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AN INVESTIGATION OF THE RELATIONSHIP BETWEEN EMP GROUNDING PRACTICES AND MIL-STD-188-124

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Georgia Institute of Technology
Engineering Experiment Station
Atlanta, Georgia 30332

28 February 1979

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This program was performed to assist and advise the Defense Nuclear Agency (DNA) in identifying facility grounding, bonding, and shielding measures appropriate for electromagnetic pulse (EMP) protection and for electromagnetic interference (EMI) control, i.e., electromagnetic compatibility (EMC). Presently, the specific philosophy and requirements for achieving EMP protection are distributed throughout several documents. From a review of this EMP literature, a consolidated summary of the EMP grounding and shielding

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20. ABSTRACT (Continued)

philosophy, requirements, and rationale was developed. Since the requirements for achieving power safety, lightning protection, and generalized EMC have recently been set forth in MIL-STD-188-124, the rationale for its specific requirements which are different from the EMP requirements are also presented. Based on this summary of the EMP requirements and on the rationale for the Standard's requirements, the areas in which differences exist were defined. The specific EMC and EMP requirements in these difference areas are presented. The relationships between the two sets of requirements in each difference area and the reasons for the differences were investigated and are discussed in detail. As a result of these investigations, both specific changes in MIL-STD-188-124 and potential approaches are recommended to resolve the differences; for the differences which are not as easily resolved, specific further investigations are recommended.

PREFACE

This report presents the results of a comparative analysis of the grounding requirements set forth by MIL-STD-188-124 with the grounding requirements appropriate for EMP hardened facilities. This analysis was performed at the request of the Defense Nuclear Agency (DNA) under RDT&E RMSS Code B360 78464 099QAXCA11004 H2590D as Contract DNA001-78-C-0390. The program was monitored by Capt. M. A. King of DNA. The overall goal of DNA in the support of this investigative effort is to minimize the cost of implementing EMP protective measures in structures and facilities conforming to MIL-STD-188-124. A modification of the requirements of the Standard is sought to achieve this goal without voiding the intent of the Standard and without significantly increasing its cost of implementation.

The work described in this report was performed by personnel of the Electronics Technology Laboratory (ETL) of the Georgia Tech Engineering Experiment Station. The described work was directed by Mr. J. A. Woody, Project Director, under the general supervision of Mr. D. W. Robertson, Director, Electronics Technology Laboratory. Technical supervision was provided by Mr. H. W. Denny, Head of the Electromagnetic Compatibility Group. The report was coauthored by Mr. Woody and Mr. Denny.

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I. INTRODUCTION

MIL-STD-188-124, "Grounding, Bonding and Shielding for Common Long Haul/Tactical Communication Systems," was issued 14 June 1978. The stated purpose of this standard is "to ensure the optimum performance of ground-based telecommunications C-E equipment installations by reducing noise and by providing adequate protection against power system faults and lightning strikes.... The requirements of (the) standard are intended to reduce noise and electromagnetic interference.... It is also intended to provide for the protection of personnel, equipment, buildings and structures against the hazards posed by electrical power faults and lightning strikes." It is to "be used in the design and engineering of new ground-based military communication systems, subsystems, and equipment installations. This includes radio, satellite ground terminals, telephone central offices, microwave and data communications systems, as well as C-E transportables."

The achievement of electromagnetic pulse (EMP) protection is not a stated objective of MIL-STD-188-124. Note, however, that many of the facilities covered by the standard can reasonably be expected to have EMP protection requirements imposed either during initial construction or at some later point in the lifetime of the facility (or structure). In so far as possible, standardized practices applicable to such facilities and installations potentially requiring EMP hardening should reflect or accommodate EMP practices.

Initially, some of the requirements set forth in MIL-STD-188-124 appear to be at variance with certain measures considered as needed for EMP protection. Application of MIL-STD-188-124 without regard for EMP protection may create a situation in which subsequent EMP requirements are very expensive and difficult to integrate. The purpose of this investigation was to identify those grounding and shielding measures in MIL-STD-188-124 which might impact the incorporation of EMP hardening into a facility. The measures are identified, the differences are discussed, and recommendations of appropriate courses of action are set forth.

II. HISTORICAL PERSPECTIVE

Until the last few years, a somewhat paradoxical situation existed relative to the incorporation of grounding measures into the design and construction of facilities housing electronics complexes. Although certain measures were known to be quite effective in enhancing electromagnetic compatibility, minimizing shock hazards, and protecting against lightning, they were seldom given adequate attention during the design and construction phases except for those safety requirements imposed by local electrical codes. Various remedial steps were taken after operational difficulties or personnel hazards were noted. This approach was never entirely satisfactory and became even less permissible as facilities and equipments grew to be more complex and costly.

At best, the role of grounding in EMI control has tended to be rather poorly defined. As a result, various sets of frequently conflicting rules grew up around grounding. Each subdiscipline -- power, lightning protection, data processing, RF -- possessed its own set of rules. Because of the varied situations encountered in practice, the application of a given set of rules often produced unsatisfactory results. For example, the rules followed for power grounding did not fully accommodate lightning protection needs nor could they be applied to the effective grounding of RF systems. So long as each subdiscipline was handling the grounding for its own system, each had a way of solving its own problems. However, when these various functions became integrated into a complex facility the various approaches to grounding proved confusing or were in direct conflict.

Evolving along independent lines and faced with a more concisely defined environmental threat, the EMP protection discipline has defined a relatively cohesive approach to grounding [1]. The EMP threat is well defined--it is characterized by a very high amplitude ($\approx$ 50 kV/m), short duration ($<$ 1 μsec) pulse whose energy is primarily contained at frequencies below 100 MHz [2]. (The question facing the EMP designer is not whether the threat exists or what its nature is, but rather if the facility is to be protected against the threat. In contrast, the designer of a facility containing equipments which may suffer (or cause) EMI may not know if an EMI threat exists or, if it does, what its nature is.) Based on this well defined threat, the EMP grounding philosophy with precise principles was developed. (These principles are reviewed in the next Section.) Unfortunately, some of these protection principles are different from those for lightning protection or EMI.

The widespread growth of solid state equipments, particularly digital types, has led to increased system vulnerability to environmental electromagnetic (EM) influences. The potentially most disruptive and damaging of these influences are internal stray power frequency currents and the external high power RF radiations, lightning discharges, and EMP. These threats have intensified the need for a unified approach to effective grounding.

One of the first directed studies of the impact of a facility's grounding networks on EM environmental effects in equipments was conducted for the Navy in 1960 [3]. A NASA effort in 1961 demonstrated the benefits of integrated grounding in the reduction of the overall noise level in a facility [4]. The Air Force sponsored in 1964 the development of grounding practices for instrumentation systems which resulted in a set of defined practices for noise minimization [5]. Another NASA study in 1969 [6] identified the grounding requirements needed in space vehicle launch facilities. The basic goals and principles of EMP grounding were set forth in 1971 in handbook format [1]. In 1972, results of an engineering study of the grounding aspects of a facility hardened against EMP were reported [7]. All of these efforts along with several others were critically reviewed [8] under a comprehensive program which began in 1972 under Federal Aviation Administration (FAA) sponsorship with added support from the Air Force Communications Service (AFSC). Evolving from this program were a set of proposed standards (one for facilities and one for equipments) [9], [10] and a three-volume handbook [11] covering not only grounding but also bonding and shielding as well. The two standards were adapted into MIL-STD-188-124 and the handbook is being adapted into MIL-HDBK-419 (Proposed).

The original standards* were formulated from the extensive review of grounding state-of-the-art [8], from on-site inspections of a number of FAA, NASA, and Air Force facilities, and from extensive discussions with engineering, operational, and procurement personnel. The primary objectives reflected in the standards were to formulate controllable design and installation practices that (1) achieve electrical safety, (2) afford improved protection against lightning, and (3) lessen the incidence of unintentional interactions, i.e., EMI, between the elements of an electronics complex and between the local RF environment and elements of the complex. The grounding elements of the National Electrical Code (NEC) [12] are reflected in the standards' requirements and the essential features of building and personnel protection against lightning [13], [14] are also incorporated.

The purpose of this FAA and AFCS sponsored program was to analyze the grounding needs of an electronics complex and formulate a coordinated set of rules and practices which would satisfactorily meet the requirements for power safety, lightning protection, and generalized EMI control. EMP protection was specifically exempted from consideration at that time. (It was planned to integrate EMP requirements into the standards at a later date.) The immediate requirement, however, was to meet the protection and EMI-related needs.

Many of the facilities to which MIL-STD-188-124 is applicable may also require EMP hardening. Therefore, to avoid conflicts of application, the EMP requirements and the MIL-STD-188-124 requirements should be compatible in so far as possible. The next two sections review and summarize the EMP and MIL-STD-188-124 requirements, with the goal of clarifying and comparing their objectives and methodologies. The fifth

*The basic overall philosophy behind the standards and the rationale for the more significant requirements are contained in Reference 8.

section examines specific areas of conflict and reviews possible avenues for resolution. The last section sets forth the conclusions and recommendations for further actions.

III. BASIS AND FEATURES OF EMP GROUNDING

The general grounding concepts supporting a cohesive approach to EMP protection are stated as rather broad principles in Reference 1. Specific techniques of implementation are contained in a variety of other sources. This summary of the EMP approach to grounding is based upon a review of more than 60 different articles and documents.

3.1 THE ENVIRONMENTAL PERSPECTIVE

EMP presents a harsh electromagnetic environment with lightning being the closest comparable source. The effects of EMP can cover a large geographical area--these effects are not localized like lightning. Thus, EMP can cause upset, or even damage, over broad areas which do not necessarily experience blast effects. The EMP field exhibits a much higher amplitude, faster rise time, and shorter duration than the field developed by a lightning discharge. The higher rates of change can cause more severe voltage breakdown problems ($v = Ldi/dt$) and the higher intensity and shorter duration presents a more severe hardening problem than exists for lightning.

Frequently, mission requirements are such that the system must remain operational during the brief exposure to the EMP event, i.e., the operation of the system can not wait until the environment passes. The need to remain operational is particularly true in the case of multiple high altitude detonations. (Generally, the interruptions (not damage) caused by lightning can be ignored.) The effects of an EMP event can be much more long lasting than the duration of the pulse would indicate. Because of cascading effects, one EMP event can interrupt service portions of a large system for as long as 20 to 40 minutes [15].

Since the EMP environment is significantly different from any other man-made or natural EM environment, the protection measures that are routinely incorporated for protection from non-EMP environments are not adequate. For example, the structures that are intended to house equipments in non-EMP environments are typically not designed or constructed with an aim toward providing extensive EM shielding. Traditionally, EMI shielding is provided on an as-needed basis for "quick fixes" or "retro-fixes" at the system or equipment level. This approach may result in unnecessary difficulties in time and expense when EMP protection for the facility is required to be installed. Under some circumstances, the incorporation of EMP protection may require that reconfiguration or rework of major portions of the shields and ground networks of the facility be done, which may be impossible in an operating facility. Therefore, a different concept, the zonal approach, of facility/system/equipment hardening has been formulated for EMP protection. In essence, the EMP approach to grounding is to accommodate, and not compromise, zonal hardening. Thus, EMP grounding must first be examined from the perspective of zonal hardening.

3.2 ZONAL HARDENING

The EMP approach [16], [17], [18] to facility hardening seeks to establish environmental zones defined as shown in Figure 1. The shielding characteristics (effectiveness) of each zonal boundary determines the degree of reduction of the environment from the lower ordered zones to the higher ordered ones. None of the boundaries are assumed to be a perfect shield, thus each one provides only partial suppression to the EM environments external to it. Even though any particular boundary may be far from perfect, use of this approach to hardening simplifies configuration control and installation of shields in existing facilities. The use of the term zonal boundary rather than a shield removes the implication that each boundary must exhibit a high degree of shielding effectiveness.

An integrated approach to shielding and grounding based upon this zonal concept is illustrated in Figure 2. In this approach, simplicity and uniformity of application are achieved by requiring that each zonal boundary be treated the same regardless of whether it is a good or poor

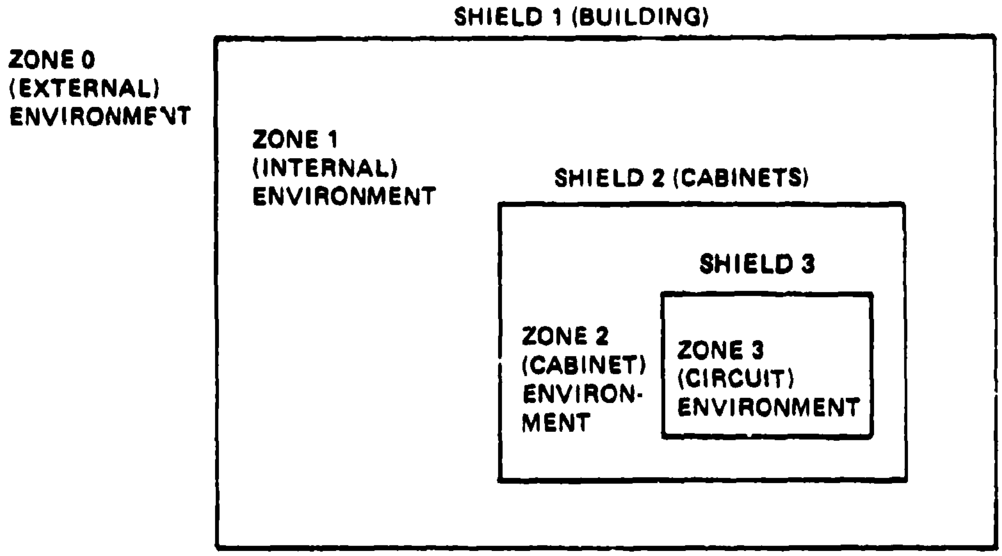


Figure 1. EMP Environmental Zones.

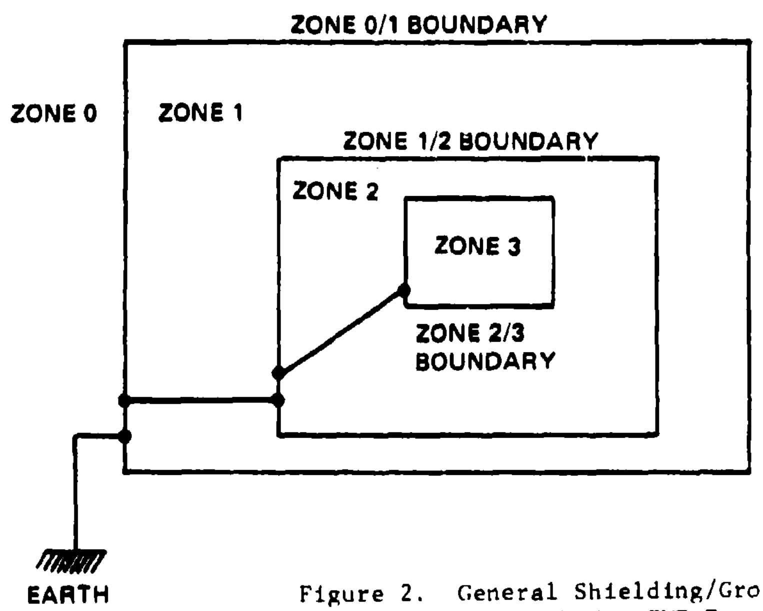


Figure 2. General Shielding/Grounding Approach for EMP Protection.

shield. (The zonal boundaries are used to control internal potential differences of external origin while grounding is used primarily to control internal potential differences of internal origin.)

To limit damaging potentials within a given zone, all metal parts within a zone, including the outer surface of the next higher order zonal boundary, are to be grounded to the inner surface of the zonal boundary with a single ground conductor. The ground system in a given zone is to maintain a single point configuration to minimize loops and control the shield/ground system topology. Ground wires must not penetrate zonal boundaries so that the shielding effectiveness is not compromised. If local codes require ground wires to penetrate zonal boundaries, they must be treated as any other penetration, i.e., with limiters, filters, or other protective measures.

This integrated approach to shielding and grounding is not expected to degrade the EMC properties of a facility and may even enhance them. It is expected to definitely simplify the inclusion of EMP protection into the facility, if needed, at a later date.

3.3 PARTICULAR REQUIREMENTS

For this approach to shielding and grounding, some of the practices in specific areas are different from those reflected in MIL-STD-188-124. The general areas of differences include:

- Exposed conductors
- Ground network configurations
- Frequency criteria
- Signal interfaces
- Shield seams

The first two on this list exert the most significant impact on facility and equipment standards. They are thus explored in some detail here. The remaining three will be discussed in Section V as they relate to specific paragraphs of MIL-STD-188-124.

3.3.1 Exposed Conductors

When electrically long conductors are exposed to EMP fields, they act as effective collectors of energy. If these conductors interface with or penetrate zonal boundaries, they can transfer the collected energy to the zonal boundary or into the next zone.

The typical external conductors are power cables, communication cables, antenna towers, antenna feed cables and waveguides, ground conductors, earth electrode conductors, utility pipes, etc. Note that the majority of these types of conductors are also found in all of the facility zones. Thus, the approach to handling such conductors should be uniform for each zone even though the need for effective hardening becomes more critical in the lowest numbered zones, i.e., as the intensity of the environment increases.

The external conductors should be routed and installed in a manner that does not appreciably extend the effective electrical size of the facility. To minimize the EMP energy collected by such conductors, physical lengths should be kept as small as possible. For example, the earth electrode subsystem should be kept as small as possible to minimize the coupling of EMP energy to the facility [16]. Preferably, it should be installed underneath the facility so that it does not appreciably extend the electrical size of the facility.

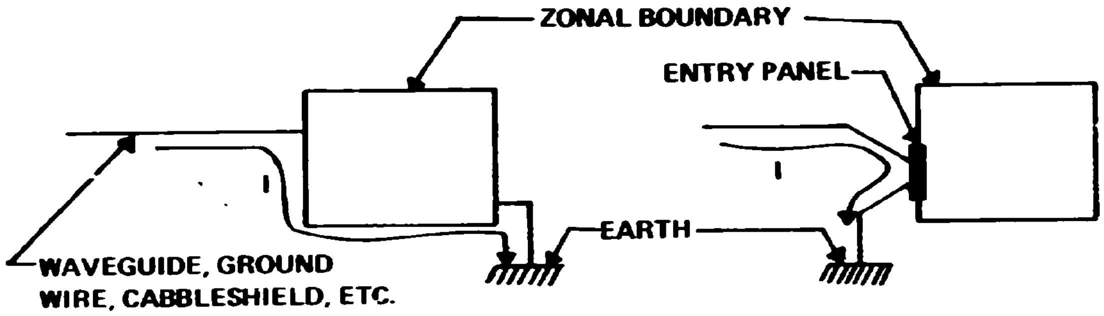
A counter example of an exposed network of conductors whose electrical size cannot be reduced is an antenna tower. For this type structure, the earth electrode subsystem is recommended to be separated from the main facility ground system [16]. This separation is intended to minimize the conduction of the EMP energy collected by the tower into the facility earth electrode subsystem and, thus, lessen the likelihood of coupling of the energy into the facility.

The second area of specific concern to EMP hardening is the treatment of the interfaces between such external conductors and zonal boundaries. Such interfaces include both connections to and penetrations through zonal boundaries. The EMP recommendations [1] are that these interfaces be appropriately treated so as not to degrade the shielding effectiveness of a zonal boundary in such a way that would allow unnecessary EMP energy to penetrate into a "protected" zone. The EMP approach [17] is to divert collected currents away from the zonal boundary.

If the boundary is a metallic shield, then ground conductors, waveguides, cable shields, etc. should be bonded to the outer surface of the shield and not allowed to penetrate the shield so that they do not conduct the EMP energy into the next zone. If the conductors are signal or power conductors which must penetrate the shield, then appropriate limiters and filters are to be used. Water, sewage, and other utility pipes can be decoupled from a zonal boundary with a 5-meter length of nonconducting pipe inserted near the boundary. A spacing of at least 5 meters [16] should be provided between the metal part of such interrupted utility pipes and other conductors that enter the zonal boundary to minimize coupling.

Large currents induced in penetrating conductors* by EMP and, thus, flowing across large sections of a zonal boundary can diffuse through the boundary to create internal fields, even if the boundary is a good shield. To minimize the area over which these currents flow, the use of a single entry panel is recommended [16], [17]. This entry panel is a small controlled area at which all penetrating conductors are collected. Figure 3 illustrates the single entry panel concept If the EMP-produced current is confined to the immediate vicinity of the entry panel, then little of the current flows across the remainder of the boundary to penetrate the shield or excite flaws and openings such as windows, doors, seams, etc. This reasoning is particularly valid for good (i.e., solid metal) shields; however, the same approach is used for less effective shields, such as structural steel networks, in order to maintain uniform treatment for all zonal boundaries regardless of their particular shielding effectiveness properties.

*"Penetrating conductors" as used here refers to all signal lines, power lines, control lines, ground wires, waveguides, cable shields, utility pipes, etc. that must enter or be connected to a zonal boundary.



a. ZONAL BOUNDARY WITHOUT SINGLE ENTRY PANEL

b. ZONAL BOUNDARY WITH SINGLE ENTRY PANEL

Figure 3. Current Path on Zonal Boundaries.

Additional reasons for requiring a single entry panel at each zonal boundary are to aid in controlling zonal boundaries and to simplify the installation or upgrading of shields at zonal boundaries. If conductors of all types are permitted to randomly cross zonal boundaries, then even limited shielding effectiveness at a boundary can be negated. Further if a shield is to be installed or upgraded at a zonal boundary during retrofitting operations, random boundary crossings can make the retrofit very expensive and very difficult to implement. For this reason, the concept of a single entry panel is extended even to zonal boundaries that may have low shielding effectiveness.

3.3.2 Ground Network Configurations

Within each zone, the grounding systems (for signals and safety) should be implemented in such a manner that they perform their intended function while not seriously degrading the EMP shielding effectiveness of any of the zonal boundaries. Also, the ground systems should be implemented such that the EMP-related voltages and currents which they "pick up" are minimized. For example, the length of ground wires should be minimized so they will be inefficient monopole antennas and the area of "ground loops" should be minimized so they will be inefficient loop antennas.* In addition to these basic requirements, the ground systems must interface with the zonal boundaries at the single entry panels. Random and uncontrolled interconnections between conductors create loops that may serve as efficient collectors of EMP energy.

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*To illustrate the order of magnitude of the voltages and currents that may be induced in small loops exposed to EMP fields, estimates of these voltages and currents are presented in the Appendix. The open circuit voltage and short circuit current in two representative size loops ($A \approx 1\ m^2$ and $10\ m^2$) are approximated. The results of the analysis indicates that both the induced voltages and currents in such conductors can be relatively high (see Table A-1). Thus, the selection of an appropriate ground configuration must take into account the possible effects of high voltages as well as high currents.

Furthermore, uncontrolled interconnections make the defining of zonal boundaries difficult and can make the upgrading of the shielding of such boundaries very difficult. For these reasons, the EMP hardening approach recommends that a single-point ground configuration be employed within the shielded areas (zones). If a multiple point ground configuration is required by a particular system, such as a computer, within a zone, then a hybrid ground configuration should be implemented. The hybrid ground configuration, as illustrated in Figure 4, is one in which a multiple point ground network is grounded at a single point to the interior of the zonal boundary.

Two acceptable configurations for single-point ground systems are illustrated in Figure 5 [16]. The single lines between each component in these configurations represent <u>all</u> connections (power, signal, ground, etc.) between the components. The lines, for example, can represent ducts or raceways into which are laid all conductors passing between components. All signal and power cables should be protected with shields, conduit, or on closed ducts. Open or closed cable trays can be used, so long as their reduced shielding effectiveness is recognized. Care must be exercised to ensure that loops are not formed by the duct or cable tray system.

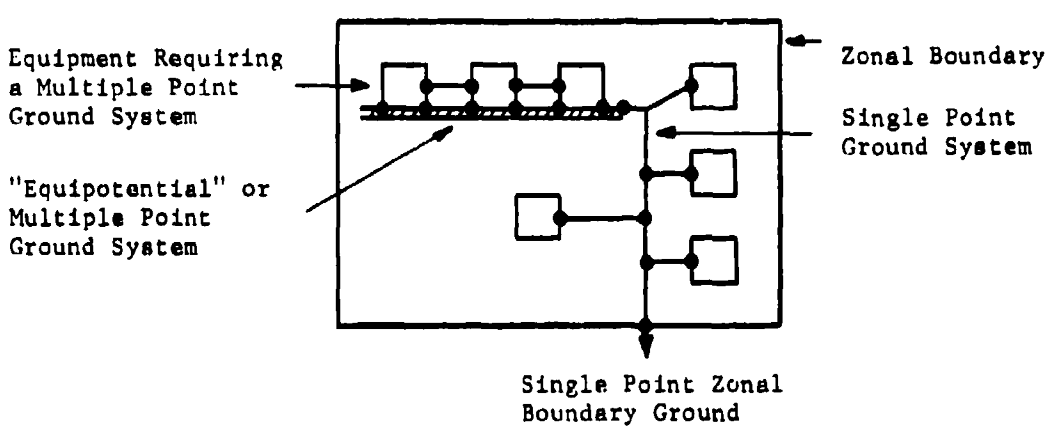

Figure 4. Typical Hybrid Ground Configuration

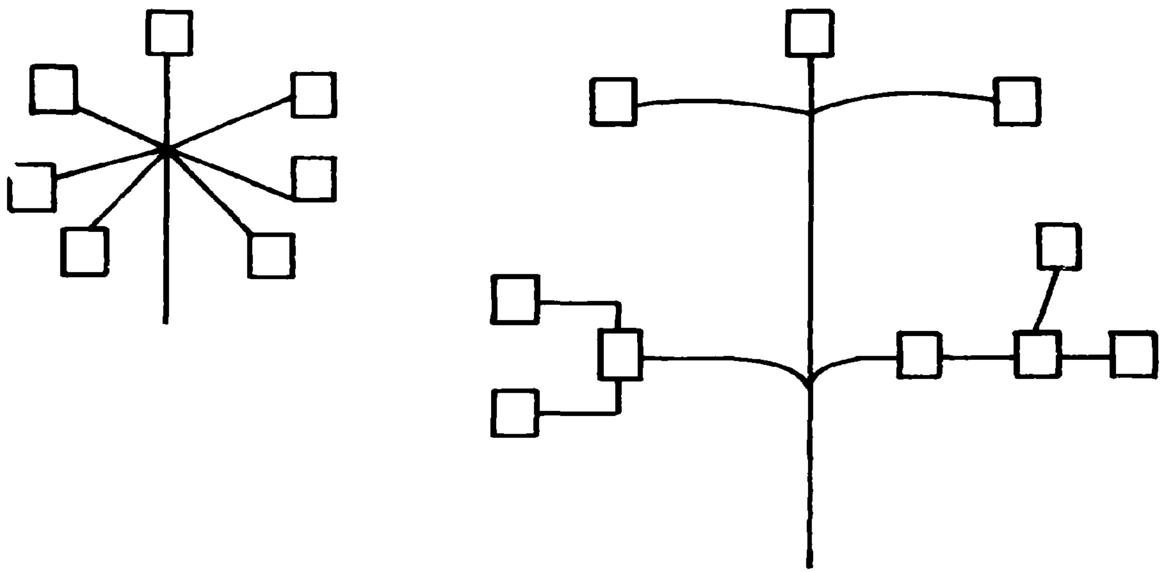

Figure 5. Typical Ground Configurations for EMP Protection.

IV. MIL-STD-188-124 RATIONALE

As noted earlier, the inclusion of EMP protection in MIL-STD-188-124 was not an original goal. Therefore, the perspective of MIL-STD-188-124 is different from that outlined in the preceeding section. In this section, the philosophy and rationale behind the major requirements in the Standard are presented.

4.1 EARTH ELECTRODE SUBSYSTEM

The objectives which are sought by the earth electrode subsystem specified by Para. 5.1.1.1 of MIL-STD-188-124 are summarized as follows:

a. Provide a path to earth for the discharge of lightning strokes in a manner that protects the structure, its occupants, and the equipment inside.

b. Insure that any faults to earth on the distribution system supplying the facility have a sufficiently low impedance path back to the substation or generating station to reliably cause transformer station high voltage breakers to trip and clear the fault.

c. Restrict the step-and-touch potential gradient in areas accessible to persons to a level below the hazardous threshold even under lightning discharge or power fault conditions.

d. Assist in the control of noise in signal and control circuits by minimizing voltage differentials between the signal reference networks of separate facilities.

e. Form a natural sink for noise from atmospheric lightning and other natural sources.

These objectives can be met with a number of different electrode configurations if they have a sufficiently low resistance to earth. The most likely candidates are a wire grid or mesh, a horizontal ring, a horizontal star arrangement, or a combination of one of these with ground rods. The mesh minimizes touch and step potentials; the star offers the lowest impulse impedance; and the ring offers the most cost effective tradeoff between resistance and installation costs while offering reasonable protection against step and touch potentials.

Precedence exists for the use of a ring configuration since it has been relied upon for the lightning protection of telephone company microwave tower installations [2],[19]. Therefore, a ring and ground rod configuration located around the periphery of the facility was selected as the most cost effective configuration.

The Standard requires the rods and interconnecting cable to be located 2 to 6 feet outside the drip line of the structure in order to maximize the contact between the conductors and wet or damp earth. This practice is also commonly recommended for lightning protection to direct lightning currents away from the facility instead of under the facility.

Many probable site locations are in areas of high soil resistivity. At such locations, the basic earth electrode configuration may not provide the 10 ohms of resistance required by Para. 5.1.1.1.3.1. (Ten ohms is a value generally recognized as effective for lessening lightning damage [20].) Other incidental metal objects and structures buried in the vicinity of the facility can be used to obtain a lower resistance contact with the earth. Therefore, the recommendation to bond such objects to the earth electrode system is included to take advantage of whatever contact they may offer. Another advantage to bonding to such objects is to lessen the chances of hazardous flashover in the event of a lightning strike to the facility or when the return current is conducted into the facility from a stroke to exterior power lines or signal cables.

The Standard also requires that the earth electrode subsystem of towers within 20 feet of the facility be interconnected with the earth electrode subsystem of the facility. The basis for this requirement is to provide a dedicated lightning current path for the purpose of reducing the flow of such currents in cable shields, waveguides, and other signal conductors. Of equal importance is the fact that interconnecting the two earth electrode subsystems reduces the overall resistance to earth. The dividing distance of 20 feet optimizes the spacing between ground rods (the length ground rod originally specified in Reference 9 was 10 feet). This optimum spacing occurs at about twice the length of a single rod [11, Vol. II]; therefore, the recommended distance (spacing) is 20 feet.

4.2 FAULT PROTECTION SUBSYSTEM

The fault protection subsystem set forth in MIL-STD-188-124 is a dual system. The necessary low resistance fault current return path inside a building is provided by the grounding (or green) conductor required by the NEC and by the interconnected facility ground network.

The "green wire" network consists of an auxiliary, noncurrent-carrying conductor (insulated or bare) run with the supply conductors to the equipments being serviced. This conductor is intended to interconnect all exposed metal surfaces of equipments and electrical supporting structures, which may become accidentally energized, with the ac power neutral and with other grounded objects such as utility pipes, structural elements, etc. The green wire ground interconnects with the power neutral only at the service disconnect for the facility; it is connected to the cabinets or housings of the electrified equipments.

For effective fault protection, this low resistance path must be provided between the location of the fault and the transformer supplying the faulted line. The resistance of the path must be low enough to cause ample fault current to flow so as to rapidly trip breakers or blow fuses. Thus, the purpose of this NEC grounding conductor, is to provide a positive and reliable fault clearance path to rapidly de-energize a faulted circuit and at the same time prevent hazardous voltages from appearing between exposed objects subject to human contact. This approach also reduces potential fire hazards by promoting rapid clearance of power faults. It promotes personnel safety by restricting both the magnitude of voltages between exposed objects and the time of exposure to a hazardous voltage--a critical element in the protection against electric shock [21].

The second portion of the fault protection subsystem consists of the interconnected metal objects throughout the facility; i.e., structural steel members, pipes, tubes, and electrical supporting structures, such as conduit, cable trays, raceways, enclosures, and cable sheaths. The motivation for interconnecting all these metal elements together is to provide supplemental, backup paths for additional fault protection; provide fault clearance paths in the event these elements become energized; and provide multiple paths of reduced impedance to lessen noise differentials between elements of the structure caused by stray power currents.

4.3 LIGHTNING PROTECTION SUBSYSTEM

The lightning protection requirements set forth by MIL-STD-188-124 reflect the philosophy and requirements of the National Fire Protection Association's "Lightning Protection Code" (NFPA No. 78). The requirements contained in Paragraphs 5.1.1.3.2 through 5.1.1.3.7 are patterned after the requirements set forth by Underwriters Laboratories in UL 96A, "Master Labeled Lightning Protection System." (The requirements of UL 96A are more specific and stringent than those on NFPA No. 78.)

The requirement for cross bonding between lightning down conductors and metal objects located within 6 feet of the down conductors is a requirement common to the National Electrical Code and the lightning protection codes. (See Paragraph 2163 of NFPA 78 and Paragraph 89 of UL 96A as well as Art. 250-46 of the National Electrical Code.)

The use of structural steel members for down conductors is permitted by the lightning protection codes (Para. 2195 of NFPA 78 and 104 of UL 96A). Where electrically continuous structural members exist (for example, in towers), they are less expensive and electrically more effective than dedicated lightning down conductors. Structural steel typically provides several alternate paths for lightning current and exhibits less inductance than do the standard sized lightning down conductors. Therefore, structural steel members can provide a better path for lightning currents than that provided by external down conductors.

For towers (Paragraph 5.1.1.3.8). a separate earth electrode system is required if the tower is greater than 20 feet away from the main facility. Two or more lightning discharge paths are required either through the tower legs or through auxiliary down conductors bonded to the tower legs. Since waveguide runs between the tower and the main facility offer a low impedance, direct path from the tower into the facility and terminating equipments, special precautions are to be taken and multiple grounding is recommended. Three paths to earth along the waveguide run are to be established. In this way at least one effective diversion of the stroke current to earth is expected to be achieved and thus the chances that the current will enter the facility or the equipment inside will be decreased (but not eliminated).

4.4 SIGNAL REFERENCE SUBSYSTEM

Within the facilities to which MIL-STD-188-124 is to be applied, signals encompassing a wide range of frequencies and amplitudes are present. For example, there are the primary power sources, including the dc battery banks for standby and special uses as well as the 60 Hz primary power, involving large currents of several amperes. Extensive communications systems, primarily involving frequencies between 300 Hz and 300 kHz, exist within the facilities. The signals in these systems are characterized predominately by voltage amplitudes considerably less than 1 volt at low current levels. Such systems are particularly susceptible to the noise generated by stray leakage currents from the power sources. The ground network for these systems are to be isolated from the facility ground system except for one interconnection.

Any digital signals that may be present involve the generation and transmission of frequencies well above the audio range. Even where the basic data is in the audio range, the rise and fall times of the pulses frequently require that adequate RF grounding of the network be achieved. Therefore, grounding of these digital signals considers both the low and high frequency properties of the ground reference network.

RF communication and radar systems employ frequencies from HF to well into the microwave frequency region. Therefore, signal grounding for these systems must encompass adequate signal referencing at the high frequencies. Many installations are exposed to the high level RF environment produced by multiple transmitters, both civilian and commercial, located nearby. To protect sensitive equipment from such high level signals, the grounding philosophy reflects the equipment design and cable shielding procedures normally employed by RF systems. This grounding philosophy embodies multiple interconnections between equipment and structural members.

Since a zero impedance conductor network cannot be realized, a common reference plane is not possible which will adequately ground the wide range of signal amplitudes (and frequencies) encountered in long haul communications facilities. The first step reflected by MIL-STD-188-124 in the development of an interference-free signal reference system is to assure that the ac power neutrals are not connected to the NEC grounding (green) conductor at any point other than at the neutral of the service disconnect (usually there is only one for a facility or for a major serviced area of a facility).* The Standard includes appropriate requirements to assure that the isolation between the ac neutral and the signal reference ground are not compromised. This isolation is expected to go a long way toward reducing many of the stray-current noise problems frequently encountered in such facilities. Since low frequency circuits and systems are particularly susceptible to power line related noise and other low frequency interference, a

*In an EMP-hardened facility, the neutral passes through the entry panel as any other ungrounded conductor; it must be properly treated. If the facility must meet the requirements of the NEC, then the green wire must be properly treated at the zonal boundary.

single-point grounding network which provides a reference for low frequency signal circuits is to be laid out and installed in a manner that minimizes stray currents and voltages between low frequency equipments.

Some installations [7],[22] have included equipment cabinets and racks in their single-point ground system. In addition to implementing a single-point ground for signal circuits, another single-point ground network is provided to which the equipment cases, cabinets, and racks are connected. The successful implementation of this "equipment ground" requires that electrical isolation be maintained between the equipment housings and structural elements. Experience has shown that such isolation is extremely difficult to maintain [4],[6]. When this approach is used with equipment employing coaxial signal connections, preservation of the integrity of the single-point grounding system becomes even more difficult. For example, in order to maintain the integrity of the system, all coaxial shields and connectors must be isolated from structural components and equipment cabinets. Such requirements tend to be at variance with traditional construction techniques and consequently are very difficult to implement and maintain.

Internal to equipments, the circuit reference is to be isolated from the equipment enclosure. The circuit reference ground is then connected to the facility ground system through an insulated ground bus that interconnects with the ground buses from other equipment locations in a tree configuration as illustrated by Figures 3 and 4 of the Standard.

Some unwanted currents will unavoidably be present in the signal ground reference network and the network will present some non-zero impedance; therefore, this ground reference tree should not be used as the signal return path between equipments or systems. Instead, the signal paths between equipments should be of balanced configurations and appropriately twisted and shielded to the extent necessary to prevent unwanted signals from coupling to the signal line via capacitive and inductive paths.

Primary ac power to the low frequency circuits are to be supplied only through appropriately shielded transformers. All switches, controls, meters, etc., should be insulated from the enclosure or connected into the circuit so as to not electrically connect the circuit ground to the cabinet ground. In these equipments, the safety or power fault protection ground wire should be connected to the equipment case since this is the part with which human contact is likely. Faults to circuit ground are taken care of with the signal ground reference network.

High frequency equipment utilizes the multiple-point ground system traditionally employed in such equipment. The circuit signal ground reference is typically attached to the equipment enclosure at a sufficient number of points to achieve a low impedance connection at the frequencies of interest. The Standard requires that the equipment enclosures be bonded together with the building structural steel, cable trays, conduit, heating ducts, piping, etc., to form as many parallel paths as possible. This interconnected mass of metal is intended to reduce the effective impedance of the grounding system and assists in the shielding of sensitive equipment within the structure. These multiple interconnections (which admittedly form many loops--see Appendix) between equipments and the structural elements reflects a pragmatic belief that such interconnections will occur sooner or later anyway. Traditionally, designers, engineers, installation personnel, and maintenance personnel are not oriented toward achieving or maintaining any degree of isolation between equipment cabinets and structural elements. Conversely, the greater tendency is to interconnect wherever convenient.* Thus, the

*The pragmatic approach is taken because the costs to re-educate an entire community to begin <u>not</u> making multiple interconnections were considered to be excessive. The first step chosen was to formulate a set of practices considered to offer a substantial step forward in grounding technology without necessitating a basic philosophical shift by the National Electrical Code and Lightning Protection Code communities.

philosophy behind the multiple interconnections incorporates an attempt to employ traditional practices to advantage. In high level RF environments, the multiple interconnections are expected to minimize differences in RF potentials between irradiated elements of the structure and equipment. (As noted in Section II, multiple bonding of structural elements has been shown to be advantageous in lowering the overall background EM noise level in a facility.)

Low Frequency Versus High Frequency. If one type of ground system is appropriate for low frequency signals and another is appropriate for high frequency signals, then obviously a dividing line between high and low frequencies must be defined. In addition to the question as to what dividing frequency is appropriate, there is the question as to whether the signals of concern should be those external to the equipments or system (i.e., the environment as coming either external or internal to the facility (or structure)) or those internal to the equipments or the system (i.e., those desired signals which are associated with normal functioning such as basic data rates, baseband signal ranges, carrier frequencies, etc.). In MIL-STD-188-124, the division between high and low frequency grounding is a band of frequencies between 30 kHz and 300 kHz. This particular frequency range is based upon the operating frequencies internal to the system.

In new facilities to which MIL-STD-188-124 is to be applied, the actual operating signals within the system are more definable than the external environmental threat. A general idea of the probable types of equipment that are to be installed in the facility is available. It is known in advance that certain types and classes of equipments (such as telephone type circuits) are more likely to be interfered with by power frequency currents and voltages than other types (such as RF systems). Relative to the external environment, certainly RF sources such as radio transmitters and radars are capable of causing interference. (Since the lightning hazard is viewed more as likely to disrupt system operation from burnout, protective measures are geared more at protecting against the direct strokes than from the EM fields generated by lightning.) Unfortunately, the RF environment is typically not known prior to facility construction.* Therefore, tailoring the dividing frequency for the external environment at different locations is not considered possible (at least not through the vehicle of the Standard). (Conceptually, it would be possible to standardize the methodology, or process, of arriving at a dividing frequency based on a unique system-environment pairing; the details would be somewhat involved, however. Furthermore, by being different for different locations, equipment standardization would be difficult.) From this perspective, the Standard sets the dividing line between high and low frequency based upon the recognized problem posed by low frequency interference sources (primarily stray power currents and fields) to low frequency systems.

Other frequencies have been used or suggested [8] as the dividing line between low and high. Practically all, if not all, have relied upon the type of rationale outlined above in that they have tended to focus on the primary operating frequency range of a system with the idea that in these ranges the associated circuits are most sensitive and thus most vulnerable to extraneous signals of comparable frequencies.

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*A strong recommendation is contained in Reference 8 that an RF survey be conducted prior to selecting the site so that appropriate design measures can be implemented to enhance the compatibility of the final system with the environment.

V. SPECIFIC DIFFERENCES

The principle differences between the requirements of MIL-STD-188-124 and those for EMP protection fall in the following areas:

- Exposed conductors
- Ground system configurations
- Frequencies for which each type signal ground configuration should be utilized
- Signal interfaces
- Shield seams

5.1 EXPOSED CONDUCTORS

The major concern here is the relative location and effective size of the earth electrode subsystem.

Requirements

MIL-STD-188-124

- "Minimum Configuration The basic earth electrode subsystem configuration shall consist of driven ground rods...placed 0.6m (2 feet) to 2m (6 feet) outside the drip line of structures...." (Para. 5.1.1.1.3)
- "Additional Considerations Where 10 ohms are not obtained... alternate methods for reducing the resistance to earth shall be considered...." (Para. 5.1.1.1.3.2)
- "Other Underground Metals Underground metallic pipes entering the facility shall be bonded to the earth electrode subsystem... Structural pilings, steel reinforcing bars, tanks, and other large underground metallic masses near the periphery of the structure shall be bonded...to the earth electrode subsystem...." (Para. 5.1.1.1.6)

EMP Protection

- The earth electrode subsystem should be as small as possible [15],[16]
- "Preferably, the external ground should be near or under the facility shield." [16]
- The maximum distance between the earth electrode subsystem and large underground metal bodies for which bonding is required should be clearly stated.

Discussion:

For the earth electrode subsystem, the MIL-STD-188-124 requirements seek to provide as low resistance as possible, to permit alternate configurations to be used, and to insure compatibility with the Lightning Protection Codes. As noted in the previous section, an approach consisting of the combination of a perimeter counterpoise and ground rods was considered cost effective. Interconnection of the earth electrode subsystem with other underground metal objects lowers the net resistance to earth and provides enhanced lightning protection. By design, this approach produces an extended earth electrode subsystem.

By contrast, the EMP approach seeks to keep the earth electrode subsystem as small as possible to minimize the collection of EMP energy. Since its purpose is to make good contact with the earth, primarily for lightning and fault protection, this subsystem readily couples to EMP energy in the earth. Therefore, EMP protection philosophy strives to have the earth electrode subsystem installed underneath the facility. Various conductor configurations are acceptable so long as they do not appreciably increase the electrical size of the facility.

Recommendation:

A compromise is recommended that would retain the requirement for a minimum resistance of 10 ohms to be achieved yet restricts the configuration of the earth electrode subsystem such that it does not extend more than 2 feet outside the drip line of the facility. This 2-feet maximum would not apply when other underground metal objects are located within 6 feet of the earth electrode subsystem; such objects should be either bonded to the earth electrode subsystem or relocated more than 6 feet away. If these changes are made in the Standard and if, at a given site, the resistance requirement of less than 10 ohms can not be met with the permitted configuration, it will then be necessary to make a determination for the particular facility as to whether to extend the size of the earth electrode subsystem or accept the resistance provided by the minimum configuration.

5.2 GROUND SYSTEM CONFIGURATIONS

Specific concerns exist with the differences in the Fault Protection, Lightning Protection, and Signal Reference Subsystem requirements.

5.2.1 Fault Protection Subsystem

Requirements

MIL-STD-188-124

- "Building Structural Steel All main metallic structural members... should be...grounded to the facility ground system." (Para. 5.1.1.2.2)

- "Pipes and Tubes ...all metallic piping and tubing and the supports thereof should be...grounded to the facility ground system." (Para. 5.1.1.2.3)

- "Electrical Supporting Structures Electrical supporting structures shall be grounded to the facility ground system..." (Para. 5.1.1.2.4)

- "Conduit...

  c. Conduit brackets and hangers shall be electrically continuous to the conduit and to the metal structures to which they are attached." (Para. 5.1.1.2.4.1)

- "Cable Trays or Raceways ...All cable tray assemblies shall be connected to ground within 0.6m (2 feet) of each end of the run and at intervals not exceeding 15m (50 feet) along each run." (Para. 5.1.1.2.4.2)

- "Wiring System Enclosures All electrical and electronic wiring and distribution equipment enclosures...shall be grounded." (Para. 5.1.1.2.4.3)

- "Metallic Power Cable Sheaths Metallic cable sheaths...shall be connected to ground." (Para. 5.1.1.2.4.4)

- "AC Distribution Systems ...The fault protection subsystem grounding conductor (green wire) shall be installed in accordance with the National Electrical Code..." (Para. 5.1.1.2.5.1)

- "Standby AC Generators Motor and generator frames and housings shall be grounded in accordance with...the National Electrical Code. The generator neutral shall be grounded directly to the earth electrode subsystem..." (Para. 5.1.1.2.5.2)

- "AC Outlets The ground terminal of AC outlets shall be connected to the facility ground system with a copper conductor meeting the requirements of Article 250 of the National Electrical Code. The ground terminals in all receptacles on wire mold or plugmold strips shall be hard wired to the equipment ground network." (Para. 5.1.1.2.5.3)

- "Electrical Motors and Generators The frames of motors, generators and other types of electrical rotating machinery shall be grounded to the fault protection subsystem, according to Article 430 of the National Electrical Code." (Para. 5.1.1.2.5.4)

- "DC Power Sources One leg of each DC power system shall be grounded with a single connection directly to the earth electrode subsystem..." (Para. 5.1.1.2.5.5)

EMP Protection

- All metallic objects that are subject to becoming accidentally electrified should be grounded in such a manner so as not to violate the zonal shielding/grounding concept.

- The configuration of the fault protection subsystem should be such that the number of loops are minimized and such that this subsystem is connected to each zonal boundary at its single entry point [16].

- The configuration of the fault protection network should be controlled and spelled out.

Discussion:

Both sets of requirements are for the purpose of achieving personnel and equipment protection while not jeopardizing the respective EMI and EMP protection goals.

The MIL-STD-188-124 requirements are in conformity with the NEC for simplicity. The least expensive, while yet effective, approach is the interconnection of all the metal elements including the structural steel and the earth electrode subsystem by the most direct path.

For EMP protection, however, the multiple, random interconnections of all metal elements within a facility, with each other, and with elements outside the facility create unacceptable loops that can be relatively efficient collectors of energy. In addition, in the event of a requirement to retrofit such a facility for EMP protection, these interconnections make the realizaion of zonal shields with single, controlled entry points very costly and difficult to implement.

Recommendations:

In facilities requiring EMP protection, one approach for resolving this conflict is to define the zonal boundaries during the design phase and then require that MIL-STD-188-124 be implemented within each zone. This approach involves isolating the fault protection subsystem within a zone from the inner surface of that zone's boundary and from the outer surface of the next higher order zonal boundary except for a single interconnection. All signal, power, and ground conductors will have to be routed into each zone through this single entry point (panel). Some wording (not technical objectives) in MIL-STD-188-124 will have to be changed to reflect this approach.

Implementation of this approach will increase costs since it is somewhat different from traditional practices. In addition to the increased cost, this approach will require that considerable effort be placed on assuring that user and maintenance personnel do not violate the single point grounding scheme. Since EMC and lightning protection objectives are met by the requirements as presently stated in MIL-STD-188-124, it is clear that the additional costs associated with implementing and maintaining this approach must be directly attributed to the added requirements for EMP protection.

Because of these increased costs and difficulties, this approach is not recommended across the board for all facilities. Each facility to which MIL-STD-188-124 is to be applied should be evaluated in advance for its relative need for EMP protection. If it is not expected that a particular facility will need to be provided with EMP protection, then the establishment of zonal boundaries is probably not cost effective. It is recommended that a set of guidelines be developed for help in deciding in advance which facilities should be designed and constructed to accommodate the installation of EMP protection, either during construction or at a later date.

5.2.2 Lightning Protection Subsystem

Requirements:

MIL-STD-188-124

- "Down Conductors ...Any metal object within 1.8m (6 feet) of the lightning down lead shall be bonded to the down conductor (see NEC Art. 250)...." (Para. 5.1.1.3.2)

- "Structural Steel Substantial metal structural elements of buildings and towers shall be acceptable substitutes for lightning down conductors provided they are...bonded to the earth electrode subsystem." (Para. 5.1.1.3.5)

- "Earth Electrode Subsystem (Towers) ...If the tower is adjacent to another structure such that the minimum distance between the tower and the structure is 6m (20 feet) or less, one earth electrode subsystem encompassing both...shall be provided. For distances greater than 6m (20 feet), separate earth electrode subsystems shall be installed." (Para. 5.1.1.3.8.1)

EMP Protection

- The zonal boundaries (whether they are continuous metal shields or open arrays of conductors) should be well defined without random crossings of ground conductors.

- The zone 0/zone 1 boundary (facility shell) should only be connected to the earth electrode subsystem at one point (except in the unique case of a continuously welded metallic enclosure).

- The number of zone 0 conductors connected to this zonal boundary should be minimized and they should all connect at a single entry point.

- Earth electrode subsystems for adjacent towers should be independent of the facility earth electrode subsystem.

Discussion:

The requirements in the Standard are in accordance with the Lightning Protection Code [13] and the requirements of Underwriters Laboratories for Master Labeled systems [14]. They are designed to prevent flrshover and minimize personnel shock hazards. The distance that a person could reasonably bridge with extended arms is accepted as 1.8m (6 feet). Therefore, all metal objects, including structural steel, within 1.8m (6 feet) of the lightning protection subsystem must be bonded to it. On tall structural steel buildings, these bonds must be located at both the top and bottom of the building to prevent hazardous voltages due to the fast risetimes (V = Ldi/dt) of the lightning current pulse. Since the structural steel is required to be interconnected with the lightning protection subsystem in several places, it is frequently more practical and less expensive to use the structural steel as down conductors instead of installing supplemental down conductors. The use of a common earth electrode subsystem for the facility and adjacent towers is to help protect facility equipment from lightning damage [2] and to lower the overall resistance to earth of the "site" earth electrode subsystem.

From the EMP hardening point-of-view, the random interconnections of the lightning protection subsystem with structure, equipment and fault protection networks creates unacceptable loops and could prohibit the single point entry of, or connection to, zonal boundaries. The use of the structural steel as down conductors prevents the realization of a single connection to zonal boundaries and the earth electrode subsystem. Finally, the use of a common earth electrode subsystem for adjacent towers permits the tower, which may be a relatively efficient collector of EMP energy, to couple EMP energy directly to the facility earth electrode subsystem and thus, to the facility and its equipment (i.e., the tower extends the electrical size of the facility) [16].

<u>Recommendations</u>:

These sets of requirements are not compatible. At the present time, they cannot be consolidated without major changes in either one or both of the sets. Therefore, additional investigations definitely need to be conducted to identify appropriate compromises in one or both of the sets of requirements such that they can be consolidated. The purpose of these investigations is to formulate a set of facility lightning protection practices that meet the <u>goals</u> of the Lightning Protection Code and that are compatible with EMP protection <u>needs</u>.

However, it is specifically recommended that the earth electrode subsystem for the facility and adjacent towers separated not more than 6 m (20 feet) be interconnected together with the dedicated conductors named in MIL-STD-188-124. The towers and associated facilities are expected to be integrally connected by waveguide, shields of coaxial cables, ac power safety grounds, etc. to provide fault and lightning protection. Thus, interconnecting them by two more paths is not expected to materially increase the amount of EMP energy coupled to the facility. In fact, these connections of bare wire in contact with the soil could in fact reduce the actual coupling into the facility by increasing the overall size of the "site" earth electrode subsystem and, thus, lower its overall resistance to earth.

5.2.3 Signal Reference Subsystem

Requirements:

MIL-STD-188-124

- "General ...Where units are distributed throughout a facility the signal reference ground subsystem shall consist of one of the following:
  - a. For higher frequencies, an equipotential ground plane.
  - b. For lower frequencies, a single point ground.
  - c. For hybrid (combination of higher and lower frequencies), an equipotential ground plane." (Para. 5.1.1.4.1)
- "Higher Frequency Network The more extensive the equipotential ground plane, the more effective it is...The equipotential plane shall be connected to the building structure shell and earth electrode subsystem at many points." (Para. 5.1.1.4.2)
- "Higher Frequency Network ...provides an equal potential (sic) plane with the minimum impedance between the associated electronic components, racks, frames, etc." (Para. 5.1.2.1.2)
- "Hybrid Signal Reference Network Hybrid signal reference networks are combinations of the above such as where an equipotential plane is installed in one part of the facility to meet the requirements of a higher frequency terminal and a single point system is interconnected to the same earth electrode subsystem to meet the distributional requirements of lower frequency signals." (Para. 5.1.2.1.3)

- An "equipotential" ground plane, i.e., a multipoint ground system, should not be used if avoidable (except in the unique case of the connection to the earth electrode system of a well shielded facility which is a continuously welded metallic enclosure).

- Where a multiple point ground system is required, e.g., where dictated for automatic data processing equipment installations, the "equipotential" plane must be confined to a single zone and should be grounded with a single connection to the interior of that zone's boundary.

Discussion:

As noted previously, the rationale for requiring a multiple point ground system is based primarily on the difficulties and relatively high costs associated with achieving and maintaining a single point ground at higher frequencies. If a multiple point ground system or, as designated by MIL-STD-188-124, an "equipotential" ground plane is to be installed, then its desirable features are that it be extensive and that it be interconnected with all metal objects in the facility. In general, the more extensive, i.e., larger, the mass of metal in a given volume the lower the resistance/impedance expected between any two points. Multiple interconnections assist in reducing the ground plane impedance and tends to simplify implementation and maintenance.

From the EMP perspective, an equipotential ground plane distributed throughout a facility renders the implementation of the EMP approach (zonal shields with single point entries) a very complex task. Further, random, multiple interconnections restricts the defining and implementing of zonal boundaries and creates undesired loop collectors of EMP energy which lessen the achievable hardness.

Recommendations:

The approach recommended previously in Section 5.2.1 is expected to accommodate the needs for both EMI and EMP protection. This recommendation to implement the requirements of MIL-STD-188-124 only internal to zonal boundaries and not across such boundaries applies for both the fault protection and the high frequency signal reference subsystems. For example, an adaptation of the "equipotential plane" illustrated in

Figure 2 of MIL-STD-188-124 can be implemented in each zone such that it is isolated from the zonal boundaries except for the interconnection at the single entry panel. Again, all signal and power conductors would have to cross each zone boundary at the single entry panels. However, as noted previously the costs associated with implementing and maintaining such an approach must be considered. Therefore, as recommended in Section 5.2.1, the guidelines for selecting appropriate facilities should be developed and the additional cost of implementing this approach in the specific selected facilities should be assigned directly to the EMP requirements.

5.3 DIVIDING FREQUENCY

The dividing frequency is that band of frequencies below which MIL-STD-188-124 requires the use of a single point signal reference subsystem and above which a multiple point signal reference subsystem is required.

Requirements:

MIL-STD-188-124

- "Lower Frequency Network ...lower frequency equipments from dc to 30 kHz and in some cases to 300 kHz...." (Para. 5.1.1.4.3)
- "Signal Reference Subsystem (C-E Equipment) ...Depending on... interface operating frequencies, the type of signal reference network(s) will vary...." (Para. 5.1.2.1)
- "Lower Frequency Network ...shall be used where the highest interface frequency is below 30 kHz and may be used where the highest interface frequency is up to 300 kHz...." (Para. 5.1.2.1.1)
- "Higher Frequency Network ...shall be used...where interface frequencies are over 300 kHz and may be used...where interface frequencies are as low as 30 kHz" (Para. 5.1.2.1.2).
- "Lower frequencies includes all voltages and currents...from dc to 30 kHz and may extend up to 300 kHz depending on the electromagnetic and physical aspects of the equipment, subsystem, and/or facility involved. (Audio and tone signaling devices operate in the lower frequency ranges.)" (Appendix B, page 45, Footnote 1)

- "Higher frequencies include all voltages and currents...down to 300 kHz and may extend lower to 30 kHz depending on the electromagnetic and physical aspects of the equipment, subsystem, and/or facility involded. (Digital equipment, i.e., teletype, data and other binary signaling devices operate at higher frequencies.)" (Appendix B, page 45, Footnote 2)

EMP Protection

- If a multiple point ground is required such that a dividing frequency is necessary, this frequency should not depend solely on equipment interface frequencies.

- The dividing frequency should be dependent on the system and on the environment.

Discussion:

Since separate signal reference subsystems are required by MIL-STD-188-124 for lower and higher frequency equipments, a dividing frequency is necessary. The Standard defines this "dividing frequency" as a band of frequencies between 30 kHz and 300 kHz. Frequencies below this band are defined as lower frequency; frequencies above this band are defined as higher frequencies; and the frequencies within this band may be either. The rationale for choosing a dividing frequency based upon equipment interface frequencies is presented in Section III.

EMP protection philosophy is based upon the properties of the EMP environment. Therefore, any dividing frequency should reflect these properties as well as the operating frequencies of the equipment and associated system. That is, the selection of the dividing frequency must take into account the frequency of the anticipated environment, the operating frequency of the equipment, and their relationship to the configurations of the proposed ground networks.

Recommendations:

In order to resolve this difference, it is recommended that the relationships between the anticipated EM environmental frequencies, the equipment/system operating frequencies, and the various ground network configurations be investigated. This investigation should address the two following questions:

- When connected to a given ground configuration, how does the susceptibility of the equipment or system vary with the EM environment and its frequency?

- How does this susceptibility vary with changes in the configurations of the ground reference subsystem?

Until these two questions are answered, the most practical way of choosing a dividing frequency is to base it on some system operating frequency (see Section 4.4). It is therefore recommended at the present time that the highest of the interface signal frequencies be used as required in MIL-STD-188-124. If the dependence of the susceptibility of equipment on the ground configuration as a function of the environmental frequency is determined, then specific guidelines can be formulated for choosing the dividing frequency. This dividing frequency may ultimately be based on the equipment, its susceptibility, its operating and interface frequencies, or the frequency of the anticipated environment.

5.4 EQUIPMENT SIGNAL INTERFACES

The primary concerns relative to equipment signal interfaces are the routing of signal returns and the routing and/or grounding of shields on interfacing cables.

5.4.1 Signal Returns

Requirements:

MIL-STD-188-124

- "Equipment Signal Isolation (DO) Lower frequency signals should be isolated from the equipment case...." (Para. 5.1.2.1.1.1)

- "Equipment Signal Reference Ground Terminal (DO) An insulated equipment signal reference ground terminal should be provided on each equipment case...." (Para. 5.1.2.1.1.2)

- "Signal Interfaces (DO) The signal inputs and outputs of all lower frequency equipment should be balanced with respect to the signal ground. The signal lines should be balanced twisted pairs." (Para. 5.1.2.1.1.3)

EMP Protection

- The single point reference system should not be permitted to be used as the signal return path.
- Signal interfaces should not be permitted to violate the single point ground concept and create unacceptable loops.
- The signal path should be routed with the signal return, i.e., the lower frequency signal reference system, to minimize loop areas.

Discussion:

As presently stated, these Paragraphs in MIL-STD-188-124 are "Design Objectives" (Note the use of the verb should instead of shall). Paragraph 1.5 in the Standard states that design objectives are non-mandatory. Therefore, equipments which do not meet these design objectives can be designed, purchased, and installed in a facility and thus compromise the single-point grounding features of the lower frequency signal reference subsystem. Such equipment could meet the mandatory requirements of this Standard and yet violate the single point ground concept and, thus, the intent of the Standard. For example, lower frequency equipments that do not have their signal references (grounds) isolated from the equipment cases could still meet the mandatory requirements in this Standard. In the absence of Paragraphs 5.1.2.1.1.1, 5.1.2.1.1.2, and 5.1.2.1.1.3 being mandatory requirements, the Standard can be interpreted so as to allow the ground system to be used as a signal return or to form loops in the low frequency signal ground system. Either way the intent of MIL-STD-188-124 will be compromised.

Since the Standard, as it is presently written, permits the single point ground system to be used as a signal return path, improved compatibility with EMP protection requirements would result if the signal path were routed with the ground system conductors. In this way, the area of loops produced by the signal conductor and its return would be minimized.

Recommendation:

It is recommended that Paragraphs 5.1.2.1.1.1, 5.1.2.1.1.2, and 5.1.2.1.1.3 of MIL-STD-188-124 be changed from design objectives to mandatory requirements. Obviously this change would require that equipment meeting these requirements be made available. The extra costs associated with this action is recognized; however, it may overall be less expensive than installing a single point ground system and then permitting all equipment connected to it to violate the intent and purpose of the ground system.

5.4.2 Interface Cable Shields

Requirements:

MIL-STD-188-124

- "Overall Shields ...shall, as a minimum, be grounded at each end. They shall also be grounded at junction boxes, patch panels, distribution points and at other intermediate points along the cable run. Overall shields shall be grounded to cases, cabinets or conducting surfaces," (Para. 5.1.2.1.1.5)

- "Shield Terminations of Coaxial and Other Higher Frequency Cables All connectors shall be of a type and design that provide a low impedance path from the signal line shield to the equipment case. If the signal circuit must be isolated from the equipment case, and if the shielding effectiveness of the case must not be degraded, a connector of a triaxial design that properly grounds the outer cable shield to the case shall be used. Shields of coaxial cables and shielded balanced transmission lines shall be terminated by peripherally grounding the shield to the equipment case. Coaxial shields and connector shells shall be grounded at junction boxes, patch panels, signal distribution boxes and other interconnection points along the signal path." (Para. 5.1.2.1.2.3)

EMP Protection

- Since shields on interface cables must be grounded at each end, these cables should be routed with the single point ground system [16].

- Such shields should not be connected to any of the facility ground systems at intermediate points.

Discussion:

The MIL-STD-188-124 requirements are to provide better overall shielding by totally enclosing the signal lines in a shield. This agrees with the EMP zonal boundary concept as long as the cable shields are not grounded at intermediate points. Large loops which could be relatively efficient collectors of EMP energy should be avoided and, thus, the signal interface should be routed with the ground system to make the area of this zonal boundary loop as small as possible.

Recommendation:

Requirements that deal with cable routing in EMP hardened facilities need to be added to MIL-STD-188-124. It is anticipated that all such cables would be routed according to some variation of the configurations illustrated in Figure 4 (see Section 3.3.4). However, before such an action can be implemented, a set of guidelines, as discussed in Section 5.2.1, must be developed for choosing those facilities which do, or may, require EMP protection.

5.5 SHIELD SEAMS

Requirements:

MIL-STD-188-124

- "Welding...

  b. On members whose largest dimension is greater than 5 cm (2 in.) but less than 30 cm (12 in.), one weld of at least 5 cm (2 in.) in length shall be provided.

  c. On members whose largest dimension is greater than 30 cm (12 in.) two or more welds, each not less than 5 cm (2 in.) in length, shall be uniformly spaced across the surface of the largest dimension. The maximum spacing between successive welds shall not exceed 30 cm (12 in.)." (Para. 5.2.6.1)

EMP Protection

• Welds in shield seams should be either continuous or the seam should have a 10cm overlap with fasteners (welds) located every 7.5 to 10cm to provide EMP shielding [23].

Discussion:

These requirements of MIL-STD-188-124 are intended to be the minimum requirements for bonds of sufficient extent to support the load demands and provide adequate electrical bonds. These procedures are not intended to provide EMP shielding. (The shielding requirements are given in Section 5.3 of the Standard.) Where a high degree of shielding is required to protect against EMP or any other intense EM environment, it will be necessary to increase the bond requirements for shield seams beyond those now given in 5.2 of the Standard.

Recommendations:

Add a note to Section 5.3 of MIL-STD-188-124 as follows:

> It should be noted that the minimum bond requirements given in Section 5.2 may not be sufficient to provide the required degrees of shielding.

An acceptable alternative action would be to strengthen the requirements of the Standard to reflect those of Reference 23. The above supplementary note will probably still be appropriate.

VI. CONCLUSIONS AND RECOMMENDATIONS

The relationship between the grounding philosophies and the requirements set forth for achieving EMP protection and for providing EMC have been investigated. A discussion of this relationship and specific recommendations for resolving the identified differences are presented in Chapter V. The following general conclusions and recommendations are based on these investigations:

1. Specific differences do exist between the EMP grounding practices and the MIL-STD-188-124 requirements. These differences are primarily a result of the different electromagnetic environments of concern.

2. Specific proposed changes in the requirements of MIL-STD-188-124 have been identified which will make it more compatible with the EMP practices. It is suggested that the recommendations in Chapter V for specific changes in the Standard be brought to the attention of the organization responsible for MIL-STD-188-124 with strong recommendations for adoption. With the exception of 3 below, these specific changes will not significantly affect the construction and maintenance difficulties nor the cost of the facility. Therefore, it is suggested that they be implemented in <u>all</u> facilities to simplify retrofitting in the future.

3. The specific recommendation to change Paragraphs 5.1.2.1.1.1, 5.1.2.1.1.2, and 5.1.2.1.1.3 in MIL-STD-188-124 from "Design Objectives" to mandatory requirements is reiterated. This change is deemed necessary in order to prevent the routine installation of lower frequency equipment that will compromise the single point ground concept.

4. The EMP requirements and some of the lightning protection requirements set forth in NFPA 78 and UL 96A are incompatible as they presently exist. The only way to unify these two sets of requirements is to change one or both of them. It is recommended that possible changes in these two sets of requirements be formulated. These changes must be evaluated to insure that they achieve <u>both</u> the EMP and lightning protection goals.

5. A recommended approach for resolving the differences related to the configuration of the ground systems is suggested only for those facilities known to require EMP protection (see 6 below) now or in the future. The following steps are recommended for implementing this approach:

- Define the zonal boundaries during the design phases of the facility.

- Implement the requirements of MIL-STD-188-124 only within each zone.

- Insure that the resulting ground systems do not contact or cross zonal boundaries except at the single entry panels.

Since this approach is significantly different than the traditional approach for simply EMC, fault protection, and lightning, it will increase the cost and difficulty associated with implementing and maintaining the various ground systems. This additional cost must be assigned to the EMP requirements since this approach is not necessary for fault protection, lightning protection, and EMC.

6. Due to the additional cost associated with constructing and maintaining a facility designed to accommodate EMP protection, it is not considered cost effective to arbitrarily require that all facilities be designed to accommodate the installation of EMP protection. Therefore, it is recommended that a set of guidelines be developed for use in deciding, prior to construction, if a facility needs EMP protection. These guidelines should set forth the criteria for selecting such facilities or installations. If it is decided that it will not immediately require EMP protection, the formulated guidelines should aid in making the decision of whether to design the facility so as to accommodate the installation of EMP protection at a later date. This decision must be based on a trade off between the probability of EMP protection being required in the future and the cost of requiring the facility to be designed to accommodate EMP protection if it is never needed.

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APPENDIX

ANALYSIS OF A LOOP CONDUCTOR IN AN EMP FIELD

Single point ground configurations as well as multiple point ground configurations can form loops within ground systems. Loops in the single point ground configuration are open circuited at the equipment as shown in Figure A-1, whereas multiple point ground systems have closed loops. (The ground system in Figure A-1 would be a multiple point ground configuration if the equipment signal reference was connected to the equipment case.) The objective of this analysis is to determine the open circuit voltage and short circuit current in such a loop when it is exposed to a plane wave EMP field. This voltage and current is related by the terminal impedance of the loop.

A.1 OPEN CIRCUIT VOLTAGE

The open circuit voltage in a single turn loop can be calculated from Faraday's Law [A-1]:

$$v = \frac{-d}{dt} \int_S \underline{B} \cdot \underline{ds}$$

$$= -\mu \frac{d}{dt} \int_S \underline{H} \cdot \underline{ds} \qquad \text{(A-1)}$$

where

v = induced open circuit voltage

$\underline{B} = \mu \underline{H}$ = vector flux density of EMP field

μ = permeability of medium in loop

= $4\pi \times 10^{-7}$ henry/meter for free space

$\underline{H}$ = vector magnetic field.

$\underline{ds}$ = unit surface element vector

S = surface bounded by loop

t = time

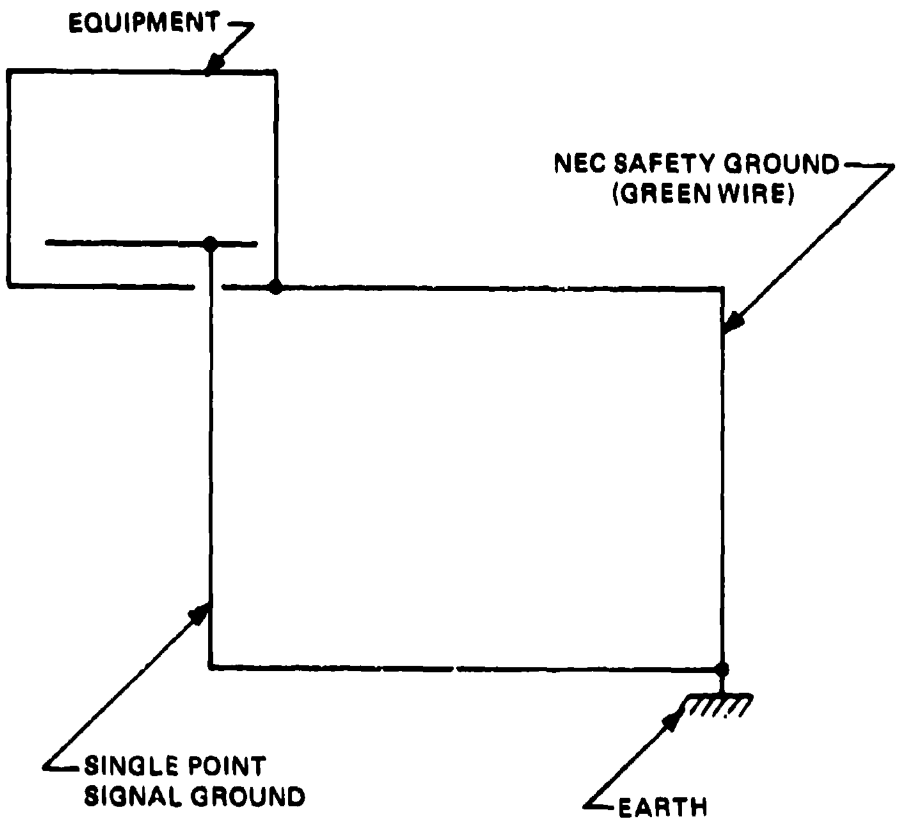

Figure A-2. Typical Loop in the Ground System of a Facility.

To determine the "worst-case" voltage, assume $\underline{H}$ is perpendicular to the plane of the loop, i.e., $\underline{H}$ is parallel to $\underline{ds}$. Also, assume $\underline{H}$ is uniform over the area of the loop to simplify calculations.* Thus,

$$v = -\mu \frac{d}{dt}(HA) = -\mu \frac{d}{dt}\left(\frac{E}{\eta_o} A\right)$$

$$= \frac{-\mu A}{\eta_o} \frac{dE}{dt} \tag{A-2}$$

where

A = the area of surface S in square meters

E = electric field intensity

$\eta_o = 120\pi = \frac{E}{H}$ = intrinsic impedance of free space.

The generalized, worst-case EMP electric field is given by [A-2]

$$E(t) = 5.25 \times 10^4 \left[\exp(-4 \times 10^6 t) - \exp(-4.76 \times 10^8 t)\right] \tag{A-3}$$

in volts per meter. Combining Equations (A-2) and (A-3) gives the open circuit voltage as

$$v = \frac{(4\pi \times 10^{-7})A}{120\pi}(5.25 \times 10^4)\left[-4 \times 10^6 \exp(-4 \times 10^6 t)\right.$$

$$\left. + 4.76 \times 10^8 \exp(-4.76 \times 10^8 t)\right]$$

$$= A\left[7 \times 10^2 \exp(-4 \times 10^6 t) - 8.33 \times 10^4 \exp(-4.76 \times 10^8 t)\right] \tag{A-4}$$

---

*For small loops, this uniform $\underline{H}$ assumption will yield accurate results. For large loops, assuming $\underline{H}$ is uniform will not take into account the phase variation [$\exp(-jkr)$] across the loop. Thus, any actual ringing of the voltages and currents will not be predicted. However, the calculated maximum values should be the same order of magnitude as the actual values with an anticipated maximum amplitude error factor of 2.

The time at which this voltage is maximum can be found be setting its first derivative with respect to time equal to zero and solving for the value of t (t_m) that satisfies the resulting equation:

$$\frac{dv}{dt} = A\Big[(7 \times 10^2)(-4 \times 10^6)\ \exp(-4 \times 10^6 t_m)$$

$$- (8.33 \times 10^4)(-4.76 \times 10^8)\ \exp(-4.76 \times 10^8 t_m)\Big] = 0$$

or

$$2.8 \times 10^9\ \exp(-4 \times 10^6 t_m) = 3.97 \times 10^{13}\ \exp(-4.76 \times 10^8 t_m)$$

then

$$\exp(4.76 \times 10^8 t_m - 4 \times 10^6 t_m) = \frac{3.97 \times 10^{13}}{2.8 \times 10^9}$$

$$= 1.42 \times 10^4.$$

Therefore

$$t_m \approx 2 \times 10^{-8}\ \text{sec} \tag{A-5}$$

The maximum open circuit voltage is now found by substituting Equation (A-5) into (A-4), or

$$v_{max} = A\left[7 \times 10^2\ \exp(-8 \times 10^{-2}) - 8.33 \times 10^4\ \exp(-9.52)\right]$$

$$= 6.4 \times 10^2\ A\ \text{volts}. \tag{A-6}$$

If the loop is 1 meter on a side, then $A = 1\ m^2$ and $v_{max} = 640$ volts. If the loop is 3.16 meters (i.e., $\sqrt{10}$) on a side, then $A = 10\ m^2$ and $v_{max} = 6.4$ kV.

A.2 LOOP IMPEDANCE

The terminal impedance for a loop is given by [A-3]:

$$Z = R_\Omega + R_r + jX \tag{A-7}$$

where

$$R_\Omega = \text{ohmic resistance}$$

$$R_r = \text{radiation resistance}$$

$$X = \text{loop reactance.}$$

If the loop is assumed to be a perfect conductor, then $R_\Omega = 0$. Further, the radiation resistance for a loop is given by*

$$R_r = 60\pi^2 kaN^2 \tag{A-8}$$

where

$$k = \frac{2\pi}{\lambda} = \text{phase constant}$$

$$\lambda = \frac{2\pi c_o}{\omega} = \text{wavelength in meters}$$

$$\omega = 2\pi f = \text{radian frequency}$$

$$c_o = 3 \times 10^8 \text{ m/sec} = \text{speed of light}$$

$$a = \frac{A}{\pi} = \text{radius of an equivalent circular loop}$$

$$N = 1 = \text{number of turns.}$$

Substituting these equations for the variables in Equation (A-8) gives

$$R_r = \frac{60\omega\sqrt{\pi^3 A}}{c_o} \tag{A-9}$$

---

*Figure 3.27 in Reference A-3 shows that this equation gives a straight line approximation to the exact radiation resistance which oscillates around the straight line.

If the distributed capacitance associated with the loop is ignored, then the loop reactance is due to its self inductance, or $X = \omega L$. The effect of the distributed capacitance will be to filter (roll-off) the higher frequency components and thus increase the rise time (decrease the rate of rise) of the induced voltage and currents. Thus, ignoring the distributed capacitance will result in worst-case rise time and spectrum distribution. The self inductance of a square loop of round wire is [A-4]

$$L = 0.02032\ \ell \left(\ln\frac{2\ell}{d} + \frac{d}{2\ell} - 0.774 + \mu\delta\right) \qquad \text{(A-10)}$$

where

L = inductance in microhenrys

ℓ = length of side in inches

d = wire diameter in inches

μ = permeability of conductor

= 1 for copper

δ = skin effect factor

For a large diameter wire ($d \simeq 0.5$ in), $\delta < 0.1$ [A-4] and, hence, $\mu\delta < 0.1$. Therefore, from Equation (A-10) the inductance can be approximated by

$$L \simeq 0.02032\ \ell \left(\ln\frac{2\ell}{d} + \frac{d}{2\ell} - 0.774\right) \qquad \text{(A-11)}$$

and the reactance of the loop becomes

$$X \approx 0.02032\ \omega \ell \left(\ln \frac{2\ell}{d} + \frac{d}{2\ell} - 0.774\right). \quad \text{(A-12)}$$

The total terminal impedance of the loop can now be approximated by substituting Equations (A-8), (A-9), and (A-12) into Equation (A-7):

$$Z \approx \frac{60\omega\sqrt{\pi^3 A}}{c_o} + j\left[0.02032\ \omega\ell\ \left(\ln\frac{2\ell}{d} + \frac{d}{2\ell} - 0.774\right)\right]. \quad \text{(A-13)}$$

A.3 SHORT CIRCUIT CURRENT

The time-domain, short-circuit current, $i(t)$, in a single turn square loop (area = A) of round wire can be calculated as the inverse Fourier transform of this current in the frequency domain, $I(j\omega)$. The frequency domain, short-circuit current is given by

$$I(j\omega) = \frac{V(j\omega)}{Z}$$

where

$V(j\omega)$ = frequency-domain, open-circuited voltage

= Fourier transform of the $v(t)$ in Equation (A-4)

Z = Loop terminal impedance given in Equation (A-13).

Since,

$$v(t) = A\left[7 \times 10^2 \exp(-4 \times 10^6 t) - 8.33 \times 10^4 \exp(-4.76 \times 10^8 t)\right]$$

then,

$$V(j\omega) = A\left[\frac{7 \times 10^2}{4 \times 10^6 + j\omega} - \frac{8.33 \times 10^4}{4.76 \times 10^8 + j\omega}\right]. \quad \text{(A-14)}$$

Therefore,

$$I(j\omega) = \frac{A\left[\dfrac{7 \times 10^2}{4 \times 10^6 + j\omega} - \dfrac{8.33 \times 10^4}{4.76 \times 10^8 + j\omega}\right]}{\dfrac{60\omega\sqrt{\pi^3 A}}{c_o} + j\ 0.02032\ \omega\ell\left(\ln\dfrac{2\ell}{d} + \dfrac{d}{2\ell} - 0.774\right)} . \qquad \text{(A-15)}$$

This equation for $I(j\omega)$ can be simplified by using the break-point approximation technique [A-5]. First, the magnitude of the expression given by Equation (A-15) is plotted as a function of f $(\frac{\omega}{2\pi})$. This curve is then approximated by straight line asymptotes and, finally, a simplified expression for $I(j\omega)$ is derived from this asymptotic approximation. Equation (A-15) and, hence, this simplification is not accurate at the higher frequencies where the electrically small criteria is violated. However, to get an order of magnitude approximation to the short circuit current, this equation and technique are assumed to hold at the higher frequencies. Since Equation (A-15) is a complicated expression in terms of A, the area of the loop, this simplification of Equation (A-15) is performed for specific values of A, i.e., $A = 1\ m^2$ and $A = 10\ m^2$.

For $A = 1\ m^2$, the magnitude of $I(j\omega)$ is plotted as a function of frequency in Figure A-2*. This curve is then approximated by the dotted straight line asymptotes as shown on the figure. For this asymptotic approximation, the break frequencies are found to be

$$f_1 = 6.36 \times 10^5 \text{ Hz, i.e., } \omega_1 = 4 \times 10^6 \text{ radians/sec}$$

$$f_2 = 7.58 \times 10^7 \text{ Hz, i.e., } \omega_2 = 4.76 \times 10^8 \text{ radians/sec}$$

and thus, a simplified expression that approximates $I(j\omega)$ is

*For reference purposes, the magnitudes of Z and $V(j\omega)$ given in Equations (A-13) and (A-14), respectively, are also plotted in the Figure.

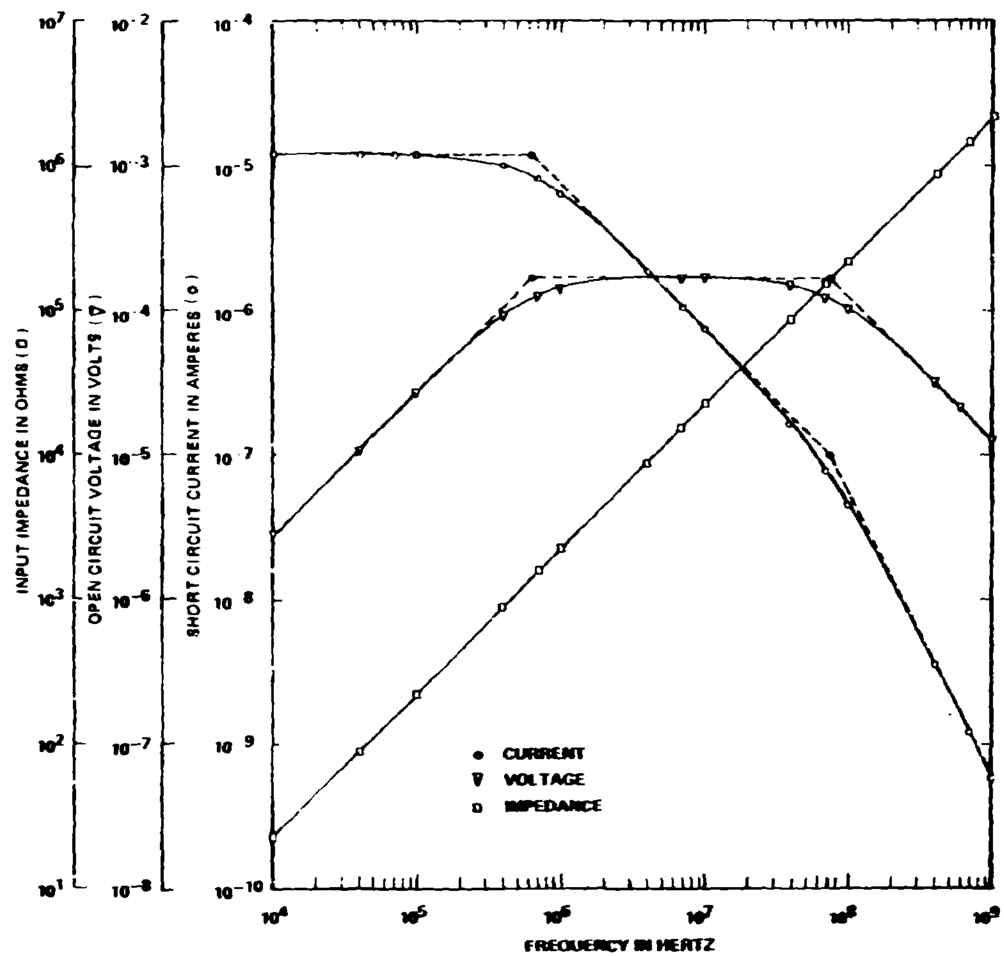

Figure A-2. Asymptotic Approximations for Voltage and Current in a 1 m^2 Loop.

$$I(j\omega) = \frac{K}{\left(\frac{j\omega}{4 \times 10^6} + 1\right)\left(\frac{j\omega}{4.76 \times 10^8} + 1\right)} \tag{A-16}$$

The constant K is evaluated by using the asymptotic values of the curve at a specific frequency. At $f = f_e = 1 \times 10^4$ Hz($\omega_e = 6.28 \times 10^4$ radians/sec),

$$|I(j\omega_e)| \approx 1.2 \times 10^{-5}$$

$$\left|\frac{j\omega_e}{4 \times 10^6} + 1\right| \approx 1$$

$$\left|\frac{j\omega_e}{4.76 \times 10^8} + 1\right| \approx 1.$$

Substituting these asymptotic values into Equation (A-16) gives

$$1.2 \times 10^{-5} = \frac{|K|}{(1)(1)}$$

or

$$K = 1.2 \times 10^{-5}.$$

Therefore,

$$I(j\omega) = \frac{1.25 \times 10^{-5}}{\left(\frac{j\omega}{4 \times 10^6} + 1\right)\left(\frac{j\omega}{4.76 \times 10^8} + 1\right)}$$

$$= \frac{2.28 \times 10^{10}}{(4 \times 10^6 + j\omega)(4.76 \times 10^8 + j\omega)} . \tag{A-17}$$

The inverse Fourier transform of Equation (A-17) gives the short circuit current as

$$i(t) = 48.3 \left[\exp(-4 \times 10^6 t) - \exp(-4.76 \times 10^8 t)\right] \qquad \text{(A-18)}$$

The time at which this current is maximum can be found by setting its first derivative with respect to time equal to zero and solving for the value of t (t_m) that satisfies the resulting equation:

$$\frac{di}{dt} = 48.3 \Big[(-4 \times 10^6) \exp(-4 \times 10^6 t_m)$$

$$+ (4.76 \times 10^8) \exp(-4.76 \times 10^8 t_m)\Big] = 0$$

or

$$4 \times 10^6 \exp(-4 \times 10^6 t_m) = 4.76 \times 10^8 \exp(-4.76 \times 10^8 t_m)$$

$$\exp(4.76 \times 10^8 t_m - 4 \times 10^6 t_m) = \frac{4.76 \times 10^8}{4 \times 10^6}$$

$$= 1.19 \times 10^2.$$

Therefore,

$$t_m \approx 1 \times 10^{-8} \text{ sec.} \qquad \text{(A-19)}$$

The maximum short circuit current is now found for a square loop 1 meter on a side by substituting Equation (A-19) into (A-18), or

$$i_{max} = 48.3 \exp(-4 \times 10^{-2}) - \exp(-4.76)$$

$$= 46 \text{ amps.}$$

For $A = 10\ m^2$, the magnitude of $I(j\omega)$, Equation (A-15), is plotted as a function of frequency as shown in Figure A-3.* This curve is then approximated by the dotted straight line asymptotes as shown on the figure. From this approximation, the break frequencies are found to be

$$f_1 = 6.36 \times 10^5 \text{ Hz, i.e., } \omega_1 = 4 \times 10^6 \text{ radians/sec}$$

and

$$f_2 = 7.58 \times 10^7 \text{ Hz, i.e., } \omega_2 = 4.76 \times 10^8 \text{ radians/sec}$$

and, thus, a simplified approximation of $I(j\omega)$ is

$$I(j\omega) = \frac{K}{\left(\frac{j\omega}{4 \times 10^6} + 1\right)\left(\frac{j\omega}{4.76 \times 10^8} + 1\right)} \tag{A-20}$$

Evaluation of the constant K as before gives $K = 7.22 \times 10^{-5}$. Therefore,

$$I(j\omega) = \frac{1.37 \times 10^{11}}{(4 \times 10^6 + j\omega)(4.76 \times 10^8 + j\omega)} \tag{A-21}$$

and, thus,

$$i(t) = 290.3 \left[\exp(-4 \times 10^6 t) - \exp(-4.76 \times 10^8 t)\right]. \tag{A-22}$$

The time at which this current is found to be maximum is $t_m \simeq 1 \times 10^{-8}$ sec. Therefore, the maximum short circuit current for a square loop $\sqrt{10}$-meters on a side is found to be

$$i_{max} = 290.3 \exp(-4 \times 10^{-2}) - \exp(-4.76)$$

$$= 276 \text{ amps.}$$

*Again, $|V(j\omega)|$ and $|Z|$ are plotted in Figure A-3 for reference.

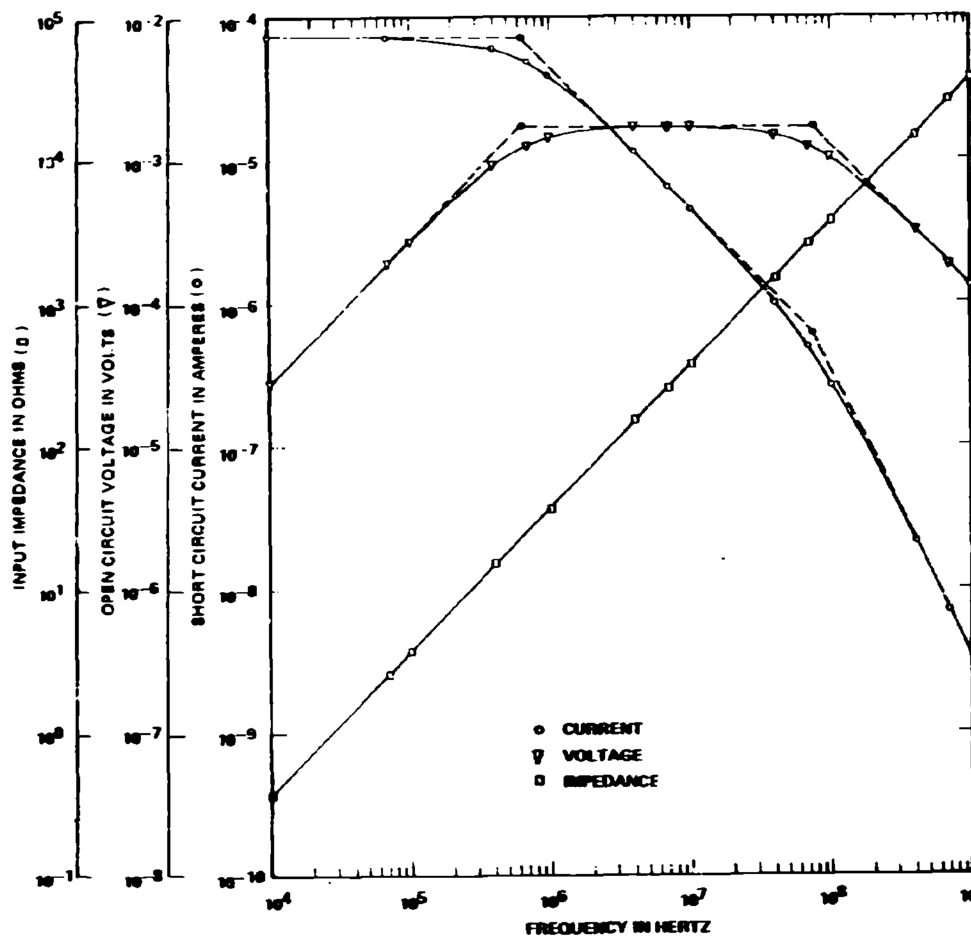

Figure A-3. Asymptotic Approximations for Voltage and Current in a 10 m^2 Loop.

A.4 SUMMARY OF RESULTS

The results of the analysis of two square loops ($A = 1\ m^2$ and $A = 10\ m^2$) of round wire (d = 0.5 in.) exposed to a worst-case EMP environment are summarized in Table A-1. The maximum open circuit voltage is that voltage which could exist between the equipment's case and signal reference if the signal ground is of a single point ground configuration (see Figure A-1). As the area of the loop was increased by a factor of 10, this voltage increased from 640 v to 6.4 kv, also a factor of 10. The maximum short circuit current in Table A-1 is that current which could flow in the loop if the equipment's signal reference is connected to the equipment case, i.e., a multiple point ground configuration. As the area of the loop was increased by a factor of 10, this current increased from 46 A to 276 A, a factor of 6. Thus, for a given increase in the loop area, the relative increase in the open circuit voltage is greater than the relative increase in the short circuit current.

Table A-1. Results of analysis of square loop* in EMP field**.

Area of Loop (m^2)	Maximum Open Circuit Voltage (v)	Maximum Short Circuit Current (A)
1	640	46
10	6400	276

*Diameter of wire = 0.5 in.

**$E(t) = 5.25 \times 10^4 \left[\exp(-4 \times 10^6 t) - \exp(-4.76 \times 10^8 t)\right]$

Based solely on this analysis, the best configuration for the ground system can not be determined. Such a determination must also consider whether the specific equipment/system is more susceptible to high voltages (associated with the single point ground configuration) or high currents (associated with the multiple point ground configuration). Also, the final selection of the signal ground configurations must take into account the effects of conducted currents, specifically stray 60 Hz ac power currents, on the equipment/system.

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ATTN: STVL
ATTN: RAEV
ATTN: DDST
ATTN: RAAE
ATTN: RATN
2 cy ATTN: VLIS
4 cy ATTN: TITL

Defense Technical Information Center
12 cy ATTN: DD

Defense Advanced Rsch. Proj. Agency
ATTN: TIO

Federal Emergency Management Agency
ATTN: Plans & Operations (EO)

Field Command
Defense Nuclear Agency
ATTN: FCPR

Field Command
Defense Nuclear Agency
Livermore Division
ATTN: FCPRL

Joint Strat. Tgt. Planning Staff
ATTN: JPST
ATTN: JLTW-2

DEPARTMENT OF DEFENSE (Continued)

Joint Chiefs of Staff
ATTN: J-5 Nuclear Division
ATTN: SAGA
ATTN: J-3
ATTN: J-3 WWMCCS Council Support Office
ATTN: J-3 WWMCCS & Telecommunications

National Central Security Service, Pacific Area
ATTN: Central Sec. Serv., Pac. Area

National Communications System
ATTN: NCS-TS, D. Bodson

National Security Agency
ATTN: TDL

Net Assessment
ATTN: Military Assistants

Undersecretary of Defense for Rsch. & Engrg.
ATTN: Strategic & Space Systems (OS)

DEPARTMENT OF THE ARMY

Headquarters
Department of the Army
ATTN: DAMO-TCV-A

Deputy Chief of Staff for Rsch., Dev., & Acq.
Department of the Army
ATTN: DAMA-CSS-N

Harry Diamond Laboratories
Department of the Army
ATTN: DELHD-N-P
ATTN: DELHD-I-TL
ATTN: DELHD-N-RBA
4 cy ATTN: DELHD-N-EM

Multi Service Communications Systems
Department of the Army
ATTN: DRCPM-MSCS-APB, M. Francis

U.S. Army CINCPAC Support Group
ATTN: Communications Electronics Div.

U.S. Army Communications Command
ATTN: CC-OPS-WR

U.S. Army Communications Sys. Agency
ATTN: CCM-AD-LB
ATTN: CCM-RD-T, CCM-AD-SV

U.S. Army Computer Systems Command
ATTN: Technical Library

U.S. Army Nuclear & Chemical Agency
ATTN: Library

DEPARTMENT OF THE NAVY

Navy Electronic Systems Command
ATTN: Technical Library
ATTN: PME 117-20

DEPARTMENT OF THE NAVY (Continued)

Naval Ocean Systems Center
ATTN: Code 4471

Naval Postgraduate School
ATTN: Code 0142

Naval Research Laboratory
ATTN: Code 2627

Naval Ship Engineering Center
ATTN: Code 6174D2

Naval Surface Weapons Center
ATTN: Code F32
ATTN: Code F31
ATTN: Code F30

Naval Telecommunications Command
ATTN: Deputy Director Systems

Office of Naval Research
ATTN: Code 715

Office of the Chief of Naval Operations
ATTN: OP 98
ATTN: OP 94

Strategic Systems Project Office
Department of the Navy
ATTN: NSP-43

DEPARTMENT OF THE AIR FORCE

Air Force Communications Service
ATTN: XP

Air Force Security Service
ATTN: XRX

Air Force Geophysics Laboratory
ATTN: SULL

Air Force Weapons Laboratory
Air Force Systems Command
ATTN: SUL
ATTN: NTO
ATTN: DYC

Assistant Chief of Staff
Studies & Analyses
Department of the Air Force
ATTN: AF/SA

Deputy Chief of Staff
Operations, Plans, & Readiness
Department of the Air Force
ATTN: AFXOK

Deputy Chief of Staff
Research, Development, & Acq.
Department of the Air Force
ATTN: AFRDQ

Foreign Technology Division
Air Force Systems Command
ATTN: NIIS Library

Headquarters Space Division
Air Force Systems Command
ATTN: DYS

DEPARTMENT OF THE AIR FORCE (Continued)

Headquarters Space Division
Air Force Systems Command
ATTN: SKF

Commander in Chief
Pacific Air Forces
Department of the Air Force
ATTN: Communications Electronics

Rome Air Development Center
Air Force Systems Command
ATTN: TSLD

Strategic Air Command
Department of the Air Force
ATTN: NRI-STINFO Library
ATTN: XPFS

DEPARTMENT OF DEFENSE CONTRACTORS

American Telephone & Telegraph Co.
ATTN: M. Gray for W. Edwards

BDM Corp.
ATTN: L. Jacobs

Boeing Co.
ATTN: V. Jones
2 cy ATTN: H. Hendrickson

Computer Sciences Corp.
ATTN: H. Blank

ESL, Inc.
ATTN: J. Marshall

General Electric Company—TEMPO
ATTN: DASIAC

GTE Sylvania, Inc.
ATTN: M. Cross
ATTN: E. Motchok

Institute for Defense Analyses
ATTN: Classified Library

IRT Corporation
ATTN: L. Duncan
ATTN: D. Swift
ATTN: R. Wheeler

R & D Associates
ATTN: C. MacDonald
ATTN: W. Graham, Jr.
ATTN: R. Schaefer
ATTN: B. Gage

R & D Associates
ATTN: J. Bombardt

SRI International
ATTN: A. Whitson
ATTN: G. Carpenter

Electronics Technology Laboratory
ATTN: J. Woddy
10 cy ATTN: H. Denny