Continuous peripheral bonding of the shield is best.

Table 9

Grounding and Bonding Principles for Controls

POWER SAFETY	LIGHTNING	EMC	EMP	SIGNAL SECURITY
Green wire grounding conductor must be run with power conductors and connected to equipment cases.	The ground lugs of terminal protection devices shall be bonded to the distribution frame or junction box where mounted. The distribution frame or junction box must be grounded to the nearest structural frame member and, by extension, to the lightning down conductor. The shields of penetrating control lines shall be bonded to the entrance panel, or to the facility ground with a minimum length conductor. Control cable shields shall be bonded to antenna tower structural members at the point of departure from the tower.	Both ends of shielded cable shall be terminated to case or enclosure. Continuous peripheral bonding of the shield is best. Filters and TPD's installed for noise suppression and transient protection must be directly grounded to the enclosure of the protected equipment. TPD's installed in distribution frames and junction boxes must be terminated directly to the ground bus or to the mounting enclosure. The ground bus and the mounting enclosure must be bonded to the fault protection subsystem with minimum length conductors.	Both ends of shielded cable shall be terminated to case or enclosure. Continuous peripheral bonding of the shield is required. Filters and TPD's installed for noise suppression and transient protection must be directly grounded to the enclosures of the protected equipment. TPD's installed in distribution frames and junction boxes must be terminated directly to the ground bus or to the mounting enclosure. The ground bus and the mounting enclosure must be bonded to the fault protection subsystem with minimum length conductors.	Control circuits penetrating the CAA must be treated as BLACK conductors. They must be enclosed in continuous conduit which are peripherally bonded at each end. They must be powered from BLACK power. All penetrations through the CAA barrier must be thoroughly filtered. Both ends of shielded cable shall be terminated to case or enclosure. Continuous peripheral bonding of the shield is best. Filters and TPD's installed for noise suppression and transient protection must be directly grounded to the enclosures of the protected equipment. TPD's installed in distribution frames and junction boxes must be terminated directly to the ground bus or to the mounting enclosure. The ground bus and the mounting enclosure must be bonded to the fault protection subsystem with minimum length conductors.

Table 10

Grounding and Bonding Principles for Personnel Support Equipment

POWER SAFETY	LIGHTNING	EMC	EMP	SIGNAL SECURITY
All exposed elements of electrical equipment and appliances should be grounded via the green wire ground to the fault protection subsystem, with the following exceptions: (1) Certain types of high current, 220-volt appliances such as ranges, ovens, and dryers commonly are designed such that the neutral is grounded to the frame. These appliances shall not be grounded to the fault protection subsystem, to structure, nor to utility pipes. (2) Doubly insulated, portable equipment does not need to be grounded, as per the National Electrical Code.			Waveguide-below-cutoff personnel entryways must be peripherally bonded to the supporting structure/shields.	

These lightning surge currents must be safely conducted to earth at the transformer/breaker location rather than through other, uncontrolled paths. This requirement can best be met with a low resistance earth electrode system at the power transformer/breaker/switchgear site.

The purpose of the mats or grids under high voltage apparatus is to limit to safe values the step-and-touch voltages that are produced during high current fault conditions and during lightning surge arrester firings. In this way, if a fault occurs while personnel are in the substation or switchgear room, the voltages to which they are exposed remain within nonlethal ranges. Mats and grids are also effective in establishing a low resistance contact with earth. This low resistance is helpful in minimizing the voltage differential between objects in contact with the mat and personnel or objects not in contact with the mat.

As a further protective measure against hazardous step-and-touch potentials during faults and lightning discharges, all metal objects, such as gates, fences, towers and barriers, which are in the immediate vicinity of the transformer/breaker site must be electrically interconnected with the grounding system for the site.

At engine generator (E/G) locations, low resistance contacts with earth are typically installed. In indoor locations where operating personnel may be reasonably isolated from intimate contact with earth, the necessary fault protection reference for E/Gs can be achieved through the installation of a copper bus bar of adequate cross section around or throughout the E/G area. This bus in turn is multiply connected to the fault protection subsystem or to the earth electrode system. The neutrals of the E/Gs are typically connected to this grounding bar through current limiting resistors. These resistors limit short circuit current from the generators to values which will not destroy the generator windings in the time period required for the breakers to trip or for fuses to blow.

A dedicated fault current return path must be installed between all potential fault locations and the source at E/Gs , transformer secondaries, and service disconnects. Thus all electrically powered equipment and the conduit, raceway, breaker panels, and junction boxes associated with the electrical distribution system must be electrically interconnected with the source neutral. (This electrical interconnection is the so-called "green wire", or the "grounding conductor" specified by the National Electrical Code.)

In order to prevent ac return current from flowing in the power grounding network, the neutral must not be grounded at any point following the first disconnecting means of a separately derived system or the building (i.e., "main") disconnecting means of an ac supply originating outside the building served.

The generators, transformers, power converters, and power conditioners within the C^3I facilities constitute "separately derived systems." Article 250-5(d) of the National Electrical Code defines separately derived systems as "a premise wiring system whose power is derived from generator, transformer, or converter windings and has no direct electrical connection, including a solidly connected grounded circuit conductor, to supply conductors originating in another system." Separately derived systems are grounded for fault protection and personnel safety in the same way as normal ac supply systems. The wye windings of generators and the wye secondaries of transformers are bonded to the fault protection subsystem. Article 250-26 of the Code specifies that a bonding jumper sized in accordance with Table 250-94 be used to interconnect the equipment grounding conductors of the derived system to the grounded conductor. Further, this connection may be made at any point between the source and the first disconnecting means for that separately derived source. Confusion can arise between "the first disconnecting means for a separately derived system" and "the building disconnecting means" for normal commercial service. (Notice the use of the phrase "building disconnecting means" as opposed to the traditional phrase "main disconnecting means.") Clearly the intent for either separately derived sources or normal commercial ac service is (1) to have the grounded conductor (as defined in Article 250-25) made common with the grounding conductor so as to complete the fault return path and (2) to prevent the grounded conductor from contacting the grounding conductor at any point beyond the service disconnect for that particular ac service. Thus, the interconnection of the neutrals of transformer or generator wye windings to building steel and the interconnection of the neutral conductor to the grounding conductor at the first disconnect following the transformer or generator fulfills the requirements of the Code. Beyond this disconnect, no connections may be made between the grounded conductor (the neutral) and the safety grounding conductor. As a matter of fact, except where single phase loads are involved, the neutrals are not continued beyond the disconnect of separately derived systems or the disconnect for the building, as appropriate. Where single phase loads are served, both the neutral and the grounding conductor are continued to the loads. The grounding conductor MUST BE RUN WITH THE PHASE CONDUCTORS, which include the neutral.

A major category of equipment that is exempted from this prohibition of grounding of the neutral includes ranges and clothes dryers. These personnel support equipment typically have their neutrals connected to the frames. Consequently, these appliances should not have their frames interconnected with the remaining elements of the facility grounding system, including utility pipes.

The safety grounding principles as applied to each of the 10 generic facility elements are summarized in the first column of Tables 1 through 10.

Lightning

The lightning protection requirements seek to protect personnel, buildings, and equipment from the high voltage and current transients produced by lightning discharges. A major element of this protection is achieved by providing a means by which a lightning stroke can bypass the facility and enter the earth without causing damage. The stroke current must first be intercepted before it penetrates the structure. Air terminals are provided for this purpose. Preferential paths must then be offered which the stroke current will follow instead of any others. To provide these preferred paths, down conductors are designed to have large diameters and are routed to be as straight and short as possible. Finally, a low impulse impedance connection with the earth must be made.

Because of the inherent inductance of the down conducting path, "side flashes" between the down conductors and internal conducting objects within the facility can occur. The internal conducting objects must be interconnected with the down conductors to prevent this flashover. However, EMP and TEMPEST protection practices prohibit unprotected conductors from penetrating the EM boundary, which in many facilities is the exterior wall of the structure. Fortunately, the connection for preventing flashover can be made without violating the EMP restrictions by bonding the cross conductors to the outside and the inside, respectively, of the exterior wall (with no direct penetration).

An essential addition to the air terminals, down conductors, and earth connection for the protection of electrical and electronic equipment is the installation of lightning arresters and terminal protection devices (TPDs) on all external power, communications, data, and control lines that penetrate the facility boundary. These devices must respond in a sufficiently short time to limit the surge voltages produced by the lightning discharge to levels which can be tolerated by the equipment inside the facility. To obtain least response time and to limit the overshoot voltage of the arresters and TPDs, these devices must be properly grounded. They must be installed such that their leads are kept to minimum lengths and kept very near to facility ground conductors.

These and other grounding and bonding related lightning protection measures are contained in the second column of Tables 1 through 10.

Electromagnetic Interference

Each of the electronic subsystems found in C^3I facilities contain several pieces of equipment which must work together as an integrated unit. Communication and data transfer between the equipment consists of analog, digital, RF or audio signals. Extraneous energy from other equipment within the facility or from sources outside the facility can degrade performance or damage components.

To prevent such interference or damage from occurring, it is necessary that the level of the interfering signal at the susceptible component be reduced by:

1. Relocating the sensitive equipment inside a shielded volume, and
2. Shielding and filtering the power and signal conductors.

Notice that grounding, in and of itself, is not part of the interference control process. Yet the method of grounding filters and equipment cases and the bonding of cable shields can influence the performance of shields and filters and other EMI protective measures.

Grounding is required for lightning protection and for electrical safety. In most installations, signal references will not remain isolated from the safety and lightning protection grounds. For example, signal paths between equipment often use unbalanced transmission lines in which the low, signal return side is electrically interconnected with the case. Since the case must be grounded for electrical safety, the signal reference ground and the power safety become common. This interconnection between the signal reference and the power safety ground gives rise to the frequently mentioned "ground loops." An illustration of the manner in which ground loops contribute to interference and noise problems is given in Figure 3. The stray currents I_C, flowing in the common "ground" produces the common-mode voltage, V_G, between interconnected equipment. Such voltages can produce a differential noise voltage in the terminating loads of the equipment which can disrupt the intended operation of the system or damage circuit components. The degree of interference or upset experienced in a given situation is dependent upon the impedance of the common path, the amplitude of the stray current in the path, the common-mode rejection of the cabling between the equipment and the internal circuitry of the equipment, and the relative susceptibility of the circuits to the coupled noise currents. Typically, the most serious contributors to "ground loop interference" are the very high stray power currents present in the fault protection subsystem of C^3I facilities. These currents commonly arise from electrical wiring errors which interchange the neutral (white) and grounding (green) conductors. Other contributors to troublesome grounding network noise currents are filter capacitors in shunt across power lines and improperly wired electronic equipment. Particular attention needs to be paid to locating and correcting excessive stray power currents wherever they exist.

A frequently encountered recommendation for eliminating "ground loop noise" in signal and data circuits is to install a single point ground. The single point ground seeks to isolate all of the signal processing circuitry in the interconnected equipment from the fault protection subsystem except for one connection. To achieve a truly single point grounded complex of equipment requires extraordinary attention to assuring that all pieces of equipment except one are completely isolated from the fault protection subsystem. Not only must the complex be laid out to be fed from a single ac power source, but also no hardwired signal, control, or other type of lines may interconnect with other equipment outside the complex. Not only are these constraints difficult to achieve at initial installation but they are also impractical to maintain over any extended period of use. Consequently, single point grounded systems are being replaced with multiple point grounded systems. In addition, as noted in the previous section, even in those locations where single point ground networks are said to be installed, normal installation practices typically produce a multiple point, interconnected grounding system.

The merits of the multiple point ground are that:

1. It is straightforward to install since it does not demand special training nor procedures; and

2. It is simple to maintain during normal operation and through successive upgrades or retrofits.

The electromagnetic interference and electromagnetic compatibility related grounding principles are listed in the third column of Tables 1 through 10.

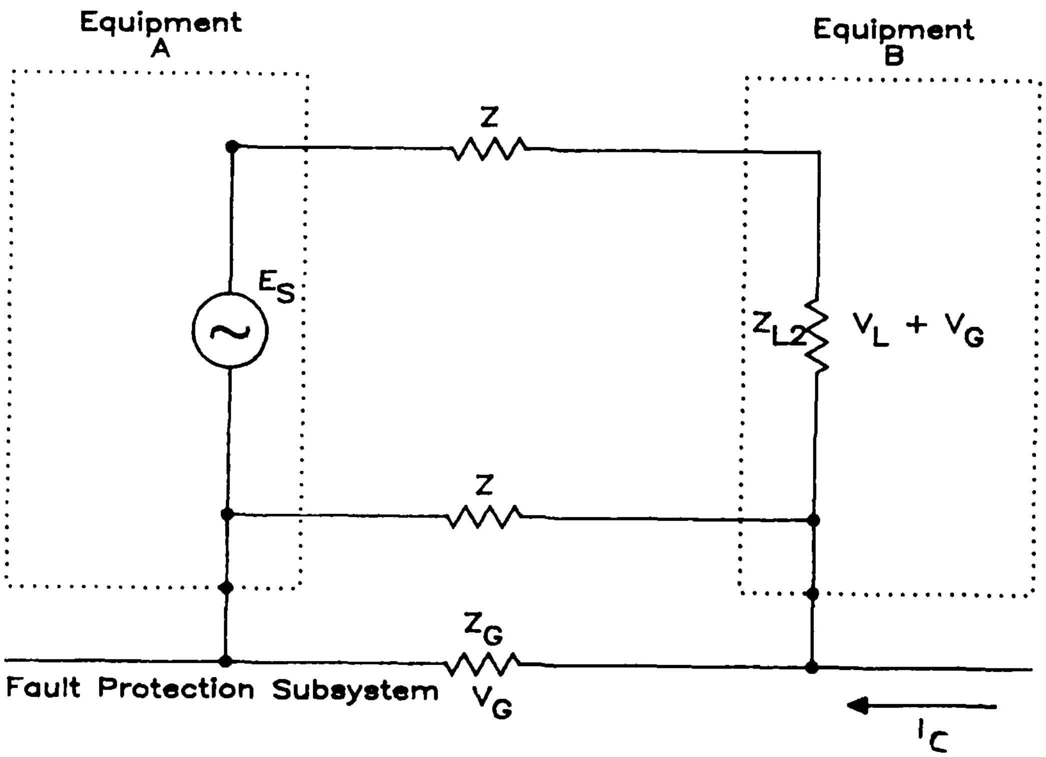


Figure 3. Common-Mode Coupling of Stray Current Noise into Electronic Equipment.

Electromagnetic Pulse

The electromagnetic pulse (EMP) generated by a nuclear explosion presents a harsh electromagnetic environmental threat with lightning being the closest comparable threat. Exo-atmospheric nuclear bursts can develop pulses of electromagnetic energy whose amplitudes can approach 50,000 volts/meter over geographical regions nearly the size of the continental United States. Such high amplitude, short duration electromagnetic fields can induce currents into long unprotected conductors sufficient to cause operational upset and component burnout in C^3I equipment.

Since the EMP threat is significantly different from any other man-made or natural EM threat, the measures that are routinely incorporated for protection from nonEMP environments are not adequate. For example, the structures that are intended to house equipment in nonEMP environments are typically not designed nor constructed with an aim toward providing the extensive EM shielding needed for EMP protection.

Effective EMP protection requires the construction of a closed EM barrier surrounding the susceptible equipment. The realization of an EM barrier involves (1) the construction of an effective shield, (2) the treatment of shield penetrations and apertures, and (3) correct grounding and bonding. Shielding involves the use of metallic barriers to prevent the direct radiation of incident energy into the system and internal enclosures and to minimize the coupling of energy to cables and other collectors which may penetrate these barriers. Shielding is the basic element of any barrier design, and little EMP protection is possible without its proper use. A completely solid shield is not possible since mechanical and electrical penetrations and apertures are necessary. These openings must be properly treated, or "closed," to prevent unacceptable degradation in the effectiveness of the shield. Grounding and bonding, by themselves, do not directly provide protection against EMP. However, they form an integral part of, and are inseparable from, enclosure shield designs and penetration and aperture treatments. Proper grounding and bonding techniques and practices must be followed if violations in the integrity of EMP shields and of penetration and aperture treatments are to be avoided.[10, 11]

In some existing C^3I facilities, it may be possible to enclose the entire building containing critical equipment, including power, inside a well-bonded metal shell. In most situations, however, surrounding the total building with a metal shell will be extremely difficult and extraordinarily expensive. For these majority of cases, shielding of only part of the volume of the building will be realistic. In perhaps a small number of facilities, the necessary amount of EMP protection can be achieved by only shielding individual equipment enclosures.

Inside a volume, shielded with solid metal, the primary purpose of grounding is to achieve electrical safety.

A facility not totally shielded may be conveniently divided into electromagnetic zones.[9] Outside the structural walls of the facility is defined as Zone 0. Inside the facility outer walls, but outside equipment enclosures or internal shielded rooms is then Zone 1. Thus, the facility outer structural walls become the Zone 0/1 boundary. (For underground facilities, the rock-earth overburden may be considered to be the Zone 0/1 boundary.) Zone 2 is then inside the electronic enclosure or inside the shielded room, if present. Higher ordered zones may also be defined, according to the level of compartmentalization employed.

In the absence of a solid metal, well-bonded shield for the Zone 0/1 boundary, certain steps can be taken to minimize the coupling of EMP energy into the facility. Minimal steps include implementing low resistance bonds across structural joints and assuring that utility pipes are effectively bonded to the earth electrode subsystem where they cross, or to the facility ground subsystem at the point where the pipes enter the facility. Fast acting surge suppressors should be installed across entering power and signal lines. More substantial steps include augmenting the shielding properties of the structure by installing wire mesh or sheet metal. The added metal must be continuously joined at the seams and joined to the existing structural steel members with soldered or welded connections. More comprehensive EMP treatment involves rerouting utility, electrical, and signal conductors into the facility through a well-shielded entry vault or through an entry plate welded to existing structural members. The entry vault or plate should be positioned at or below grade level with a short interconnection with the earth electrode subsystem. Surge arresters and TPDs should be returned to the entry vault walls or to the entry plate with minimum length conductors.

The EMP-related grounding principles are summarized in the fourth column of Tables 1 through 10.

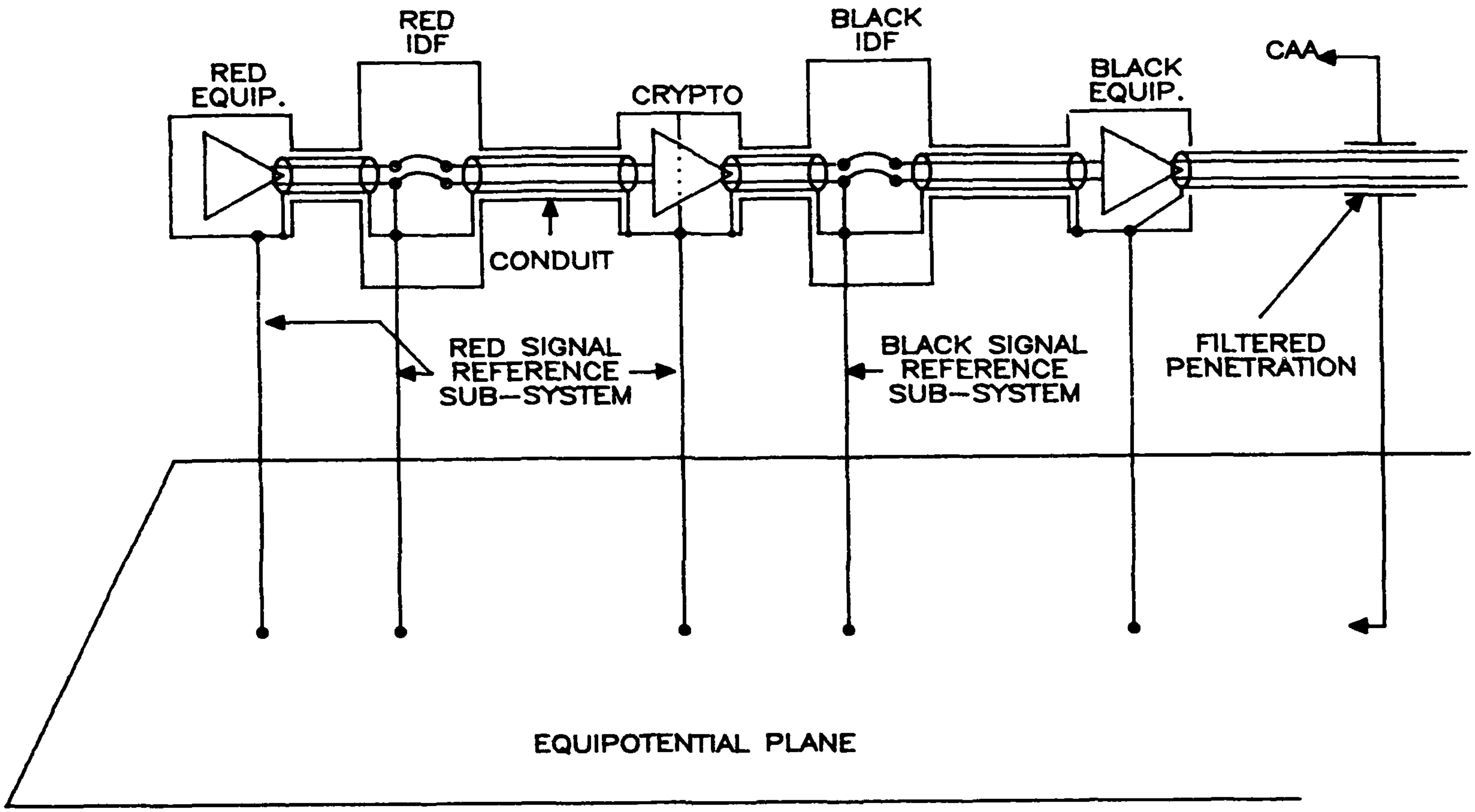
Signal Security

Equipment that processes classified information may produce signals capable of unauthorized detection. To prevent such security compromises, measures must be taken to reduce sensitive data signals to levels low enough to make detection impossible in areas accessible to unauthorized personnel. These measures include controlled grounding practices.

The recommended approach to TEMPEST grounding is illustrated in Figure 4. Notice that all equipment cabinet grounds, RED* signal grounds, and BLACK signal grounds are made to the ground reference established inside

*RED - A term applied to wire lines, components, equipment, and systems that handle national security signals, and to areas in which national security signals occur.

BLACK - A term applied to wire lines, components, equipment, and systems that do not handle national security signals, and to areas in which no national security signals occur.



NOTE: GREEN WIRES NOT SHOWN

Figure 4. Typical Recommended TEMPEST Signal Reference Subsystem.

the controlled access area (CAA).* Both RED and BLACK cable shields are peripherally bonded to equipment cabinets at both ends. The low sides of BLACK data lines are connected to cable shields in the BLACK IDF (Intermediate Distribution Frame) and both are grounded to the reference plane. Notice that BLACK cables should exit the controlled area via fitered couplings through the Controlled Access Area boundary.

Figure 5 depicts the grounding approach recommended for AC power distribution in secure facilities. Note that both the neutral and phase conductors are filtered. As discussed earlier, the neutral is grounded only at the service disconnect. The cases of all subsequent distribution panels, filter enclosures, technical power panels, and equipment are all interconnected with the deliberately installed grounding conductor. Note that the equipment cases are connected to the BLACK signal reference system which is grounded to the reference plane.

The grounding principles pertaining to signal security are listed in the fifth column of Tables 1 through 10.

Application of these environmentally-related grounding principles to elements of C^3I facilities is illustrated in Appendix B. The collective requirements are applied to the structure, the earth electrode subsystem, the lightning protection subsystem, the power subsystem, and electronic equipment. Accompanying figures illustrate the requirements in each case for representative situations likely to be encountered.

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*Controlled Access Area (CAA) - The complete building or facility area under direct physical control which can include one or more Limited Exclusion areas, Controlled Black Equipment Areas, or any combination thereof.

Limited Exclusion Area (LEA) - A room or enclosed area to which security controls have been applied to provide protection to a RED information processing systems' equipment and wire lines equivalent to that required for the information tranmitted through the sytem. An LEA must include a RED equipent area.

Controlled BLACK Equipment Area (CBEA) - a BLACK Equipment area is not located in a Limited Exclusion Area but is afforded the same physical entry control which would be required if it were within a Limited Exclusion Area.

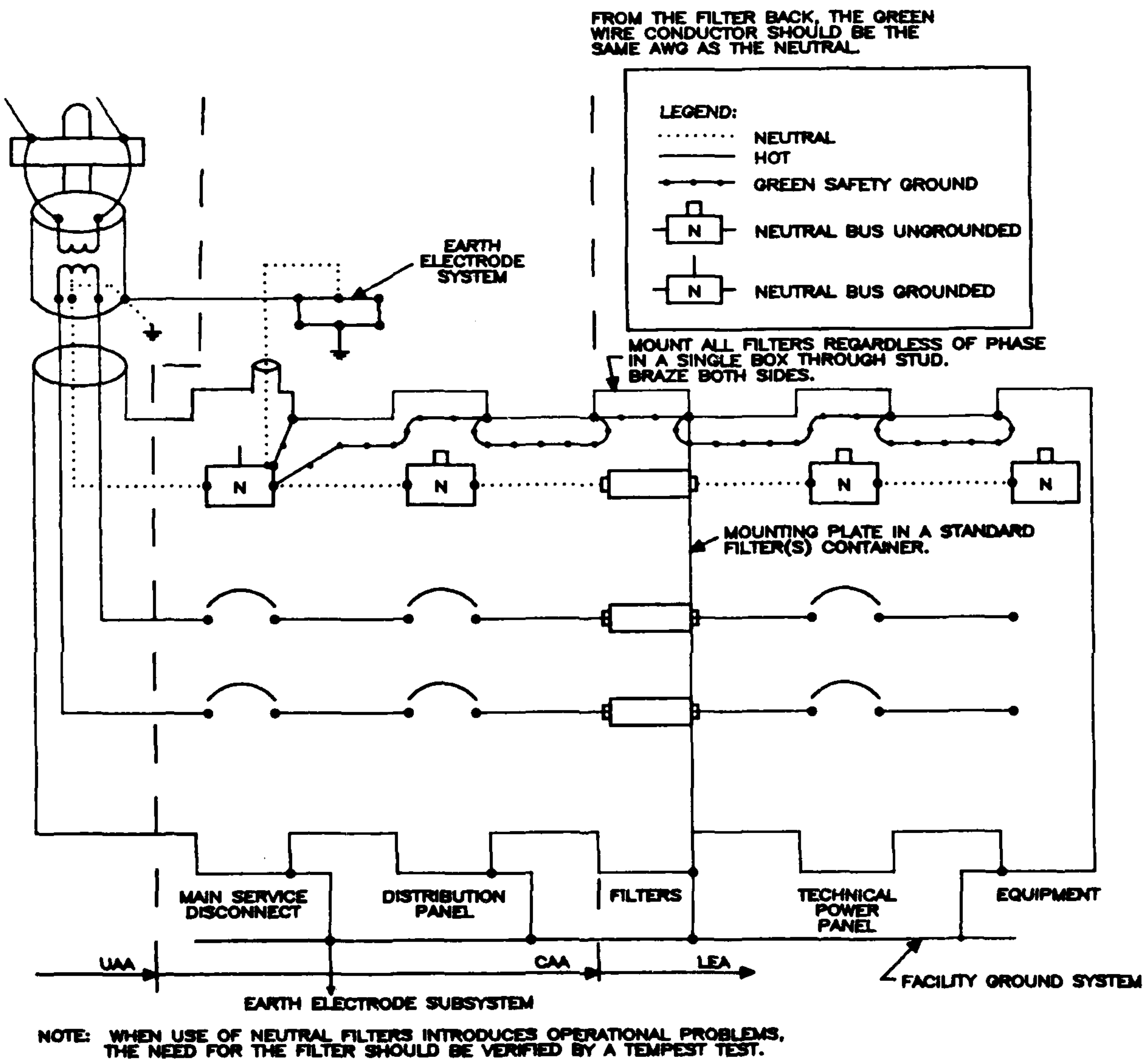

Figure 5. Recommended Power Grounding for Secure Facilities.

4 GROUNDING DESIGN PROCEDURES FOR EXISTING FACILITIES

To install the described grounding and bonding networks in an existing facility, it is recommended that the following steps be taken:

1. Conduct a detailed survey of ALL grounding networks and bonds in the facility. All networks including power safety grounds, connections to the earth electrode subsystem to include water pipes and lightning protection ground rods, utility pipe interconnections, electronic equipment grounds to include the interconnections with the power safety grounding subsystem, tower grounds, and building and structural interconnections with the grounding networks must be accurately defined. Update all drawings, paying specific attention to including all electronic equipment grounding interconnections with the power safety and lightning grounding networks.

2. Carefully examine all accessible bonds for looseness and evidence of corrosion. Clean and tighten all deficient bonds. Measure a representative sampling of bonds using the procedures of MIL-HDBK-419A, Volume II.

3. Also using the recommended procedures of Volume II of MIL-HDBK-419A, measure the stray ac current levels on accessible conductors of the fault protection subsystem and on electronic equipment signal ground conductors. Any stray power current readings in excess of 1 ampere should be thoroughly checked out to find the cause. Currents in excess of 5 amperes are likely to be the result of electrical wiring errors either in the ac supply system or inside electronic equipment. All such errors should be located and corrected immediately.

4. Compare the updated as-built grounding drawings with the recommendations of this report.

5. Evaluate cost and operational impacts of upgrading the facility grounding networks and bond networks as recommended.

6. Prepare plans and schedules to implement the modifications necessary to achieve an integrated grounding network for the facility.

7. Define and implement a routine schedule for inspection and maintenance of bonds. Set up a maintenance log or file and keep it updated.

8. Inspect all impacted grounding networks and electrical supply circuits for unauthorized changes and wiring errors following any new installation or rework.

9. Carefully document all additions and changes to grounding networks. Update all affected drawings.

5 SUMMARY

C^3I facilities perform an essential function in national defense. Their mission is to supply reliable data processing and message transfer even under adverse conditions. To accomplish this mission, safety against electrical faults must be provided, protection against lightning strikes and transients must be achieved, immunity to electrical noise and electromagnetic interference must be realized, signal security must be implemented, and hardness against EMP must be installed. Integral to this electrical and electromagnetic protection are correct grounding and bonding, where grounding is concerned with the configuration and sizing of the electrical interconnection networks while bonding addresses the techniques of achieving electrically reliable and electromagnetically tight connections throughout the grounding networks. Bonding is also an essential aspect of achieving effective electromagnetic shielding.

This report presents the results of a comprehensive study to characterize the C^3I facility, define the grounding and bonding requirements for generic facility elements, and formulate a self-consistent set of practices appropriate for existing facilities. Major control documents in the five electrical/electromagnetic environments of electrical safety, lightning, EMI, TEMPEST, and EMP were reviewed in detail. Particular emphasis was placed on assessing the applicability of MIL-STD-188-124A and MIL-HDBK-419A requirements and practices to existing facilities. It is concluded that the presently defined grounding and bonding requirements and practices are generally adequate for all C^3I facilities, new and existing.

The five environmental requirements range from providing protection for personnel against high current faults in electrical substations to preventing the detection of classified data signals by unauthorized persons. When considered separately, the grounding and bonding requirements imposed on the ten generic facility elements by the five environments appear to be in conflict in certain areas. Other requirements (for example, the MIL-STD-188/124A Equipotential Plane for electronic equipment) could be difficult or expensive to implement in existing facilities exactly as spelled out. Through an assessment of the fundamental protection needs of personnel, buildings, and electrical/electronic equipment, an integrated grounding network was evolved. This network (1) reflects the requirements of electrical safety, lightning protection, EMI, TEMPEST, and EMP and (2) reflects the realities and practicalities of attempting to retrofit existing installations which must remain operational while the work is being done. For instance, an alternative approximation to the Equipotential Plane will be specified for those facilities where installation of the ideal network is impractical.

The set of integrated grounding networks and bonding practices for the elements of a generic C^3I facility is given in Appendix A. The recommended practices are intended to reflect the goals, if not all the details, of MIL-HDBK-419A and MIL-STD-188-124A. Since the Handbook and Standard are primarily applicable to new construction, some of the practices may need to be modified for implementation in an existing facility. Operational disruption and physical incompatibilities can prevent achievement of the ideal. Therefore, the recommended practices seek to (1) alleviate situations which do not conform to present protection principles and (2) approach the configurations desired in a new facility, while reflecting pragmatic consideration of installation and maintenance costs.

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APPENDIX A:

RECOMMENDED GROUNDING AND BONDING PRACTICES FOR EXISTING C^3I FACILITIES

This appendix contains the recommended grounding and bonding practices necessary to implement a unified Facility Ground System. The practices have been integrated to reflect the collective requirements and, consequently, the ten facility elements are not shown separately. However, it is not possible to present all requirements on a single illustration. Multiple drawings are therefore used to separately describe the particular requirements related to the earth electrode subsystem, structure, lightning protection subsystem, power subsystem, and signal reference subsystem. Summary listings of particular requirements are included with the drawings. Circled numbers in the text refer to specific points on the respective drawing.

EARTH ELECTRODE SUBSYSTEM

The earth electrode subsystem establishes a low resistance electrical connection between the various elements of the facility and the earth. This connection is necessary for lightning protection, power fault protection, reduction of step-and-touch potentials, and minimization of potential differences between interconnected facilities. The subsystem must be properly installed and steps must be taken to ensure that it continues to provide a low resistance connection to earth throughout the life of the facility. To achieve these objectives, the earth electrode subsystem should be designed, installed, and maintained in accordance with the practices in the following paragraphs, as illustrated in Figure A-1.

The overall recommended procedure* is

- identify the detailed requirements that the earth electrode subsystem must fulfill for the particular C^3I facility of concern;

- install the minimum configuration, augmenting as necessary for unique installations or for unusual site conditions;

- interconnect the facility earth electrode subsystem with tower grounds, substation ground grids, and other buried metal objects;

- measure the resistance to earth; and

- supplement the minimum configuration, as necessary.

<u>Minimum Configuration</u>

(1) - The basic configuration consists of interconnected ground rods uniformly spaced around the perimeter of the facility.

(2) - The rods and interconnecting cable should be located at least 2 feet (0.6 m) outside the drip line of the facility to ensure that rain, snow, and other precipitation wets the earth around the rods.

- The rods must be driven into undisturbed earth or into thoroughly tamped or compacted fill areas. The rods and cables must not be placed in backfill that has not been compacted nor has had adequate time to settle. If rods must pass through drainage gravel, the rods must extend far enough to provide at least 2 meters of contact with the undisturbed earth underneath.

(3) - The ground rods should be copper clad steel, a minimum of 10 feet (3 m) in length, and equal to or greater than 3/4 in. (1.9 cm) in diameter. The copper jacket should not be less than 0.012 in. (0.3 mm) thick.

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*For a complete description of the design procedure for an earth electrode subsystem, consult MIL-HDBK-419A, Volumes I and II.

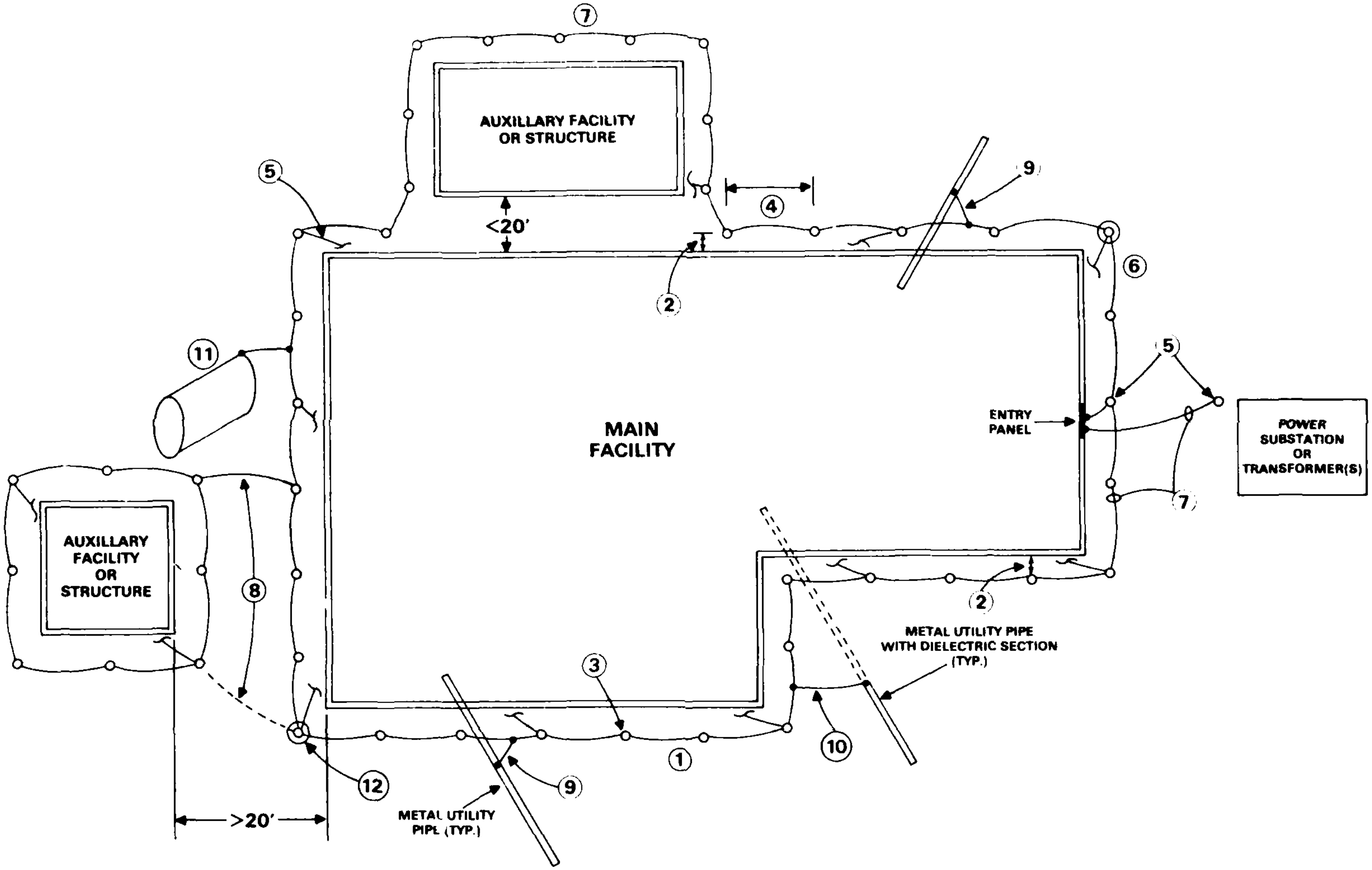


Figure A-1. Configuration and Interconnections of the Earth Electrode Subsystem.

- If the soil resistivity is known to be very high (e.g., greater than 20,000 ohm-cm), longer ground rods should be used. Follow the procedure described in paragraph 1.2.2.3 of MIL-HDBK-419A, Vol. II.

- At sites where the water table is more than 10 feet (3 m) below the surface during any season or where the frost line is more than 10 feet deep, longer ground rods should be used to maintain contact with the permanently moist, or unfrozen soil. The length of the rods should be chosen such that they extend at least 2 meters into the permanently moist, unfrozen soil. In permafrost, chemical treatment of the soil around the rods may be used to assure rod contact with unfrozen soil. (See Paragraph 2.9, Vol. I of MIL-HDBK-419A.)

(4) - The rods should be installed at nominal 20-foot (6-m) intervals around the perimeter of the facility.

- If geological or architectural constraints do not permit driving the ground rod at the desired locations, the spacing between rods may be varied so long as the average spacing approximates one to two times the rod length, the spacing between any two rods is not less than the length of the rods used, and the total number of rods around the facility is equivalent to 20-foot spacings.

(5) - At each facility or structure, independent of size, a minimum of two ground rods located at diagonally opposite corners must be installed.

- At each facility, a ground rod must be installed at each of the following locations:

  - near each lightning down conductor,
  - near the power service entrace to the facility,
  - at each power transformer in Zone 0, and
  - at each entry panel on the Zone 0/1 boundary.

(6) - The rods around the periphery of the facility or structure must be interconnected with a No. 1/0 AWG, or larger, bare, stranded, rope-lay, copper cable which closes on itself to form a closed loop. Do not lay the interconnecting cable in drainage gravel under any circumstances.

- To minimize resistance variations due to changes in weather and to lessen the possibility of mechanical damage, the tops of the ground rods should be at least 1 foot (0.3 m) below grade level and the interconnecting cable should be buried at least 2 feet (0.6 m) below grade level.

Interconnections With Other Earth Electrode Systems

(7) - The earth electrode systems of all facilities and structures which are common to the site and which are interfaced via signal, control, or power cables must be interconnected.

- If the structures are spaced closer than 20 feet (6 m), they should have a common earth electrode system installed that encircles both facilities.

(8) - If the distance between the structures is equal to or greater than 20 feet, they should each have a separate earth electrode system installed in accordance with the minimum configuration described above and their electrode systems must have one or more interconnections.

- The interconnecting cable must be a No. 1/0 AWG or larger, bare, stranded, rope-lay, copper cable which is buried at least 2 feet below grade. The buried bare cable should also be used as a guard wire for buried interfaces between the structures.

- The interconnecting cable must be bonded to each earth electrode subsystem.

Other Undergrounds Metals

(9) - All metal water and sewer pipes, conduits, and shields of cables entering the facility must be bonded to the earth electrode subsystem at the point of entry.

(10) - Metal portions of utility pipes with dielectric sections must be kept greater than 3 feet (1m) away from the earth electrode subsystem or must be bonded to the electrode subsystem with a minimum length of No. 2 AWG bare copper cable.

- If the metal pipes and conduits are routed through one or more "EMP entry panels," they are to be peripherally bonded to the entry panel which is then connected to the earth electrode subsystem.

- If the metal pipes are not routed through "EMP entry panels," they are to be individually connected to the earth electrode subsystem with a minimum length of No. 2 AWG bare copper cable.

(11) - To the extent reasonably accessible, all structural pilings, steel reinforcing bar, metal tanks, and large underground metal objects within the periphery of the facility should be connected in a like manner to the earth electrode subsystem. All of these connections to the earth electrode subsystem must be made with a minimum length No. 2 AWG bare copper cable.

Resistance to Earth

- The net resistance to earth of the overall earth electrode system with all interconnections should not exceed 10 ohms as measured with the fall-of-potential method.

- The resistance to earth should be measured after the installation of the electrode system and all connections to it as described previously are completed.

- Measurements using the fall-of-potential method (see MIL-HDBK-419A, Vol I, Paragraph 2.7) should be performed every 21 months to determine if the 10 ohm resistance requirement is met and if any deterioration has occurred since the last measurement.

Supplemental Configurations

- If the measured resistance to earth of the overall electrode system exceeds 10 ohms, the electrode system may be supplemented to lower the net resistance.

- All supplements to the earth electrode system must be in addition to the minimum configuration and interconnections described previously.

- Methods of supplementing the minimum configuration include increasing the number of ground rods; adding buried, bare copper, horizontal wires; adding buried plates; and adding buried grids.

- The design and installation procedures for these supplemental configurations are given in detail in Paragraph 1.2.2.3 of MIL-HDBK-419A, Vol. II.

- The supplemental electrodes must be bonded to the basic electrode subsystem with bare No. 1/0 AWG, or larger, cable.

Alternate Configurations

- An alternate configuration may be necessary if the minimum configuration cannot be installed for any of the following reasons:

  - geological features of the site,

  - architectural or landscape constraints, or

  - a specific configuration is required to minimize step potential (e.g., a grid under a substation).

- If existing constraints necessitate the installation of an alternate configuration, the minimum electrode configuration must still be installed to the maximum extent possible and then the alternate configuration added.

- Alternate configurations for the earth electrode system include buried, bare copper, horizontal wires; buried plates; and grids.

- The design procedures for these alternate configurations are described in detail in Chapter 2 of MIL-HDBK-419A, Vol. I.

Other Requirements

(12) - One or more grounding wells must be provided at each site to provide access to the electrode system. (For illustration see Figure 1-12, MIL-HDBK-419A, Vol. II.) At least one of the ground wells must be located in an area with access to open soil so that resistance-to-earth measurements can be performed. It is recommended that grounding wells be located at other critical points such as at interconnections between electrode systems and at connection points for other buried metal objects.

- All bonds in concealed locations must be brazed or welded. Any bonds between dissimilar metals, such as between a copper wire and cast iron or steel pipe, must be thoroughly sealed against moisture to minimize corrosion. Bolted clamp connections are to be made only in manholes or grounding wells, must remain dry, and must be readily accessible for maintenance. (For specific details on the construction of bonds, see Paragraphs 1.2.4 and 1.7 of MIL-HDBK-419A, Vol. II)

- If earth electrode subsystems installed in accordance with the above procedures do not provide the required low resistance to earth, enhancement of the soil resistivity around the electrodes may be necessary to lower the resistance to the desired value. Appropriate techniques for enhancing the soil resistivity are detailed in Paragraph 2.9 of MIL-HDBK-419A, Vol. I.

STRUCTURE

The structure provides physical support and weather protection for equipment and personnel. All structures provide some degree of protection, however slight, from the electromagnetic environment as well. To maximize this protection, the structure should be effectively bonded and periodically interconnected with the Signal Reference Subsystem, the Fault Protection Subsystem, and the Earth Electrode Subsystem as shown in Figure A-2 and A-3.

Structural Bonding.

By integrating the structure into these subsystems, maximum advantage can be taken of the much lower impedance offered to current flow by the structural paths over that provided by conventional grounding conductors. This lowered impedance path is particularly noticeable at signal frequencies well above power frequencies and for fast risetime transients as produced by lightning. However, structural paths are not effective unless they are electrically continuous between the points being interconnected. Consequently, all joints between structural members should be well bonded, using either directly welded joints or through the use of bonding jumpers thermically welded to the joined structural members. ① In existing facilities, many, if not most, of the structural joints will not be accessible for welding. However, benefit is gained by joining those joints that are accessible by welding or with jumpers.

Structural support members should be interconnected with the earth electrode subsystem ②. If a shield consisting of welded or bolted steel plates or soldered wire mesh is installed inside or outside the structural walls, the structural members must be bonded to the shield at least every 15 m (50 ft.), both vertically and horizontally, with a minimum of two connections at opposite corners of the shielded volume.③ (See Figure A-3.) None of the bonding jumpers may penetrate (extend through) the shield walls.

Grounding plates required by the Signal Reference Subsystem may be attached to structural members with low resistance bolted connections or brazed or welded directly to the structural members. ④ If an Equipotential Plane, as specified by MIL-STD-188-124A, is installed, these grounding plates and interconnecting cables may be omitted. The Equipotential Plane itself must be frequently bonded to the structure or to the inside walls of the shield. Grounding conductors may not penetrate the shield.

Entry Panels.

Entry panels for the penetration of cable, conduit, and pipes into the facility and their connection to the facility ground network may be necessary to realize specified levels of shielding. If entry panels are required, they must be bonded to the structure ⑤ by:

- circumferential bonding to the installed shield;
- welding to rebar or wire mesh; or
- welding to structural steel columns.

The exterior of the entry panel must then be grounded to the earth electrode subsystem with a No. 2 AWG, or larger, copper conductor.

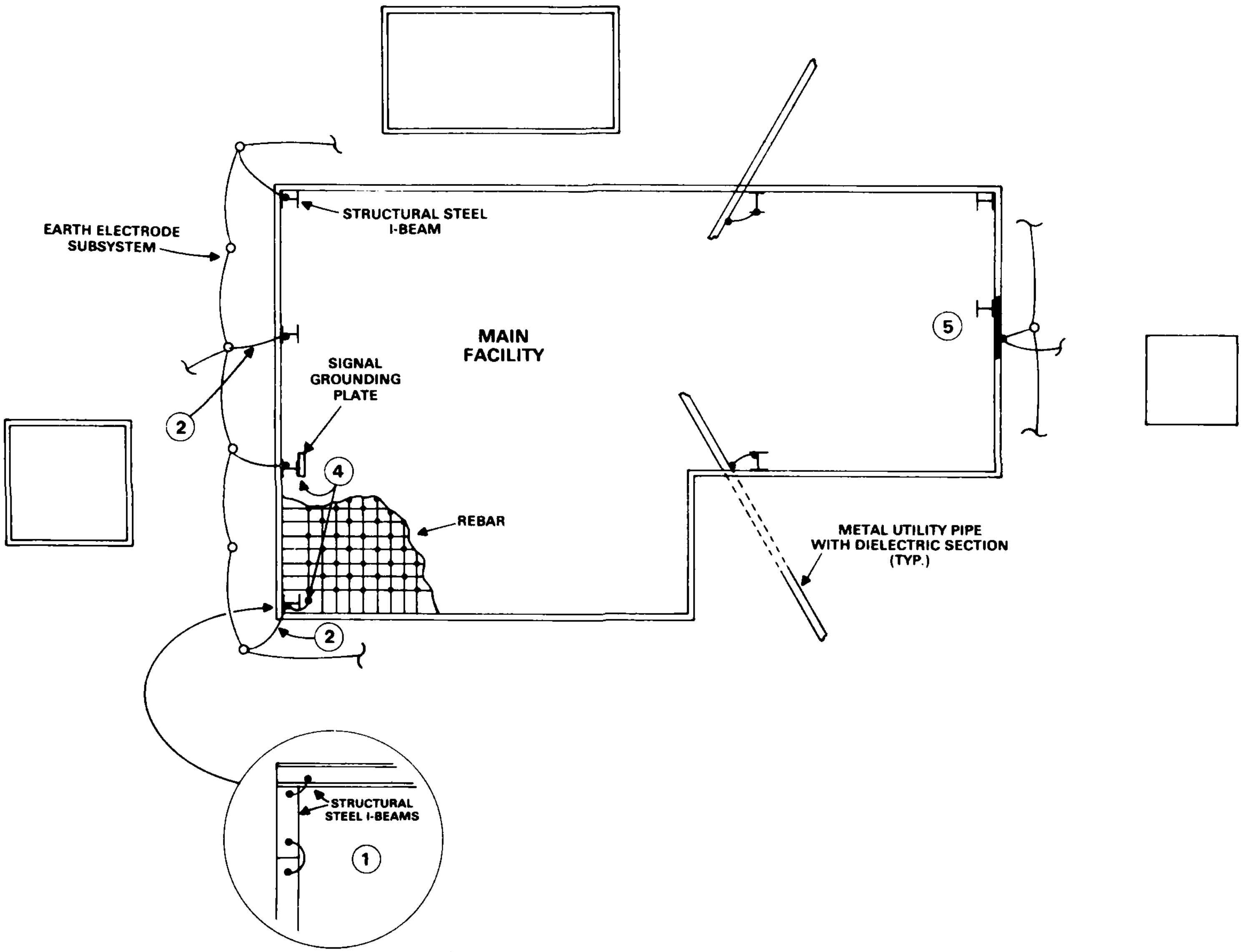


Figure A-2. Structural Grounding and Bonding for Unshielded Facilities.

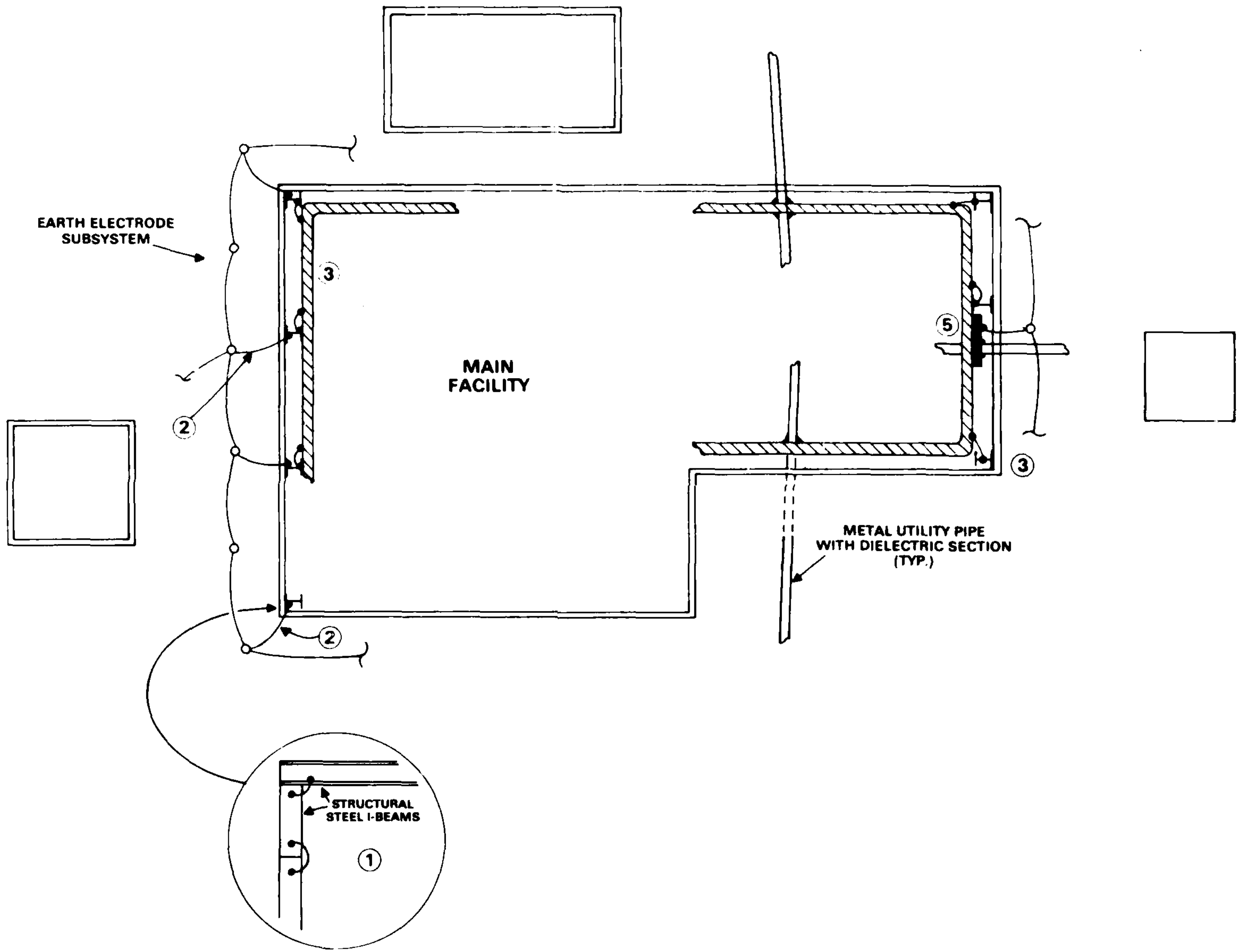


Figure A-3. Structural Grounding and Bonding for Shielded Facilities.

LIGHTNING PROTECTION SUBSYSTEM

The lightning protection subsystem is a network of grounded conductors distributed over the structure to intercept direct lightning strokes. As shown in Figure A-4 and A-5, the lightning protection subsystem typically consists of:

- air terminals
- down conductors
- surge arresters, and
- earth connections

All C^3I facilities which may be subject to a direct lightning discharge must have a lightning protection subsystem installed. To ensure that the lightning protection subsystem does not degrade any facility function while adequately protecting the facility, it should be installed in accordance with MIL-HDBK-419A, and the following grounding and bonding requirements.

(1) - The air terminals system must be connected to the earth electrode subsystem via a network of down conductors.

- The down conductors must be copper, copper-clad steel or aluminum wire or cable sized in accordance with Table 1-2, Volume II of MIL-HDBK-419A. Structural steel columns may be used as the lightning down conductors provided they are electrically continuous and of sufficient size.

(2) - Each down conductor must be connected to nearby steel structural elements within 1 m of the top and bottom of the down conductor and must terminate in an earth electrode subsystem ground rod. They must not penetrate shields. The down conductors should provide the straightest and shortest possible lightning path between the air terminals and the ground rods.

(3) - The down conductors should be evenly spaced over the exterior of the structure. At least 2 down conductors are required on opposite corners of the structure. For larger buildings (with a perimeter exceeding 250 ft.), provide additional down conductors so that the spacings are no less than 50 ft. and no greater than 100 ft. For taller buildings with heights exceeding 60 ft., provide one additional down conductor for each additional 60 ft. but do not space less than 50 ft apart.

(4) - The following external metal objects must be grounded to the lightning protection subsystem: vents, ladders, safety rails, stairways, gutters, platforms, metal walls, and any other metal objects which may be exposed to a lightning stroke or are within 2 m of a lightning ground conductor. For the purposes of bonding metallic bodies to the main down conductors, conductors of no less than No. 6 AWG may be used.

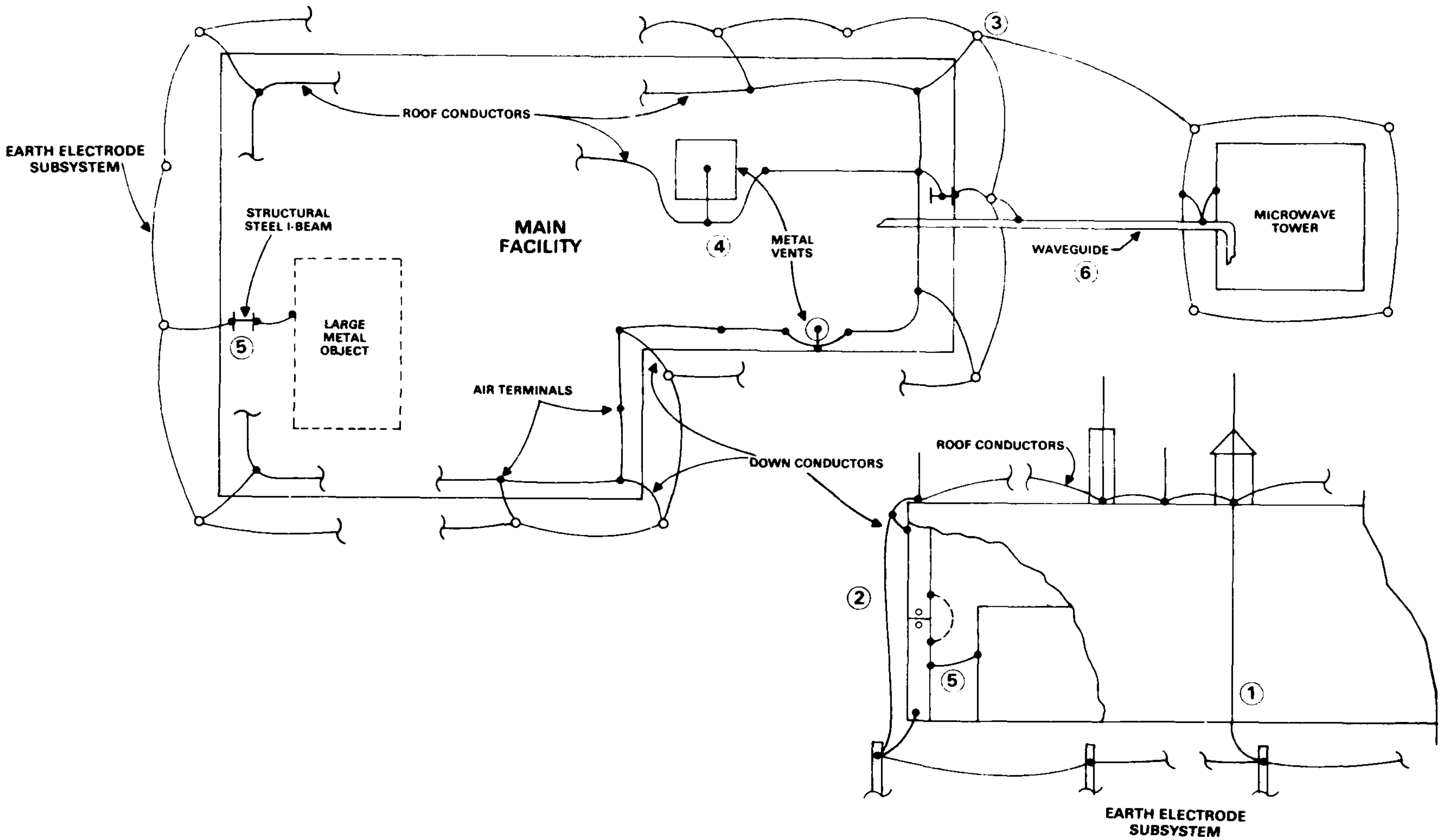


Figure A-4. Lightning Protection Network for Unshielded Facilities.

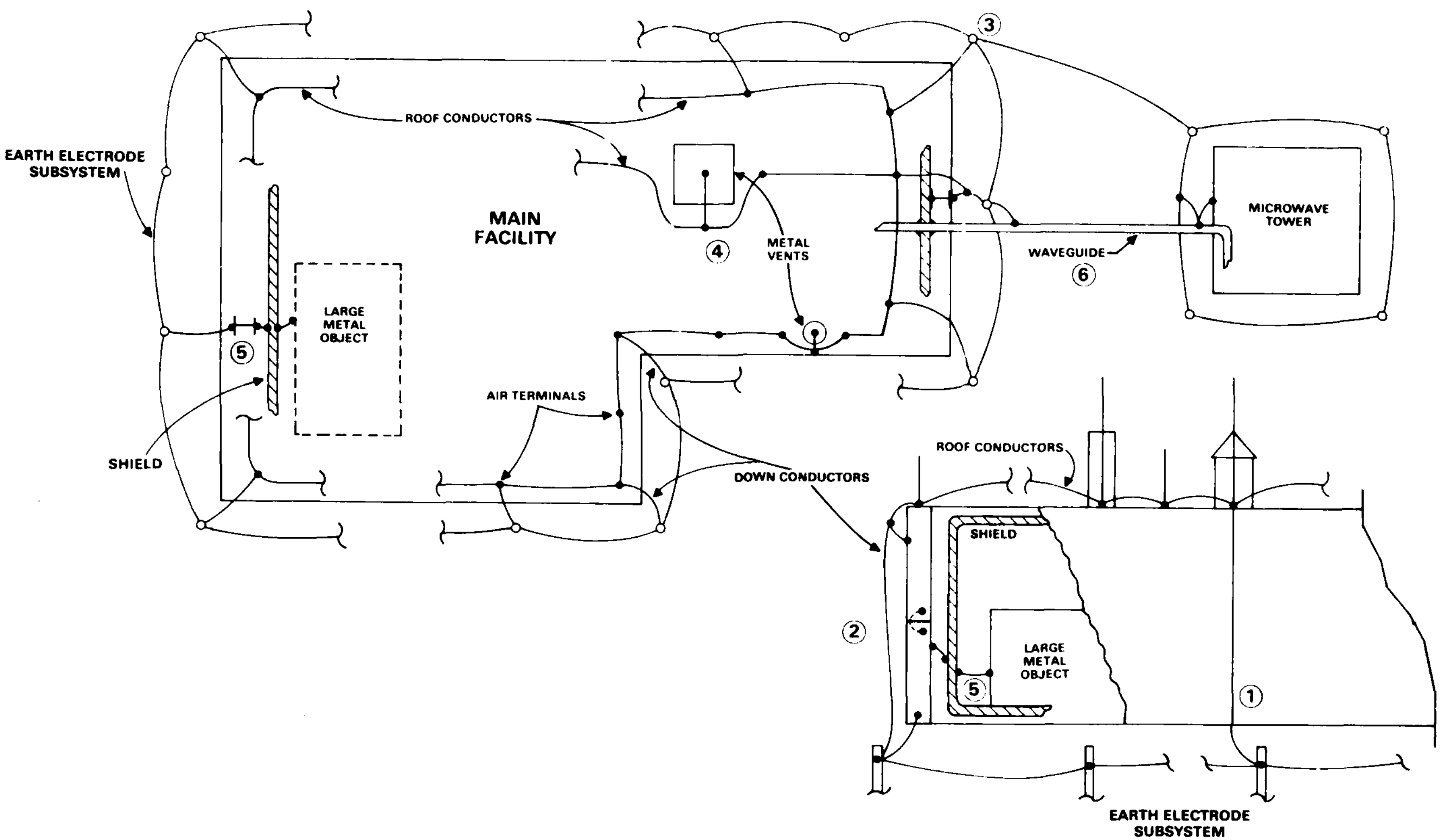


Figure A-5. Lightning Protection Network for Shielded Facilities.

(5) - The following internal metal objects within 2 m of a lightning down conductor must be grounded to the lightning protection system: shielded rooms, equipment racks, utility pipes, and any other large metal objects. Grounding conductors must not penetrate the structure or shield boundaries. Instead, grounding conductors should be bonded to the inside of structural steel or shield boundaries and to the exterior sides of such boundaries or walls, but not routed through such barriers. For the purposes of grounding internal metallic bodies, conductors or no less than No. 6 AWG may be used.

- The following buried metal objects must be connected to the earth electrode subsystem: metal pipes (except fuel lines), tanks, metal conduit, metal well casings, and any other large metal object.

- On towers, lightning down conductors should be bonded to the tower structure every 3 m along their downward paths.

(6) - Waveguide and shielded cables extending from an external structure or tower into the facility should be bonded with a minimum length conductor to the entrance panel, the earth electrode subsystem, or the lightning protection subsystem at the facility penetration point and at the point of departure from the tower. For this purpose, conductors of no less than No. 6 AWG may be used.

- The ground terminal of surge arresters or terminal protection devices (TPD s) must be bonded to their mounting enclosures with minimum length conductors. The enclosure must be directly mounted to the housing of the protected equipment or bonded with a minimum length conductor. If installed at the power service entrance, surge arresters must be grounded along with the neutral to the common ground point with a minimum length conductor.

POWER SUBSYSTEM

The power subsystem in a C^3I facility includes both alternating current (ac) and direct current (dc) generation, distribution and conditioning equipment. The purpose of this subsystem is to provide highly reliable electrical power for the HVAC, communications, data processing, controls, and personnel support subsystems. Adequate fault protection must be provided wnile maintaining EMI protection, EMP hardness, and signal security. To fulfill these requirements, the following steps must be taken (See Figures A-6 and A-7):

(1) - The enclosures and frames of every unit in a substation* (e.g., transformers, switchgear, transfer switches, etc.) external to the structure must be connected directly to the substation's ground grid or its earth electrode subsystem with a conductor sized in accordance with Article 250-94 of the National Electrical Code (NEC).

(2) - The neutral of every external substation transformer must be connected directly or through grounding resistors to the substation earth electrode subsystem. The connecting cable must be sized in accordance with Article 250-94 of the NEC.

(3) - Any metallic protective barrier, such as a fence, which exists around the substation must be connected to the substation's earth electrode subsystem with a minimum length of No. 1/0 AWG copper conductor. These connections must be made at each corner of the fence, as a minimum, and at additional locations such the spacing between any two interconnecting points is not more than 50 feet (16 m).

(4) - If the commercial power substation or transformer is located directly on the C^3I site, or is an integral element of the site, the earth electrode subsystem for the substation or transformer must be connected to the earth electrode subsystem of the facility with a No. 1/0 AWG, stranded, rope-lay copper cable buried at least 2 feet (.6 m) below grade.

(5) - If an entry plate exists at the point of power service penetration into the facility structure, the neutral shall be grounded to that entry plate. (If a grounding conductor is routed with the power conductors into the facility, it shall also be grounded to the entry plate.) The entry plate must be connected to the structure's earth electrode subsystem with two No. 1/0 AWG copper cables.

*A "substation" may consist of a single transformer.

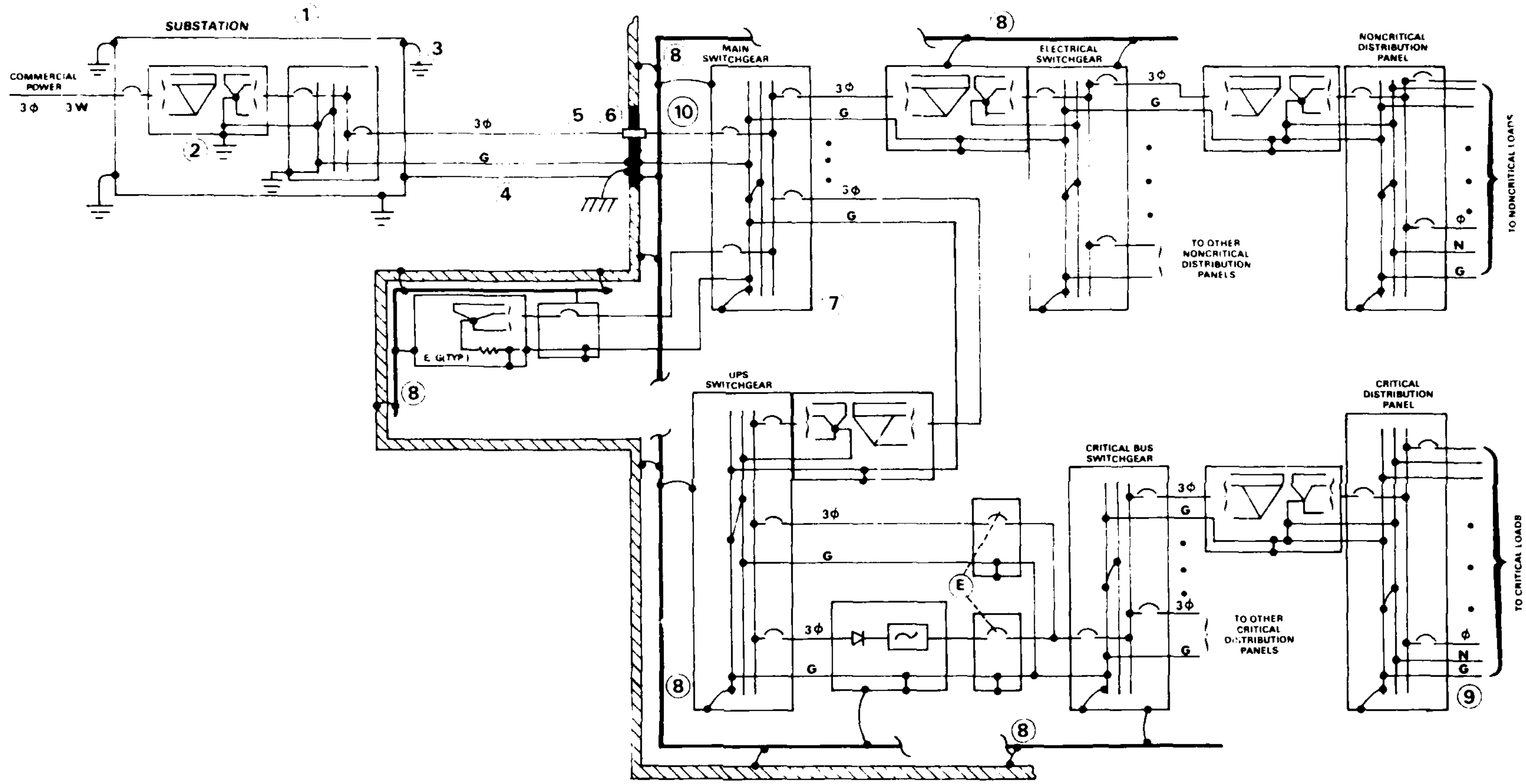


Figure A-6. Power Subsystem Grounding and Bonding in Totally Shielded Facilities.

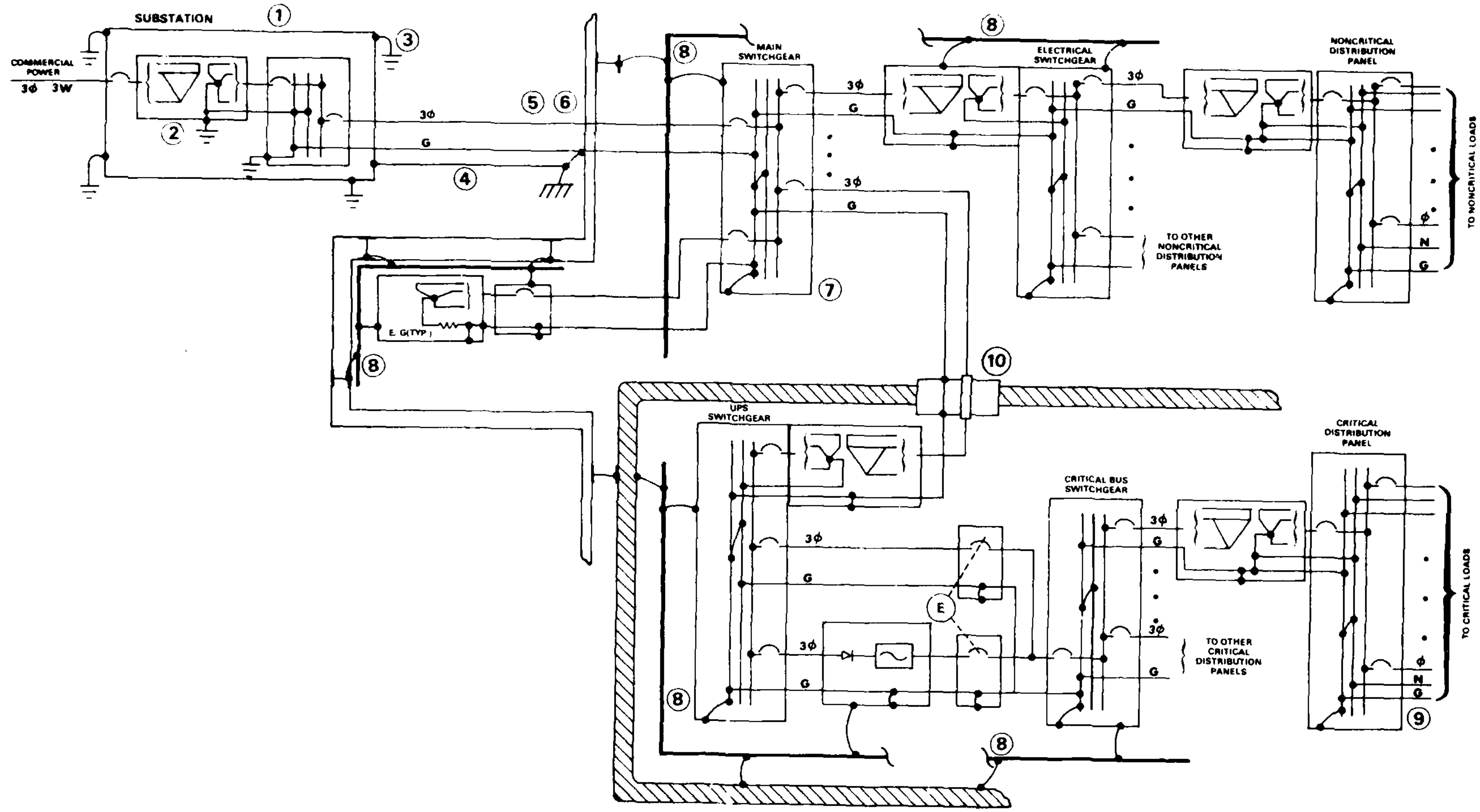


Figure A-7. Power Subsystem Grounding and Bonding in Facilities with Internally Shielded Areas.

- If an EMP Zone 0/1 boundary has been defined, the power service neutral and the grounding conductors shall be bonded to the exterior of the Zone 0/1 boundary.

(6) - If a Zone 0/1 boundary does not exist, then grounding of the neutral will be accomplished at the facility service entrance panel in accordance with the requirements of the NEC.

- If the neutral is routed from the transformer or other building services, it shall be grounded to entry plates which exist on exterior walls of the structure. If the neutral penetrates any subsequent protected (shielded) areas, it shall not be grounded at that point. It shall be filtered equal to that employed on the phase conductors.

(7) - The neutral shall not be grounded at any point on the load side of the disconnecting means for separately derived systems or, where no indoor unit substations are present, on the load side of the building disconnecting means.

<u>Note:</u> The wye secondary of each indoor unit substation transformer (a separately derived system) shall be connected directly to the Facility Ground System with a minimum length of conductor sized in accordance with Article 250-94 of the NEC.

(8) - The engine-generator (E/G) room and all electrical rooms, power vaults, UPS and power conditioning rooms, battery rooms, and other heavy electrical equipment rooms shall have a grounding bus bar of at least 1 in. by 1/4 in. (25 mm x 6 mm) installed around the perimeter of the room. A bonded wire grid having not more than 2 ft. by 2 ft. (0.6m X 0.6m) grid size underlying the entire equipment area may be used instead of the bus bar.

- Each bus bar or grid shall be connected to the Facility Ground System at multiple points (minimum of two with spacing between connections not exceeding 20 feet (6 m)) with minimum length No. 1/0 AWG copper cables or through direct bonds to structural members and to the earth electrode subsystem. These connections must not directly penetrate the Zone 0/1 boundary or any other protected area boundary.

- The neutrals of engine driven generators shall be grounded through a resistance or grounding transformer to the E/G room bus bar or wire grid with conductors sized in accordance with Article 250-94 of the NEC.

(9) - A grounding conductor, sized in accordance with Article 250-95 of the NEC, shall be routed with all power conductors to equipment locations within the facility. This grounding conductor shall be connected to the cabinets, enclosures, or frames of all electrical generation, conditioning, distribution, and switching equipment from which power conductors originate, terminate or pass through. It shall also be connected to the cabinets, enclosures, or frames of

the load equipment to which the power conductors supply electrical energy.

- The grounding conductor may be bare. If insulated, the insulation shall be green or shall be permanently marked with green paint or labels within 3 inches (7.5 cm) of each end and of intermediate connection points to cabinets, enclosures, or frames.

- The equipment grounding conductor shall be bonded at multiple points to the electrical supporting structures (conduit, raceways, wireways, cable trays, junction boxes, etc.). These bonds should be made at each end of the supporting structure, but not farther apart than 50 feet (16 m).

(10) - Neither unfiltered neutrals nor grounding conductors shall be permitted to directly penetrate the boundaries of any protected area (TEMPEST CAA boundaries, EMP zonal boundaries, and shielded room walls). At such penetration points, the neutral must be filtered equal to the main phase conductors; the grounding conductor must be directly bonded to the interior and exterior surfaces of the boundary without direct penetration of the grounding conductor through the boundary.

- Except for ranges and clothes dryers, the frames of kitchen and other personnel support equipment should be grounded to the fault protection subsystem via the green wire grounding conductor. The frames of ranges and clothes dryers are permitted by Article 250-60 of the NEC to be grounded to the neutral. Therefore, the frames of ranges and clothes dryers should NOT be connected to the structure, to utility pipes, nor to any other element of the Facility Ground System, except as through the grounded circuit conductor.

COMMUNICATIONS, DATA PROCESSING, AND CONTROLS

Communications, data processing, and control circuits can be considered collectively relative to their grounding and bonding requirements. Although they may differ in the frequency ranges over which they work and in the specific nature of the waveforms employed, these three C^3I subsystems are alike in that:

1. The voltage and current levels of the signals are low relative to power circuit voltages and currents;

2. They are subject to interference from power system currents and voltages, from signals coupled from other subsystems, and from external sources.

3. the solid state devices which perform the signal processing are highly susceptible to permanent damage from lightning, EMP, and power equipment switching transients; and

4. the equipment and the persons which operate it must be protected from electrical faults.

For these subsystems, MIL-STD-188/124A specifies that a Signal Reference Subsystem utilizing an Equipotential Ground Plane be installed in new facilities. (Details of layout and construction are contained in MIL-HDBK-419A.) In existing facilities, unless an overhead grid is employed, installation of an Equipotential Ground Plane is likely to be difficult and expensive because existing equipment may need to be completely removed from the area in order to install an Equipotential Ground Plane on the floor. It is necessary, however, to interconnect communication, data processing, and control cabinets with the Facility Ground System. This interconnection may be implemented with (1) the Signal Reference Subsystem described herein or (2) an Equipotential Ground Plane as described in MIL-HDBK-419. Therefore, the recommended approach is to take specific steps to interconnect communication, data processing, and control cabinets with the Facility Ground System as illustrated on Figure A-8 and A-9.

Specific steps in the implementation of a Signal Reference Subsystem in an existing facility are as follows:

(1) - If an entry panel exists, the shields of all cable penetrations should be circumferentially bonded to the entry panel and the signal conductors must be appropriately filtered. If a metal zonal boundary exists without an entry panel, the shields should be circumferentially bonded to the boundary. If neither an entry panel nor a zonal boundary exists, the shields should be peripherally bonded to the first equipment cabinet to which they terminate.

(2) - In the event that an overhead or underfloor grid cannot be installed, install a Signal Reference Subsystem consisting of 6" x 4" x 1/4" copper plates interconnected with No. 1/0 AWG copper

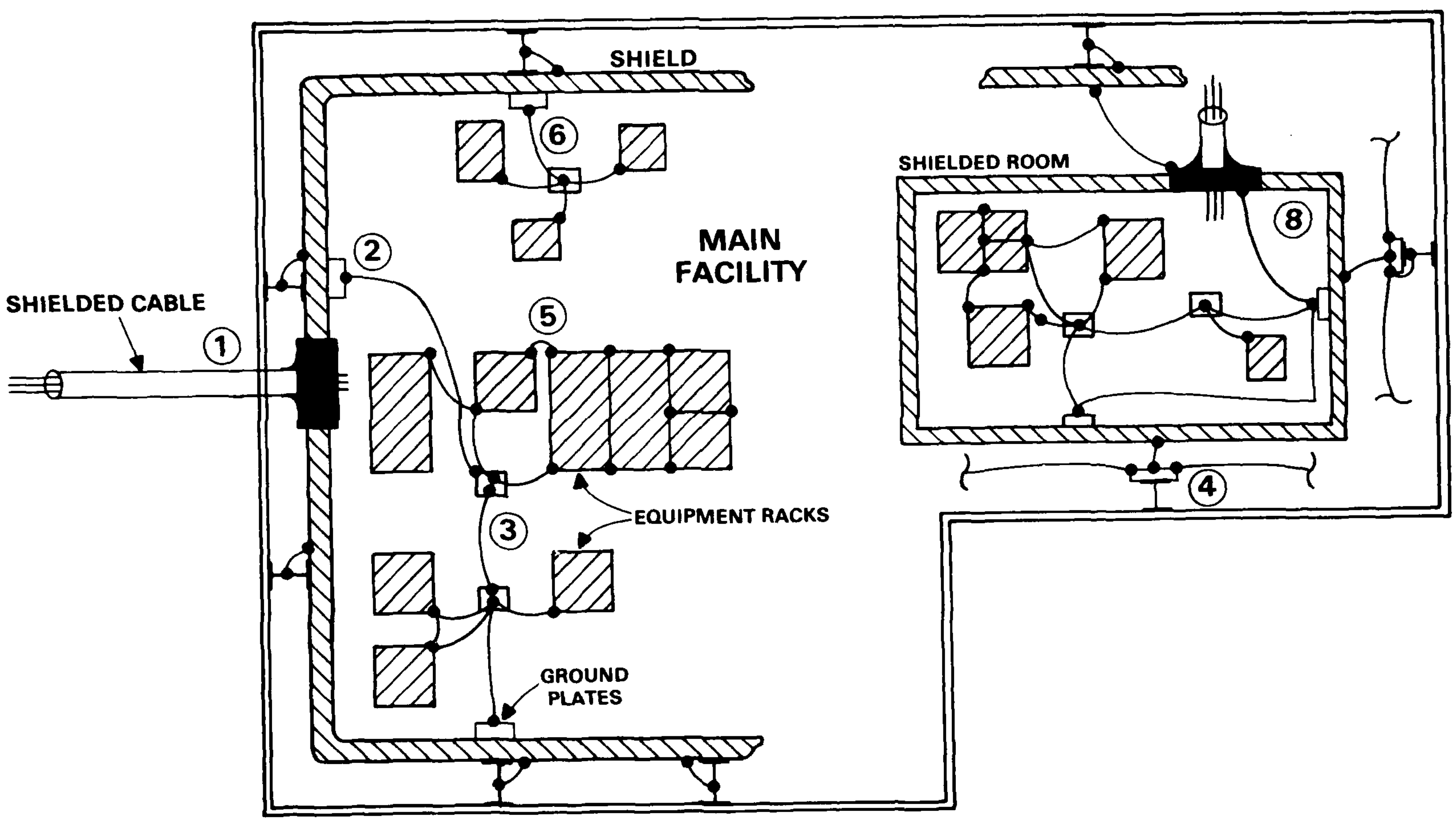


Figure A-8. Signal Reference Subsystem for Shielded Facilities.

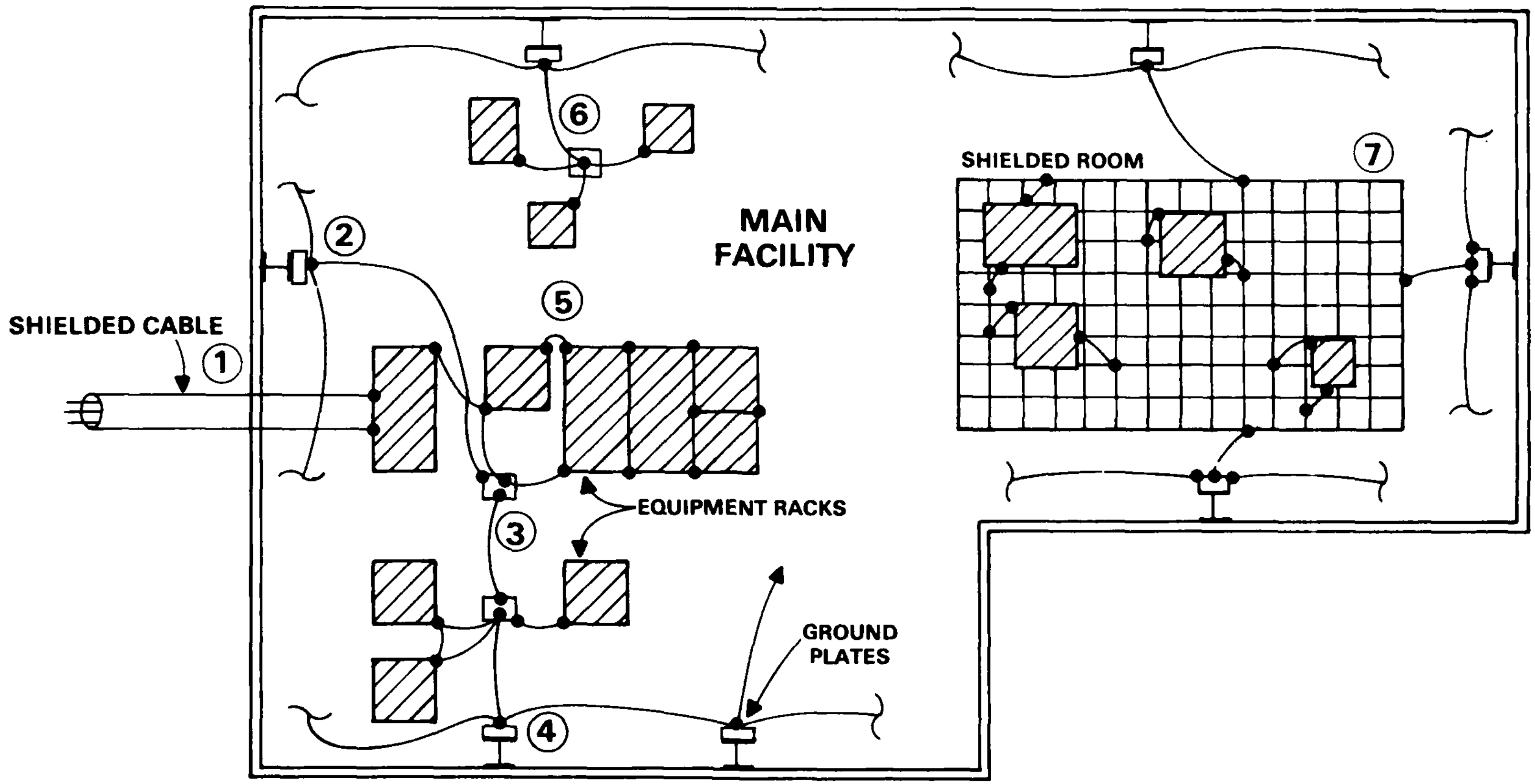


Figure A-9. Signal Reference Subsystem for Unshielded Facilities.

cables. At least two separate conductive paths must exist between any two points in the network.

③ - The ground plates must be installed in all equipment locations such that each equipment cabinet can be connected to a plate with a No. 6 AWG copper cable which is less than 20 feet (6 m) long.

④ - The ground plates should be directly bonded to structural steel where possible. If it is not feasible to mount the ground plates on structural steel, the ground network must be interconnected with the structural framework at multiple locations using No. 1/0 AWG copper cables.

⑤ - Equipment cabinets within 20 feet (6 m) of each other must be interconnected with a No. 6 AWG copper cable, in addition to being connected to a ground plate.

⑥ - If specific manufacturers insist upon a "single point" ground for their systems, such a configuration may be installed only for the specific equipment of concern. It is noted, however, that a single point ground configuration is <u>not recommended</u> and the grounding conductor cannot penetrate any zonal boundaries.

⑦ - Where space and accessibility exist, a wire mesh grid (i.e., an Equipotential Plane) may be installed at floor level or overhead instead of the above cabling network, as shown in Figure A-9. Equipment enclosures and racks should be bonded to this wire mesh. This mesh should be bonded to structure at each point where structural members are accessible.

⑧ - If additional metallic zonal boundaries (e.g., shielded rooms) exist inside Zone 1, they must be multiply interconnected with the Zone 1 ground network. In no instance, may a ground conductor directly penetrate a zonal boundary. Grounding conductors inside a shield must terminate to the interior wall of the shield. The grounding path may be continued through the shield with a solid stud or bar peripherally bonded, preferably with welding, to both sides of the shield.

- Coaxial signal lines penetrating nonshielded facilities should have their shields bonded peripherally to the terminating equipment.

- Coaxial signal cables penetrating shielded facilities should be brought through the building or room shield via appropriate coaxial feedthroughs.

- The recommended treatments for noncoaxial signal lines are illustrated in Figure A-10 and A-11 for shielded and unshielded facilities, respectively.

⑨ - The signal lines should be brought through an electromagnetically tight penetration box containing terminal protection devices and appropriate signal lines filters.

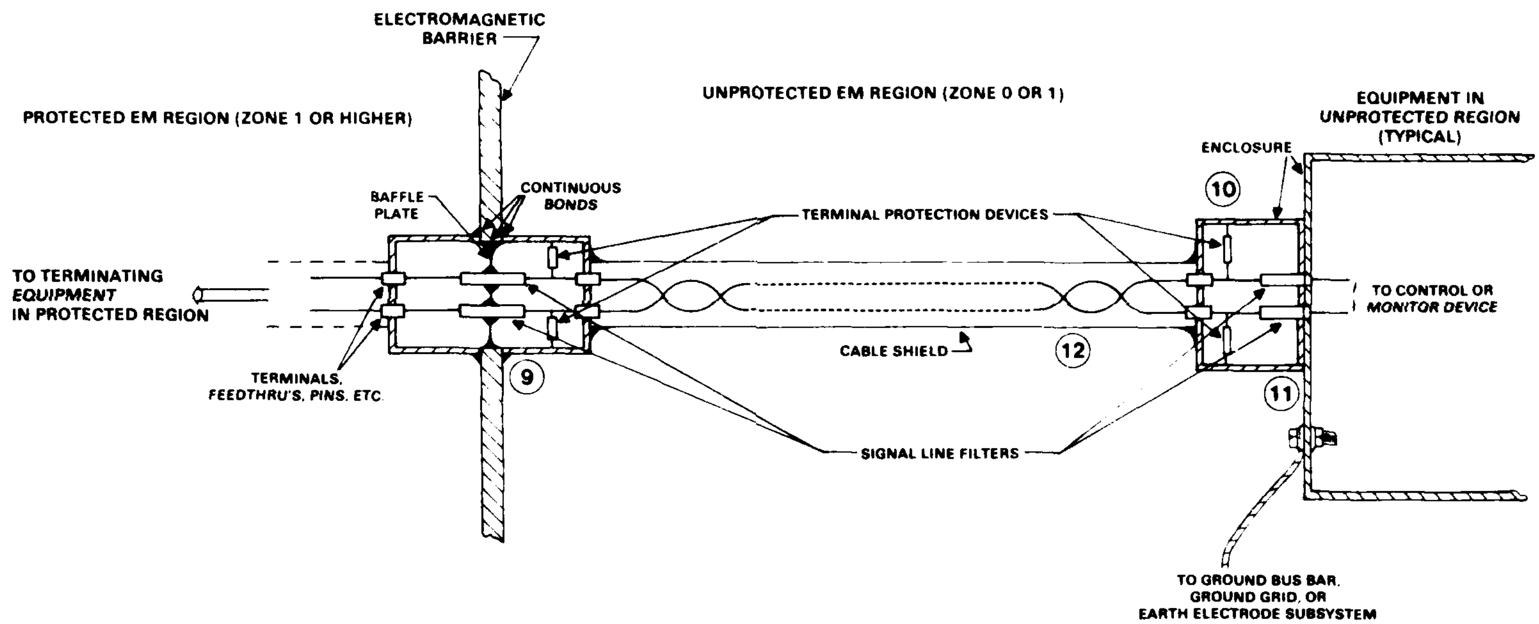


Figure A-10. Grounding and Bonding of Noncoaxial Signal Lines in Shielded Facilities.

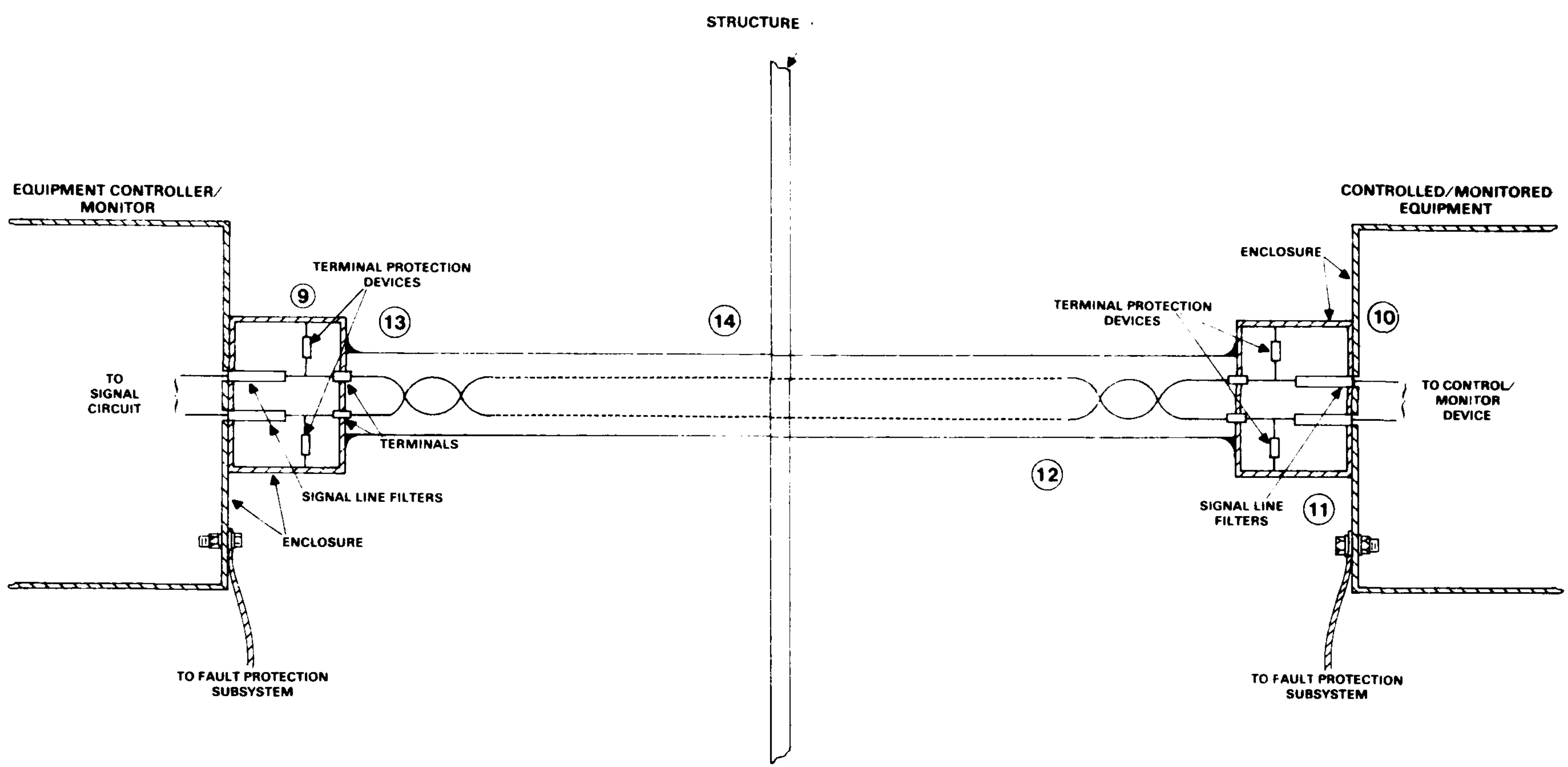


Figure A-11. Grounding and Bonding of Noncoaxial Signal Lines in Unshielded Facilities.

(10) - Similarly at the point of penetration of the signal lines into equipment in the unprotected (unshielded) region, terminal protection devices along with signal line filters should be used to limit transient energy coupling into the equipment outside the shield.

(11) - The equipment outside the shield should have its enclosures grounded to the earth electrode subsystem for the facility.

(12) - Cable shields should be peripherally bonded at each end. No pigtails should be permitted.

(13) - For nonshielded facilities, both ends of the signal line should have terminal protection installed.

(14) - Shielded, twisted pair cable should be used. The shields should be peripherally terminated on each end.

APPENDIX B:

ASSESSMENT OF GROUNDING AND BONDING PRACTICES IN SELECTED C^3I FACILITIES

INTRODUCTION

Background

The main text of this report (subsequently referred to as the Integrated Practices Report) provides a set of recommended grounding and bonding practices for the generic C^3I facility. These practices reflect the unique requirements imposed on C^3I facility elements by the electrical and electromagnetic "environments" to which facility equipment and personnel will be exposed and the various rules and guidelines with which designs and installations must conform.

Providing the necessary protection to C^3I equipment, personnel, and information so as to allow the facility mission to be accomplished, without compromise of information security, requires the installation and maintenance of effective fault and lightning protection along with measures to suppress the coupling of electromagnetic energy either into or out of the facility. Integral to the protection and hardening measures are comprehensive and cohesive grounding and bonding to establish fault return and lightning discharge paths, close joints and apertures in electromagnetic shields, provide low impedance filter return paths, and minimize the development of troublesome voltage differentials between interconnecting equipment.

There are ten facility elements which can be expected to be encountered in almost every C^3I facility: structure, power generation and distribution, non-electrical utilities, HVAC, earth connection, lightning protection, communications, data processing, control and security (both physical and communications), and personnel support. The electrical/ electromagnetic "environments" within which these ten elements must operate or must conform are: electrical safety, lightning, electromagnetic compatibility, electromagnetic pulse (EMP), and signal security.

Each of these five "environments" have an associated set of design or performance practices which impact the installation and construction of grounding and bonding networks in the C^3I facility. For example, electrical fault protection measures are defined by the National Electrical Code.[2] The Lightning Protection Code[3] defines those external networks appropriate for protecting the structure and its occupants against direct lightning discharges. Grounding, bonding and shielding practices needed for the electromagnetic compatibility of electrical and electronic equipment are addressed by MIL-STD-188/124A[6] and by MILHDBK-419.[7] Signal security is presently addressed by NACSIM 5203[4] and by MIL-HDBK-419. EMP hardening principles are reflected in MIL-STD-188/124A and MIL-HDBK-419. (EMP hardness measures are *not yet* formally organized into a military standard or handbook. EMP design handbooks specifically directed at C^3I facilities are currently being developed and should become available in the near future.)

The ten facility elements must be installed and integrated so that they perform their individual functions and yet not disrupt the functioning of any of the other nine. The grounding and bonding practices of each are directly or indirectly affected by the controlling documents. The manner in which certain control measures are implemented in response to the requirements called out in one controlling document can significantly impact the effectiveness of the measures called out in another document. Therefore, it is essential that the collective requirements imposed by the five "environments" be considered when implementing the specific networks and interconnections of each of the ten elements in existing as well as new facilities.

The Integrated Practices Report assembles the grounding and bonding practices appropriate for existing facilities. Existing facilities often pose a unique challenge to implementing those practices developed for new construction. In a new facility, the designer (presumably) can exercise control over all aspects of the construction whereas in an existing facility many obstacles and restraints will be encountered. In the typical existing C^3I installation, for example, the grounding and bonding networks are likely to have been configured, installed and maintained by different individuals, or even by different organizational units. Typically, the various organizational units have different mission responsibilities and thus their approaches to the installation of grounding networks are likely to be very different. Further, the various organizational units having concerns with grounding may not have coordinated the configuration and installation of the various grounding networks. As a result, it is possible for the grounding networks installed for fault protection or signal security, for example, to be in violation of the principles of EMP hardening or lightning protection.

The purpose of this phase of the effort was to survey and examine the grounding networks and bonding practices at selected C^3I facilities to evaluate the installed networks and observed practices relative to those set forth in the Integrated Practices Report. The sites reviewed included the PAVE PAWS East installation at the Cape Cod Air Force Station, MA; the Satellite Readout Station at Buckley Air National Guard Base, CO; and the NORAD Cheyenne Mountain Complex near Colorado Springs, CO. In addition, plans for a WWMCCSDPCE Building, Baumholder, Germany, were also reviewed.

This appendix contains the results of this comparative review.

UHF OVER-THE-HORIZON RADAR

Facility Description

The PAVE PAWS (East) facility is an over-the-horizon radar installation located at the Cape Cod Air Force Station, Massachusetts. The facility consists of a 120-foot tall Technical Building, a Power Plant, and ancillary support structures including a commercial power substation, security fences, gate house, guard towers, and SATCOM terminal.

The Technical Building houses (1) the RF equipment for interfacing with the antenna array, (2) the computer equipment for controlling the radar and for signal processing, (3) a communications room, (4) a Technical Operations Room, and (5) power conditioning for the electronic equipment. Two sides of the Technical Building provide physical mounting of the antenna array elements and act as reflector faces for the antennas.

The Power Plant contains the engine-generators used to provide backup and emergency power. The switchgear, controls, and instruments for controlling the engine-generators and for selecting between emergency power and commercial power are also contained within the power plant.

The Technical Building and the Power Plant are totally shielded buildings with the walls, floor, and top constructed of thick (estimated to be approximately 3/8 inch) steel plates welded together and to the supporting steel superstructure. All penetrations for power and signal lines, air, and utilities are thoroughly treated to prevent the coupling of unwanted electromagnetic signals into the facility. Treatments include the peripheral welding of all conduit and pipe at the point of penetration through the shield, the use of EMP/EMI filters and surge arresters on signal and power lines, and the use of waveguide-below-cutoff air intake and exhaust vents. Noted in particular was that the supporting structural steel members were carefully welded to the floor pan of the shield. The Technical Building and Power Plant are joined via a completely shielded corridor through which the power cables are routed to the Technical Building.

C^3I equipment are distributed throughout the Technical Building. Principal locations include the Technical Operations Room (TOR), the Communications Rooms, the Radar Room, Radar Array Rooms, Telephone Equipment Rooms, and the Computer Room. Other C^3I equipment include the SATCOM system and long wire antennas.

Earth Electrode Subsystem

A comprehensive earth electrode subsystem (EES) consisting of a No. 1/0 bare stranded copper buried cable interconnecting 3/4 inch by 10 feet ground rods is installed. As shown in Figure B-1, the EES encircles the Power Plant and Technical Building and interconnects with the security fence grounding system as well as with the on-site commercial power substation ground. The building shields of the Technical Building and Power Plant are multiply

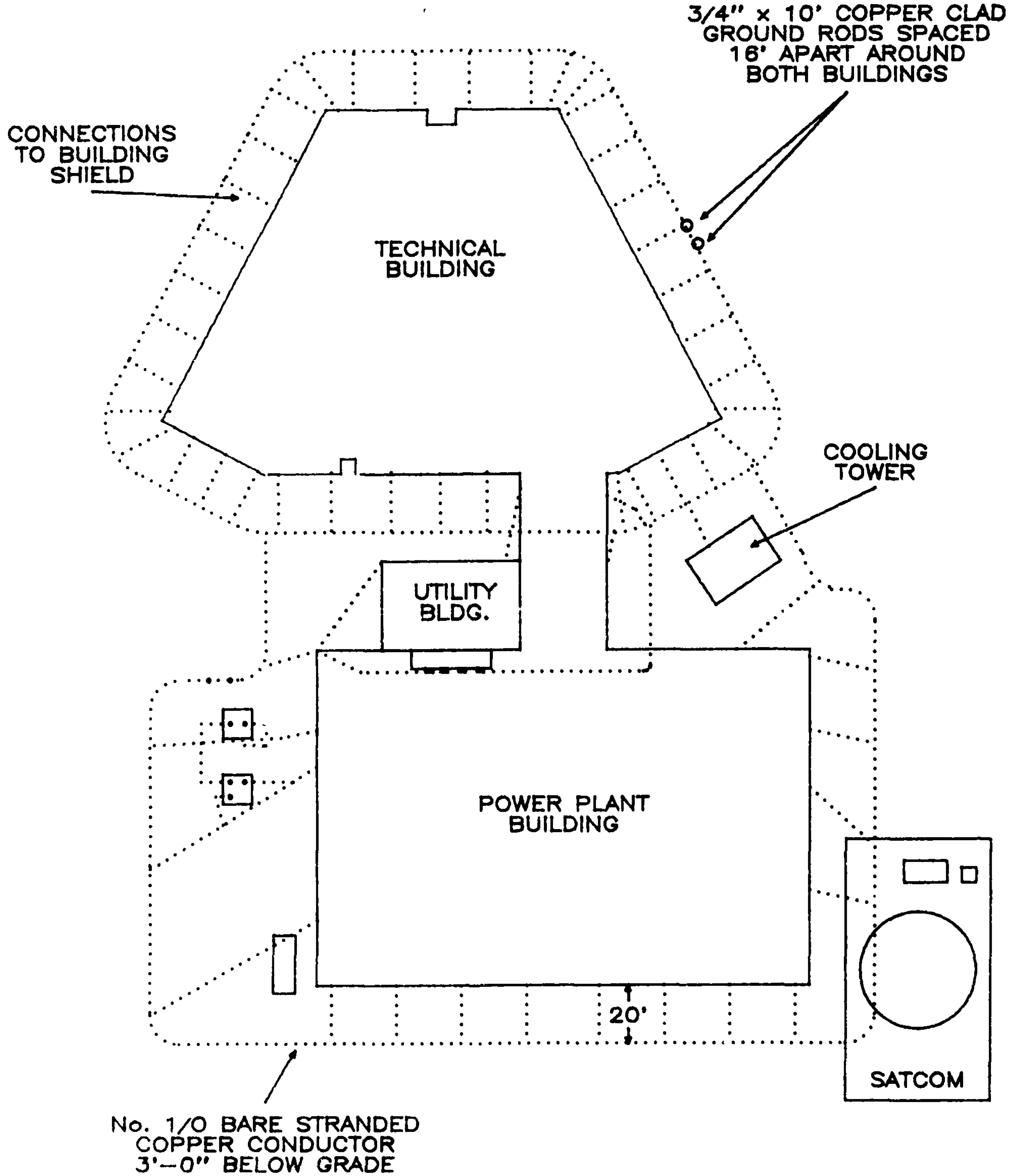


Figure B-1. Earth Electrode Subsystem for PAVE PAWS (East) Technical and Power Plant Buildings.

grounded to the EES. The lightning protection subsystem installed on the Technical Building, the Power Plant, the guard tower, and other structures is also grounded to the EES.

Electric Power Distribution

Electric power is obtained from two commercial 22.9 kV 3-phase, three-wire delta feeds terminating into two 5000 kVA transformers. The secondaries of these transformers are four-wire, 2.4 kV wye configurations with neutral grounding resistors. The 2.4 kV phase conductors enter the Power Plant through EMP power line filters whose cases are welded to the Power Plant shield. From the EMP filters, the incoming power is routed inside conduit to the main switchgear. A system ground bus is located inside the switchgear; this ground bus is bonded to the interior of the Power Plant shield with a No. 1/0 copper cable.

The six engine-generators located within the Power Plant have their neutrals grounded to the Fault Protection Subsystem via grounding resistors which serve to limit fault current as well as provide a means for monitoring fault conditions. The Fault Protection Subsystem consists of an Equipment Grounding Conductor (the "green" wire) routed from the switchgear ground bus to equipment cabinets and transformer enclosures. The Fault Protection Subsystem interconnects all electrical equipment and its supporting structures (conduit, and raceway) together, to the structure, to the earth electrode subsystem, and to the commercial substation ground and transformer neutrals. The connection to the structure is through the deliberate bonding of the switchgear neutral to the shield. The connection to the earth electrode subsystem and substation ground and neutrals is via the building shield. No grounding conductors penetrate the shield. The Fault Protection Subsystem thus establishes grounding paths from any exposed electrical cabinet or enclosure back to the power source, whether it be a transformer, an engine-generator, or the commercial power substation.

Intermediate transformers converting the 2400 volts to 480/277 and subsequently to 120/208 volt service are installed delta-wye with secondary neutrals grounded to their cases, to the fault protection subsystem, and, in some instances, to structure. Neutrals are continued to single phase load equipment but not to subsequent stepdown transformers nor to three phase loads.

Signal Grounding

The Computer Room in the Technical Building is an EMI shielded enclosure which is completely contained inside the building EMP shield. Inside the Computer Room is a raised floor composed of two-feet square conducting panels resting on a steel grid. The grid is supported by one-foot high pedestals on two-foot centers. The pedestals are bonded to the floor of the EMI shielded room with conducting copper tape.

A Signal Reference Grid (SRG) composed of copper cables crossing on two-foot centers lies under the floor panels. The cables are bolted with U-bolts at the cross over points to provide a multiply interconnected grid. This grid lies on plywood placed on the floor of the shield. However, both the EMI shield and the SRG are solidly connected to the building steel which passes through the room (see Figure B-2). The EMI shield is completely welded around

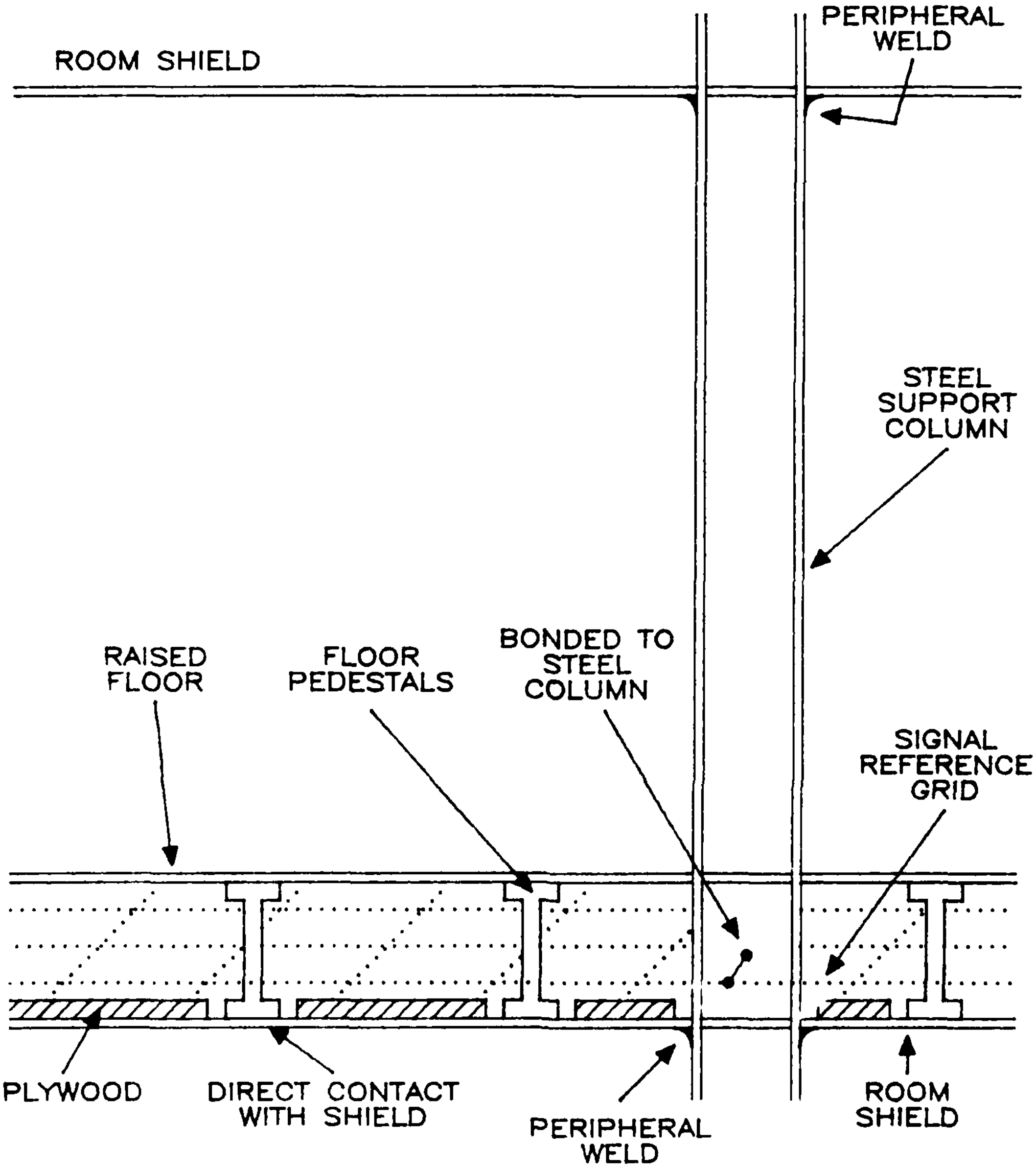


Figure B-2. PAVE PAWS (East) Computer Room Grounding.

all penetrations and the SRG is either welded or bolted to the building column steel. Thus, the SRG and the inside of the shielded room are integrally bonded together through their common interconnection to building steel.

Sverdrup and Parcel Study

During the visit, attention was directed to grounding and lightning protection study conducted by Sverdrup and Parcel and Associates, Inc., St. Louis, Missouri. Subsequently, a copy of the report "ON-SITE GROUNDING AND LIGHTNING PROTECTION STUDY, CAPE COD AIR FORCE STATION, Contract DACA87-84-C-0064, 31 May 1985"[12] was obtained.

The stated purpose of the Sverdrup and Parcel survey was to verify and update the existing facility drawings and to determine conformance of the existing installation with applicable codes for electrical power system grounding and lightning protection. Resistance measurements were made of various bonding connections to obtain an indication of the condition of the grounding network. In addition, soi resistivity measurements were made at several locations around the site and the earth electrode subsystem resistance was measured. Finally oscilloscope measurements were taken in the computer room to assess the noise environment on the ground network.

The report notes that the grounding system is an accordance with MIL-HDBK-419 in that it has both high frequency elements and low frequency elements installed.

A conclusion of the report is that the grounding system was well designed and maintained, although some discrepancies and deficiencies were found. Several bonds were found to be loose; many of these were corrected on the spot. A recommendation in the report was that a survey and maintenance program more stringent than that presently in effect be established to correct loose or corroded bonding connections more frequently.

The analysis of the oscilloscope displays recorded in the computer room led to the recommendation that the filters in the power supply neutrals be removed from the circuits feeding the computer room.

Two other recommendations made were:

1. Add two additional lightning downleads on the Technical Building; add air terminal plus down leads on some exposed equipment on both the Technical Building and the Power Plant; and replace several grounding clamps.

2. Install deep grounding rods to lower the resistance of the earth electrode subsystem to 10 ohms.

Assessment of the PAVE PAWS Grounding Networks

In general, the grounding networks installed in the PAVE PAWS (East) facility do appear to conform with MIL-HDBK-419 and the National Electrical Code. The earth electrode subsystem is well laid out and should provide an adequate path for the dissipation of lightning discharges to the elements of the facility.

The fault protection subsystem effectively interconnects exposed metal structures together and to the neutrals of transformers and generators. All elements of the fault protection subsystem become common through the frequent connections to the building shield.

The shield itself appears well made and well maintained. No instances of violation of shield integrity were noted.

Relative to the recommendations made in the Sverdrup and Parcel Report, No. 1 is endorsed. Recommendation No. 2 will bring the earth electrode subsystem in compliance with the MIL-STD-188/124A and MIL-HDBK-419. As to the benefits expected from installing deep ground rods, little difference in the overall performance of the facility is likely to be experienced. Because of the well-shielded construction of the facility, the primary effect of an earth electrode resistance below 10 ohms will be a slight reduction in threats of lightning damage to external structures and associated lightning and power facilities. Unless clear evidence of poor facility performance traceable to the slightly elevated earth electrode resistance is available, the enhancement is not considered to be warranted.

The recommendation to remove the filter from the ac neutral feeding the EMI-shield Computer Room is in error. To avoid an unprotected penetration into the shielded volume of the Computer Room, the neutral must be filtered or grounded to the shield room wall at the entrance. However, grounding of the neutral at the screen room wall will violate the National Electrical Code and the recommendations of the Integrated Practices Report. Before any such actions are taken, specific steps should be taken to assure that the measured voltages are indeed the result of filter currents and not caused by interchanged neutral and grounding conductors, as is often found in many facilities. If, upon correcting any electrical wiring errors, the stray voltages remain, consideration should be given to installing a dedicated isolation transformer or appropriate power conditioner inside the shielded room to provide transient and noise free ac power for the computing equipment.

SATELLITE READOUT STATION

Facility Description

The Ground Data System, illustrated in Figure B-3, consists of four communications satellites -- the Overseas Ground Station (OGS) Satellite, the SATCOM Satellite, and two Conus Ground Station Satellites (CGS-I and CGS-II) -- Overseas Ground Stations (OGS), Conus Ground Stations (CGS), the Ground Communications Network (GCN), land lines connecting with system users, and remote Data Reduction Central connected via microwave link.[13] The Satellite Readout Station at Buckley Air National Guard Base, Aurora, Colorado, is an example of a Conus Ground Station. It provides satellite tracking along with signal transmission to and from the satellite.

The Station consists of a technical building which houses signal processing equipment and the power plant which houses electrical equipment and switchgear. Two satellite tracking antennas are mounted on large pedestals with the pedestals and reflectors totally enclosed in large radomes. An auxiliary antenna tower is located near the technical building.

Technical Building

The Technical Building contains the signal processing and data reduction equipment. Located within the Technical Building are the satellite tracking and receiving sets along with equipment for data distribution, data reduction, ground communications network maintenance, message processing to include encryption/decryption, microwave link termination, and others.

The Technical Building is a totally shielded facility, with all conductive penetrations (power lines, signal/control cables, and utilities) entering through filtered and/or welded ports. Except for some coaxial lines feeding antennas mounted on the adjacent tower, all penetrations into the Technical Building enter through a below-grade, shielded cable entrance vault. The overall building shield itself is constructed with 10 gauge steel with welded seams. Waveguide-below-cutoff entry ways augumented with shielded doors are used for personnel access. No windows into the shielded volume were noted. The shield rests on a concrete pad. The structural steel frame supporting the Technical Building is constructed inside the shield.

Internal Grounding Network Configuration

A schematic diagram of the grounding system associated with the Technical Building is shown in Figure B-4. The grounding system is configured as a "single-point tree." Notice that the grounding networks inside the building are indicated as isolated from the shield.

All equipment and electrical system grounds terminate to a Station Earth Ground Point (SEGP). The SEGP consists of a 3" diameter x 54' long steel pipe inside an outer 5" diameter x 63' long 6" steel pipe with the two insulated from each other with a third PVC pipe. The top end of the outer steel pipe is peripherally welded to the floor of the shield. The inner insulated pipe continues upward through the shield floor to connect to the

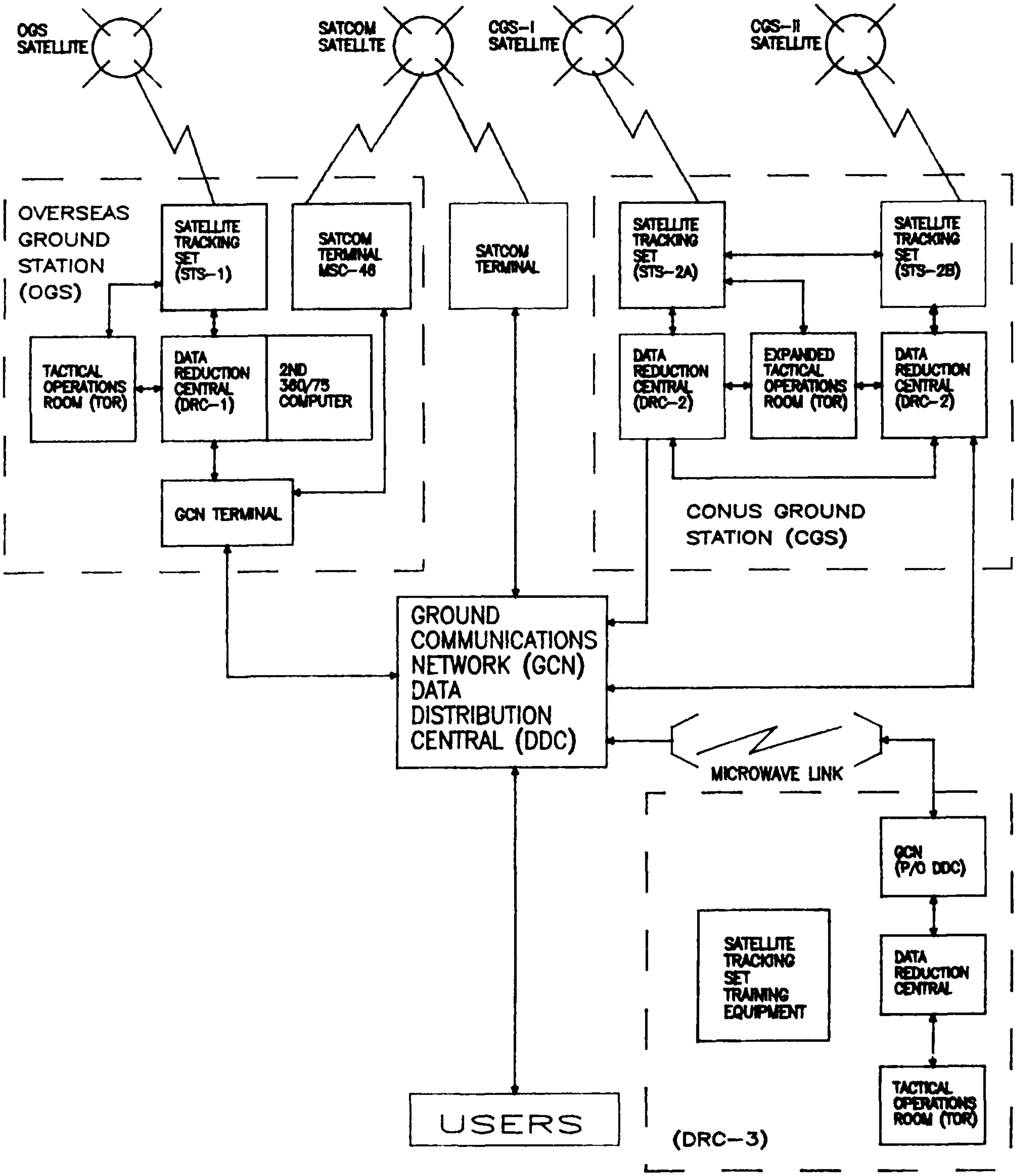


Figure B-3. Block Diagram of Ground Data System.

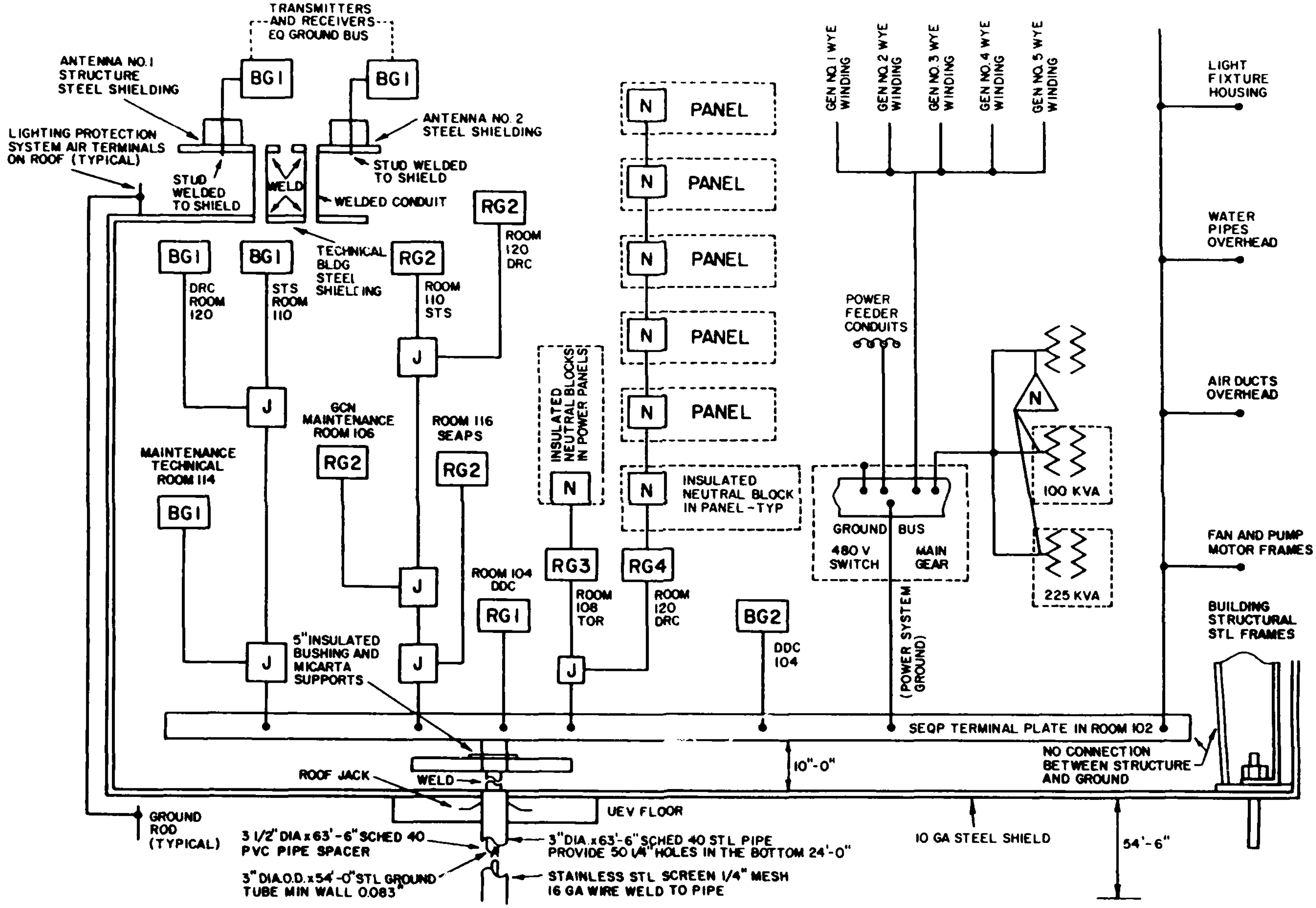


Figure B-4. Schematic Diagram of the Grounding Networks in the Technical Building of the Buckley Satellite Readout Station.

SEGP Terminal Plate. Thus, before any of the equipment ground connections are made, the SEGP is completely isolated from the shield and the structure except for the path through soil.

All equipment and electrical grounding connections are made to the SEGP Terminal Plate using tree, or star, ground network configurations. Note, in particular, that the motor generator winding neutrals are interconnected together and then connected to the ground bus inside the 480V main switchgear. A "Power System Ground" conductor connects this switchgear ground bus to the SEGP Terminal Plate. The neutrals on the secondary sides of stepdown/isolation transformers are also connected to the switchgear ground bus. Nonelectrical utilities, HVAC ductwork, and electrical machinery frames/chassis are similarly grounded to the SEGP Terminal Plate. On Figure B-4 it is specifically noted that no (deliberate) connection exists between the SEGP Terminal Plate and the structure (and, presumably, the shield).

At the time of the visit, an expansion of the Technical Building was under construction. The new addition is also a totally shielded structure and fully integrated with the existing structure. As a part of this new construction, a new grounding electrode was being installed. The new grounding electrode was to be connected in parallel with the existing SEGP as shown in Figure B-5. The configuration of the new electrode is similar to the original one, namely consisting of a 3 inch copper pipe inside a larger steel one with the two separated with a PVC liner. The new ground electrode was to be interconnected with the existing SEGP with two 500 MCM copper cables.

RED and BLACK grounds are configured as separate single-point "trees" which interconnect only at the SEGP.

Equipment Grounding Interconnections

Figure B-6 is a sketch of the manner in which standard equipment racks are grounded. The racks themselves are insulated from the (raised) floor by phenolic blocks. All power conductors, including neutrals, are brought into the racks through line filters. An entrance filter box is used to provide isolation against the coupling of interference signals or noise on power cables. A more detailed sketch of the grounding inside a typical equipment cabinet or rack is shown in Figure B-7. Individual equipment modules/chassis are grounded via two means: (1) the green safety wire is grounded to the ground plug of the outlet strip supplying ac power for the module; and (2) a separate ground conductor interconnects the equipment module with the shield of the signal cable entrance box. Signal cables between racks enter and leave via these signal entrance boxes.

RED and BLACK equipment cabinets are handled in a similar manner. For example, Figure B-8 depicts the arrangement of the ground conductors for the RED/BLACK racks.

Signal and power cables external to equipment racks are routed within conduit which are mounted on isolators, as illustrated in Figure B-9. The conduit do not connect to the equipment racks. An isolating section is

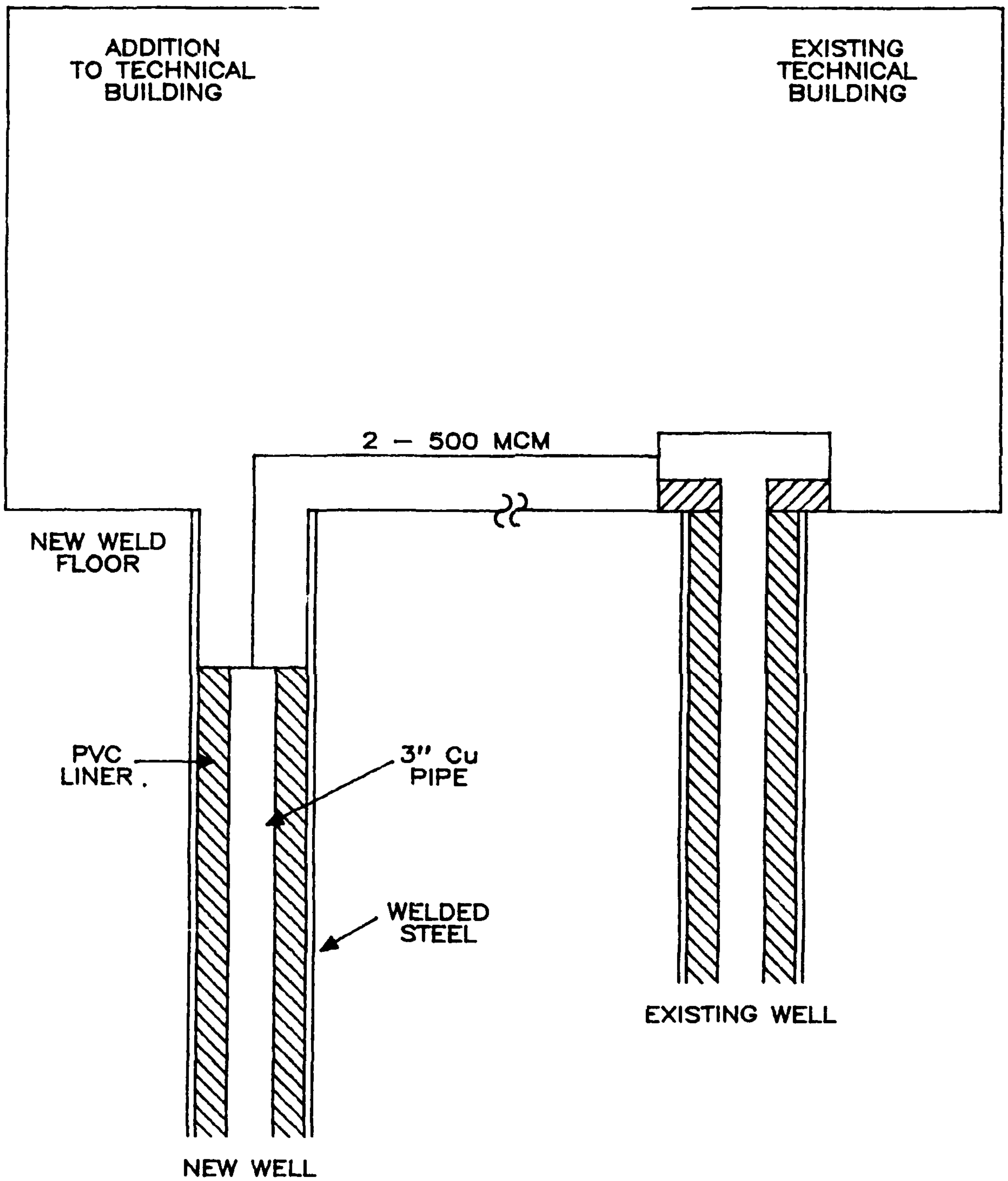


Figure B-5. Interconnection Between New and Existing Grounding Wells.

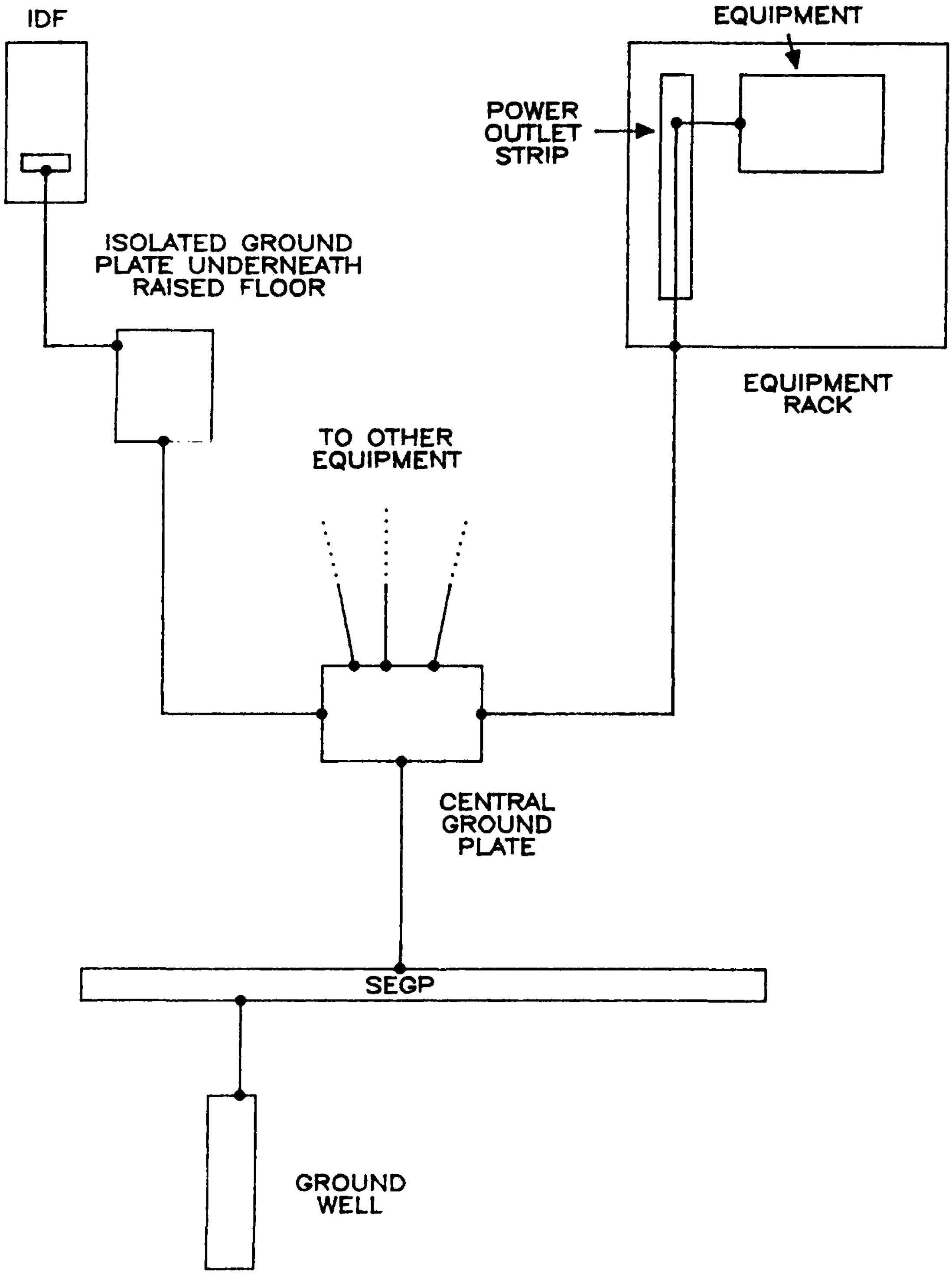


Figure B-6. Grounding of Equipment Racks.

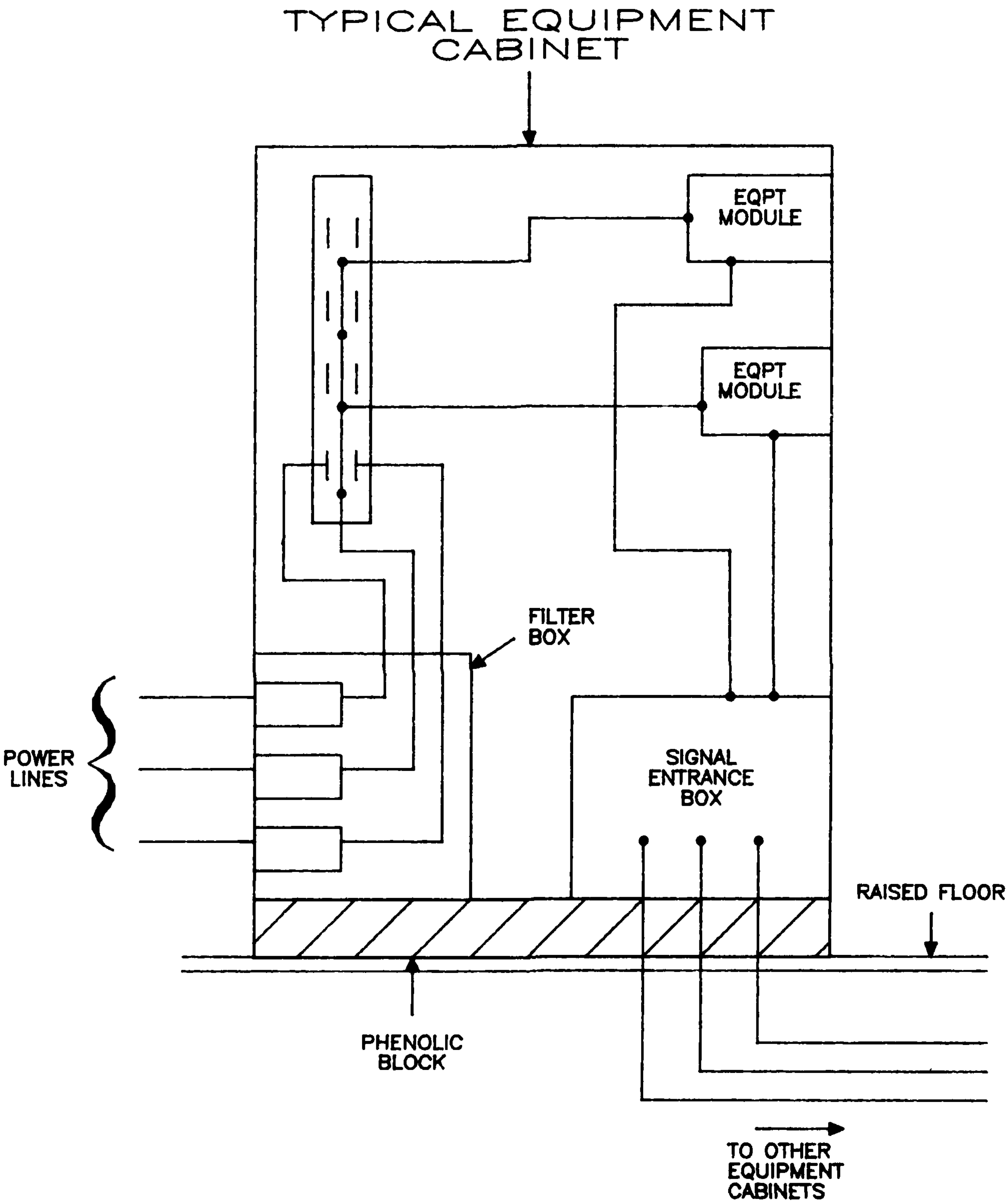


Figure B-7. Equipment Cabinet Grounding.

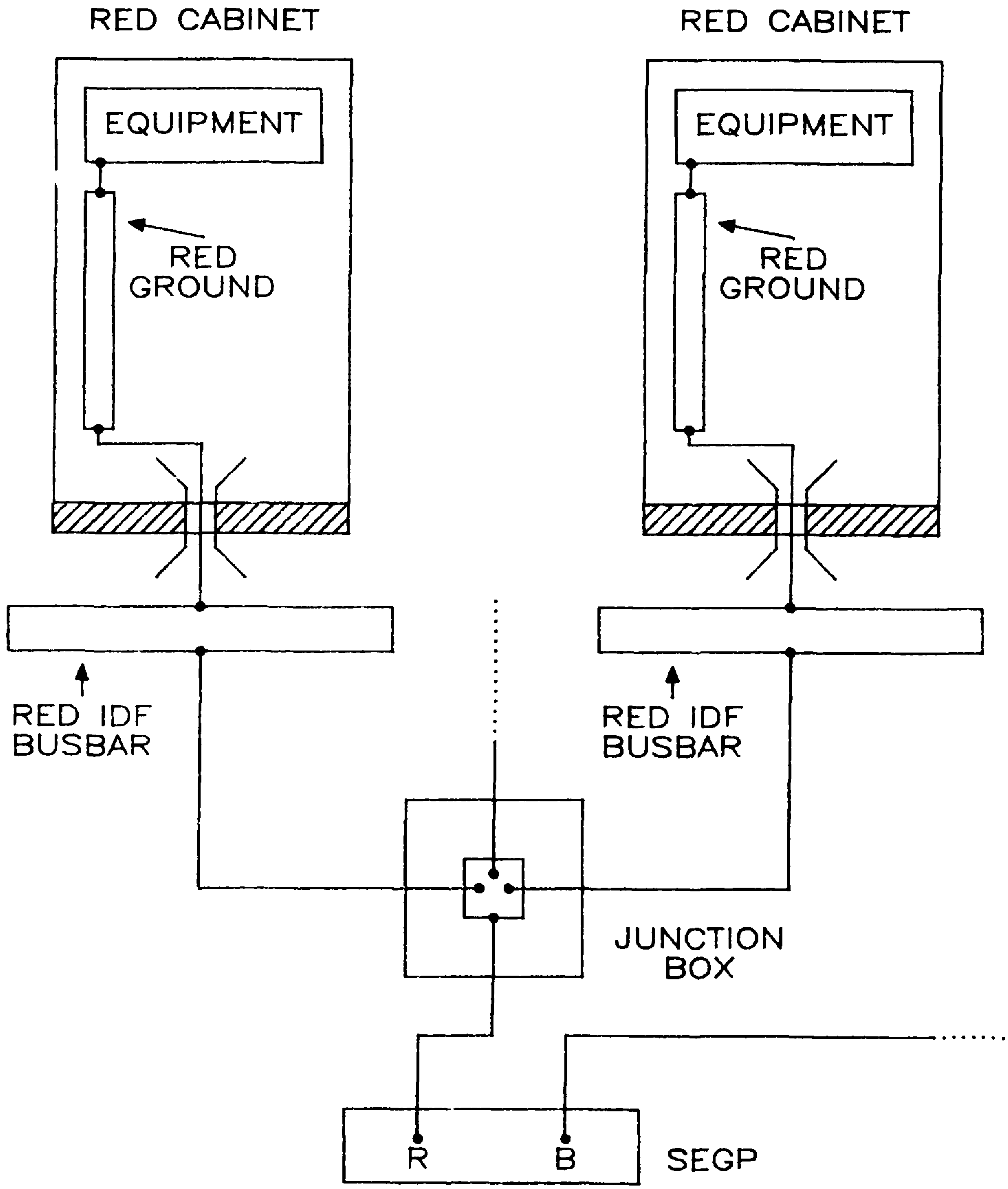


Figure B-8. Red Equipment Grounding.

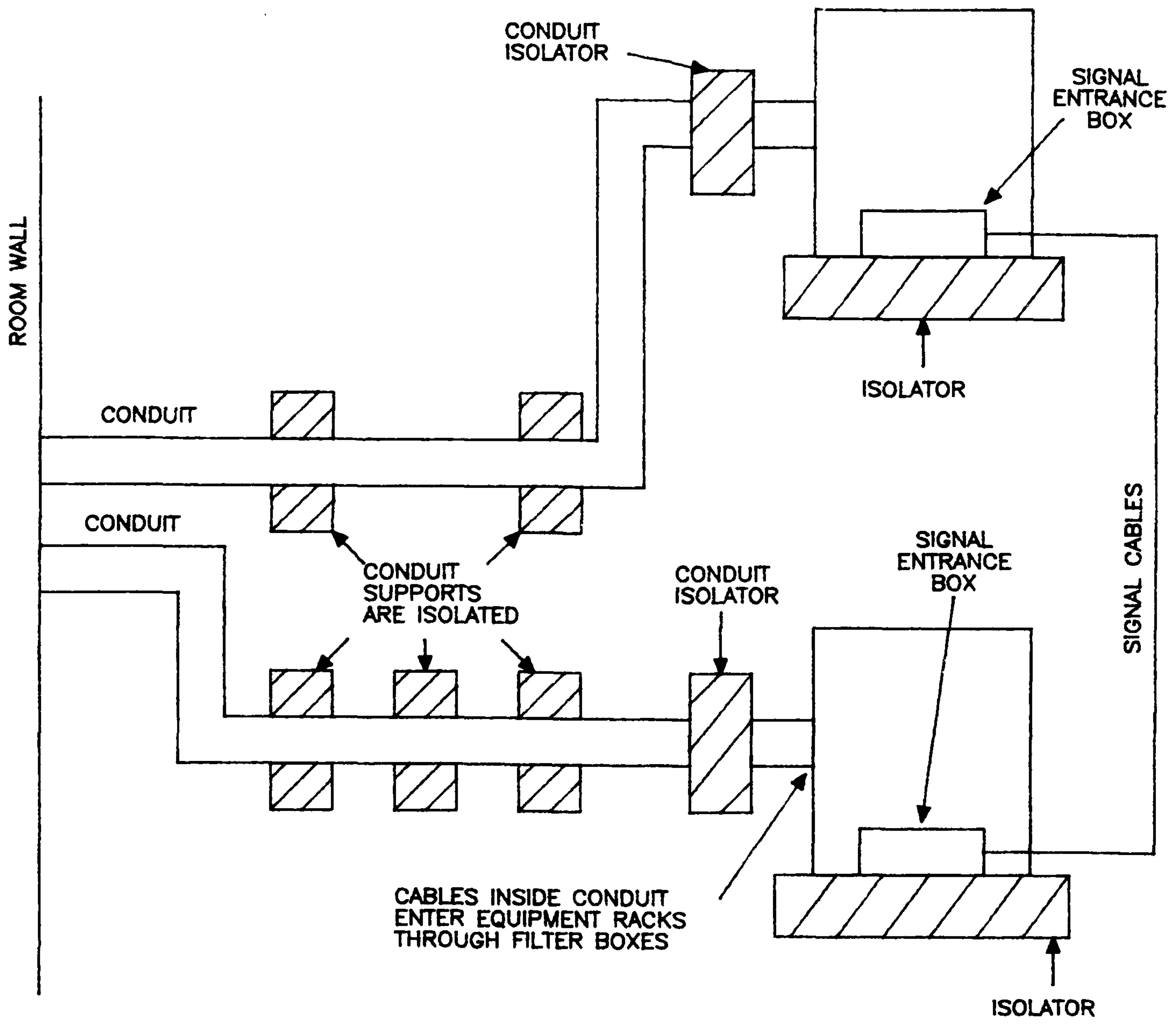


Figure B-9. Isolation of Equipment Cabinets and Conduit from Structure/Shield.

inserted into the conduit at the signal entrance boxes for the racks. Cables interconnecting RED equipment with BLACK equipment enter and leave through these signal entrance boxes.

Lightning Protection Network

Lightning air terminals are mounted on top of the Technical Building with down conductors routed outside the shield to separately installed ground rods. The ground rods themselves are not directly bonded to either the shield nor to the SEGP.

Power House

Adjacent to and connected to the Technical Building is the Power Plant which contains the motor generators, transformers, switchgear, and other support equipment. The Power Plant is also totally shielded similarly to the Technical Building. The two buildings are interconnected with a shielded corridor through which are routed the power cables supplying the Technical Building, thus avoiding the need for subsequent filtering and surge suppression before entering the Technical Building.

Within the Power Plant are five 650 kW three-phase diesel electric generators plus associated switchgear and control circuitry. The neutral of each generator is grounded through a 0.0075 ohm resistor. Current transformers in the neutral ground lead are used to detect ground fault conditions. The generator neutrals also connect to an isolated neutral ground bus in the 480 volt main switchgear. As noted above, this switchgear neutral is connected to the SEGP Terminal Plate.

Satellite Tracking Antennas

The general layout of the Antenna Building is shown in Figure B-10. The pedestal base contains the transmitter room, the motor generator room and the mechanical equipment room. The transmitter room is well shielded with shielded doors provided for access.

The radomes have lightning air terminals installed on top. Two down conductors connect the radome air terminals with ground rods positioned on opposite sides of the antenna building. Other down conductors connect the air terminals mounted on the antenna support structure with two other ground rods located orthogonal to the radome grounding rods. The available drawings indicated that these two pairs of ground rods are not directly interconnected.

According to site personnel, the tower legs are grounded with individual ground rods. Tower leg joints are not bonded with auxiliary conductors.

The RF receiver front end equipment is located at the rear of the antenna reflectors. This RF equipment is totally contained inside shielded enclosures.

The satellite up-link transmitters are located in shielded equipment rooms at the base of the pedestals. The shield from the pedestal equipment

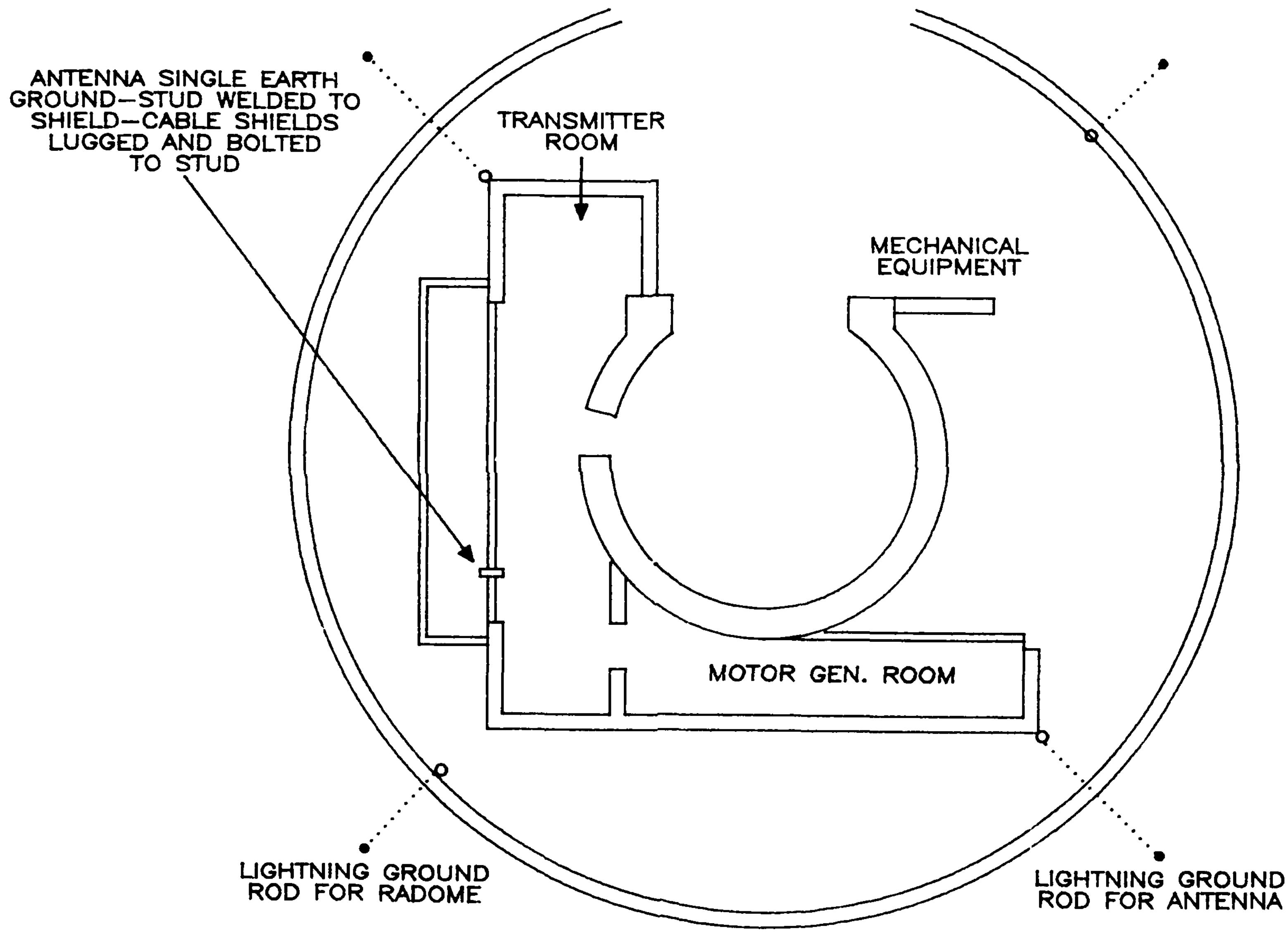


Figure B-10. Antenna Building Grounding System.

room is continued into the Technical Building through welded, 6 inch pipes as illustrated in Figure B-11. RF, power, and control cables are routed inside these pipes between the technical building and the antenna.

Evaluation of the Grounding Networks Installed in the Satellite Readout Station

General Observations

According to the drawings, the grounding networks are carefully structured to produce a single point tree configuration with a single connection to earth, i.e., the SEGP. Superficially, the signal and power grounding system appears to be isolated from the shield and from the lightning grounds.

Signal Ground Isolation

Although the drawings indicate otherwise, it is not likely that the signal ground system is truly isolated from either structure or the shield. It seems highly probable that the various utility elements, i.e., light fixtures, water pipes, air ducts, and fan/motor frames, are multiply interconnected to the structure and to the shield. It is recommended that resistance tests between cabinets and the shield be performed to confirm that this contact exists. Since the building shield-structure combination is so widely accessible throughout the facility, with the combination expected to exhibit a low resistance contact with earth (because of sitting directly on the concrete support pad), low resistance paths are likely to exist between all exposed equipment cabinets and racks and the shield and structure.

Station Earth Ground Point (SEGP)

The operation of the Station Earth Ground Point is difficult to assess. Inside the Technical Building, the signal and power grounding conductors connect to the SEGP Terminal Plate which is welded to the inner pipe of the SEGP. The degree of contact made by this inner pipe with soil would appear to be slight because the inner pipe stops more than 6' before the end of the outer pipe. The outer pipe does make intimate contact with soil; however, the inner pipe is insulated from the outer pipe. It is presumed that electrical contact between the SEGP Terminal Plate and soil is made via water seeping up from the bottom of the outer pipe.

Lightning Protection

Effectively, the antenna towers are bonded to the Technical Building shield via the welded 6" steel pipe extending between the equipment rooms in the base of the antenna pedestal and the Technical Building. Thus in the event of a lightning strike to either the radome or the antenna itself, the stroke energy can be expected to follow the pipe from the tower structure to the building shield and then to the outer 5" pipe of the SEGP to earth.

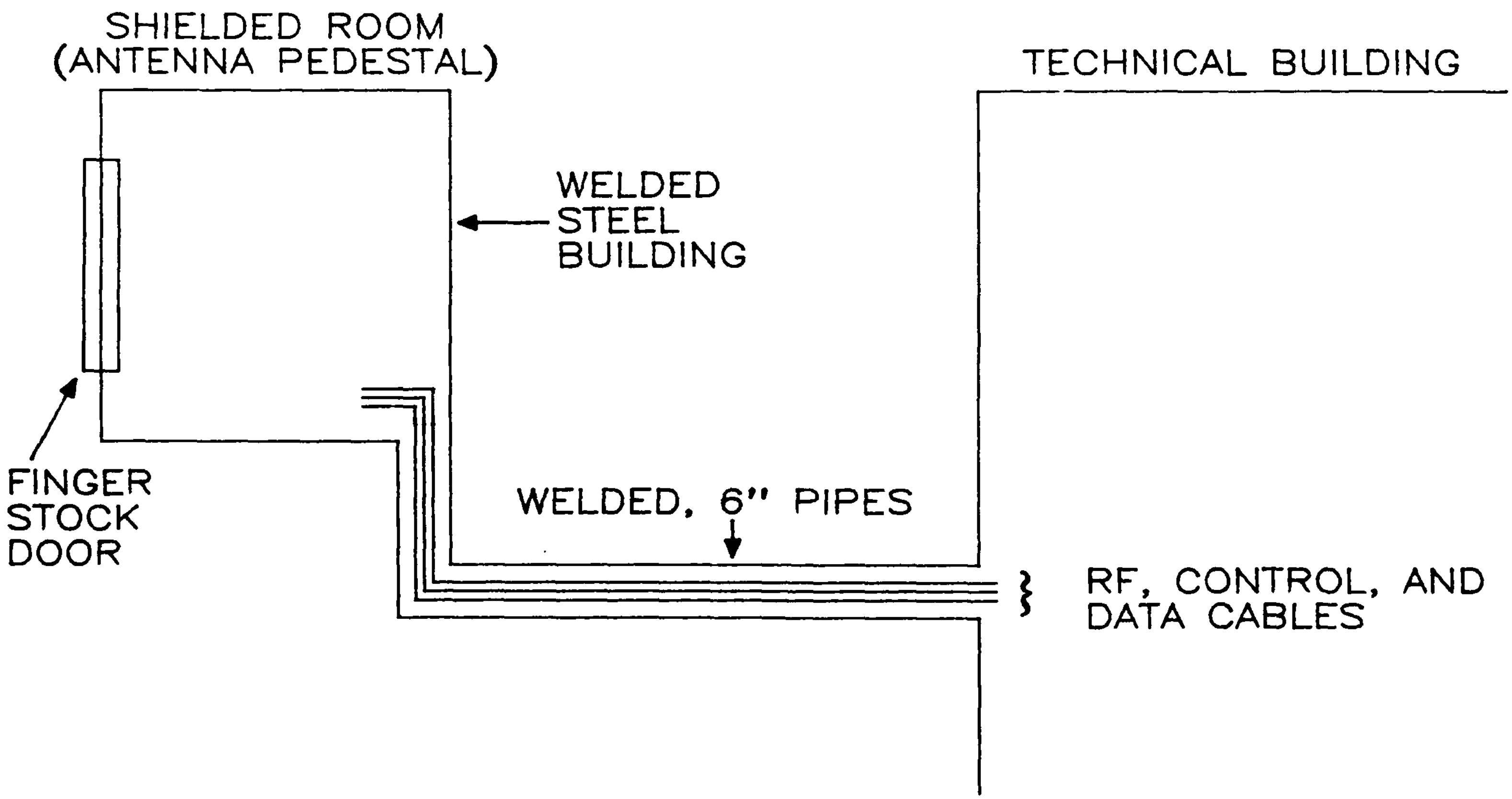


Figure B-11. Shielding of Cables Between Antenna and Technical Buildings.

A primary concern with this approach to earth grounding is the threat of potential damage to equipment inside the Technical Building or in the antenna towers from a lightning strike to either the towers or to the building itself. If the internal equipment is not bonded to the same earth point as the shield, very high potential differences between the equipment and the shield could develop during a lightning strike. At those points where conductors penetrate the shield (e.g., at cable or pipe entrances) and at the SEGP where the 3" pipe enters the 5" pipe, very large transients will be produced, with serious damage possibly resulting. To eliminate this threat, it is recommended that the SEGP be bonded to the shield.

To further reduce the likelihood of lightning-induced hazards being produced in this manner, installation of added ground rods with an interconnecting buried cable around the antenna towers is recommended. The existing ground rods should be bonded to this cable. In addition, consideration should be given to adding ground rods and a buried bare cable around accessible portions of the Technical Building. However, it is not considered necessary to encircle the entire Technical Building and Power House complex with ground rods and interconnecting cable. The added ground rods and cable should be bonded to the building shield.

It is recommended that the lightning down conductors installed on the Technical Building be bonded to the building shield near the bottom. Because of its close proximity, the communications antenna tower should be cross bonded to the Technical Building shield. This antenna tower should have a minimum of four 10' ground rods installed, one at each corner of the tower base, if not already installed. (No evidence of any such tower ground rods was noted during the inspection nor on the drawings.) Each ground rod should be bonded to the tower legs with at least a No. 1/0 bare copper cable.

TEMPEST Grounding

The RED/BLACK grounding approach installed in the Buckley Satellite Readout Station reflects the single point grounding philosophy contained in TEMPEST control documents issued prior to MIL-HDBK-419. The approach used in the Technical Building is not wrong, per se, and therefore it is not necessary to make any significant changes. However, in the event of future major rennovations, consideration should be given to simply interconnecting all equipment items as recommended in the Integrated Practices Report and as detailed in MIL-HDBK-419. In fact, it is likely that the RED and BLACK grounds are already interconnected in the existing installation in spite of the indications to the contrary on current drawings.

NORAD CHEYENNE MOUNTAIN COMPLEX

Site Description

The NORAD Cheyenne Mountain Complex (NCMC) consists of eleven, well shielded buildings housing electronic computing and signal processing equipment plus offices and personnel support facilities. In addition, the complex contains an electrical bay, a chiller building, an air handling building, and a diesel power plant. The general layout of the complex is shown in Figure B-12. Except for external antennas and the commercial power substation, the electrical and electronic elements of the facility are located deep within Cheyenne Mountain.

Each building is enclosed in a 3/8-inch welded steel skin. The building skins are interconnected with wide copper straps and with stranded No. 4/0 copper cables. The buildings sit on large coiled springs.

Power Distribution System

The power distribution system for the NCMC is illustrated on Figure B-13. AC power for the site is supplied by a commercial power feed from a 34.5/4.15 kV substation located outside the mountain or by a bank of six diesel electric 4160-volt generators located in the Power Plant Building. Each of these power sources interconnect with redundant ("A" and "B") power buses through the 4160-volt Main Switchgear in the Electrical Bay. From the Electrical Bay, the "A" and "B" buses are routed to various Power Centers located throughout the complex. In the Power Centers, the voltage is transformed down to 480/227 volts for distribution to various loads, including lights, motors and other heavy loads, power converters, and other stepdown transformers.

As part of the NORAD POWER UPGRADE program,[14] the original 34.5 kV substation has been replaced by a new, relocated substation. Two 4160-volt power cables installed along the roof of the north tunnel route commercial power from the substation through an isolation switch to EMP power line filters located on the third floor of the Electrical Bay. These commercial feeders are configured as three phase (delta) conductors with ground. From the EMP power line filters, the commercial power is fed to the "A" and "B" buses of the 4160-volt Main Switchgear (also frequently identified on drawings and in other documentation as "5 kV Switchgear").

The diesel generators are connected via the Generator Switchgear to the Main Switchgear. Power distribution from the generators to the switchgear is three-wire delta with ground (i.e., only the phase conductors, not the neutral, are run from the generators to the switchgear).

From the 4160-volt Main Switchgear, power is distributed via parallel feeds to 12 Power Centers (These power centers are designated PC1 - PC7, PC9 - PC-12, and PC-15) located throughout the Complex. PC-14 is fed from the Generator Switchgear buses and serves only power plant loads. (Currently, there is no power center designated PC-8 nor PC-13.) This distribution is also three-wire delta with ground.

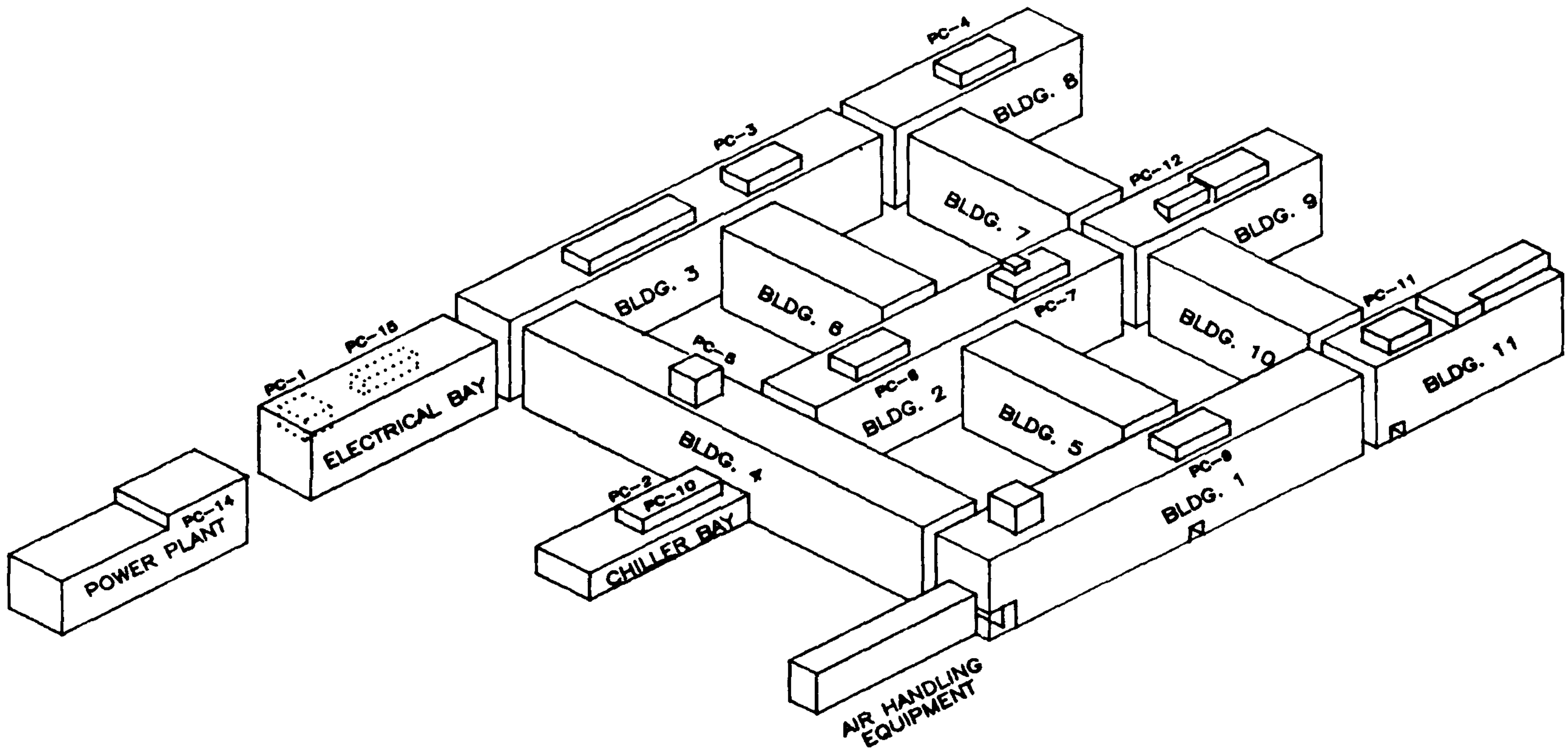


Figure B-12. Location of Power Centers Within the NCMC.

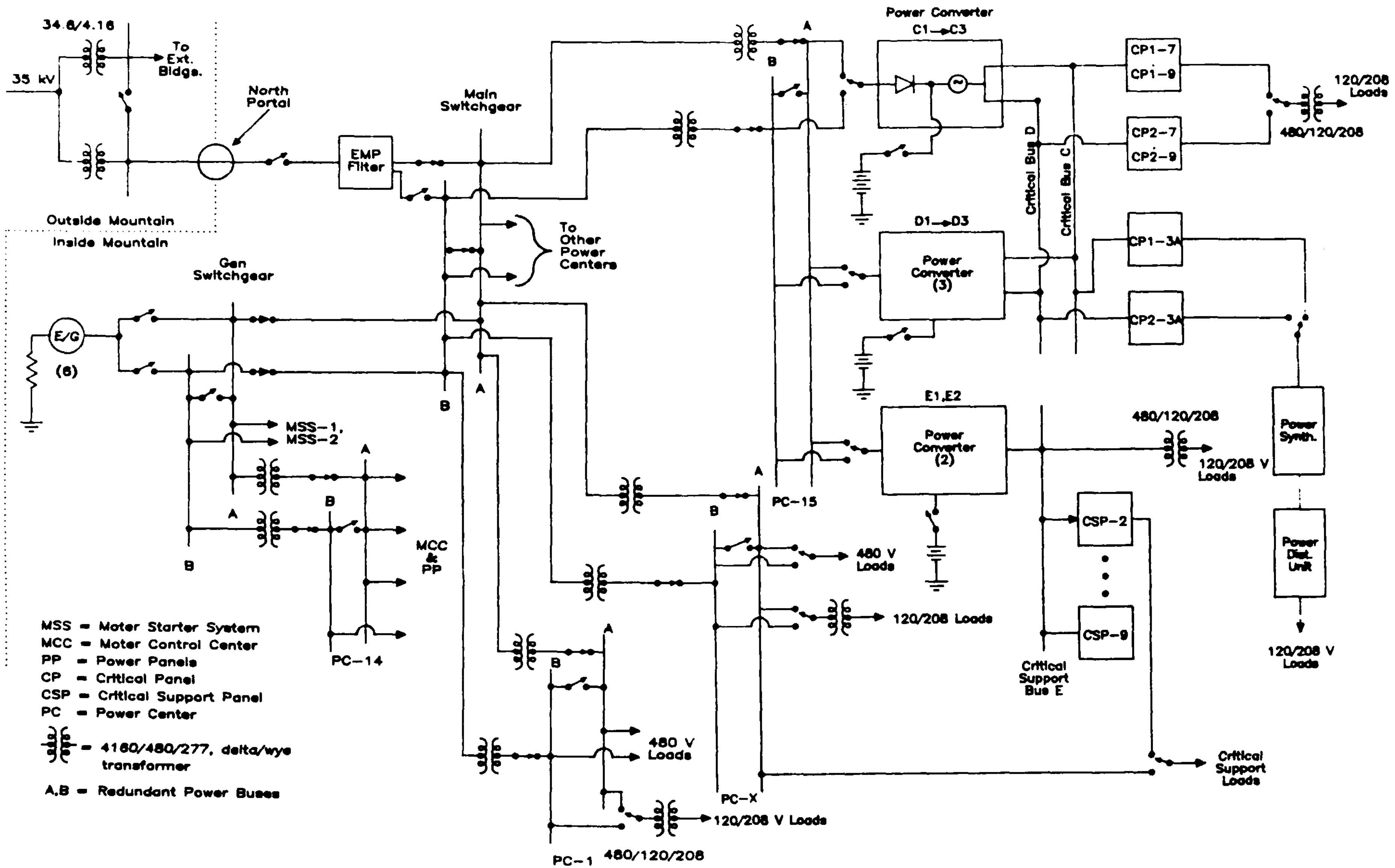


Figure B-13. Schematic Layout of NCMC Power Distribution System.

Redundant ac feeds are continued to each Power Center. Two 4160-volt feeds are routed from the "A" and "B" buses in the Main Switchgear or, in the case of PC-14, from the two buses in the Generator Switchgear. The 4160-volt feeds connect to the delta primaries of 4160/480/277 volt stepdown transformers located in the Power Centers. The wye secondaries of these transformer have their neutrals grounded at the transformer to building steel. Power Centers 1, 2, and 10 supply 480 volt, 3-phase ac power to the heavy equipment in the electrical and AC chiller bays. In each of these three power centers, there is at least one 480/208/120 step-down transformer for single phase loads. Grounding conductors are routed with the three phase conductors.

Similarly, dual 4160-volt power feeds are routed to each of the remaining power centers. In the power centers, 4160/480/277 volt stepdown transformers supply the 480 volt "A" and "B" buses. Supplied from these buses are 480-volt, 3-phase heavy equipment loads and various lighting and electronic and light equipment loads. To supply the lighting, utility outlets and noncritical electronic loads, the 480 volt supply directly feeds 480/208/120 stepdown transformers. This 480 volt supply is routed as 3-wire delta with ground to the these low voltage transformers. From these transformers, single phase electrical power is delivered via a supply conductor ("black wire") and a neutral conductor ("white wire") along with a grounding conductor ("green wire"). The neutrals of the secondaries of the stepdown transformers are grounded to the transformer cases and to building structure (shield) at the transformer location.

As part of the NORAD POWER UPGRADE, a new Power Center, PC-15 was constructed in the Electrical Bay. PC-15 provides critical power to various locations throughout the facility. It contains eight 500 KVA power converter (ac-dc-ac) modules which supply 480 volt power to Critical Buses C and D and to Critical Support Bus E. The power converters consist of rectifier/inverters that (1) condition the incoming ac through recitification and subsequent electronic generation of the output ac or, in the event that the incoming ac is interrupted, (2) converts battery-supplied dc to the desired output ac. Three of these converters in parallel supply Critical Bus C and three others in parallel supply Critical Bus D. Two paralleled converters supply Critical Support Bus E. Various dedicated 120/208 volt circuits are served from these three buses.

In addition, complex power conditioners are being installed for certain loads, principally computers, which have experienced excessive power-circuit related outages. These power conditioners consist of a "Power Synthesizer", a "Power Distribution Unit," and associated switching. The Power Synthesizer is fed directly from Critical Buses C and D. The 480-volt output of the Synthesizer is fed through a junction box to the Power Distribution Unit. The Power Distribution Unit contains a 480/208/120 volt stepdown/isolation transformer. The upset-sensitive loads are supplied from the secondary of this transformer.

In summary, the various "power sources," i.e., the 4160-volt generators, the 34.5/4.16 kV substation transformers, the 4160/480/277 volt transformers, and the 480/208/120 volt transformers, are either wye wound, as in the case of the generators, or have wye-wound secondaries, as in the case of the transformers. The neutrals are grounded at the generator or at the transformer. Between each "source" and subsequent 3-phase load, the three phase conductors and a grounding counductor are routed to various equipment loads or to subsequent 480/208/102 transformers. The neutrals of the 208/120 volt secondaries are grounded to the transformer enclosure and to building steel. The neutral conductors are routed to single phase loads along with the grounding conductor.

Facility Ground System

A simplified schematic of the NCMC grounding network is shown in Figure B-14.

The 34.5 kV substation has a main ground grid installed 24 inches below finished grade. All switchgear, transformers, conduit and metal support structures within the substation compound are grounded to this grid. The ground grid is interconnected with the city water main with a No. 4/0 copper cable.

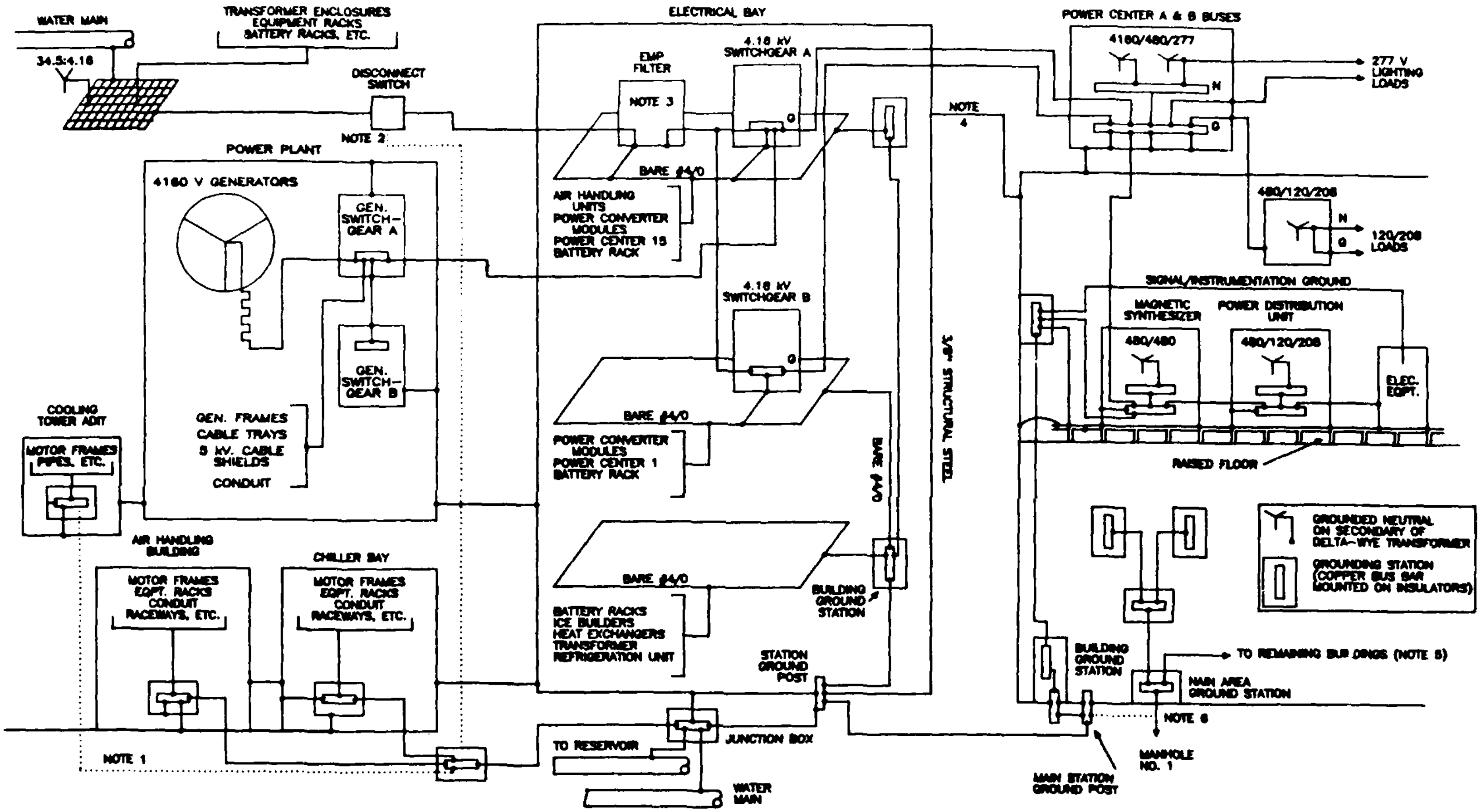
Extending the ground connection from the substation grid into the mountain are two 4/0 copper cables routed with the 4160-volt power feeds through the disconnect switch to the EMP filters located on the third floor of the Electrical Bay. These commercial power feed grounding conductors are connected to the switchgear cabinets and to building steel.

Also located on the third floor of the Electrical Bay are Bus "B" of the 5 kV (4160 Volt) switchgear, a battery rack, air handling units, and other equipment. The enclosures of these pieces of equipment are interconnected with a stranded No. 4/0 bare copper conductor routed beneath the floor slab. This equipment grounding conductor is configured as shown in Figure B-14. This grounding conductor is connected with a No. 4/0 copper cable to an insulated copper bar located in an existing Grounding Station located on the third floor. (This Grounding Station is part of the grounding network which was installed in the building at original construction.) An insulated No. 4/0 copper cable is routed from the third floor Grounding Station to the Building Grounding Station on the first floor.

Bus "A" of the 5 kV switchgear is located on the second floor of the Electrical Bay. This switchgear and other equipment on the second floor are similarly interconnected with a bare No. 4/0 stranded copper cable routed beneath the floor slab. Another No. 4/0 bare copper conductor is bonded to this second floor grounding conductor and routed down to the Building Grounding Station located on the first floor.

On the first floor are located the battery racks for the uninterruptible power system (UPS). These battery racks and the other equipment located on the first floor are interconnected with a stranded No. 4/0 bare copper ground conductor embedded in the concrete slab. This ground conductor is also connected to the insulated copper bar in the Building Grounding Station.

The insulated ground bar in the Building Grounding Station is connected to an intentional "Ground Post" with an insulated No. 4/0 copper cable. This Ground Post is welded to the floor panel of the Electrical Bay and extends through the floor panel. Thus, the grounding conductors on each of the three



NOTES:

1. The grounding conductor between the cooling tower grounding station and the junction box in Chamber 4 could not be verified.
2. The grounding connection between the disconnect switch and the junction box in Chamber 4 could not be verified.
3. The actual termination of grounding conductors at the EMP filter could not be established.
4. Bonding connections between buildings consist of multiple solid, flat and stranded wire conductors.
5. See Figure 15 for configuration of Electronic Grounding Network.
6. The termination of the grounding conductor for the main Area Ground Station could not be defined.

Figure B-14. Schematic Layout of the NCMC Grounding System.

floors are connected together and to the steel enclosure of the Electrical Bay through this Ground Post connection. Also connected to this Electrical Bay ground post are two No. 4/0 copper cables connecting to a similar post in Building 3 (often called the South Building). (The ground post in Building 3 is frequently referred to in other reports and on engineering drawings as the "Main Ground Station" or "Main Ground Post" for the entire facility.) Further connected to the Electrical Bay Ground Post are two cables extending to a junction box located underneath the Power Plant Building. From the junction box underneath the Power Plant Building are two No. 4/0 grounding cables extending to the water mains coming in from outside the mountain and one No. 4/0 cable connected to pipes coming from the internal water reservoirs. Also extending from the junction box is a No. 4/0 cable extending to a second junction box located in Chamber 4 near the Air Handling Building. The Building Ground Stations for the Air Handling and Chiller Buildings also connect into this second junction box via No. 4/0 cables.

The generators in the Power Plant are 4.16 kV wye wound. The neutrals of these generators are grounded through resistors. The resistors are grounded to the ground bus in the generator switchgear. The frames of the generators, switchgear cabinets, and other metallic structures in the Power Plant are also interconnected with the switchgear ground bus. A No. 4/0 cable extends from the Generator Switchgear ground bus to the Main Switchgear ground bus.

From both Main Switchgear Racks in the Electrical Bay, No. 4/0 ground conductors are routed with the three phase conductors to the various Power Centers located throughout the complex. In each power center, the neutrals of the secondaries of the 4160/480/277 volt delta/wye transformers are connected to a neutral bus bar mounted on isolators. Also mounted in the associated switchgear/breaker cabinets is a ground bus bar bolted to the cabinets and to building steel. The neutral bus bar is interconnected with the ground bus. The ground cables from the Main Switchgear attach to this ground bus in the power center cabinets.

The power centers supply 480 volt power to three phase motor loads, subsequent 480/120/208 transformers, and 277 volt single phase loads, such as lights. The neutral is routed only to the single phase, 277 volt loads. A grounding wire is also routed to these single phase loads. To the three phase loads and the stepdown or isolation transformers, a grounding conductor is routed with the phase conductors. The load-associated grounding conductors are routed with the phase conductors and terminate to the metal enclosures of the loads or transformers.

The wye secondaries of the stepdown transformers are connected to the housings of the transformers and to building steel. From the transformers to the various 120/208 volt single phase loads are routed both the neutral and the grounding conductor. The grounding conductor terminates to the housing of the load equipment or to the ground terminal of wall outlets.

As noted earlier, some equipment locations (principally those containing critical computing equipment) have special power conditioning equipment installed. This equipment consists of a "power synthesizer" and a "power distribution unit." Power from the power center is delivered to the synthesizer as three-phase with ground. The grounding conductor terminates to a ground terminal inside the synthesizer. The secondary of the synthesizer has its neutral also connected to this ground terminal. This ground terminal is grounded to the cabinet of the synthesizer and subsequently to the raised floor, building steel, and to the grounding conductor inside a nearby Grounding Station. Conditioned ac power is provided by the synthesizer to the power distribution unit as three-phase with ground. The interconnecting grounding conductor ties the ground terminal in the synthesizer with the ground terminal inside the power distribution unit. The ground terminal in the power distribution unit similarly is tied to the enclosure and subsequently to the raised floor, building steel, and the Grounding Station. From the power distribution unit, single phase power is supplied to the computing equipment. The neutral and the grounding conductor are routed to the load equipment from the power distribution unit. The grounding conductor terminates to the load equipment housing.

Also installed in the NCMC is a tree-configured, isolated "electronic" ground bus network consisting of insulated No. 4/0 conductors in conduit radiating from a Main Area Ground Station located on the first floor of Building 3 to various Building Ground Stations and, in some cases, to subsequent Equipment Ground Stations, as depicted in Figure B-15. Connecting into this tree are the RED and BLACK grounding conductors used by TEMPEST equipment. The Equipment Ground Stations are also used as ground points for terminating "instrument" or "signal" grounding conductors. Early operational experience, however, revealed excessive noise problems with this "electronic" ground network. Consequently, the original connection between the bus bar in the Main Area Ground Station and the Main Ground Post (described earlier) was removed, and rerouted to a connection (to something not determined) in "Manhold No. 1." (This investigation could not determine if this condition still exists.)

Ground and Bonding Evaluation

The interconnected network of grounding conductors run with the phase conductors, the welded building steel, the bonding conductors between buildings, the connections to water pipes, and the external substation grid provides the fault protection grounding network for the NORAD complex.

The earth electrode subsystem for the complex is provided by the substation grounding grid and the interconnected water main outside the mountain. The resistance of the substation grid was measured to be 11.2 ohms in 1984.[15] The resistance to earth of the incoming water pipe was found to be less than 1 ohm. With the grid bonded to this water pipe, the net ground electrode resistance to earth for the entire complex will essentially be that offered by the water pipe. Thus the primary path to earth between the grounding system for the complex will be via the water pipe through the single No. 4/0 cable from the substation grid. In the event of a primary fault to ground in the substation on the incoming 35 kV transmission line, the fault clearance path to earth would be through the 4/0 cable to the water main. This single cable would probably be unable to handle the fault current because of its length and small size. It is recommended that this cable be either augmented with another No. 4/0 or be replaced with a 500 MCM bare copper cable buried directly in the earth.

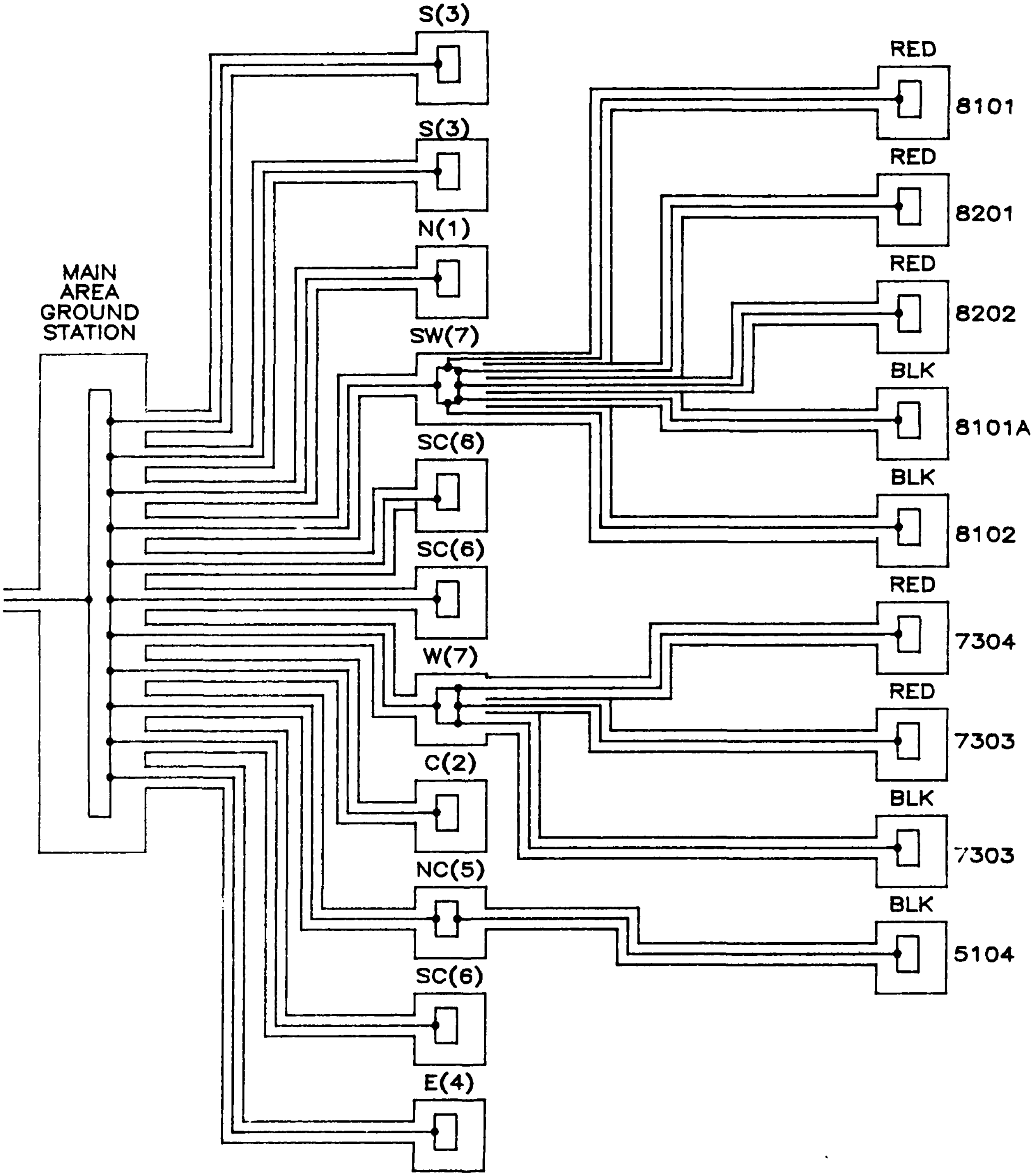


Figure B-15. Configuration of the NCMC "Electronic" Ground Network.

The mountain itself provides protection against a direct lightning strike to the substation and buildings located near the entrance and against direct strikes to the buildings and equipment inside the mountain. The primary threat of lightning-related damage thus will arise from strikes to the 35 kV transmission line feeding the substation. The path to earth for lightning strikes to the transmission line near the substation will be through the 4/0 conductor from the substation grid to the water main. This 4/0 conductor is considered adequate to handle such discharges. The above recommended additional cable between the substation grid and the water main would add an extra measure of margin against lightning discharge currents and the power follow currents accompanying the firing of lightning arresters.

Each of the steel buildings is supported by large coiled springs; thus, some incidental contact likely exists between the metal of the buildings and the adjacent granite of the mountain. The additional ohmic contact between the buildings and the granite is present through electrical contact with (1) utility pipes routed through the tunnels and (2) conduit support frames held in place by rock bolts. (The effective resistance of these multiple contacts is not known.) Such incidental contact with the granite can be expected to provide some degree of dissipation of EMP and lightning energy entering the site via the power conduit and the utility pipes or of the radiated energy which directly penetrates the rock overburden. (The residual threat from penetration of the overburden has been assessed as small.[16])

The exact treatment of the two No. 4/0 grounding conductors run with the 4.16 kV commercial power feeds into the mountain at the point of entrance into the Electrical Bay could not be determined. Therefore, it can only be said how they SHOULD be treated. They SHOULD NOT be allowed to enter the shielded volume of the Electrical Bay as untreated conductors; that is, these grounding conductors either should be filtered along with the phase conductors in the EMP filters, or should be bonded to the case of the EMP filters. The unprotected grounding conductors entering the complex from outside the mountain must be totally enclosed inside EMP-hard conduit from the point of departure from the substation to the point of termination inside the Electrical Bay. Otherwise, these grounding conductors could possibly couple EMP energy into the buildings.

The generators, transformers, power converters, and power conditioners within the complex constitute "separately derived systems."* Separately derived systems are grounded for fault protection and personnel safety similarly to normal ac supply systems. The wye windings of generators and the wye secondaries of transformers are bonded to the fault protection subsystem.

*Article 250-5(d) of the National Electrical Code defines a separately derived system as one whose power is derived from generator, transformer, or converter windings and has no direct electrical connection to supply conductors originating in another system.

In Article 250-26, the National Electrical Code specifies that a bonding jumper sized in accordance with Table 250-94 be used to interconnect the equipment grounding conductors of the derived system to the grounded conductor. Further, this connection may be made at any point between the source and the first disconnecting means for that separately derived source. (Emphasis added.) Confusion can arise between "the first discconnecting means for a separately derived system" and "the building disconnecting means" for normal commercial service. (Notice the use of "building disconnecting means" as opposed to the traditional "main disconnecting means.") Clearly the intent in each situation is (1) to have the grounded conductor (i.e., the neutral or other conductor as defined by Article 250-25) made common with the grounding conductor (i.e., the "green wire") so as to complete the fault return path and (2) to prevent the grounded conductor from contracting the grounding conductor at any point beyond the first service disconnect for that particular ac service. Thus, the interconnecting of the neutral of transformer or generator wye windings to building steel and the interconnection of the netural conductor to the grounding conductor at the first disconnect following the transformer or generator fulfills the requirements of the Code. Beyond this disconnect, no (intentional) connections should be made between the grounded conductor (the neutral) and the safety grounding conductor (the green wire). As a matter of fact, up until single phase loads are encountered, the neutrals are not continued beyond the transformers or the generators. Where single phase loads are served, both the neutral and the grounding conductor are continued to the loads.

Wiring errors frequently result in the neutral and grounding conductors being interchanged on the load side of the disconnecting means. As a result, load currents can return to the service through the fault protection subsystem, i.e., the building ground which includes structure, raceways, conduit, equipment cabinets, room/building shields, etc. With the well bonded fault protection subsystem present in the NORAD Complex, the power frequency voltages are typically low enough such that personnel hazards are not generated. However, stray currents of 20 amperes or more have been measured. Such large currents can produce voltage differentials between various points in the fault protection subsystem sufficient to cause data errors and other noise interference problems in interconnected electronic equipment. Even where massive, as it is in the NORAD complex, the fault protection subsystem contains sufficient inductance to allow short duration switching transients and power line disturbances to generate large amplitude voltage differentials between equipment grounded to the fault protection subsystem. These voltage spikes, in addition to causing data errors, can damage sensitive solid state devices inside the grounded equipment. Elimination of all improper interconnections between neutrals and grounding conductors is strongly recommended even where power conditioners are installed. There are perhaps many situations where correction of such wiring errors coupled with the use of appropriate transient suppressors or filters would remove the need for expensive power conditioners.

However, in a facility of the complexity and extensiveness of the NCMC, voltage differentials are always likely to be present between various equipment locations. Filter capacitors, other power line conditioning components, and even improperly designed electronic equipment will be responsible for a certain quantity of stray current in the fault protection subsystem. Consequently, electronic equipment at various locations within the facility and grounded to different points on the subsystem will experience voltage differentials between them. If such equipment must interconnect through signal, data, or control lines, these voltage differentials pose a threat of disruption or damage to circuits and components on both ends of the line. Therefore, strong consideration should be given to using appropriate signal isolation devices, such as common mode chokes, isolation transformers, unbalanced-to-balanced baluns, opto-isolators, or fiber optic links, to counter this common-mode noise interference threat wherever possible.

Where the equipment which must communicate are co-located, as in a central computer complex, the common ground reference provided by an integrally bonded raised floor should be adequate to minimize voltage differentials to noninterfering levels. The added precaution of providing well conditioned power, grounded in the manner described in the previous section, has proven effective in essentially eliminating power system upset and damage to the sensitive equipment. Even these measures, however, will not remove the threat of interference between those systems located remotely from one another which also must communicate with each other. For these situations, appropriate signal isolation measures must also be employed on every interconnecting link.

As described, the "electronic ground bus network" in the Complex consists of Equipment Ground Stations interconnected with insulated No. 4/0 copper cables in conduit to Building Ground Stations and finally to the Main Area Ground Station on the first floor of Building 3. The termination of this network from the Main Area Ground Station to other than the fault protection subsystem creates the likelihood that the electronic ground bus network will be at a different reference potential than the building ground. Thus, equipment or circuits referenced to this electronic ground bus network will be at a different potential than the safety ground. Any such referenced equipment or circuit which must interface with another which is grounded to the fault protection subsystem, i.e., building ground, will encounter possibly serious common-mode interference problems. As a minimum, the originally intended connection between the Main Area Ground Station in Building 3 and the Main Station Ground Post also in Building 3 should be reinstalled.

WWMCCSDPCE BUILDING

For the fourth site assessment, the Concept Submittal* drawings for the WWMCCSDPCE Building in Baumholder, Germany were examined. (The available information did not permit a functional description of the facility to be prepared.)

Facility Description

As planned, the WWMCCSDPCE Building is a split level structure with a ground-floor administrative area and a basement computer and support area. As shown in Figure B-16, the ground floor consists of a 17 ft. by 40 ft. administrative office area plus a workshop. At the end of the building and adjacent to the workshop is an approximate 9 ft. by 35 ft. covered loading dock. In the basement underneath the administrative offices is located an RF shielded room for computers and for media storage. This shielded room contains approximately 390 square feet. Outside the shielded room, but still underground, are work areas along with the support facilities of electrical, CBR filter, UPS, battery, engine generator, and chiller rooms.

Shield Penetrations

Typical wall sections showing shield construction details are shown in Figure B-17. Several penetrations into shielded rooms are required. In addition to doors for personnel and equipment access, there are power line penetrations along with signal penetrations for data, telephone, fire alarms, and security monitors. In addition, there are HVAC ducts, chilled water lines for computer room air conditioners, halon exhaust vents, and drains.

Figure B-18 illustrates the planned methods for handling air duct and pipe penetrations. Each is acceptable. However, at the interface between the honeycomb in the air duct and the room shield, a soldered or welded bond is preferable to the indicated bolted connection. If a bolted connection must be used because of access limitations, EMI gasketing should be used between the mating surfaces. At the pipe penetration, the steel penetration collar should be welded completely around its periphery to the shield. Peripheral welding of the pipe to the penetration collar is correctly indicated.

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*Representing only 35 percent of the final plans, the drawings do not cover all grounding and bonding details of concern in the final facility. Consequently, the absence of comments on a particular facility element does not necessarily mean that the element conforms to the recommendations of the Integrated Practices Report, only that it is not included in the available drawings. For example, significant elements of shield construction such as seam bonding, mounting of shielded doors, and filter installation for power and signal conductors could not be evaluated.

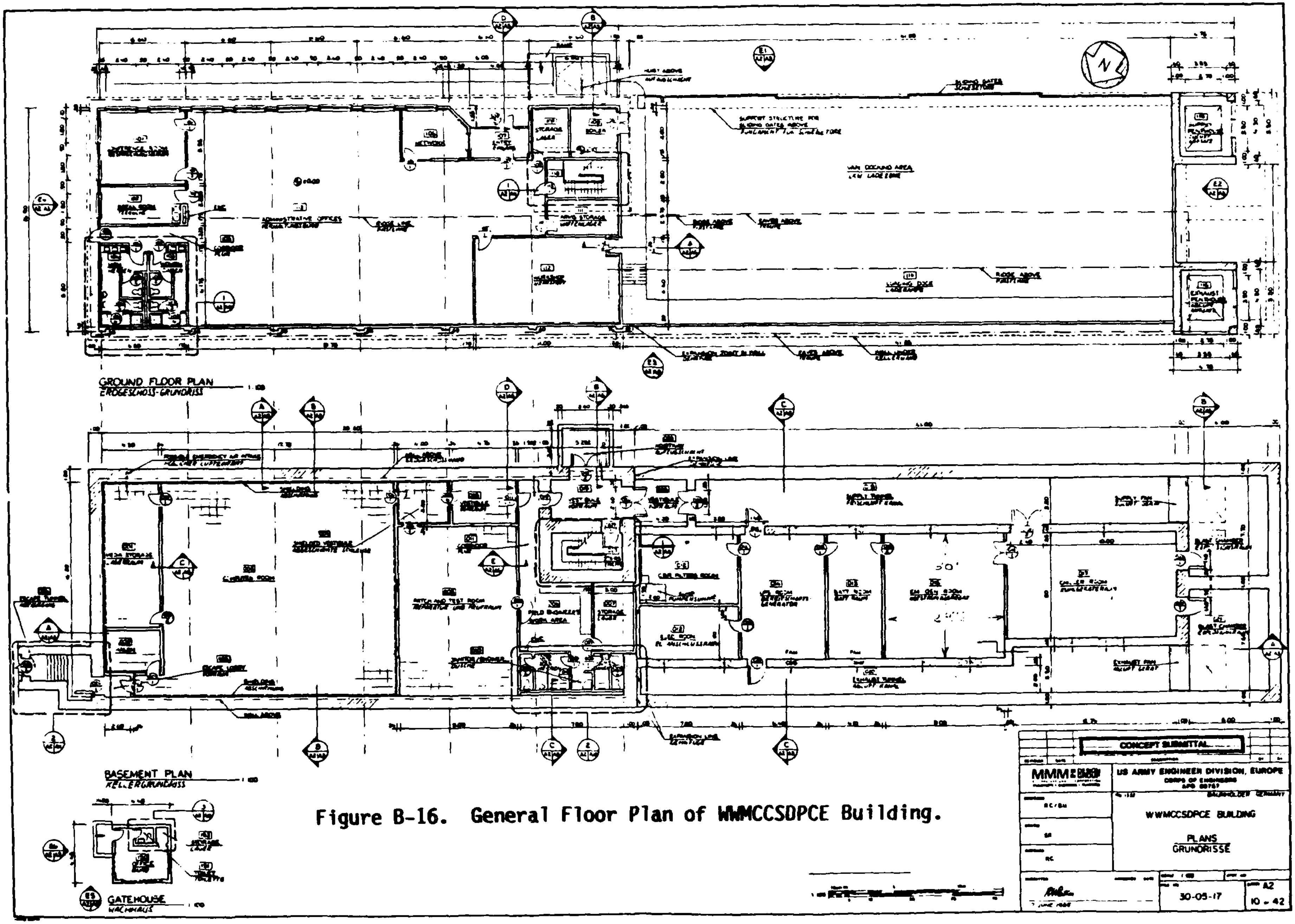


Figure B-16. General Floor Plan of WWMCCSDPCE Building.

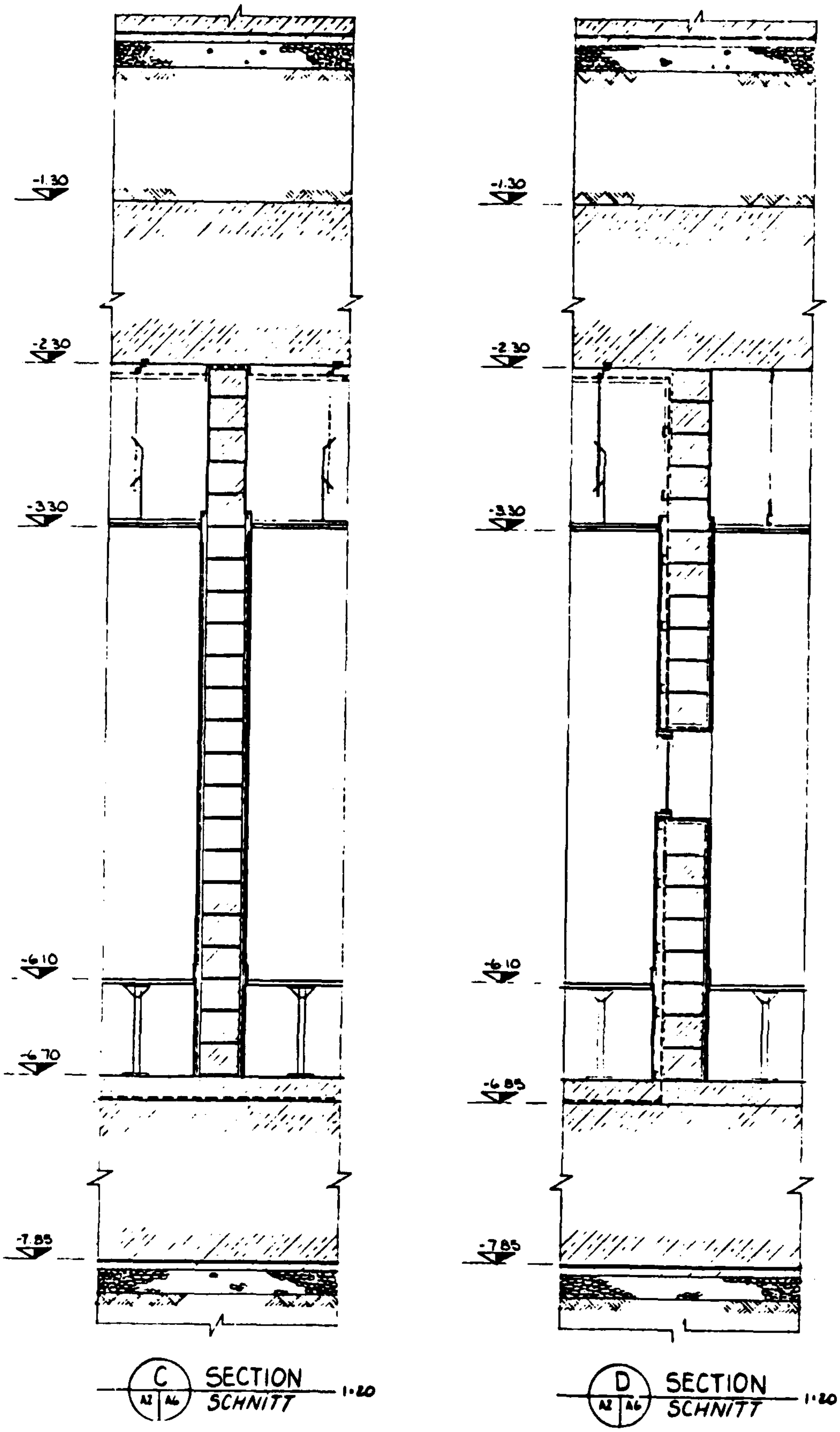
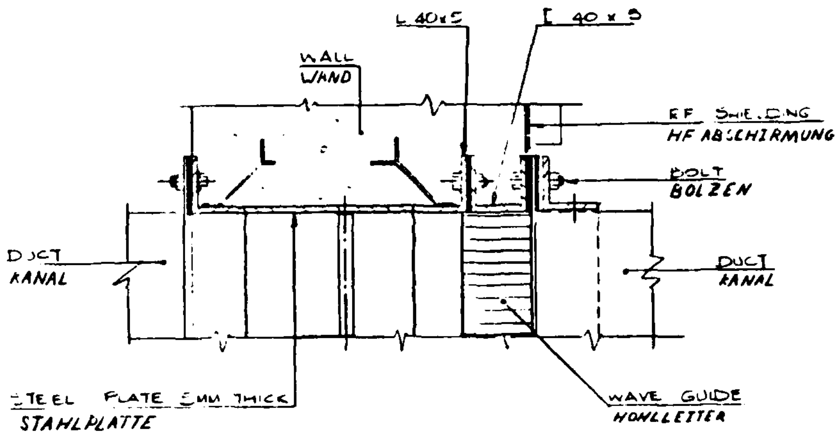


Figure B-17. Typical Planned Shield Wall Construction.



1 WAVE GUIDE DUCT PENETRATION NTS
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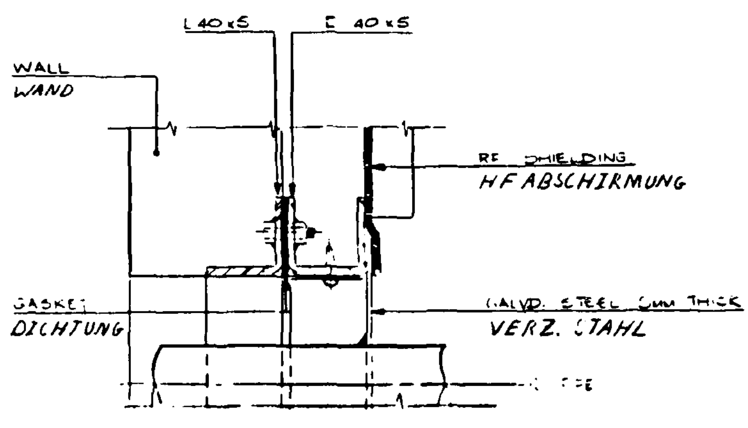

4 WAVE GUIDE PIPE PENETRATION NTS

Figure B-18. Planned Treatments of Shield Penetrations.

Grounding and Lightning Protection

Figure B-19 shows the earth electrode conductor as a steel strip encircling the building and (presumably) buried. The steel strip forms a rectangle with dimensions of 281 ft. by 61 ft. Assuming that the strip is flat, 0.5 inches wide, and buried 1 foot deep and that the soil resistivity is 50,000 ohm-centimeters, the calculated resistance of the earth electrode system using the equation for a buried straight wire from Table 2-5 of MIL-HDBK-419 is 7 ohms, which is considered adequate for the facility. Although not needed in terms of resistance, supplemental ground rods should be installed to stabilize the resistance to earth during periods of low rainfall or during extreme cold conditions which could cause the soil to freeze to the depth of the buried strip. As a minimum, a 10-foot rod should be placed at the termination point of each lightning down conductors.

Steel is not a good material for the earth electrode strip. Because of corrosion, the expected lifetime of the steel will be much less than that of facility. Subsequent replacement will likely be difficult and expensive. Further, determination of the need for replacement will require excavation for visual inspection because electrical measurements performed after construction is complete can not be relied upon to reveal degradation of the earth electrode system. Either copper or copper-clad steel should be used, as recommended by MIL-HDBK-419 and prescribed by MIL-STD-188/124A.

The lightning protection network is laid out appropriately for the profile of the building. As determined from Figure B-19, the planned spacing between air terminals is approximately 50 feet. (The height of the air terminals was not given.) MIL-HDBK-419 suggests a spacing of 25 feet or less for air terminals less than 2 feet in height. Applying the analyses of Paragraph 1.3.2.1.2, Volume II of MIL-HDBK-419, however reveals that spacings of up to 50 feet are acceptable for 3-foot high air terminals. If air terminals less than 2 feet in height are used, the spacing should be less (no more than 25 feet) than that shown on the drawing. If the indicated spacing is used, however, the air terminals should be specified to be 3 feet in height. The number and routing of down conductors is appropriate for the air terminals as placed.

Two electrical grounding conductors are shown. One of these provides the electrical system ground connection with the earth electrode strip. Since this grounding conductor does not have to penetrate the shield, it is acceptable as shown. The other grounding conductor is indicated as providing an earth ground for the RFI filters located at the power entrance into the shielded room. For the filters to be effective they must be well bonded to the shielded room wall at the penetration point. Thus in terms of filter performance, this grounding conductor contributes nothing. The safety grounding conductor for the shielded room power conductors should be routed with the conductors themselves and should originate at the transformer neutral or at the above grounding conductor in the breaker in the electrical room, as applicable. Instead of routing the second grounding conductor to the RFI filters, it should rather be used to bond the room shield to the buried ground ring. Four of these connections -- one at each of the down conductors positioned near the shielded room -- should be installed.

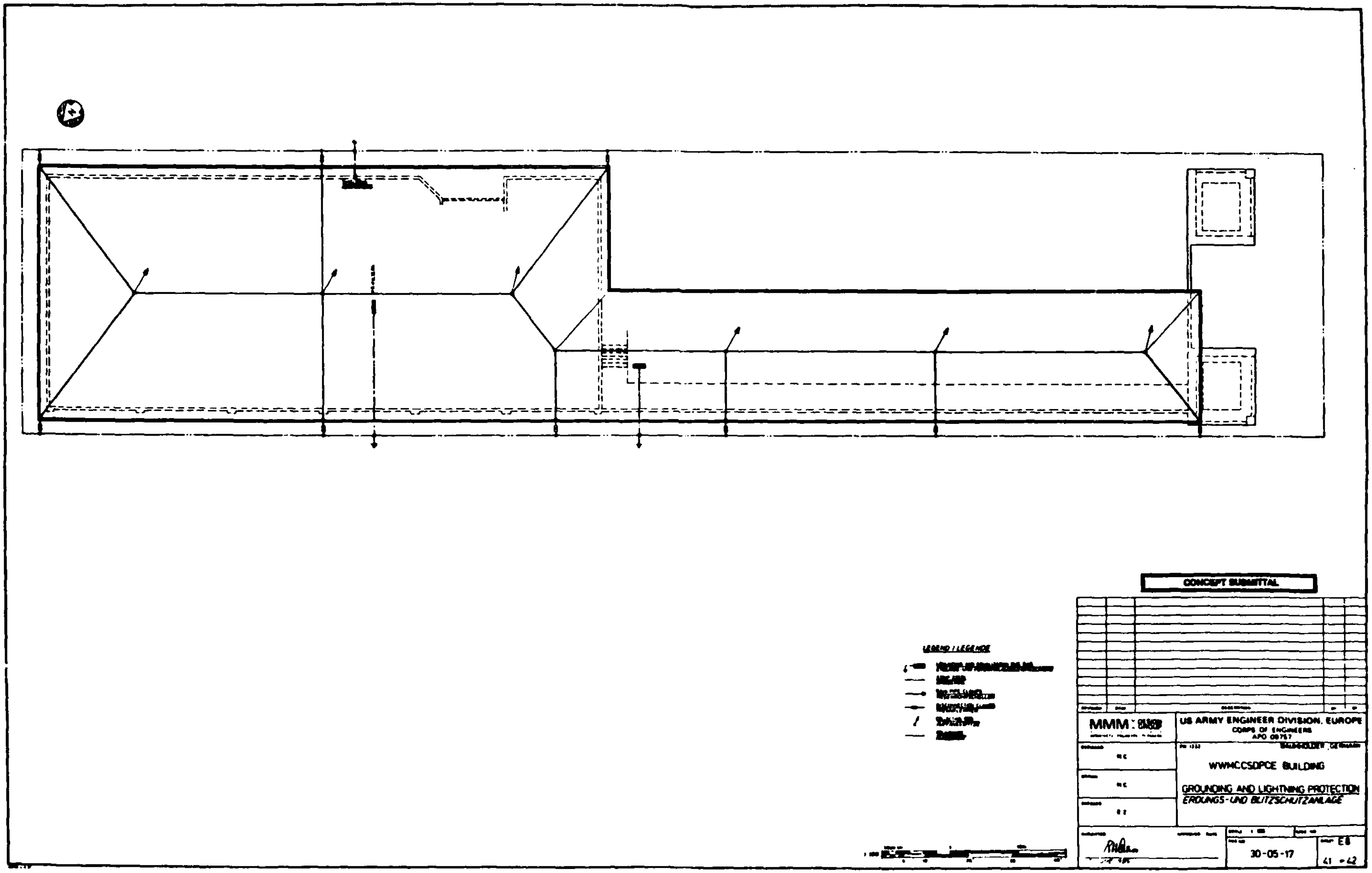

Figure B-19. Planned Earth Electrode and Lightning Protection Subsystems.

CONCLUSIONS AND RECOMMENDATIONS

The objective of this survey and analysis was to examine the grounding and bonding networks of four representative C^3I installations and compare the practices at each site with the recommendations set forth in the Integrated Practices Report, also prepared under this contract. The sites visited were: PAVE PAWS (East), Cape Cod, MA; Buckley Satellite Readout Stations, Aurora, CO; and the NORAD Cheyenne Mountain Complex, Colorado Springs, CO. The fourth set of practices were those reflected in Concept Submittal drawings for a planned WWMCCSDPCE Building, Baumholder, West Germany. The information on which the analyses are based was obtained from facility drawings, reports, and on-site observations and discussions with site personnel.

The general conclusions resulting from this study are as follows:

1. According to the drawings, the electrical safety grounds conform to the practices of the National Electrical Code and MIL-HDBK-419. They are appropriately configured for separately derived systems, of which the sites have many. However, these facilities, and any other containing sensitive electronic equipment, should have all single phase circuits inspected closely to locate and correct neutral/ground wire interchanges. These wiring errors occur frequently and can significantly contribute to "ground system noise" problems, particularly in computers and other data processing equipment. This straightforward step could result in a reduction in ground noise interference sufficient to remove the need for expensive power conditioners.

2. Signal grounding networks are inconsistently configured among the three facilities.

   (1) The PAVE PAWS installation, being the newest of the three, most closely conforms to the practices of MIL-HDBK-419. As presently installed, the signal reference grid in the computer room is redundant to the ground paths provided by the shield itself. Although the grid is laid on plywood, it is bonded to the steel support columns which in turn are welded to the shielded room floor and ceiling. Effectively, then the signal grounding inside the computer room is multiple-point, which in itself is not bad.

   (2) At the Buckley Satellite Receiving Station, the RED/BLACK grounding networks topologically conform to single point trees. Specific steps have been taken to insert isolators in conduits at equipment cabinets and between equipment cabinets and the raised floors. However signal cable shields terminate to the cabinets directly, which they must for proper operation. Further, electrical ground wires connect to the cabinets directly, which is required for electrical safety. Thus, it is reasonably projected that the various equipment cabinets are electrically bonded through multiple paths to the

structure. System performance and signal security do not appear to be adversely affected and so no corrective action is considered necessary. In fact, future upgrades should consider installing a multiple point ground conforming to MIL-HDBK-419.

(3) The signal grounding network in the NCMC as configured does not work as intended as evidenced by the severe noise problems which have been experienced. The noise problems encountered early in the life of the facility were likely the collective result of electrical wiring errors (white/green wire interchanges or inappropriate electronic equipment wiring), large unbalances in the loading between the three phases of the power system, or circulating currents produced by power line filters. As part of the effort to counter the noise problems, the electronic ground network was disconnected from the power/safety ground and building steel. This network-to-building/site ground connection should be re-established. In addition, a program to comprehensively inspect the single phase wiring in the facility, to stress equal load distributions between phases of the power system, and to minimize filter leakage currents should be implemented. Such efforts could lessen the future need for power conditioners.

3. The lightning protection subsystems at the sites exhibit varying degrees of conformance with the recommendations of the Integrated Practices Report. The lightning protection subsystem at the PAVE PAWS site closely conforms to MIL-HDBK-419. The most recently recommended additions will bring it into full compliance. At the NCMC, the grounding conductor between the new power substation grid and the city water main is considered too small and should be supplemented or replaced with another cable. Previous studies have concluded that the threat of lightning damage to equipment internal to the site is low. At Buckley, the lightning down conductors should be bonded to building shields as described in MIL-HDBK-419. The lack of a direct connection between the SEGP and the building shield is considered a deficiency.

4. The earth electrode systems likewise exhibit varying degrees of conformity with the recommendations of the Integrated Practices Report. The earth electrode subsystem at the PAVE PAWS site offers an excellent example of a properly configured installation. Its failure to meet the 10 ohms resistance requirement is not considered a serious deficiency. The relatively low value of its resistance and its interconnected and distributed layout are expected to produce fault and lightning capabilities sufficient for the site.

   The Buckley earth electrode subsystem should be augmented with the installation of a buried conductor/rod combination around at least a portion of the Technical Building and around the antenna towers. Lightning down conductors and building structures/shields should be interconnected with this added subsystem.

Except for the commercial substation grid, an earth electrode subsystem conforming to MIL-HDBK-419 does not exist in the NCMC. Some incidental contact with earth inside the mountain is present via the rock bolts. The lack of a well-defined contact with earth is not considered a serious problem because (1) electrical fault protection is comprehensively implemented and (2) the threat from a direct lightning stroke is minimal. (If the need every arises, a low resistance contact with earth inside the mountain possibly could be established by extending existing piping into fuel and water reservoirs, or by removing or bypassing insulator junctions if they exist.)

The earth electrode subsystem design for the WWMCCSDPCE Building is deficient in the choice of materials and the lack of ground rods. Additional interconnections with structural steel should be made.

The differences between the signal grounding practices at the sites are attributable to the fact that the facilities were designed and constructed at different times and thus reflect the prevailing concepts of signal grounding existing at the time of the design. Overall, signal grounding is not as uniformly controlled and coordinated as power system grounding. The difference is presumed to reflect that signal grounding is typically the concern and responsibility of individual users while power grounding is the responsibility of the site or base engineer. Since the equipment mixes will be unique to reflect the different mission responsibilities of each facility, it might be argued that the signal grounding networks must be tailored for that specific facility. However, it must recognized that signal grounding is not separable from power grounding and they should be jointly designed, installed and maintained as an overall facility element rather than as an individual subsystem (as in computer, communications, or security) components. In addition, the user must recognize that the performance of the signal grounding network is impacted by the correctness of the facility electrical wiring, by the facility electrical load distribution, by the internal wiring practices of electronic equipment, and by the correct sizing and use of power line filters. Thus a general recomendation is that all grounding, to include signal grounding, be made the responsibility and be placed under the control of one office or agency at the facility so as to establish and maintain long term coordination and uniformity. Further, greater emphasis needs to be placed on sorting and keeping current all drawings related to grounding. At least one correct and up-to-date copy of all grounding related drawings should be maintained at one central location at each site.

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