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AIR SYSTEMS
ELECTROMAGNETIC INTERFERENCE
CORRECTIVE ACTION PROGRAM

TECHNICAL MANUAL

ELECTROMAGNETIC COMPATIBILITY THEORY AND PRACTICE MANUAL

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PREFACE

Naval Air Systems, including aircraft, avionics, engines, and support equipments, are conceived, procured, and deployed for the sole purpose of delivering ordnance on a target. A major inhibitor to the effectiveness of these air systems is Electromagnetic Interference (EMI) which results from electrostatic discharge, ambient Radio Frequency (RF) energy, system cross talk and High Powered Microwaves (HPM). There are numerous documented cases of catastrophic failure due to EMI such as lightning striking an aircraft, in one instance knocking off the nose and tail of an aircraft (this P-2 survived); torpedoes being dropped from helicopters close aboard the parent ship (radar induced); lost communications in and around cloud formations; inadvertent folding of rotor blades when illuminated by a radar; inadvertent folding/unfolding of wings aboard carriers; and burnout of micro switches when illuminated by a high powered radar.

It is commonly recognized that good bonding, shielding and grounding are important in the control of EMI. However, in high energy areas such as in and around carrier decks, 60 dB of attenuation may not be sufficient to protect the more sensitive high technology digital circuit components; the energy levels associated with these areas have proven sufficient to penetrate the smallest of enclosure openings and burnout critical circuits associated with flight control systems.

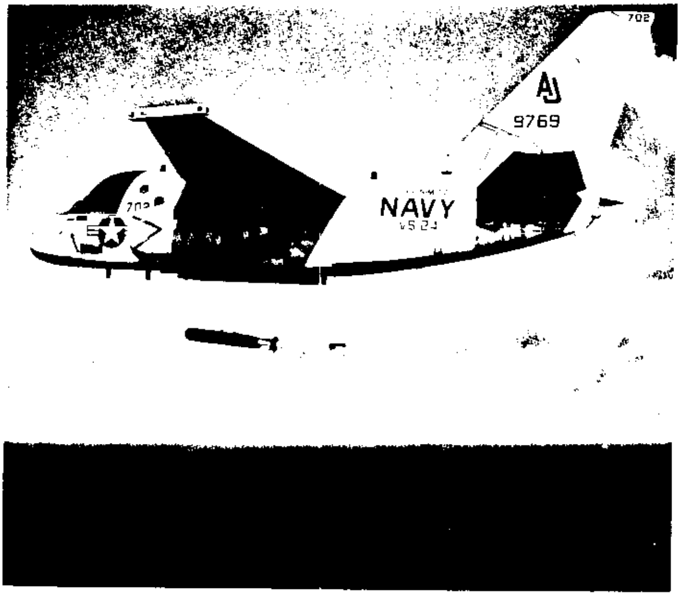
As electronic technology has moved from the vacuum tube to semiconductors and integrated circuits, the sensitivity of electronic circuits to external energy levels has dramatically increased; the ability to generate higher power levels has also increased. Recognition of these phenomena, coupled with the inherent difficulty of protecting electronic circuits, has warranted investigation of HPM as a potentially exploitable warfare technology. As it is speculated that HPM could be used as potential weapons against hardware and personnel, EM hardening and its preservation will become even more important.

This document presents the theory of EM propagation and practical approaches to EM hardening assurance and maintenance. The information contained in this document is useful in controlling electrostatic discharge, providing protection against EM pulses (thunderstorms and nuclear blast), preventing external RF energy from influencing air systems, and attaining Electromagnetic Compatibility (EMC) between air system components.

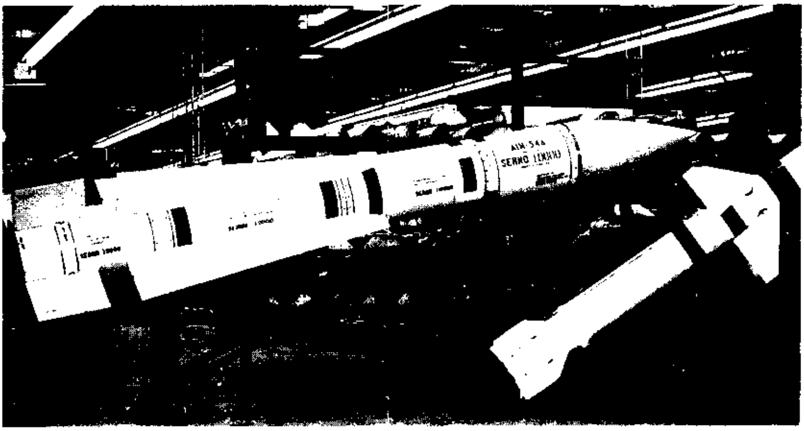
Over and above the technical aspects of this document, discussions are presented relative to the business environment in which EMI control features must be addressed. Since this document is principally directed to Naval Aviation Depots, discussions are focused on depot management. Understanding this process is important in the total context of attaining EMC in Naval aircraft.

The information contained in this document is for the use of engineers, artisans, and planners at the Naval Aviation Depots and anyone having an influence on the control of EMI and the attainment of EMC in Naval air systems. It is not intended that this information unduly restrict personnel working in the EMI environment from accomplishing their assigned tasks. Rather, the data is provided as a stimulus to the development of better methods of attaining EMC. In all cases, technical judgement, sound engineering practices and prudent use of available resources shall prevail.

Any conflict between the materials presented herein and other related guidelines or requirements shall be referred to Naval Air Systems Command, Code 5161, for resolution.



S-3 Torpedo Launch



Missile Processing at Depot

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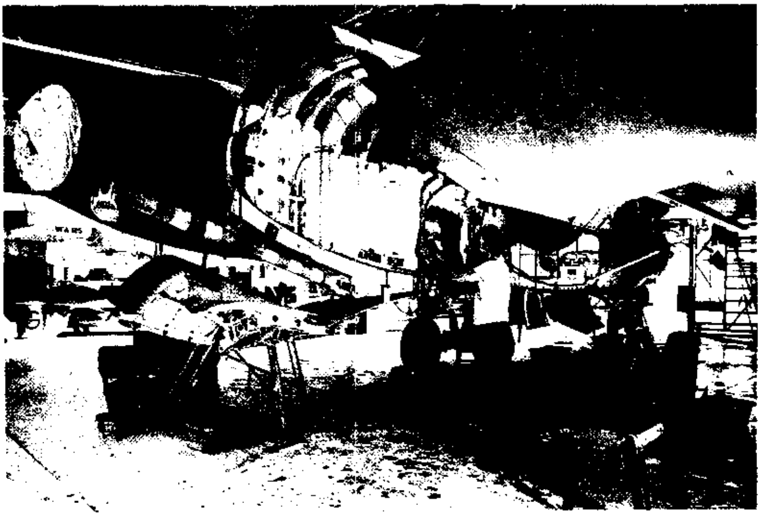

Major Modification to F-14

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CHAPTER 1
INTRODUCTION

Complex avionic systems provide a technological edge in warfare systems, making Electromagnetic Compatibility (EMC) both a force multiplier and a force enabler. A principal mission worthiness determinant of a Naval air system is its ability to operate in a hostile electromagnetic environment. When an air system can operate without being influenced by the electromagnetic environment or without causing adverse electromagnetic influence on other friendly systems, the system is said to have EMC. Air system designers place emphasis on preventing and controlling Electromagnetic Interference (EMI) with the proper use of bonding, grounding, shielding, and filtering. Designers carefully position components within the system, choosing wire routing schemes and minimizing enclosure penetrations to maximize EMC. Careful attention to these design parameters during the subsequent production cycle yields an air system that is known to be hardened against EMI.

1.1 Purpose

When an air system is placed in operational use, many adverse factors degrade its built-in hardness. Corrosion, vibration, and high force levels associated with landings and tactical maneuvers combine to degrade the existing EMI control features. It becomes the responsibility of the fleet and depot maintenance organizations to restore these lost air system EMI control mechanisms. The purpose of this document is to provide Naval Aviation Depot personnel with practical information for fulfilling this responsibility.

The environment in which Navy maintenance activities operate places many restrictions on the engineers, artisans and technicians. The restrictions associated with funding limitations, facility availability, work content control and fleet operational requirements often preclude the depots from maximizing the EMC of processed units. The presentations contained in this document recognize these restrictions and are written with practicality in mind.

The Naval Air Systems Command (NAVAIR) has established and maintains NAVAVNDEPOT's at Norfolk, VA; Cherry Point, NC; Jacksonville, FL; Pensacola, FL; North Island, CA; and Alameda, CA; to process aircraft, engines, missile components, aircraft components and aircraft support equipment. NAVAIR has also assigned the Naval Avionics Center located in Indianapolis, IN, to process selected avionic systems. Over and above the designated production programs, each depot provides instrumentation calibration support and in-service engineering services for Naval aircraft, weapon systems, electrically initiated air launched ordnance and support equipment. For the depot programs to be effective, their products and associated technical documents must exhibit quality EM characteristics. Therefore, under the Air Systems Electromagnetic Interference Corrective Action Program (ASEMICAP), NAVAIR has initiated steps to provide management and technical support services to assist the NAVAVNDEPOT's in performing their mission. In addition, the Air Industrial Electromagnetic Compatibility (AIEMC) portion of ASEMICAP has been initiated to institutionalize EMI considerations in aircraft weapon system engineering, depot work package development, and maintenance program execution at the NAVAVNDEPOT's. Under AIEMC, all Naval Air System programs are addressed.

This document is provided as an assist to the Naval Aviation Depot (NAVAVNDEPOT) engineers, journeymen, and technicians responsible for restoring an air system's EM characteristics. Although the focus of these discussions is depot processing of aircraft, the information is applicable to and of use to all personnel associated with the design, maintenance and logistics support of Naval aircraft, installed systems and support equipment.

To ensure that the recommended elements are viable, will improve Naval aviation and are compatible with the overall objectives of the DoN, AIR-5161 maintains a working relationship with the other Naval Systems Commands, particularly NAVSHIPS and SPAWARS. Through these liaisons, program elements addressing aircraft EMI hardness, compatibility with shipboard operations, operational frequency allocations, and overall weapon system compatibilities within the battle group are examined. Those program features that are identified as having the highest probability of improving fleet readiness are recommended to CNO for inclusion in the overall Navy E^3 program.

The Air Industrial Electromagnetic Control sub-program of ASEMICAP is one E^3 element that has been implemented as a result of AIR-5161's recommendations. Since this element is technically oriented toward the improvement of in-service aircraft, AIR-5161 has instituted initiatives to ensure the Naval Aviation Depots are active participants in the E^3 technological community. Toward this end, the Naval Aviation Depots are invited to participate in the semiannual E^3 progress reviews, attend E^3 colloquiums and seminars, and participate in all E^3 technological initiatives. The depots are actively encouraged to establish and develop liaisons with all organizations working on the improvement of Naval Aviation E^3 projects. To assist the depots in establishing these liaisons, a list of points of contact is provided in appendix A.

1.2 Background

Electromagnetic interference is one of the most insidious dangers to Navy air power today. The electromagnetic environment surrounding an aircraft carrier and support ships is infinitely complex. Radiation hazards (RADHAZ) threaten personnel (Hazardous Electromagnetic Radiation Personnel (HERP)), volatile fuels (Hazardous Electromagnetic Radiation Fuel (HERF)), and sensitive ordnance (Hazardous Electromagnetic Radiation Ordnance (HERO)). Electromagnetic fields on or around the flight deck commonly dump aircraft computer programs necessary for the operation of mission essential equipment; personnel are injured and sensitive equipment damaged by Electrostatic Discharge (ESD) from unintended and unsuspected collectors, i.e., Support Equipment (SE); and unprotected ordnance may be detonated or launched without command. Therefore, a carrier's ability to support wartime functions can be significantly reduced by the same electromagnetic force that is essential for modern combat capability.

The search for measures to prevent EMI problems has been a long-standing concern. During World War II, the Navy rapidly expanded its development of electronic systems. As aircraft assets and mission capabilities expanded, so did EMI-related problems. Initial problems were Radio Frequency Interference (RFI) related, but state-of-the-art aviation equipment began to span a broader portion of the electromagnetic spectrum. This enlarged view of the total interference phenomenon brought about the term "EMI" which more fully describes the source and nature of the problem.

The effects of EMI were experienced long before their actual cause, or any corrective action, was understood. As the science of electromagnetics became more precise, and the advantages of electronic equipment became more widely available, the presence of EMI became more aggravating and disruptive. The present sophistication in electronics demands almost total involvement of modern equipment with some form of electromagnetics. Unfortunately, EMI threatens to reduce the effectiveness of some mission essential equipment to zero.

To engage and destroy an adversary, Navy combat aircrews are supported by aircraft equipped with electrical and electronic devices of enormous capabilities. However, if EMI is not controlled by design, or if it is due to faulty maintenance or improper operation, EMI can render a multimillion dollar combat aircraft ineffective. The presence of EMI in a weapon system will deny target acquisition or tracking, and EMI-prone Air Launched Ordnance (ALO) is as dangerous to the crew launching it as it is to any prospective target. The requirement for operations in all weather conditions makes it imperative that an aircraft weapon system not be susceptible to normally damaging lightning strikes. To direct the rapid and effective correction of EMI in current aviation assets, and to ensure future combat capabilities by designing EMC into new acquisitions, a control program was needed at the Systems Command level.

Initial efforts undertaken by specialized Navy engineering and design units were aimed at limiting EMI produced by electrical and electronic equipment. Engineering specifications and standards were developed to direct designers and manufacturers toward more compatible products; these early specifications evolved as electrical and electronic equipment progressed and knowledge of EMI grew. One such document was MIL-STD-461, "Electromagnetic Interference Characteristics Requirements for Equipment," issued in 1967. This Standard addresses aircraft, avionics, ALO and ground support equipment.

In spite of the application of these early specifications, serious interference continued. Attempts to correct problems revealed that limiting the EMI produced by individual equipment was only a partial solution. Further action would be required to increase the level of EMC among systems, particularly those systems which had to be operated simultaneously to meet mission requirements. Additionally, such factors as system design, system maintenance, operating frequency selection, and proper equipment operation were found to be highly significant considerations. Therefore, the Navy initiated additional programs to address these factors.

One of the most important developments during this early period was the reduction of interference affecting specific equipment. As an example, electronic receivers were found to be susceptible to interference from sources both in and out of their pass band. This discovery led to the establishment of a requirement that receiver characteristics be specified when a frequency allocation was being sought in connection with a new system; previously, only transmitter characteristics had been specified. This requirement focused the attention of system designers on the fact that, from an operational point of view, a receiver's interference susceptibility characteristics could be just as disruptive as the spurious emissions of a transmitter. It became clear that, for EMI to exist, an electronic triangle consisting of a source (transmitter), a victim (receiver) and a coupling path between them had to be present.

Another significant development during this period was recognition of the impact of the operating environment on the attainment of EMC among air systems. The great increase in airborne electronic systems created greater intersystem EMI;

the rapid growth in miniaturization of systems created greater intrasystem EMI. The concentration of electronic radiators on aviation capable ships, and the order of magnitude increase in the amount of (miniaturized) electronic receivers on aircraft, resulted in an EM environment unique to the Navy. This uniqueness demanded a concentrated engineering thrust for EMC in Navy aviation assets. Early corrective measures were directed toward overcoming specific problems encountered, but procedures for implementing the corrective measures were relatively ineffective on a fleet-wide basis.

In the late 1960's, the Tactical Electromagnetic Systems Study (TESS), a performance analysis of ship and task-force EM system requirements in relation to threat configurations, led to the establishment of the Tactical Electromagnetic Program Office at the Chief of Naval Operations (CNO) level. This organization was established as the activity responsible for centralized monitoring and coordination of the development, procurement, and support of all tactical electromagnetic systems. This in turn led to establishment of a Tactical Electromagnetic Program Office at NAVAIR. In spite of some progress achieved as a result of this piecemeal approach to the solution of EMI/EMC-related problems within the fleet, by late 1972 it had become increasingly evident that the Navy still faced the following threefold task:

- To design and procure aircraft whose electronic systems are electromagnetically compatible with their unique fleet operational environment.
- To identify and eliminate EMI on aviation systems and equipment currently in the operating fleet.
- To provide training for all personnel involved in the design, procurement, installation, maintenance, and operation of aircraft and their electronic systems to ensure that these individuals have an understanding of the requirements and procedures for achieving and maintaining EMC throughout the life of an aviation related system.

An organized, cohesive program was required to achieve these ends and develop standards for testing, regulating, documenting, and promulgating the corrective measures needed to achieve acceptable levels of EMC. It was for these reasons that ASEMICAP was established in 1979.

1.3 Scope

This document applies to all DOD personnel involved in the depot rework of Naval aircraft. Specifically, it is applicable to the engineers who develop depot work packages and maintenance manuals; methods and standards, and operations analysis personnel who translate the work package requirements into job specifications; planners and estimators who schedule and price the work; examination and evaluation personnel who evaluate the physical condition of the aircraft; and quality assurance personnel who certify the work performed.

The contents of this document are focused on work procedures that will reduce aircraft EMI conditions during the performance of aviation maintenance. This document provides explanations of the following:

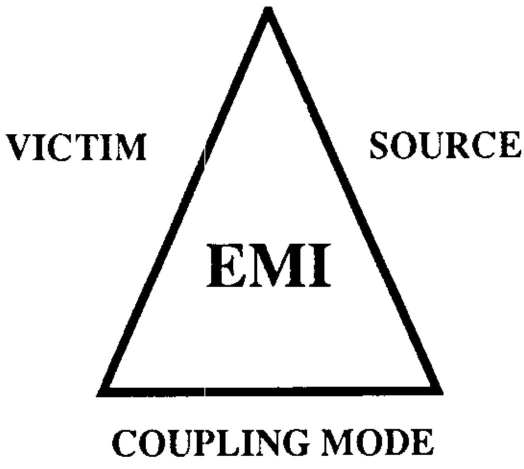
- Programs designed to improve EMI environments.
- Theory of electromagnetic propagation and effective means of controlling its energy transfer and absorption.
- Business practices of the aviation industrial community.
- Practical methodologies for controlling and improving the EMI/EMC environment.

AV-8/F-4 Aircraft Line

CHAPTER 2
PROGRAM DEFINITIONS

This section defines and discusses the principal terms commonly used in the Electromagnetic Environmental Effects (E^3) community. It is intended to provide ready reference for personnel who are new to E^3, particularly those engineers and artisans working in the depot support environment.

2.1 Electromagnetic Interference



Electromagnetic Interference (EMI) is defined as any electrical or electronic disturbance, phenomenon, signal, or emission (man-made or natural) which causes undesirable responses, malfunctions, or performance degradation. In the aircraft industry it generally relates to the control and test of components, subsystems, or "black boxes" in accordance with Military Standards 461 (control) and 462 (test).

EMI is the phenomena whereby undesirable voltages and currents appear in an electrical circuit or electronic component. These voltages and currents result from unplanned EM energy coupling between systems either through radiation or conduction. For EM coupling to occur, an emitter source and susceptor must be present. Typical emitter sources are radio and radar transmitters, power supplies, transformers, electrical generators, and local oscillators. Typical susceptors are low voltage relays, navigation instruments, computers, radio receivers, and ordnance. A particularly troublesome form of coupling is conduction coupling, usually referred to as a ground loop. This normally occurs when two devices are connected to a common ground and current is passed between the devices via this ground path. Conduction coupling may also be caused by external radiator inducing currents in coaxial cable shields which are then manifested as EMI.

As noted previously, for EMI to exist there must be a source of EM energy, a device susceptible to the energy and a coupling medium between them. Unplanned EM coupling may exist between two devices without negative effects. For instance, if the received energy is outside the bandwidth of interest or is eliminated by filtering, then the systems are compatible.

Reduction of EMI at the subsystem (box) level forms the root of E^3 control. It is difficult, if not impossible, to control EMI on a complex aircraft if its constituent subsystems are not properly designed for EMI control. Testing for compliance to the MIL-STD-460 series is a normal adjunct of environmental testing (temperature, vibration, etc.) conducted by the subsystem manufacturer. To ensure/enforce MIL-STD-461/2 EMI standards on aircraft systems, NAVAIR relies primarily on Defense Contract Administrative Services (DCAS) personnel to monitor contractor testing. NAVAIR sometimes requests the Naval Avionics Center, Indianapolis (NAC Ind), to assist on specific programs if a contractor is having problems complying or certifying compliance with the program specifications, or if a contractor does not have adequate facilities to perform the required tests. NAC field teams are dispatched to supplement specific DCAS staffs and, if needed, NAC has an in-house EMI test capability.

During the conceptual phase of a system life cycle, the expected Electromagnetic Environment (EME) in which the equipment will operate must be determined so that EMI design and test requirements can be established. This requires the support of engineering personnel knowledgeable in Navy operational and airframe platform EMC design requirements. The requirements of MIL-STD-461 are applicable to every Navy subsystem to the extent specified for that individual equipment or subsystem, its mission and intended installation.

To ensure the required tests are properly conducted throughout the development and eventual production life cycle, NAVAIR has a continuing need for:

- Several laboratories staffed and equipped to conduct EMI T&E when manufacturer testing is insufficient.
- Navy laboratories staffed and equipped to conduct independent investigations of new technology and test techniques.

With the trend of today's technology toward microprocessor-controlled systems, it is expected that the importance of EMI testing will increase in the near future. Advances in technology necessitate that NAVAIR continue to recognize the need for increasing its involvement in EMI testing by enlarging the E^3 staff and expanding the EME test capabilities of NAVAIR field activities.

2.2 Electromagnetic Compatibility

Electromagnetic Compatibility (EMC) is probably the most commonly used term of all the E^3 designations. It is traditionally defined in the broadest sense as the capability of electronic equipment or systems to operate within a defined margin in the intended operational EME at designated levels of efficiency without degradation. This definition includes the ability of the aircraft systems and equipment to operate correctly without producing uncontrolled electromagnetic emissions. EMC, as used in the aircraft industry, refers to aircraft intra- and intersystem compatibility. Intersystem compatibility, also covered by the term Electromagnetic Vulnerability (EMV), refers to a platform's ability to operate with other platforms in their intended environment. Intrasystem EMC refers to the interaction of subsystems integrated within a specific aircraft, and the ability of the aircraft to operate as a total system in its intended operational EME without degradation.

As a result of increased complexity in electronic circuits, higher power levels, and greater numbers of subsystems packaged in a single integrated system, the field of EMC is rapidly expanding. Personnel in the fields of electronics, structures, metallurgy, chemistry, and aerodynamics are beginning to specialize in the EMC field. These EMC specialists are successfully developing unique EMI control mechanisms, often without detailed analytical analyses but with a solid understanding of EMI and EMC concepts. This is a strong indication of the growth potential that exists within the EMC field.

The Navy's need to ensure EMC in its fleet operations has grown geometrically over the past several years. In the past, avionics were added to an airframe design with relative ease. Each system was self-contained and needed only power, a cockpit control and display, and its tie to the airframe to operate. Because of circuit and electronic system simplicity, the aircraft and its subsystems were not highly susceptible to EMI. Few systems were digital and transmitters operated at widely spaced frequencies. Simple blanking circuits, filters or antenna placements were sufficient to eliminate most EMC problems between equipment operating on the same frequency band or having harmonic or spurious response type EMI problems. Intra- and intersystem interference that could not be resolved had to be tolerated, with some degradation to the aircraft's mission capability: loud clicking in the ICS, false display symbology, false threat warnings, errors in fuel gauge readings, fluctuations of engine RPM, etc. Although most of these airframes are still in use, their avionics packages have been updated through airframe and avionic changes and many microcircuit and digitally-based complex systems have been retrofitted into the airframes. These hardware upgrades, while solving many of the previously experienced EMI problems, have created new problems of their own.

New aircraft such as the F-14, S-3A/B and F/A-18A utilize highly integrated avionic and weapons systems with essentially 100% digital technology which now includes the aircraft flight control surfaces. The "fly-by-wire" F/A-18A employs multiple microprocessors which can be highly susceptible to EMI problems. Also, like the F/A-18A, new aircraft are utilizing composite material technology which greatly reduces the amount of shielding protection formerly afforded by all-metal-fuselage aircraft. In short, the Navy has an increasingly urgent need to ensure that newly developed, newly modified, and newly procured aircraft avionic and weapon systems are electromagnetically compatible both with other aircraft systems and the operational EME. With the trend toward electronic micro-miniaturization, this need will increase dramatically each year.

After an aircraft has been in fleet use for several years, EMC problems may arise from such factors as bonding degradation (due to corrosion, metal fatigue, or maintenance induced degradation of shielding, metalized gaskets, etc.). Through ASEMICAP, several fleet aircraft are subjected to class evaluations each year to evaluate the aircraft's EMC condition. NAVAIRTESTCEN serves as the principal NAVAIR center for aircraft inter- and intrasystem EMC expertise, possessing aircraft support capabilities and the facilities necessary to conduct class evaluations, as part of the ASEMICAP program, and end item testing.

To ensure maximum EMC control, the Navy must be heavily involved at strategic points throughout the life cycle of a system or aircraft. Merely testing the end product will not result in effective EMC control. Rather, EMC testing must begin during conceptual design and end with the system or aircraft's retirement. An effective NAVAIR EMC assurance program requires:

- A field activity engineering staff experienced in both EMC technology and Navy aircraft systems to conduct the required T&E and assist NAVAIR throughout system life cycles.

- An aircraft EMC test laboratory (large shielded hangar or anechoic chamber) with sufficient capacity to keep pace with the growing demand for tests. Additional test laboratories will be needed in the near term and future time periods.
- An EME operating system capable of subjecting aircraft, missiles, avionic equipment and Ground Support Equipment to carrier deck EME's from 10 KHz to 40 GHz.

As better techniques for controlling EMI are identified, the Research and Development communities will expand the EMI technology base to scientifically analyze and update requirements. For instance, it is currently recognized that shielding reduces electric field strengths and that more shielding is better, but it is often difficult to calculate exactly how many dB of attenuation is required in a particular EME. Equally bothersome is the difficulty in predicting how much shielding a given design will provide. As better techniques become available to technically specify the EME parameters and the paths whereby EM energy penetrates air systems, more precise shielding requirement definitions will be possible.

2.3 Electromagnetic Pulse

A high density, short duration burst of EM energy is known as an Electromagnetic Pulse (EMP).

Two common sources of an EMP are nuclear detonations and atmospheric lightning. The frequency spectrum of an EMP ranges from 1 KHz to 1 GHz, with peak energy levels occurring between 10 and 100 KHz for a nuclear detonation and at approximately 10 KHz for lightning.

Aircraft electrical and electronic systems must be designed and maintained to ensure protection against EMP. Protection from lightning strikes is important to ensure safety of flight and mission accomplishment, while protection from nuclear detonation EMP's must also recognize higher level national security issues. It has been shown that high altitude nuclear blasts generate High Altitude Electromagnetic Pulses (HEMP's), which can disrupt electrical and electronic systems up to 3000 miles from the blast site. Therefore, a high altitude nuclear blast (above 25 miles) could black out all communication systems nationwide. Although these strong EM fields are of short duration, the concentrated energy can cause severe or permanent physical damage to unprotected systems, rendering them useless for extended periods. Such a communication loss would highly motivate hostile nations to exploit this phenomena during an all out conflict. As a result, quality EMP protection is mandatory for all strategic national communication and weapon systems.

2.3.1 Nuclear Burst EMP

Modern military systems, particularly aircraft, are laden with sophisticated electronics that are particularly vulnerable to EMP. The EMP resulting from a high altitude (exoatmospheric) nuclear burst can produce EM field strengths in excess of 50,000 volts per meter (peak) at the earth's surface, at distances thousands of miles from the point directly under the burst. Severe EMI problems have been encountered with Naval aircraft operating in a carrier deck EME nominally rated at 200 volts per meter. By simple extrapolation, the potentially catastrophic effects associated with EMP energies of 50,000 volts per meter can be appreciated. Therefore, the Navy has focused attention on the effects of EMP for more than a decade.

Avionic System Test Facility

Nuclear Blast

A means of simulating the nuclear EMP is required for both subsystem and full-scale aircraft testing. The EMP interaction must ultimately be treated as a system E^3 problem because the aircraft's metal structure forms a receiving antenna for EM energy. The aircraft's topology can increase or decrease coupled energy levels, and the coupling effects of this energy through door seams, windows, wheel wells etc., to the electronic and electrical systems are not well understood. However, it is recognized that the coupled energy can produce burnout of semiconductor or other electronic components, or cause transient disruption of digital equipment, computations, or memories. The increasing use of composite aircraft structures will cause a greater increase in the requirement for wiring, cabling and system component protection during development.

In the future, EMP interaction assessment technology should be sufficiently developed so that analysis, supported by circuit and subsystem level testing, may be adequate to achieve high confidence in the survivability of a newly designed system. Development efforts are ongoing to attain a reliable, alternative test technique to full-scale radiation testing. However, determination of a new system's survivability in an operational environment will continue to require some full-scale EMP simulation tests; EMP simulation tests will still be required to validate aircraft ECP's and verify that the EMP vulnerability of a Fleet aircraft has not changed due to operational usage and Fleet maintenance.

The Navy currently operates a sophisticated EMP test site at the NAVAIRTESTCEN. The site is configured with a Maxwell Laboratories ML-5 pulser that can generate up to 5 megawatts of energy on a 5 minute duty cycle. The pulser, suspended 30 meters above the test pad, produces nominal field strengths of 50 KV/M at the test aircraft. The existing pulser has a semi-elliptical, horizontally polarized dipole. This configuration, when upgraded, will include a vertically polarized dipole (2.5 megawatts) and a lightning simulator

(200 K amps), enabling the Navy to test and evaluate the total EMP hardness of any aircraft.

The NAVAIRTESTCEN EMP Facility permits instrumenting 90 test points within the aircraft; 16 of these points can be monitored on any given pulse. The aircraft configuration for EMP and lightning susceptibility testing can range from the basic airframe to a full mission configuration. On-board systems may be operated in a simulated mission environment to test the full impacts of EMP caused by lightning and nuclear bursts.

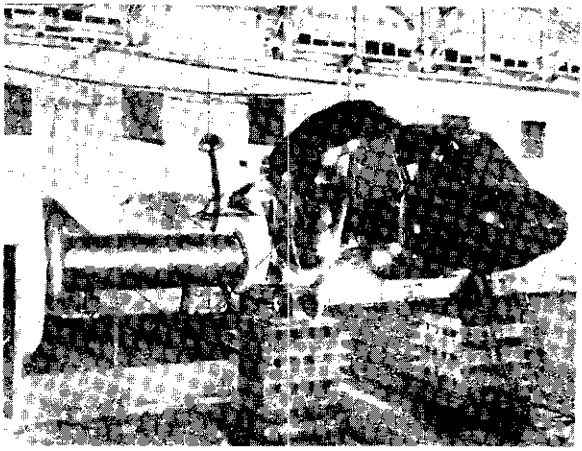
It must be recognized that high powered radiation testing has the potential for severely damaging the equipment under test. Therefore, the weapon system program managers must weigh the benefits to be gained from the tests against the possible costs associated with damaged equipment. A practical approach is to conduct incremental tests starting with a stripped down aircraft and low power pulses and, as the tests show good EMP protection, applying more equipment and power incrementally. If severe susceptibility to EMP becomes apparent at any point in the test scenario, the tests may be suspended while corrective measures are implemented.

Since 1970, three EMP simulators built for the Air Force Weapons Laboratory (AFWL) at Kirtland AFB have been used for testing aircraft including the

B-52, EC-130, LEC-135, 747 airborne command posts, and F-111. These simulators consist of a horizontally polarized dipole, a vertically polarized dipole, and a suspended radiating EMP simulator. Two new facilities have been constructed by AFWL - a larger VPD, and a mammoth trestle with a wooden platform higher than 30 meters, capable of supporting a 747 size aircraft.

The Naval Surface Weapons Center (NAVSWC) operates a simulator known as EMPRESS (Electromagnetic Pulse Radiation Environment Simulator for Ships) located on the Patuxent River at Solomons Island for testing the EMP hardness of ships and missiles. EMP testing of aircraft has been performed by NAVSWC/White Oak at NAVAIRTESTCEN since 1972, when a portable simulator borrowed from the Army was used for a short test on a P-3C aircraft. In 1976, a fixed simulator called EMPSAC (EMP Simulator for Aircraft) was constructed by NAVSWC at NAVAIRTESTCEN to simulate the horizontal electric field component of an EMP wave. In 1978, another simulator called NAVES (Navy Aircraft Vertical EMP Simulator) was constructed to provide the vertical component. These facilities have been used to test EMP hardening modifications on an A-7E and EC-130 TACAMO aircraft and will be used during all future aircraft tests.

2.3.2 Natural EMP



Lightning Test

Natural electrostatic effects most commonly relate to lightning, static charging and Precipitation Static (P-Static) which can cause severe unexpected degradation to aircraft or mission systems, and create hazards for air and ground crew personnel. Lightning is a discharge of atmospheric electricity from one cloud to another or between a cloud and the earth. Static charging occurs during normal flight operations which, when not fully discharged, may cause arcing between a tanker and an aircraft setting up for air refueling, or produce hazardous voltage levels on hovering helicopters. P-Static is static interference generated as a result of the slow discharge of large charges built up on aircraft or other objects by rain, dust particles, sleet, snow, or electrically charged clouds (Triboelectric charging). Static charge may also build on an aircraft on the ground; parking ramps are equipped with ground bonding points to help control these build-ups.

Naval aircraft are usually tested to determine if installed systems are damaged or upset as a result of lightning strikes or static discharging. The systems and equipment in older aircraft still in use today, such as the A-4, F-4, A-7, etc., are not as susceptible to damage from coupled electrical discharges because they are housed in an all-metal fuselage and use signal levels substantially higher than induced voltages or currents caused by the EM fields from lightning and static charging. Instances where systems and equipment are affected are usually corrected by using arrestors, diverters, or additional shielding. The current military specifications for system EMC requirements address lightning test requirements only from the safety of personnel and aircraft standpoint. All new aircraft are required to pass ground lightning tests.

The potential for adverse effects from lightning have increased significantly with the advent of composite materials for aircraft fuselages, structures and equipment. Through research, development and testing, much has been learned in recent years about the structural strengths of composite materials for aircraft, including the damaging effect of lightning and EM shielding characteristics. However, there is a paucity of information on how lightning and precipitation static discharges affect modern-day electrical/electronic integrated circuits.

Continued research and development by the aircraft and equipment industries, colleges and universities, and government agencies is providing excellent information on lightning characteristics and induced voltages/currents. Most aircraft work has been performed using scale modeling; because of the non-linearity of natural lightning, the linear extrapolation of data still leaves questions on how full-scale mission configured aircraft will perform under conditions of lightning and static discharges. To fully determine the effect of lightning and static discharges on aircraft mission capabilities, full-scale mission configured aircraft have to be tested and evaluated using full threat simulated lightning and static charging simulations. Unfortunately, full-scale testing tends to be cost prohibitive in that valuable avionic equipments are sacrificed during the test.

2.4 High Powered Microwaves

The power outputs from microwave tubes have grown by an order of magnitude each decade since 1940. The potential to develop powers on the order of 20 gigawatts has moved microwave technology into the arena of offensive weapons. Microwave energy sources currently available include the classic magnetron and klystron, and the newer technologies of virtual cathode oscillators (Vircator), gyrotrons, free electron lasers, and beam plasma generators. Typical operating frequencies of these sources range from .5 to 100 gigahertz (magnetron), with potential energy levels from 5 to 20 gigawatts (Vircator).

The technology to develop High Powered Microwave (HPM) weapons currently exists but, as of this writing, actual deployable weapons have not been constructed. However, it appears that such weapons may be available in the foreseeable future and it is envisioned that the first deployable weapons will be of sufficient energy to damage an aircraft or missile out to a range of 100 kilometers. These weapons are likely to be large, bulky apparatus operating in a pulsed (1 us) mode with each pulse at a different frequency. The probable transmitting characteristics are based on technological restrictions and desirable features. The Vircator is restricted to pulses of 100 nanoseconds or less; pulses operating at variable frequency are more difficult for the enemy to locate, and variable frequency pulses increase the probability of the energy striking and penetrating a resonant opening in the target.

Recognizing that this technology is not restricted to the United States, NAVAIR is currently investigating the modes under which HPM may penetrate aircraft and missiles, the likely adverse effects resulting from such penetrations, and the countermeasures necessary to prevent these effects. The Navy's HPM hardening program is divided into three areas of interest: energy levels less than 1 watt/CM^2, where electronic systems are susceptible to jamming; energy levels between 1 watt/CM^2 and 1 megawatt/CM^2, where electronic systems are susceptible to operational damage; and energies greater than 1 megawatt/CM^2, where physical damage is possible. NAVAIR's attention is focused in these areas since HPM energy levels applicable to anti-personnel weapons are not currently available. Should the technology progress to the point that anti-personnel energy levels are available, attention will be focused on the appropriate countermeasures.

If currently available levels of energy from microwave generators are directed toward an aircraft or missile, the energy levels at the target could be sufficient to burn out diodes and other sensitive electronic circuit components. Developing and applying protective measures to combat HPM's is a most challenging assignment. Considerable effort has been expended on predicting and testing the effects of EMP's resulting from nuclear bursts and lightning and many of the lessons learned are applicable to the HPM problem. Unfortunately, the frequency spectrums of EMP and HPM are well separated, with the EMP spectrum falling between 1 and 100 megahertz while the HPM spectrum lies between 500 megahertz and 100 gigahertz. The degree to which microwave energy will penetrate an enclosure (aircraft or missile) is a function of the size of the openings in the enclosure and the wavelength of the energy. That is, a HPM pulse of energy will penetrate smaller openings than would be observed from a nuclear or lightning pulse. Since aircraft and missiles normally have access panels and potentially other small openings in the skin, the mechanism for HPM energy penetration is relatively high. Furthermore, it must be recognized that a properly designed HPM pulse generator would vary in frequency to maximize the probability of finding a resonant opening in the target which would allow energy penetration.

2.5 Air Systems Electromagnetic Interference Corrective Action Program (ASEMICAP)

ASEMICAP was established in 1979 in direct response to EMI problems being reported by fleet Naval Aviation Commands. One such incident involved an Atlantic fleet helicopter that suffered severe damage from EMI. It was initially believed that the aircraft had been radiated by a new weapon system from a non-allied nation. Subsequent investigation, however, determined that the EMI was internally generated within the aircraft. The net result was that the aviation community realized that a real EMI problem existed in the nation's airborne weapon system, setting the foundation for the ASEMICAP.

The purpose of ASEMICAP is to reduce or eliminate the progressive deterioration of fleet aircraft combat capability caused by E^3. The program provides technical support to the fleet by evaluating the susceptibility of Navy aviation assets to EMI. ASEMICAP is also initiating modernization efforts by requiring the evaluation of EMI considerations in the design of new and follow-on equipment. The basis for design specifications is the feedback from ASEMICAP's EMI data gathering responsibility.

The goals and objectives of ASEMICAP are to identify and correct EMI problems in fleet aviation assets to attain and maintain full combat capability. To achieve this, Naval Air weapons systems must be examined to determine if previously known EMI problems still exist, if new EMI problems have arisen while the system has been in service, and if the E^3 design and maintenance techniques are adequate.

ASEMICAP efforts are focused in four major areas:

- **Class Evaluations** - a process to examine fleet aircraft for evidence of EMI problems, quantify the problems and recommend corrective actions.
- **Fleet Problem Investigations** - a process to respond to fleet reports of suspected EMI problems. Under this program, fleet response teams are available to assist the fleet in investigating suspected EMI problems, documenting the problems, developing corrective actions, and implementing corrective actions.
- **ASEMICAP Management Information and Tracking System (AMITS)** - a database used to maintain the collection of documents related to NAVAIR E^3 problems. This database, maintained by the Naval Ocean System's Center, contains the results of class evaluation and fleet-reported

problems and the status of corrective actions, identifying those accomplished, planned, and deferred. This database system is accessible through the Defense Data Network. On-line access procedures and codes can be acquired from NAVAIR 5161 personnel. For further information, contact NAVAIR 5161 at 202-692-8600.

- **Incorporation of lessons learned into new procurements** - as better EMI control techniques and technologies are identified, and as better EMI aircraft budgeting plans are available, aircraft and system vendors will be required to deliver equipment with better EMI control characteristics.

2.6 Air Industrial Electromagnetic Compatibility

The Air Industrial Electromagnetic Compatibility (AIEMC) program was initiated in 1986 to incorporate EMC improvements into Naval aircraft as part of the depot process. Aircraft undergoing rework at the Naval Aviation Depots receive a thorough examination and evaluation of the airframe's material structure as required by the Standard Depot Level Maintenance (SDLM) specification for the aircraft. Correction of identified material deficiencies is planned, scheduled, and accomplished during the depot process. However, testing and maintenance of avionic systems is limited to those safety of flight systems necessary to safely flight test the airframe and ferry the aircraft.

The immediate objective of the AIEMC portion of ASEMICAP is to identify practical, cost effective methodologies to evaluate the EMC condition of the aircraft undergoing depot processing and to incorporate corrective action programs that will enhance the EMC of the aircraft. Attainment of this objective requires close liaison between the operating forces, type commanders, NAVAVNDEPOT's, NAVAVNDEPOTOPSCEN, and NAVAIR. This effort addresses modification of the SDLM specification to include EMI corrective action processing in the Master Data Records and Norms (Workload Standards) for the aircraft.

2.7 **Depot Rework**

Each active Naval aircraft is assigned a period end date by the CNO. This date prescribes when an aircraft should undergo depot maintenance processing in conformance with a SDLM specification. The premise is that there are certain maintenance actions that are beyond the capability of the organizational and intermediate level maintenance organizations. The period end date is computed by adding a predetermined number of months to the date the aircraft last completed depot rework. The number of months is dependent upon the aircraft's type, model, and series and is related to its normal operating environment, construction type, and maintenance history. A corrosion-prone aircraft type that is subjected to high concentrations of salt spray would have a shorter period between depot cycles than a land based aircraft that exhibits minimal corrosion susceptibility.

S-3 Launch from Carrier Deck

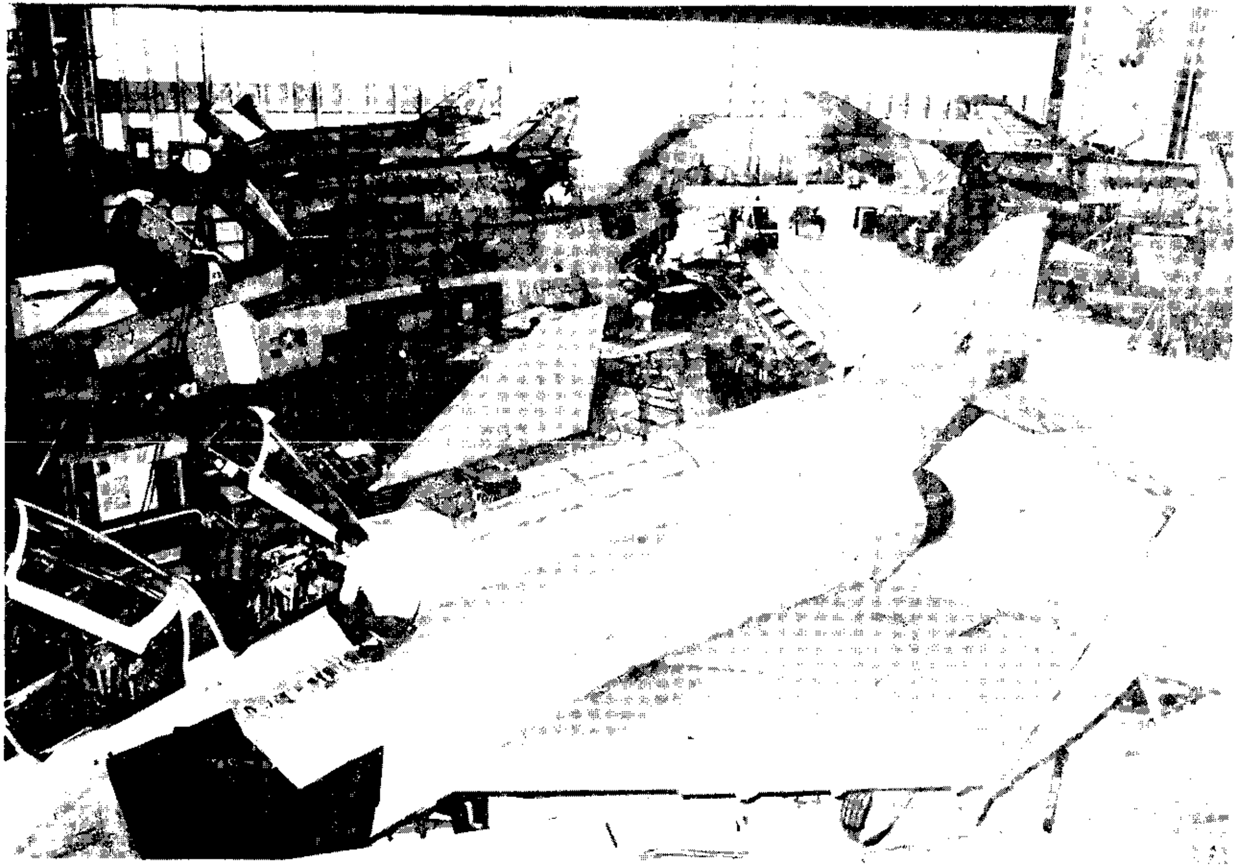
If, because of operational requirements and other factors, it appears desirable to extend a particular period end date for a specific aircraft, then a material condition inspection can be performed by one of the NAVAVNDEPOT's. If the inspection shows that the material condition is such that depot processing may be delayed, the NAVAVNDEPOT will recommend a period extension and revised period end date. Short of a full extension, the depot could recommend a restricted extension contingent on the performance of certain depot maintenance actions. If the CNO approves and funds are made available to perform these special repairs, then the aircraft would receive a period extension.

Depot level processing is typically restricted to performing structurally related maintenance actions and installing all outstanding approved airframe changes (AFC's), regardless of assigned maintenance level. The maintenance philosophy of Naval Aviation is to perform all maintenance actions at the lowest possible level. Therefore, the depots do not plan for, nor are they funded to perform, maintenance that is coded for either the organizational or intermediate maintenance organizations except for the incorporation of AFC's. Other exceptions to this standard policy are possible. For instance, NAVAIR has required and funded a total processing of the E-2C during SDLM at NAVAVNDEPOT North Island. NAVAVNDEPOT North Island produces a fully operational, mission ready E-2C upon completion of SDLM. Other exceptions are requested by operating squadrons on an as-needed basis.

Should a squadron be unable to perform certain maintenance actions because of manpower constraints or operational requirements, the squadron may request the depot perform the work in conjunction with SDLM processing. In this case, the squadron must identify and make available the requisite funds. It should be noted, however, that nowhere in the depot requirement is there a standard requirement to address EMI considerations. EMI receives consideration during E-2C processing at North Island and when a squadron submits a work request identifying a EMI/EMC related situation.

In addition to the SDLM processing of aircraft, the NAVAVNDEPOT's provide other special aircraft maintenance functions including the rework of components, missiles, engines, and ground support equipment. Special aircraft maintenance actions include "special repairs" as required to extend a period end date, repair crash damage or install an urgently needed airframe change. These services are normally performed at the depot but can be performed within a squadron's facilities. The latter occurs when limited depot talents and facilities are required and the squadron can make personnel facilities and equipment available to support the efforts.

The Depot Level Component Repair Program supports the Aviation Supply Office (ASO) by repairing failed avionic, electrical, hydraulic and mechanical components that have been turned in to the supply system for depot repair. Specific items to be repaired at each depot are negotiated between the depot and the ASO. The negotiated quantities of each type component are determined by the funds made available by ASO, the total workload of the depot, and the price for processing each item. The component process specifications are contained in the Master Data Record for the component type. The Master Data Record often refers to standard Navy documentation consisting of handbooks of maintenance instructions, handbooks of overhaul instructions, local engineering specifications and illustrated parts breakdowns. For electrical and electronic components, the Master Data Record is often very brief, simply stating "Inspect and Repair as Necessary." The objective of this program is to return the component to service at minimal cost. Once an item is repaired and passes the manufacturer's stated performance specification, the item is declared ready for issue and returned to the supply system.



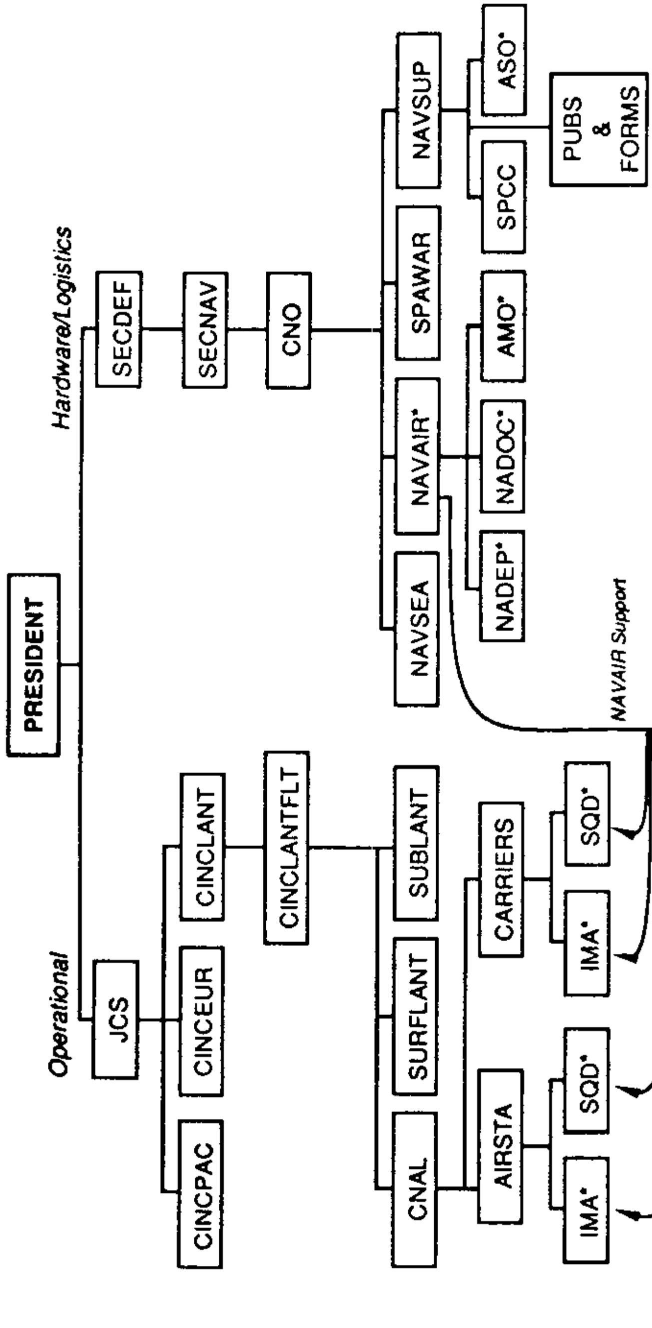
F-4 Rework

CHAPTER 3
THE AIRCRAFT REWORK BUSINESS

This section describes the relationship between the Fleet Operating Aviation Units and the organizations responsible for providing the tools of defense. A brief discussion of the organization of selected shore establishments introduces the functions of the Naval Aviation Depot. These functions are presented in detail with focus on the business and technical aspects that affect quality EMI control and the attainment of EMC.

3.1 Naval Aviation Support Organization

A high level representation of the major Commands involved in providing weapon systems and support services to the operating fleet is depicted in Figure 3-1. There are two distinct chains of Command: an operational chain and a support or shore establishment chain. The operating activities identify the threat environment and weapon system capability requirements needed to defend against the current and projected military



* Aviation Engineering/Maintenance/Logistics

Figure 3-1 Major Command Involvement

threat. The support organization converts the stated operational requirements into weapon systems hardware and support equipment requirements, and identifies logistics elements needed to satisfy the fleet requirements. The principal organizations concerned with EMI/EMC are the Operational Commanders from a Battle Force Management point of view, and the Intermediate Maintenance Activities (IMA's) and squadrons from a maintenance support point of view. To satisfy the concerns of the Operational Commanders and Fleet Maintenance Organizations, the CNO, NAVAIR, NAVSEA, SPAWAR, and NAVAVNDEPOT's must design new weapons systems with built-in EMC features. In addition, these organizations must develop corrective action programs and hardware fixes to correct existing and unanticipated EMI conditions. This section focuses on the responsibilities and procedures associated with the principal Fleet support organizations.

Within the CNO's organization exists a Deputy for Aviation Plans and Programs (OP-05), who is responsible to ensure the shore establishment is providing the required weapon systems, support equipment, and logistics support for the operating Fleet units. The CNO OP-05 deputy receives requirements from the Fleet Commanders concerning operational deficiencies in existing weapon systems, emergent threat definitions requiring weapon systems capabilities, and deficiencies in existing logistics support. OP-05 translates these operational requirements into hardware, ground support and logistics support requirements. The requirements are prioritized, budget requests are formulated, funds are received, and the system commands are directed to take appropriate action to provide the required technical support.

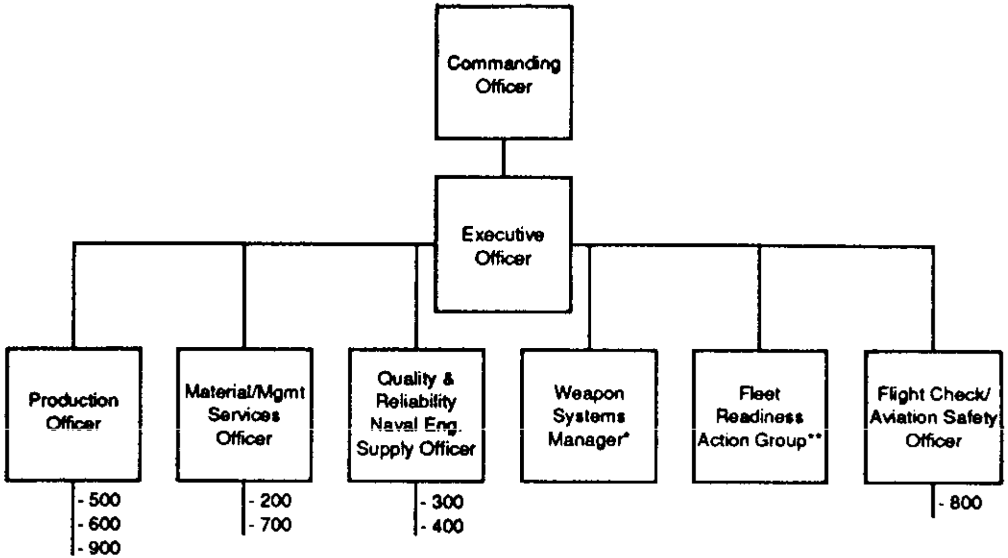
NAVAIR designs, develops, tests, procures, delivers and supports aviation weapon systems. Hardware items include aircraft, missiles, ground support equipment, radar, fire control, communication/navigation, electronic countermeasures, and flight systems. Upon delivery from the manufacturers, procured equipment is delivered to the Fleet units as designated by CNO. Support equipment is delivered on CNO guidance which normally places priority on the operating squadrons, the supporting IMA's, and the depot providing the designated support. The depot is normally the last in priority to receive equipment that is commonly used by the squadrons and IMA's. Also, for a new weapon system, support is initially provided by an interim commercial depot until capability is acquired at the organic depot.

3.2 Naval Aviation Depot Organization

The NAVAVNDEPOT's have a common organizational structure from the Commanding Officer through the department head level. This organization is specified by NAVAIRSYSCOM headquarters. Below the department head, each NAVAVNDEPOT is permitted to develop its own organization.

Prior to April 1987, the NAVAVNDEPOT's reported to the Naval Aviation Logistics Center which controlled Depot Rework Point (DRP) assignments and provided the required funding. The NAVAVNDEPOT's were then known as Naval Air Rework Facilities.

In April 1987, the Naval Aviation Logistics Center was reorganized. The name was changed to Naval Aviation Depot Operations Center (NAVAVNDEPOTOPSCEN), and was designated an Echelon 3 command reporting to NAVAIR (AIR-43). NAVAVNDEPOT's were also designated Echelon 3 commands and assigned to AIR-43. As of 1 April 1987, AIR-43 assumed the responsibilities of managing the NAVAVNDEPOT's and NAVAVNDEPOTOPSCEN was assigned the responsibility of coordinating the workloading of the NAVAVNDEPOT's; the actual mission of the NAVAVNDEPOT's did not change. Each NAVAVNDEPOT is commanded by either a Navy captain or a Marine colonel; the directorate officers who manage the assigned departments report to this Commanding Officer. Figure 3-2 illustrates a typical NAVAVNDEPOT organization.



Department

200 - Management Engineering Support Office
300 - NAVAIR Engineering Support Office
400 - Quality & Reliability Assurance Department
500 - Production Planning & Control Department
600 - Production Engineering Department
700 - Material Department
800 - Flight Check Depatment
900 - Production Department

* Special organization to manage in-service aircraft
** Special organization to support Fleet operations

Figure 3-2 Typical Naval Aviation Depot Organization

Each of the departments identified in Figure 3-2 has some involvement in the management and control of EMI in the depot products. The 300, 400, 600, and 900 departments are principally concerned with designing and building in technical controls; the 200, 500, 700 and 800 departments control funding, perform evaluations, and provide the proper materials to maximize the effectiveness of proper EMI controls. Specific activities performed by each department in attaining good EMC in the depot products follow:

200 (Management) - processes funding documents, collects financial charges and analyzes management reports. From the report analysis, 200 assists the depot in identifying the cost of doing business down to the work operation level.

300 (Product Support Directorate) - develops the depot processing specification outlining the work that must be accomplished during depot maintenance. Within these specifications, Code 300 personnel identify areas of inspection and inspection criteria. While developing these specifications, EMI/EMC requirements are addressed.

400 (Quality Assurance and Reliability) - provides guidance and instructions for producing quality products. To the maximum extent possible, Code 400 personnel include EMC as a quality factor.

500 (Production Planning and Control) - negotiates the workload schedule and cost with AIR-43 (coordinated through NAVAVNDEPOTOPSCEN). Upon approval of the workload, Code 500 personnel schedule each item for depot processing and issue the shop orders (operating documents) to the production department. Code 500 personnel have the final approval for the accomplishment of EMI/EMC work operations as governed by fleet requirements and available funding.

600 (Production Engineering) - converts technical data (publications, directives and engineering process specifications developed by Code 300) into detailed Master Data Records (MDR's). The MDR includes work description, trade skills, standard hours and flow-times required to perform the rework. The MDR will also identify all EMC engineering process specifications, and directives and publications required to rework and test an item. Production Control (Code 500) acquires shop orders generated from the MDR files to distribute to production shops as required.

700 (Material Support) - processes and stocks bit and piece parts required by the depot production shops in performing the work assignments. Code 700 personnel procure materials as specified by the repair instructions through the normal Department of Defense supply system. If the engineering group specifies peculiar parts required to control EMI, the Code 700 personnel take extraordinary actions to attain the parts through commercial sources.

800 (Flight Test) - during test flights of the completed repaired aircraft, Code 800 personnel observe the EMC qualities of the aircraft and its installed components. Should they observe an EMI problem which affects safety of flight, the production department will take corrective action.

900 (Production) - performs repair actions as specified in the work packages and as authorized by the planning department. Code 900 personnel routinely observe EMI causative factors and take corrective action.

3.3 NAVAVNDEPOT Rework Programs

The NAVAVNDEPOT's work load consists of five major programs: aircraft, missiles, engines, components, and other support. A brief description of each program follows:

Aircraft: The NAVAVNDEPOT performs Standard Depot Level Maintenance (SDLM), installs airframe modifications, repairs crash damage, and performs other special repairs as required.

Engines: The NAVAVNDEPOT repairs, overhauls, and modifies aircraft engines in support of the ASO, Fleet requirements and other depot programs.

Missiles: Two NAVAVNDEPOT's, Norfolk and Alameda, have missile programs under which they rework the guidance and control sections of missiles such as Sparrow and Sidewinder.

Components: The NAVAVNDEPOT repairs and overhauls airframe, hydraulic, electronic, and electrical components installed in Naval, Marine, and other service aircraft. The work is performed in direct support of ASO and SDLM requirements.

Other Support: This is the catch-all program under which the depots perform work that is not properly covered under the other programs. Typical workload under this program includes support for the sister services (Army, Air Force and Coast Guard - Marines are considered part of Navy), Foreign Military Assistance Programs support, shipboard related work (repair gas turbine engines installed in Spruance Class Ships, repair catapult and arresting gear installed aboard carriers), engineering change development, manufacturing, and miscellaneous requirements.

The typical NAVAVNDEPOT is physically organized to perform aircraft/airframe related workload in dedicated hanger space; the remainder of the facility is normally organized into technology centers or shops. For instance, there are shops for hydraulic repair, small airframe surface repair, large airframe surface repair, electrical equipment repair, etc. Each technology center or shop supports all of the NAVAVNDEPOT's repair programs. The hydraulic shop repairs flap actuators in support of aircraft, component, and other support programs. The same shop also repairs actuators in support of the missile and engine programs. Scheduling, performing, and controlling this workload throughout a NAVAVNDEPOT requires extensive coordination. These issues will be addressed in later sections.

The NAVAVNDEPOT's, like the rest of the Federal Government, operate under annual funding and operating budgets. For each fiscal year, the NAVAVNDEPOT develops a funding budget board based upon the negotiated workload. This budget is submitted as part of the NAVAIR annual budget submission. Upon approval of the Congressional budget, adjustments are made to the NAVAVNDEPOT workload and associated funding budget to ensure compliance with Congressional decisions. With the approved funding budget, workload mix (by program), workload induction/completion schedule and in-process work, the depot develops an operating budget that projects revenue generation, expenditures, and retained earnings. Any change in the funding budget, workload mix, induction or production schedules necessitates a change in the operating budget.

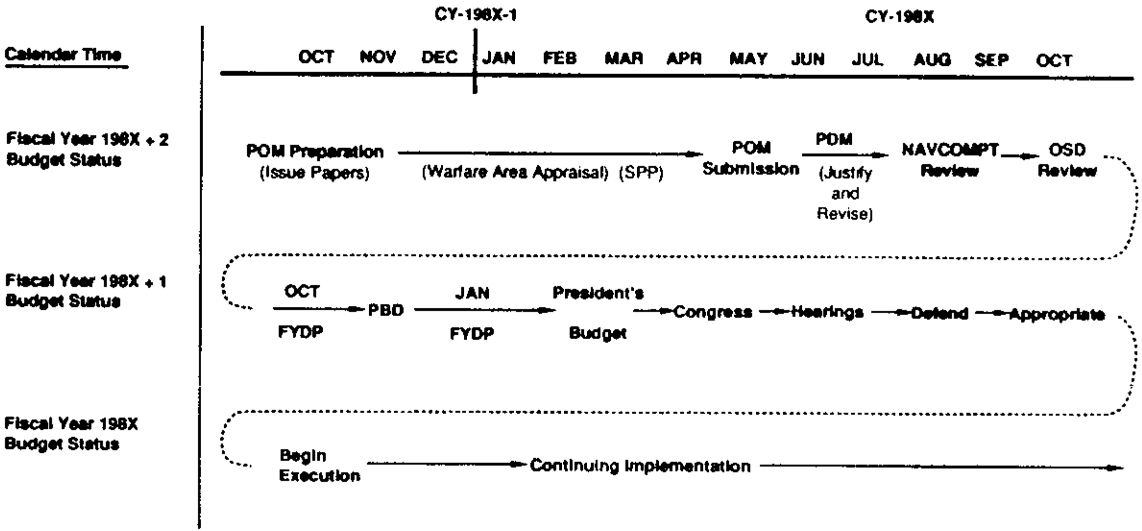
The preponderance of funds allocated to depot maintenance fall within Operations and Maintenance, Navy (O&M,N) appropriations. With this type of funding, dollars are obligated under induction of the workload and paid upon completion. However, provisions do exist for progress billing and payment for significant workload efforts. In addition, two types of work may be performed, loosely known as Level of Effort (LOE) and Completion or Fixed Price. LOE is used for such programs as Fleet calibration (other support), where the scope of effort cannot be predefined. Under LOE funding, the depot is reimbursed for actual costs up to the funding limit. It is the depot's responsibility to cease work when the funds have been expended. Under Completion or Fixed Price project orders (a type of funding document), the depot commits to deliver a given product, such as a reworked F/A-18, for a given number of dollars. It is the depot's responsibility to complete the work regardless of cost. If they should go over budget, the additional funds come from the depot's corpus (capital) and show as a credit to retained earnings.

The NAVAVNDEPOT's operate under the Navy Industrial Fund (NIF) funding system. In simplistic terms, this means they operate in a manner similar to any commercial enterprise, i.e., on a profit or loss basis. The unique difference is they have a profit objective of $0. Under NIF principles, the NAVAVNDEPOT's must reach budget and allocate all costs (both direct and indirect) to the products and services offered their customers.

As mentioned earlier, the NAVAVNDEPOT's derive their funds from the annual Congressional appropriation. However, obtaining this appropriation is a long and tedious process that begins approximately 27 months before the beginning of any given fiscal year. Figure 3-3 illustrates this cycle.

3.4 Aircraft Modification Program

The Aircraft Modification Division (AIR-102) of the Naval Air Systems Command Headquarters (NAVAIR HQ) is responsible for management and direction of the CNO-approved aircraft modification program and accomplishment of its objectives. AIR-102 is basically divided into three functional areas - management, planning, and implementation. The program consists of the definition, development, acquisition, and installation of engineering changes designed to modernize and improve the safety, reliability, maintainability, readiness and combat effectiveness of in-service aircraft. The overall program encompasses the Conversion in Lieu of Procurement (CILOP) program, Service Life Extension Program (SLEP), and the Operational



KEY

POM	Program Objectives Memorandum
PPBS	Planning, Programming and Budgeting System
PDM	Program Decision Memorandum
PBD	Program Budget Decision
SPP	Sponsor Program Proposal

Figure 3-3 Navy Planning, Programming and Budgeting System (PPBS)

Safety Improvement Program (OSIP). AIR-102 has broad directive authority over the planning, programming, budgeting, direction, control, and execution of the overall program, including resource utilization.

Aircraft modifications have been an important part of the Naval Aircraft Program for many years. Certain aircraft were able to maintain their status as first line combat aircraft and fulfill Navy requirements as a result of improved capabilities acquired through the modification program. The modification program has assisted in maintaining an adequate aircraft operating inventory during periods when funds for acquisition of new aircraft were not sufficient to ensure required force level quantities, and has assisted in correction of deficiencies which are known causal factors of mishaps.

Great advances in aircraft operational capability have enabled the Navy to stay abreast of the technological threats posed by potential enemies. A by-product of these advances is a major increase in aircraft costs. Similarly, modifications to current aircraft for modernization, extended service life, or correction of flight safety deficiencies have increased in cost to the extent that the modification program has become a major segment of the Naval aviation budget. In addition, greater numbers of aircraft will be required in the inventory to sustain future force level requirements.

The operational importance of an effective OSIP modification program, together with the growing financial investments involved, dictate increased management attention and better monitoring of program progress. In the past, aircraft update/modification programs may have been planned in a reactive or crisis mode. Funding limitations have caused decisions to be made on program priorities which prevented adequate advance budgeting to meet normal transition time frames from existing systems to the modified systems. Early planning, sound analytical preparation and a timely, logical sequence of budgeting and managerial control are clearly essential elements of the aircraft modification system.

One recent attempt at system planning and analyses with respect to OSIP Modification (MOD) (SLEP/CILOP) actions occurred as part of the Navy's major Sea-based Air Master Study conducted by CNO. The study investigated several current aircraft and produced data on how their service life might be extended or their performance capability upgraded to meet mission needs, pending replacement by a new generation of aircraft. The study utilized data from industry as well as in-house expertise to lend credibility to the resulting alternatives. This type of knowledgeable approach to the problem of maintaining adequate aviation force levels is a basic ingredient in the Navy's OSIP program.

Recommended aircraft modifications must incorporate the results of enemy threat analysis with the required operational and readiness capabilities. Cost and schedule studies must be conducted, and trade-offs must be made to assure meeting the requirements of the DoN Programming Manual. Long range planning data results should be shown in the Naval Aviation Plan and should form the basis for the DoN Five Year Defense Plan (FYDP) and fiscal planning. These, in turn, will initiate OSIP items in future budget submissions. Similarly, recommendations being effected for safety reasons must have undergone a formal safety assessment to ensure that the modification will not induce more hazards than it corrects.

Through the planning, programming, and budgeting process, OP-05 determines the most feasible way to meet and maintain required Naval aviation resources in support of overall national goals. Budgetary considerations generally restrict quantities of new aircraft to be procured. Consequently, program sponsors and material managers must determine what other actions can be taken to meet the required Navy operational capabilities. Shortfalls may take the form of capability and readiness inadequacies or insufficient force levels. Within the Naval aircraft program, these appropriation shortfalls are normally identified when the long range planning functions of the Naval Aviation Plan examine future force level requirements. Program sponsors and material managers take actions which result in future plans for greater utilization of aircraft already in the inventory. Thus, the aircraft modification program is aimed at converting aircraft in lieu of new procurements, extending service life through structural fixes, or effecting other modernizing changes to existing aircraft to retain their mission-capable status. These plans are refined, schedules are created, and preliminary funding estimates are prepared for submission in the appropriate budget year.

It is essential that all managers and planners remember that aircraft modification programs must conform to Naval material change regulations. Problems have arisen in the past when planners did not realize that change kit material required testing and suitability certification before new buys could be authorized. This in turn caused schedule delays and extensive changes in estimated costs. Proposed changes which qualify as OSIP items include aircraft conversions in lieu of procurement, increases in aircraft operational capabilities, greater combat survivability, and increased reliability, maintainability, and aircraft safety.

Significant modifications to Naval systems or equipment must be certified under Approval for Service Use (ASU) guidelines. A significant alteration is defined as a change in design or fabrication, and occurs when such changes are intended to substantially alter the operational, logistics, or other military characteristics, including reliability and maintainability. An aggregation of minor changes is considered to be a significant change if it creates interchangeability problems. Navy policy states that no significant alteration or modification to existing material be approved for production until it has been adequately tested and proves to be operationally effective, operationally suitable, and logistically supportable. For the above reasons, it is important that planners consider the T&E requirements of OSIP items when schedules and cost are compiled, since ASU may likely be withheld unless a waiver is granted. If Provisional Approval For Service Use (PASU)/ASU is required, all testing and hardware costs are chargeable to Research, Development, Test and Evaluation, Navy (RDT&E,N) funds.

Within NAVAIR, the aircraft modification Program Objectives Memorandum (POM) process is initiated in response to an annual notice. NAVAIR receives managerial guidance from individual program sponsors in the Office of the Chief of Naval Operations (OPNAV) (OP-506). This guidance defines required modification items, but additional items can be submitted to OPNAV for consideration.

The time required to process an OSIP item from initiation to execution of contract kit order is approximately 31 months. Using a 15 month lead-time for delivery of kits and equipment as an example, the process from initiation of the OSIP item to first delivery would take 46 months. During the review cycle, NAVAIR HQ, OP-05, Comptroller of the Navy (NAVCOMPT), Office of the Secretary of Defense (OSD), Office of Management and Budget (OMB), and Congress have the prerogative to adjust or delete any portion of the proposed APN-5, APN-6, or Operational and Maintenance, Navy (O&MN) budgets.

Some organizations have specific duties and responsibilities during an aircraft modification program; other organizations must be delegated authority to perform their tasks. Navy management may choose whether or not to use such organizations as Navy laboratories or ask industry to perform specific tasks or functions during the modification program planning or implementation phases. The specific high level functions of organizations involved in the execution of the Aircraft Modification Program are outlined below:

<u>OPNAV</u> - Establishes requirements, assigns priorities, and provides policy and planning guidance to NAVAIR for preparation of proposed aircraft modification programs and funding alternatives to be considered during the POM development process. Program coordinators in OP-506 specify to NAVAIR which programs are to be submitted to OPNAV for approval consideration. Following submission, other programs may be proposed by the NAVAIR program managers for OPNAV consideration. OPNAV has final decision authority on which modification programs will be sent forward to NAVCOMPT and OSD/OMB for budget consideration. OP-506R is the program sponsor and OP-501 is responsible for monitoring the budget and program implementation.

<u>NAVAIR</u> - As the manager and coordinator of all Naval aircraft programs, NAVAIR is responsible for all technical and administrative obligations. Upon receipt of guidance from OPNAV, PMA/APC/WSM's will prepare OSIP documentation. AIR-102 will coordinate all PMA/APC/WSM's inputs with respect to OSIP documentation and generate the APN-5 aircraft modification budget submittal.

Laboratories and Field Activities - NAVAIR HQ may choose where and how they desire support in the planning and execution of aircraft modification programs. Extensive experience and unique talent are available at Navy laboratories and field activities to support the Headquarters in areas such as aircraft modification planning, engineering evaluation, kit development and installation, and system T&E.

A planned program is a more easily executed program. If the proper investigations, evaluations, and justifications have been provided; ASU Waiver has been granted (if required); and budget approval has been received; execution can begin. Budgeting for aircraft modification programs is based on the Department of Defense (DOD) full-funding concept. Under this concept, an item is fully funded only when funds are programmed and available at the time of acquisition to cover the total estimated cost of the complete modification. In other words, the entire fiscal year quantity must be provided unless an exception is made under the advance procurement concept. The advance procurement concept does not apply to modification programs. Another important planning concept is to buy in a fiscal year only that quantity of kits which can be installed in the twelve month period starting from delivery of the first kit, plus reorder or administrative lead-time. This does not include planned modifications to spares.

If the program only buys preproduction, non-recurring engineering or modification kits in the initial year, approval of the Change Control Board (CCB) is not required, and funds can be directed by AIR-102 when requested by the NAVAIR program manager. In these cases, the next funded year of the program requires full CCB approval to ensure that all logistic elements are included. After CCB approval, funds are forwarded to the organic or contractor activity to begin kit production. Kit validation and verification is accomplished and tests performed, as required. Modification kit lead times vary from 6 to 36 months, depending on material lead times and kit complexity.

Kits can be installed during SDLM by contractor drive-in modification lines, Navy field teams, contractor field teams at the organizational (fleet) level, an intermediate maintenance activity (IMA) or an organizational maintenance activity (OMA). Scheduling of installations must be coordinated to take advantage of the best mix of these available methods. Basic OPNAV guidelines state that modification programs, including spares, should be completed within a maximum of five years from the initial installation year. Safety modifications must be completed within 36 months. Installation is funded with O&MN funds. Since O&MN is a one-year appropriation, costs are budgeted in the year in which the actual installa-tion will occur.

3.5 **Naval Aviation Depot (NAVAVNDEPOT) Workloading**

Within the DOD, each depot-repairable item is assigned to a Designated Repair Point (DRP) which may be a commercial firm or any DOD owned and operated facility that possesses or will acquire the capability to perform the depot repair function. During the development and deployment of a new weapon system, the developing contractor will normally provide depot repair maintenance for newly developed components on an interim basis until the ultimate DRP is established. Assignment of the DRP for new items is rather complex in that all available existing government depot repair capabilities must be considered, the cost of developing in-house government repair capability must be compared with the cost of having the system developer continue to provide support, and the commonality of the new system with existing and planned systems must be considered. These factors are considered under the "New Start" procedures and result in assignment of a specific service with the responsibility of providing depot support to all users of the weapon system component. Other factors which may be considered include existing capabilities, cost to develop new capability, current facility capacity, projected facility workload, projected item workload, projected repair price and availability of support equipment. In making the DRP assignments, NAVAIR attempts to distribute workload amongst the organic (Navy) depots to ensure each facility develops and maintains a full spectrum of technology that can be rapidly expanded during surge conditions. For critical technology areas, NAVAIR often assigns more than one organic DRP to ensure the technology is available in the event a single DRP loses its capability as a result of catastrophic events, actions of war or sabotage. The assignment of dual DRP's also provides flexibility in balancing workload between depots. Current (1986) DRP assignments by NAVAVNDEPOT are as follows:

ALAMEDA, CA

Missiles	AGM-54
	AIM-54
	AIM-7
Aircraft	*A-3, A-6
	*P-3, *S-3
Engines	J52, *TF34
	A501K, *T56

CHERRY POINT, NC

Missiles	---
Aircraft	F-4, *OV-10 *H-46, *AV-8 *C-130, *C-131
Engines	J79, T58, T74 *T76, *T400, *F402

JACKSONVILLE, FL

Missiles	---
Aircraft	*A-7, F/A-18, P-3, *C-1, *S-2
Engines	*J52, F404 TF34, TF41

NORFOLK, VA

Missiles	AIM-9
Aircraft	*A-6, *F-14, *C-118, *F-8
Engines	*J57, *TF30, *JT8D, *JT12 T56, F110

NORTH ISLAND, CA

Missiles	---
Aircraft	*F-5, F-14, *T-38, *F-4 *F/A-18, *E-2 H-46, *C-2
Engines	*J79, *T58 *T64, F110 LM1500, LM2500 F404

PENSACOLA, FL

Missiles	---
Aircraft	*H-53, *H-3, *H-1, *H-2, *H-60B *T-39D, *TA-4, *T-34B, *U-1B, *U-6A
Engines	---

* Indicates the facility is the cognizant field activity and provides engineering services for that product.

This listing shows only the major end items under the aircraft, engine and missile programs. The component program items are too extensive to list in this publication as there are over 60,000 individual component designators that are assigned DRP's, with sizes varying from small circuit cards through large helicopter dynamic components which have more work content than many aircraft programs. It should be noted that, although Pensacola does not have an engine or missile program, they are the principal DRP for helicopter dynamic components. Thus, the above listing of DRP assignments can be misleading if one is equating DRP assignment to workload.

The actual workloading of the NAVAVNDEPOT's is a complex, on-going exercise that is closely coupled to the congressional budget cycle. During the POM process, the initial projection is made for depot workloading two years hence; this is shown in

Figure 3-3. These projections are based on current workloading, current and projected efficiency and productivity factors, number of aircraft projected to be in inventory CNO's flying hour program, aircraft period end dates and projected item repair costs. The POM process is equivalent to long range planning. The depots make plans for staffing levels, trade skill balancing, and facility upgrades, and perform all other normal business management decisions based on the POM submission.

During the budget process, changes are made to the POM projections as the environment changes and decisions are reviewed by NAVCOMP and OSD. At each stage of the budget process, decisions are transmitted back to NAVAIR so that adjustments may be made in business management of the depots. Information constantly flows between NAVAIR and the depots as budget decisions are made and information is requested from such organizations as NAVCOMP, OSD, OMB and Congress. On a regular schedule (which has varied between quarterly and semi-annually over recent years), the depots, NAVAIR, NAVAVNOPNCEN and other interested commands meet to review depot programs. At these meetings, known as Fleet Readiness Support Meetings (FRSM's), the current year depot workload is reviewed to assess progress and determine corrective actions necessary. The main purpose of the meetings is to

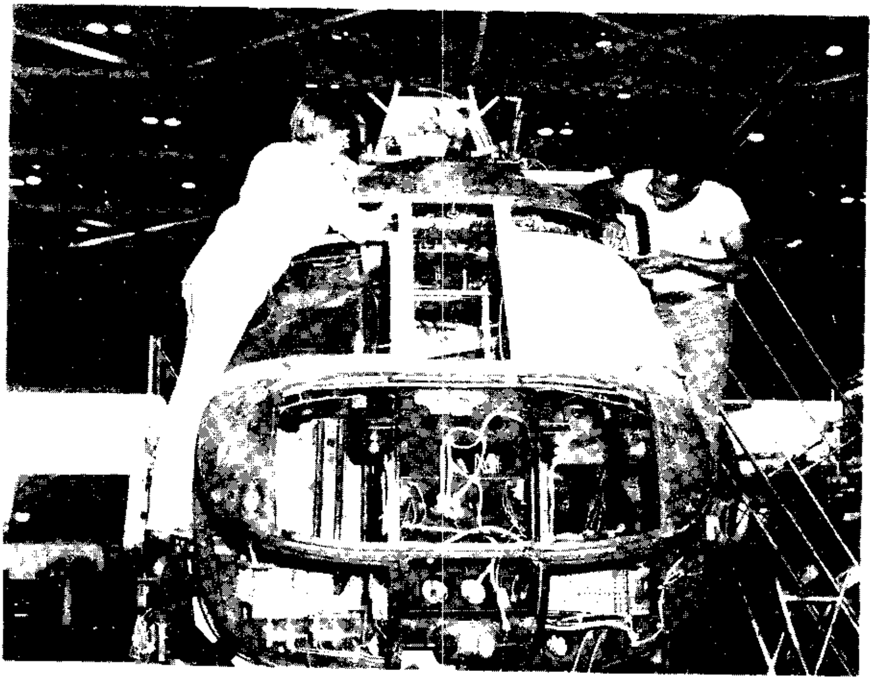
AV-8B

make adjustments in current year workload assignments based on workload generation, fleet priority changes, funding changes, etc. Other major agenda items include planning for the next fiscal year, long range planning, and a mutual exchange of information between NAVAIR, NAVAVNDEPOTOPSCEN and the NAVAVNDEPOT's.

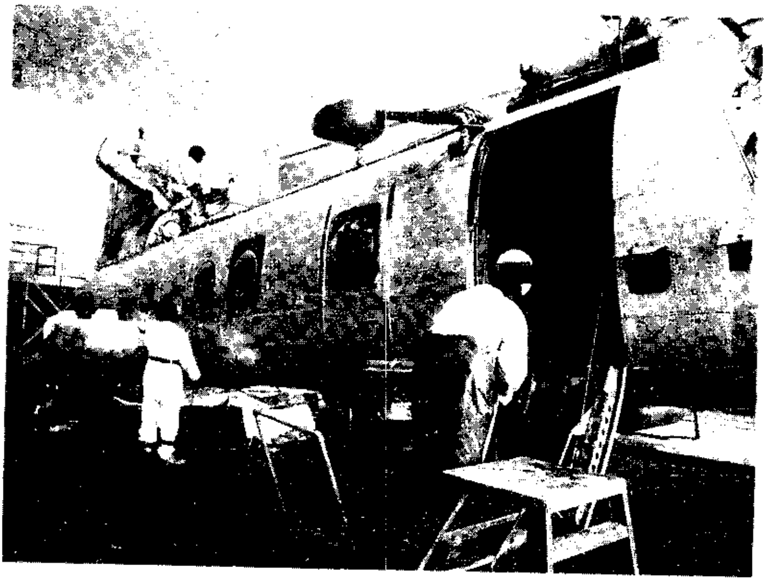
The annual budget is partitioned between each major program for the combined organic depots and transfer of funds between programs is rare and must be approved using the chain of command. Therefore, a major action at the FRSM is to adjust workload across the depots to maintain a balance between total program requirements and workload mix at each depot. For example, if component program workload is insufficient at depot B but excessive at depot A, then component workload assignments and associated funding would be moved from depot A to B. This then exceeds the total capacity at depot B, requiring aircraft workload to be moved from depot B to C. This ripple effect may require extraordinary management actions and decisions to attain a viable workload mix at each depot.

Over the years NAVAIR has attempted to maintain dual DRP's for all major technologies and workload programs. The benefit of this approach is the maintenance of good workload balances between depots. Conversely, the Air Force has focused on

Technology Repair Centers where one facility does all of the work, such as all F-4's, at a single site. It is interesting to note that, as workload requirements have shifted, the Air Force Logistics Command (AFLC) has had great difficulty managing workload at the Air Logistics Centers. As a result, AFLC is now moving to dual siting technology bases.



H-46 Depot Processing



CHAPTER 4
EMI/EMC
ENGINEERING CONSIDERATIONS

The control of EMI and the attainment of EMC is a difficult task at best. This chapter provides a compilation of the theoretical considerations associated with EMC in Naval aviation. Most of the discussions presented are technically rigorous while some, such as shielding topology, are intentionally sketchy since the technology is still evolving.

4.1 Introduction

During the life cycle of an airframe it will undergo many configuration changes. From a practical standpoint, these changes first occur during the basic design process and continue through the development and deployment cycles. Although the reasons for changes vary depending upon the period in the aircraft life cycle, their impact on EMC is essentially the same and, regardless of the reason, every configuration change must be examined in light of these EMI considerations. Every change, be it structural, electrical or electronic, impacts the aircraft's EMI environment. Some structural changes may improve this environment by providing increased shielding or improved bonding characteristics between airframe components; conversely, other changes may degrade the EMC environment by reducing the airframe's shielding or bonding characteristics. Installation or alteration of wiring harnesses, attendant to aircraft modifications, may introduce undesirable cross talk between weapon systems.

All of these factors must be considered during the design of new aircraft installations. Newer aircraft such as the F/A-18 have improved designs to control and eliminate EMI. Caution must be exercised when upgrading an aircraft such as the F/A-18 to avoid degrading the built-in EMI controls when designing improved EMI controls.

To assist NAVAVNDEPOT personnel, a brief history and theory of EM propagation and discussions of shielding, bonding and grounding are presented in the following sections. It is intended that these presentations will provide an understanding of how to design for the control of EMI.

4.2 EM Theory

The theory of EM energy propagation is based on the theoretical works of Coulomb, Gauss, Ampere, Faraday, Maxwell, Lorentz, Einstein, and others. A thorough understanding of this theory requires an appreciation of the achievements of these scientists and a comprehensive working knowledge of higher level mathematics. This discussion will introduce the theories postulated by the early 1800 scientists, the consolidation efforts of Maxwell, and the impact of special and general relativity as developed by Lorentz and Einstein. The presentation attempts to interpret these concepts in terms that may be understood by persons with varying degrees of background. The uninitiated should receive an appreciation of EM theory while the knowledgeable reader may use the discussion to relate practical real world problems to the basic theory.

In 1862, Maxwell consolidated the fragmented theories of Coulomb, Gauss, Ampere and Faraday to develop a set of four equations describing the propagation of EM energy. Maxwell found that electric fields, electric currents and magnetic fields are mutually dependent and that two additional concepts had to be considered: magnetic monopoles and displacement current. Although a magnetic monopole has not been discovered, Maxwell's equations allow for it should it actually exist in nature. The second concept was displacement current. It is recognized that electric current is the flow of electrons through a conducting medium. Displacement current is an apparent flow of electrons through a dielectric medium, such as between the plates of a capacitor.

Maxwell's unique contribution to science was to take the laws developed by the early 1800's scientists and combine them into a set of differential equations. These laws, all of which were based on experimental results vice theory, proved to be consistent with complex theories of mathematics and physics. Maxwell published his new theories in 1873 (Treatise on Electricity and Magnetism). The four equations, known as Maxwell's equations, are discussed below and numbered as presented in most textbooks. It should be noted, however, that Maxwell never actually identified his equations by number.

The first equation was a derivation of Faraday's law which experimentally showed that a time changing magnetic field within a wire loop induced a voltage in that loop proportional to the rate of change of the magnetic flux (i.e., a time varying magnetic field produces an electric field). It was also shown that the polarity of the induced voltage was such that a current flow (electron flow) would produce a magnetic field to oppose the change in flux.

Faraday's law was written: $\mathscr{V} = -\frac{d\phi}{dt}$

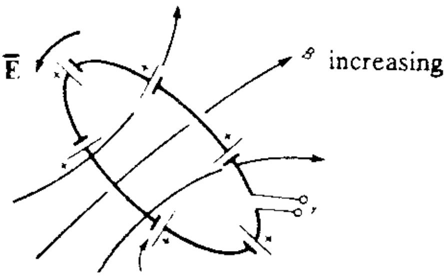
Where $\mathscr{V}$ = voltage, ϕ = magnetic flux, t = time

Through the use of the mathematical functions of curl, divergence, and vector identities, Maxwell showed that the curl of **E** is equal to minus the rate of change of magnetic flux density **B** within a closed loop. This equation, sometimes referred to as Maxwell's first equation, is:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

Where ∇ is the mathematical symbol for the determinant function and $\nabla \times E$ is read as the curl of the electric field vector, **B** is the magnetic flux density, and $\frac{d}{dt}$ indicates the rate of change with time.

If the fingers on the right hand are used to point in the direction of the E field, the thumb on the right hand will point in the opposite direction (minus) from the increasing magnetic flux density. This is known as the "right hand rule" and offers a practical way to understand curl.



(the directions of E, B and the $\nabla \times E$
as specified by Maxwell's first equation)

The second Maxwell equation was principally a derivation of Gauss's law which simply states that the sum of the electric flux emanating from a closed surface is equal to the charge enclosed. In mathematical terms:

$$\oiint \mathbf{D} \cdot \mathbf{dA} = Q \quad \text{or} \quad \nabla \cdot \mathbf{D} = \rho$$

where $\oiint$ indicates surface integration or summation over the total surface, **D** is the electric flux density, **dA** is each infinitesimal surface area segment and Q is the total enclosed charge. The dot (.) between the **D** and **dA** indicates divergence, which mathematically means sum the components of the electric field density that are normal (perpendicular) to the surface area.

Maxwell's third equation, considered to be his unique contribution, shows that a time varying electric field gives rise to a time varying magnetic field. This is the converse of the first equation and Faraday's law that a time varying magnetic field produces an electric field. The third equation has its foundation in Ampere's Law (1820) that states the summation (integral) of the magnetic field taken about a closed path equals the current enclosed by the path.

$$\oint \mathbf{H} \cdot d\mathbf{l} = I \qquad \text{Ampère's law}$$

The implication of Ampere's Law is that a magnetic field can only be produced by flow of charge, which is true for a steady magnetic field. Maxwell conceived another current, known as a displacement current, which can also produce a magnetic field. The capacitor provides the classic illustration of displacement current as shown in Figure 4-1.

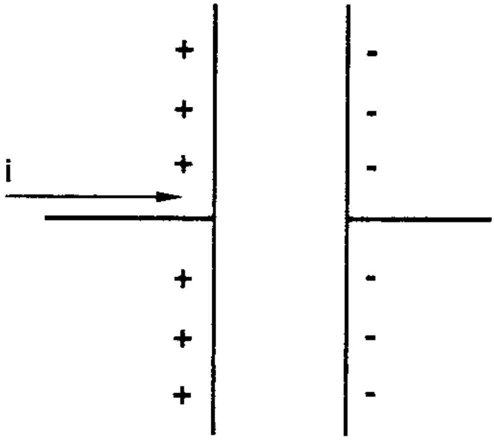


Figure 4-1. Displacement Current

As current flows into a capacitor, charge builds on each plate but no charge flows between the plates. There is, in fact, a displacement current which flows between the plates and causes a magnetic field just as the flow of charge does. Through rigorous mathematical manipulation, Maxwell showed that Ampere's Law may be generalized to:

$$\nabla \times \mathbf{H} = \mathbf{J} + \mathbf{J}_D$$

where $(\nabla \times \mathbf{H})$ is the curl of the magnetic field and is equal to the current density **J** plus the displacement current density $\mathbf{J}_D$ enclosed by the magnetic field. Again, through mathematical transformation Maxwell showed that:

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

where the rate of change of the electric flux density is equal to the displacement current. This contribution by Maxwell is considered his most significant and provided the foundation to show the propagation of EM waves through space without the presence of a source.

Maxwell's first three equations equally satisfy the concepts that electric charge causes electric fields, magnetic charge causes electric fields, and magnetic charge causes magnetic fields. However, since magnetic monopoles have not been found in nature, Maxwell's fourth equation was required to keep the first three equations in balance. Also, it has been shown experimentally that magnetic lines are always closed lines and that all magnetic lines entering a closed surface must also leave the closed surface. Therefore, the fourth equation simply states the sum of the magnetic flux density over a closed surface must equal zero or that the divergence of the magnetic flux density must equal zero. Mathematically, these are represented as:

$$\oiint \mathbf{B} \cdot \mathbf{dA} = 0$$

$$\nabla \cdot \mathbf{B} = 0$$

According to the above theory, a wire carrying an alternating current will produce a fluctuating magnetic field that surrounds the wire. A wire lying within the fluctuating magnetic field will have a current induced in proportion to the magnitude of the fluctuating magnetic field.

The preceding discussion attempts to offer relatively simplistic explanations of the origin and meaning of Maxwell's equations. A simplistic presentation of Maxwell's equations can be deceiving in that they become intuitively evident to the knowledgeable person. The theories embedded within the equations clearly describe the relationships between electric and magnetic fields. However, these equations are extremely complex in that they are a set of tightly coupled partial differential equations which cannot be solved in general. Through mathematical manipulation, Maxwell's equations can be summarized in two equations: the first describes the relationships of the electric field to current and change; the second shows the relationship between the magnetic field and current. These equations are given below:

$$\nabla^2 \mathbf{E} - \mu\varepsilon \frac{\partial^2 \mathbf{E}}{\partial t^2} = \mu \frac{\partial \mathbf{J}}{\partial t} + \nabla \frac{\rho}{\varepsilon} \qquad \nabla^2 \mathbf{H} - \mu\varepsilon \frac{\partial^2 \mathbf{H}}{\partial t^2} = -\nabla \times \mathbf{J}$$

The left hand side of these equations represents a propagating wave while the right represents the energy source of this wave. The physical significance of this relationship can be likened to the effect of throwing a pebble into a calm pool of water. When the pebble strikes the surface, it creates a traveling wave of energy manifested as expanding ripples on the pond's surface. After the energy source (pebble) has settled to the bottom (and is no longer a source), the rippling waves continue to propagate across the pond. This same phenomena occurs with EM waves. A current traveling in a wire generates propagating electric and magnetic fields that continue to travel trough space after the current has been removed. The traveling waves will continue to propagate indefinitely, undiminished in energy until they encounter resistance, just as the illustrative surface ripple will propagate until it reaches the bank of the pond. This phenomena illustrates the fact that sound scientific and mathematical concepts can be readily applied to the description and control of EMI.

4.3 Structural Engineering Considerations

The development of a structural Engineering Change Proposal (ECP) requires cognizance of EMI/EMC parameters. Although all ECP's receive many reviews during the process cycle, it remains the design engineer's responsibility to ensure good EMC. The engineers must recognize that certain areas of the airframe are more susceptible to EMI than others. Open spaces such as wheelwells, cockpits, and observation ports are particularly prone to problems associated with externally caused EMI in that these areas possess little or no shielding. Numerous cases have been reported in which external radiators, such as ships' radars, have caused the generation of hazardous currents in critical aircraft circuits. Cases have also been reported where normal radar operation has burned out all landing gear position sensors.

External radiation has also caused flight instruments to yield erroneous and misleading readings, and numerous cases have been reported where flight crews have experienced radio and ICS interference caused by external radiation impacting the circuitry within the crew stations. The problems directly associated with aircraft structures have been prevalent in all types of aircraft. With the recent advent of the composite airframe structure, these problems are potentially more common. Although many composites are made with embedded carbon fibers, which are good conductors and thus provide a degree of shielding, many composites are not as good at conducting as the classic metal airframe skins. Thus, a whole new area of engineering concern has been uncovered. With the new composites, the engineer must be concerned with the degree of attenuation being provided by a particular composite section and the bonding between the composite and adjacent sections of the airframe.

Structural engineers must maintain close liaison with electrical/electronic and chemical engineers to ensure that a particular section of the airframe provides sufficient shielding attenuation to isolate internal wiring and electrical components from the effects of external radiation. The structural/mechanical and electrical/electronic engineers must work in close harmony to ensure all critical electrical components are adequately protected either by sufficient airframe shielding, wiring harness shields, wire shields, and/or component enclosures.

In addition to concerns associated with basic airframe shielding, the structural engineer must be concerned with the conductivity of the airframe. If an access panel is designed with materials that are good conductors providing inherent shielding characteristics, but the panel is not properly bonded to the adjacent structures, then a corona generator has been designed that can significantly contribute to a degraded environment. Therefore, the structural engineer must ensure that all conducting components of the airframe are joined together with very low resistance. The DC impedance between any two conducting structures should be less than .0025 ohms. The design of these inter-faces should be such that the impedance will not go above .01 ohms during normal use and maintenance.

4.4 <u>Electronic Engineering Considerations</u>

The previous discussion focused on engineering considerations applicable to the mechanical/structural engineer in relation to EMI protection. Although the airframe structure should be designed to provide sufficient shielding of aircraft electrical/electronic components from external radiation, the electrical/electronic engineer must ensure all critical systems have sufficient shielding to maintain system integrity in the event of battle damage to the airframe, and to protect against reduced structural shielding resulting from degraded maintenance procedures.

The electrical/electronic engineer must be aware of shielding effectiveness throughout the entire airframe and must address EMI/EMC problems associated with both electric and magnetic fields generated within the airframe, and crosstalk between RF receivers and transmitters. The electrical/electronic engineer must also be concerned with TEMPEST considerations when Crypto equipment and secure communications are involved; crosstalk between wiring; and fields radiated by electrical and electronic components such as motors, generators, transformers and electronic circuit components. The engineer must be equally concerned with controlling RF fields and protecting circuit components from environmental E & H fields. There are many techniques available to the electrical/electronic engineer to control these phenomena which are discussed later in this section.

4.5 EMI Suppression Techniques

EMI suppression measures are general requirements for the design of all aircraft systems, subsystems, and components. Interference suppression, to the degree necessary for compatible operation of electrical and electronic equipment used in an aerospace system, is a military requirement.

Following proper design, care and planned maintenance can prevent or eliminate serious EMI problems. In this section, shielding, bonding, grounding, and filtering are discussed as EMI suppression techniques.

4.5.1 **Shielding**

The purpose of shielding is to prevent one component from affecting another through their common electric or magnetic field. Shielding is essentially a decoupling mechanism used to reduce radiated interactions between mechanical and electrical units. Shielding effectiveness is defined as the number of decibels (dB) by which the shield attenuates the field strength as the result of its being in place. It is dependent on:

- the material the shield is made of
- the thickness of the material
- the frequency and impedance of the impinging wave
- the distance from the source of interference to the shield
- the quantity and shape of any shield discontinuities.

The shield design process consists of first establishing the amount of attenuation needed. This is calculated by determining the difference between the strength of the undesired field level that exists without shielding and the tolerable field level. The choice of material for shielding purposes depends primarily on the type and degree of shielding performance desired. The electrochemical corrosion characteristics of the material should be considered as well. The electrical properties of shielding materials are summarized in Table 4-1.

4.5.1.1 Shielding Effectiveness for Solid Conductors

The attenuation a solid conductor provides as a shield depends on the absorption and reflection of the interfering wave. Thus the shielding effectiveness, S.E., is:

$$S.E. = A + R + B \quad dB$$

where

A = Absorption Loss

R = Single Reflection Loss

B = Multiple Reflection Correction Term

Table 4-1
Pertinent Electrical Properties of Shielding Materials

Material	σ_r	Frequency (Hz)	μ_r	σ_r/μ_r	μ_r/σ_r	$\sigma_r\mu_r$
Aluminum	0.61	all	1.0	0.61	1.64	0.61
Beryllium	0.1	all	1.0	0.10	10.0	0.10
Brass	0.26	all	1.0	0.26	3.85	0.26
Cadmium	0.235	all	1.0	0.235	4.26	0.235
Conetic*	0.0304	up to 1k	25115	1.3×10^{-6}	760×10^{3}	820
Copper (annealed)	1.0	all	1.0	1.0	1.0	1.0
Copper (hard drawn)	0.96	all	1.0	0.96	1.04	0.96
Gold	0.7	all	1.0	0.7	1.43	0.7
Hypernick	0.035	up to 1k	4529	7.8×10^{-6}	128205	160
Hypernom		up to 1k		78		
Iron (commercial)	0.0444	up to 150k	54.1	8.2×10^{-4}	1220	2.4
Iron (purified)	0.17	up to 150k	1000	1.7×10^{-4}	5882	170
	0.17	1M	700	2.4×10^{-4}	4118	119
	0.17	3M	600	2.8×10^{-4}	3529	102
	0.17	10M	500	3.4×10^{-4}	2941	85
	0.17	15M	400	4.2×10^{-4}	2353	68
	0.17	100M	100	1.7×10^{-3}	588	17
	0.17	1G	50	3.4×10^{-3}	294	8.5
	0.17	1.5G	10	1.7×10^{-2}	59	1.7
	0.17	10G	1.0	1.7×10^{-1}	1.0	0.17
Lead	0.08	all	1.0	0.08	12.50	0.08
Magnesium	0.378	all	1.0	0.378	2.66	0.378
Monel	0.04	all	1.0	0.04	25.0	0.04
Mumetal	0.03	up to 1k	19833	1.5×10^{-6}	667×10^{3}	590
NI-FE 50	0.12	up to 1k	3162	3.9×10^{-5}	25641	390
Netic (Blue)	0.1116	up to 1k	570	1.9×10^{-4}	5108	63.6
Netic (Special)	0.1263	up to 1k	440	2.8×10^{-4}	3484	55.6
Netic S3-6	0.1263	up to 1k	1000	1.26×10^{-4}	7918	126.3
Nichrome	0.02	up to 1k	18.2	1.1×10^{-3}	910	0.36
Nickel	0.2	up to 1k	100	$2. \times 10^{-3}$	500	20.0

Table 4-1 (con't) Pertinent Electrical Properties of Shielding Materials

Material	σ_r	Frequency (Hz)	μ_r	σ_r/μ_r	μ_r/σ_r	$\sigma_r\mu_r$
Permalloy 4/79	0.03	up to 1k	20667	1.45×10^{-6}	68890	620
Permalloy 45	0.04	up to 1k	2450	1.6×10^{-5}	62500	96
Permalloy 78	0.035	up to 1k	2692	1.3×10^{-5}	76923	94.23
Phosphor-Bronze	0.18	all	1.0	0.18	5.56	0.18
Platinum	0.17	all	1.0	0.17	5.88	0.17
Primag 40*	0.0116	up to 1k	1700	6.8×10^{-6}	146551	19.72
Primag 90*	0.96	up to 1k	780	4.2×10^{-4}	2364	257.4
SI-FE 4%	0.33	up to 1k	425	5.8×10^{-5}	17240	10.5
SI-FE 4% (Oriented)	0.0247	up to 1k	4787	2.4×10^{-5}	41667	550
Silver	1.06	all	1.0	1.06	0.94	1.06
Steel (cold rolled)	0.17	up to 200	224	7.59×10^{-4}	1318	38.0
	0.17	1k	212	8.02×10^{-4}	1247	36.0
	0.17	6k	153	1.11×10^{-3}	900	26.0
	0.17	8k	147	1.16×10^{-3}	865	25.0
	0.17	10k	135	1.26×10^{-3}	794	23.0
	0.17	15k	97	1.75×10^{-3}	571	16.5
	0.17	20k	86	1.98×10^{-3}	506	14.5
	0.17	30k	59	2.88×10^{-3}	347	10.0
	0.17	40k	49	3.47×10^{-3}	288	8.3
Steel (Galvanized)	0.1766	up to 1k	227	7.78×10^{-4}	1285	40.9
Steel (hot rolled)	0.1603	up to 1k	160	10^{-3}	998	25.65
Steel (stainless)	0.0284	all	1.0	0.0284	35.2	0.0284
Steel (Terne)	0.1517	up to 1k	157	9.6×10^{-4}	1035	23.8
Supermalloy	0.03	up to 1k	100000	2.9×10^{-7}	345×10^{6}	2900
Tin	0.15	all	1.0	0.15	6.67	0.15
Zinc	0.29	all	1.0	0.29	3.45	0.29

* Values given hold for magnetic induction between 3.2 and 159.2 A/m (amps per meter); above 318.4 A/m, the permeabilities at 1kHz are as follows:
Primag 40: 48 000
Primag 90: 60 000

Absorption loss (A) is the energy that is converted to heat as the wave passes through the shield. It is calculated using the following formula:

$$A = 1.314\sqrt{f\mu_r\sigma_r}\,d \quad \text{dB}$$

where

f = frequency, (Hz)

μ_r = material magnetic permeability

σ_r = material conductivity relative to copper

d = shield thickness, (cm)

Because absorption loss is independent of wave impedance, it is essentially the same for electric and magnetic fields. In general, absorption loss is low and rises as frequencies rise, but shielding magnetic material provides the best absorption loss for plane waves because $\mu \gg \sigma$ at a given d.

Single reflection loss (R) is the energy of the wave that is reflected by the impedance discontinuity between the free space and shielding mediums. It depends on the surface impedance of the shield and the interfering wave impedance. For the reflection loss to be great, the shield should have an impedance that is either very much greater than the wave impedance or very much less. In the case of a plane wave, it is more practical to use a shield with a very low impedance so conductive material is always used.

Single reflection loss is calculated using the following formula:

$$R = -20 \log_{10}[4\eta_s\eta_w(\eta_s + \eta_w)^2] \quad \text{dB}$$

where

$$\eta_s = \sqrt{j\omega\mu(\sigma + j\omega\epsilon)} \quad \Omega$$

$$\eta_w = \frac{\text{total electric field}}{\text{total magnetic field}} \quad \text{(at a given point)}$$

Reflection loss can also be calculated using the distance D (cm) from the source to the shield. This is because $\omega\epsilon \ll \sigma$ for metallic shields and, for partially conductive materials, is below microwave frequencies. Assuming point sources, the equations are as follows:

FOR LOW IMPEDANCE (MAGNETIC FIELD) SOURCE

$$R = 20 \log_{10} \{[1.173(\mu_r/f\sigma_r)^{1/2}/D] + 0.0535\, D(f\sigma_r/\mu_r)^{1/2} + 0.354\} \quad \text{dB}$$

FOR A PLANE WAVE SOURCE

$$R = 168 - 10 \log_{10}(f\mu_r/\sigma_r) \quad \text{dB}$$

D is not used since impedance is constant at 377 ohms.

FOR HIGH IMPEDANCE (ELECTRIC FIELD) SOURCE

$$R = 362 - 20 \log_{10}[(\mu_r f^3/\sigma_r)^{1/2} D] \quad \text{dB}$$

Electric fields are readily stopped by metal shields because large reflection losses are easily obtained. In general, good conductors provide better reflection loss because $\sigma \gg \mu$. Also, with certain combinations of material and low frequencies, magnetic fields are difficult to shield because the reflection losses may approach zero.

The multiple reflection correction term (B) is equivalent to the energy attenuated by reflection after the initial reflections at both surfaces. Its effect can be ignored if the absorption loss is greater than 15dB. The following equation defines the multiple reflection correction term:

$$B = 20 \log_{10}|1 - 10^{-A/10} w(\cos 0.23A - j \sin 0.23A)|$$

where

$$w = 4\,\frac{(1 - m^2)^2 - 2m^2 - j2^{3/2}m(1 - m^2)}{[1 + (1 + 2^{1/2}m)^2]^2}$$

$$m = 0.3015\, D\, (f\sigma_r/\mu_r)^{1/2}$$

4.5.1.1.1 Multiple Solid Shields

When good protection against both electric and magnetic fields is desired, the use of two or three layers of shielding material should be considered. Where magnetic shielding in high energy level environments is necessary, it is often desirable to use a multiple shield.

High permeability alloys provide good shielding for low frequency or weak magnetic fields, but tend to be less effective under the saturating effects of high level fields. A multiple shield should be used to correct this. The outer material should have a lower permeability but a higher saturation level than the inner material. Separation of the two layers will provide additional medium discontinuities which will yield multiple reflections. In some instances when much of the shield's usefulness is due to reflection loss, a multiple shield will provide greater shielding than the same amount of metal in a single sheet. Multiple shields can also provide an extended shielded frequency range, but these added advantages carry cost and weight considerations.

4.5.1.1.2 **Thin Film Shielding**

Thin shielding is loosely defined as shield thickness less than $\lambda/4$ wavelength at the propagation velocity dictated by the material. Solid material shielding theory is applicable to thin-film shields. For shields much thinner than $\lambda/4$ shield effectiveness is essentially independent of frequency. Here the multiple reflecting correction term, B, is fairly large and negative. The implication of the negative term is that the various reflections have additive phase relation-ships, and thus reduce the effectiveness of the shield. When the shield thickness exceeds $\lambda/4$, the multiple reflection term becomes negligible, and does not offset the other losses. Thus the material's shielding effectiveness increases and becomes frequency dependent.

In short, the shielding effectiveness of materials with thicknesses less than $\lambda/4$ is fairly constant; the shielding effectiveness for materials with thicknesses above $\lambda/4$ increases markedly.

4.5.1.2 **Non-Solid Shielding**

There are many applications in which the shield cannot be made of a solid material due to system design requirements. Screens and perforated materials must be used if an enclosure must be transparent or ventilated. These openings or discontinuities should be treated in the design process, to assure minimum reduction in shield effectiveness.

Wave Guide Attenuators. The effects of seams, cracks, openings, holes and other breaks in a shield can often be studied by considering the opening as a waveguide, and determining the guide attenuation. These effects can then be neutralized by designing them as waveguides below the cutoff frequency. The cutoff frequency for a waveguide, f_c, is the lowest frequency at which propagation occurs without attenuation. It is calculated below:

For cylindrical waveguides:

$$f_c = \frac{6.92}{d} \text{ GHz}$$

where

d = diameter in inches

For rectangular waveguides:

$$f_c = \frac{5.9}{b} \text{ GHz}$$

where

b = longest dimension of opening in inches

At any frequency, f, where $f < .1\ f_c$, the attenuation in dB can be approximated by:

$$\alpha = \frac{32\ell}{d} \quad \text{for cylindrical waveguides}$$

$$\alpha = \frac{27.3\ell}{b} \quad \text{for rectangular waveguides}$$

In conclusion, the above equations show that the diameter of individual openings determines the cutoff frequency, while the depth of the aperture determines the amount of attenuation.

Honeycomb Shielding Materials. Honeycomb shielding materials are specially designed, ventilation panels with openings that operate on the waveguide-below-cutoff-frequency principle. They are used when strength is required and weight is not critical. Compared with non-solid shielding materials, such as perforated metal and fine mesh copper screening, metal honeycomb provides the best attenuation of the impinging wave. Metal honeycomb enables very high electric field attenuations to be obtained through the microwave band with negligible drops in air pressure. Its disadvantages are that it costs more, occupies more space than screening or perforated metal, and is often difficult to apply because flush mounting is required. Because of these purely physical design reasons, screening and perforated metal are frequently used even though honeycomb material would provide better attenuation.

Screened Apertures. When the use of waveguide materials is impractical or otherwise undesirable, as in large ventilating holes, substantial attenuation of radiated EM energy can be obtained by covering the aperture with a wire screen or mesh. The shielding effectiveness for a screen aperture is given by:

$$S.E. = A_a + R_a + B_a + K_1 + K_2 + K_3$$

The first three terms correspond to the ones used for solid shields, while the last three terms are used because the shield is not solid.

The attenuation introduced by a particular discontinuity, A_a, can be calculated assuming that the frequency of the impinging wave, f, is well below the cut-off frequency, f_c. The cut-off wavelength, λ_c, is 2.0 times the maximum dimension of a rectangular opening, or 3.412 times the radius of a circular opening.

$$A_a = 27.3\ (d/W)\ \text{dB (rectangular opening)},\ f \ll f_c$$

$$A_a = 32.0\ (d/D)\ \text{dB (circular opening)},\ f \ll f_c$$

d = depth of opening, (cm)
W = width of opening to E-field, (cm);
D = diameter of opening, (cm).

The aperture single-reflection loss, R_a, is an interaction between the impedance of an incident wave and the aperture.

$$J = \frac{Z_a}{Z_w} = \frac{\text{APERTURE CHARACTERISTIC IMPEDANCE}}{\text{IMPEDANCE OF INCIDENT WAVE}}$$

$Z_{ar} = j\omega\mu_o W/\pi$ => impedance of hole area for rectangular aperture

$Z_{ac} = j2\pi f\mu_o D/3.682$ => impedance of hole area for circular aperture

$Z_{wh} = j\omega\mu_o r$ => impedance of conductor width between holes for magnetic fields

$Z_{we} = j/\omega\epsilon_o$ => impedance of conductor width between holes for electric fields

The multiple reflecting aperture correction term, B_a, is defined by the following equation:

$$B_a = 20 \log\left[1 - \frac{(J-1)^2}{(J+1)^2}\ 10^{-A/10}\right]$$

- applicable only when A_a is less than 15 dB.

The correction term to account for the number of like discontinuities, K_1, shows that the amount of energy transferred through a perforated shield is a function of the number of openings. K_1 can be ignored for sources close to the shield. Its equation is as follows:

$$K_1 = -10 \log an$$

where

a = area of each hole, cm^2

n = number of holes

The skin depth correction term, K_2, recognizes that at low frequencies, when the skin depth becomes comparable to the screening wire diameter or dimension between apertures, a reduction in shielding effectiveness occurs.

$$K_2 = -20 \log \left[1 + \frac{35}{1.15(\pi d^2 f \sigma \mu)} \right] \text{ dB}$$

For screening, substitute C_w for d^2; d^2 is used for perforated sheets.

C_w = conductor width between holes

d = wire diameter

The adjacent hole coupling correction term, K_3, is the result of noting that shielding efficiency was higher than expected when apertures in a shield were closely spaced and the depth of openings was small compared to aperture width. This is interpreted as the result of coupling between adjacent holes and becomes important for small openings. The equation for computing K_3 is:

$$K_3 = 20 \log_{10} [\coth(A_a/8.686)] \text{ dB}$$

4.5.1.3 <u>Seams Without Gaskets</u>

Radio frequency (RF) interference leakage problems stem primarily from improperly bonded seams. Seams that are properly bonded will provide a low impedance to RF current flowing across the seam. This is important because a relatively high RF seam impedance will cause RF voltages to develop across the seam from these skin currents. This permits RF energy to enter or leave the shielded enclosure.

To maintain shielding effectiveness, there are three considerations in the design of seams. They are:

- <u>Conductive Contact</u>: All seam mating surfaces must be electrically conductive, e.g., permanent mating of surfaces, bonded by a metal flow process.

- Seam Overlap: The two surfaces of the seams form a capacitor. Since capacitance is a function of areas, seam overlap should be as large as practical to provide sufficient capacitive coupling for the seam to function as an electrical short at high frequencies. A minimum seam overlap to spacing-between-surfaces ratio of 5 is a good rule to follow.
- Seam Contact Points: There should be firm electrical contact along the entire length of every seam. This contact can be obtained by using pressure devices such as screws or fasteners, grounding pads, contact straps across the seams, or conductive gaskets.

4.5.1.4 **RF Gaskets**

RF gasketing is briefly discussed here as a subset of the total discussion on shielding. However, this particular subject is of such importance to the EMC conditions of the Navy's latest aircraft that a separate chapter is also dedicated to the subject.

RF gasket material is most typically used when continuous welding or overlapping seams cannot be employed. RF gaskets used as temporary bonds represent considerable shielding improvement over direct metal-to-metal mating.

The major material requirements for RF gaskets include:

- compatibility with the mating surfaces
- corrosion resistance
- appropriate electrical properties
- resilience (important when gasket is repeatedly compressed and depressed)
- mechanical wear
- ability to form in a desired shape.

The form of a gasket is determined by attachment methods, force available, other gasketing functions, joint unevenness, and space available. The thickness of the gasket, like the form, is determined by joint unevenness, force available, the class of joint and the RF level.

One of the major applications for EMC gasketing is to provide an electrical bond across a seam that employs an environmental seal. Basically, there are four categories of environmental seals:

- Open: No (or little) consideration given to the transfer of air, moisture or dust.
- Dust Seal: Creating a barrier to airborne particulate transfer.
- Vapor Seal: Creating a barrier to the transfer of gaseous material (including moisture) under ambient or slight pressure differential conditions.
- Vacuum or Pressure: Creating a barrier which permits a significant pressure differential.

Of the four environmental categories, vacuum sealing is the hardest to achieve and is normally maintained by means of hermetic (air-tight) seals. Hermetic seals based on hard metal-to-metal contact are, from an EMC standpoint, equivalent to having no seam.

In using gasketing materials to attain a satisfactory EMC shield and proper environmental seal, it is necessary to apply gasket pressure. It should be noted that gaskets are subject to both minimum and maximum pressure limits to achieve a proper seal. The higher the pressure applied to the gasketed joint, the better the apparent environmental and EMI seal. However, should the pressure exceed the maximum pressure limit of the material, permanent damage to the material can result. This damage may decrease pressure across the seam and degrade both the environmental and EMI shielding characteristics. Wherever possible, gasket compression stops or grooves should be used to limit compression to the maximum recommended values.

4.5.1.4.1 **Environmental Requirements**

The EMI gasket is often required to function as an environmental seal. Therefore, selection of the sealing elastomer is as important as the EMI gasket and often extends the service life of the shield.

Environmental Seals. An EMI gasket in conjunction with an elastomer seal can provide protection from dust, moisture and vapors under low to moderate pressure. To seal against dust and moisture, flat or strip EMI gaskets joined to a sponge or solid elastomer are adequate. Sponge elastomers, characterized by compressibility, are ideally suited for use in sheet metal enclosures having uneven joints. Required closure pressures are generally low: between 5 and 15 psi. To avoid overcompressing sponge elastomers, compression stops are recommended. These stops can be built into the enclosure or embedded in the elastomer. Both techniques are illustrated in Figure 4-2.

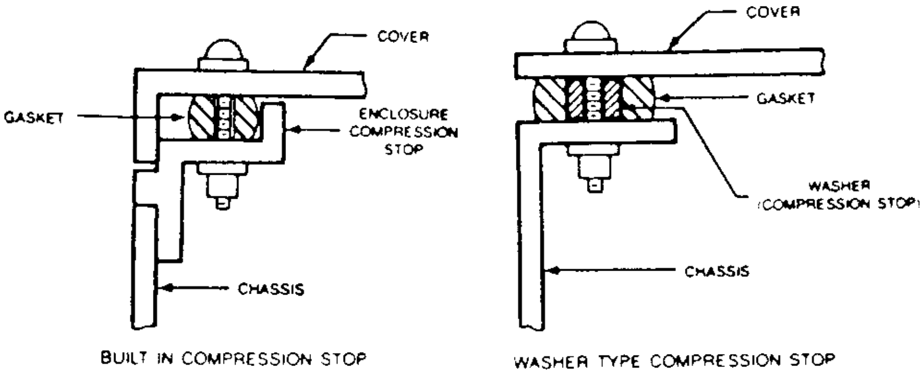


Figure 4-2. Gasket Compression Stops

Sealing against differential pressure between the enclosure's interior and exterior is best accomplished using a gasket which is contained within a groove in the enclosure. The best known seal of this type is the "O" ring. There are many variations in the cross section of such a seal (e.g., rectangular, round, "O" and various special shapes). Most seals are available in either solid or hollow cross sections.

Unlike sponge elastomers, solid elastomers do not change volume under pressure and, therefore, seal deflection must be considered during groove design. As a rule of thumb, the groove should have a minimum cross sectional area at least equal to 125% of that of the seal to accommodate deflection under worst case tolerance conditions of elastomer and groove.

Normal deflection for solid rectangular elastomer seals ranges from 5 to 15%. The pressure required to deflect solid elastomer seals is a function of the elastomer hardness and the cross section shape. Typical pressures are as low as 20 psi for low compression, low durometer material, and as high as 150 psi for high compression, high durometer material.

Pressure Seals Up To 100 psi. One of the most difficult sealing tasks in an EMI shielding seam design occurs when it is necessary to maintain a pressure differential (including vacuum) between both sides of the seam. The groove design must be such that it is almost completely filled by the gasket. To accomplish this, a close tolerance must be maintained between the gasket cross section and the groove cross section. Table 4-2 lists recommended best tolerances for elastomer materials (check manufacturer's data sheets for specific tolerances). As a general rule, the compressed gasket cross section should completely fill the groove cross section under the worst case tolerance conditions. Additionally, the surface finish around the area of the seal should be one micron or better.

Table 4-2
RECOMMENDED ELASTOMER TOLERANCES

DIMENSION mm (in)	WIDTH mm (in)	HEIGHT mm (in)
Under 2.30 (0.090)	N/A	+/- 0.13 (0.005)
2.30 (0.091) to 6.36 (0.250)	+/-0.4 (0.016)	+/- 0.25 (0.10)
6.37 (0.251) to 12.70 (0.500)	+/-0.8 (0.032)	+/- 0.38 (0.015)
12.71 (0.501) to 19.05 (0.750)	+/-1.2 (0.047)	N/A
Over 19.05 (0.750)	+/-1.6 (0.062)	N/A

Another consideration for pressure seals is the chemical permeability of the elastomer compound. This is defined as the volume (cm^3) of gas that will permeate through a specimen of one cubic centimeter in one second. Table 4-3 presents the air permeability of five compounds. It should be noted that special compounding techniques can substantially alter these values, and leakage can be reduced by using grease. However, compatibility of the grease with the seal elastomer and the application should be checked.

Table 4-3
AIR PERMEABILITY

ELASTOMER	75^0F	176^0F	250^0
Butyl	0.2	3.2	13
Nitrile*	--	4.1	15
Viton	--	8.8	36
Natural	4.9	44	71
Silicone	115	350	--

* High Acrilonitrile
Data condensed from WADC Technical Report 56-331, January 1959

Service Life. For most cases, three important factors influence seal selection: the service life of the product, seal material characteristics and environmental conditions.

EMI gasket materials are made from metals and metal/elastomer combinations. The aging rate of elastomers is dependent upon the operating environment and the material. The operating environment includes the accumulated effects of dust, lubricants, fungus, solvents, moisture, vibration and the normal environmental extremes of pressure and temperature, any of which may form a barrier or set up a chemical reaction that can cause corrosion and seal deterioration. Three elastomer materials which offer good resistance to water and hydrocarbon fluids are neoprene, silicone and fluoroelastomers. In terms of cost effectiveness, neoprene and silicone rubbers are an excellent choice. Except for specific cases, all are usable over the normal range of temperatures encountered.

4.5.1.5 Temporary Apertures

Temporary apertures include access panels or removable metallic sections on and within the aircraft. These panels or sections have seams around them that must be electromagnetically tight when closed. Finger stock and spring contact fingers are good shields in these cases. Temporary apertures cannot perform a shielding function when opened. Therefore, if it is necessary for them to be opened in RF fields, the interior circuits, components, and cables must be designed to preclude interference or damage.

Finger Stock. Finger stock is designed to maintain a continuous low RF impedance electrical bond between the door or panel and the equipment housing when the access doors and panels are closed. The best bond is achieved by metallic mesh or fingers between the mating surfaces. With metallic fingers, 5 to 10 grams of pressure per finger should be applied to the mating surface.

Spring Contact Fingers. The best arrangement of spring contact fingers around removable panels or doors is the installation of two sets of fingers at right angles to each other. One set is a wiping set; the other is in compression. The combination makes good electrical contact when the door is closed. The pressure exerted by these springs is highly important and should be carefully maintained. Cleanliness is also important.

Hinges. If hinges are used on panels, a mesh such as conductive weather stripping on the hinged side of the panel is recommended. An alternative method for shielding at the hinged side of a panel is to use metal fingers. The shielding material must be electrically and mechanically bonded to the frame at close intervals to ensure proper shielding.

Conductive Glass. It is often necessary to provide RF shielding over equipment that must be observed by the user. Examples of such equipment are meter faces, pilot-light bulbs, and oscilloscope faces. Glass coated with conductive material such as silver can provide shielding across viewing surfaces, with some loss in light transmission. Conductive glass is commercially available from a number of glass manufacturers. The quality of light transmission is dependent upon the surface resistance, decreasing for lower levels of resistance and increasing at higher resistances. Higher resistances result in decreased shielding effectiveness, however.

4.5.1.6 **Cable Shielding**

Braid, flexible and rigid conduit, and spirally wound shields of high permeability materials can be used to shield cables. The advantages of using braid are its ease of handling in cable makeup and lightness in weight. Its shielding effectiveness increases with the density of the weave, and decreases with increasing frequency.

Rigid (solid) conduit's shielding effectiveness is the same, for RF purposes, as that of a solid sheet of the same thickness and material. Flexible conduit or linked armor provides effective shielding at lower frequencies, but at higher frequencies the openings between individual links can take on slot-antenna characteristics that degrade shielding effectiveness. Degradation of shielding conduit is not usually due to insufficient shielding properties but rather the result of discontinuities in the cable. These discontinuities usually result from splicing or improper shield termination.

Spirally wound shields of high permeability materials are used to shield against devices associated with high inrush currents or incorporated switching devices that normally develop high-amplitude transients. These materials are spirally wound because they lose their shielding properties when cold worked into tubes. A protective rubber coating is recommended.

Data on the shielding effectiveness of cables is not readily available. There is no standardized procedure for collecting such information, and the large number of parameters influencing the particular cable's performance complicate the issue. These parameters include termination impedances, impinging signal direction and impedance, and cable length relative to the interference signal frequency, the particular connectors employed, and flexing requirements.

Percent Shield Coverage. Shielding effectiveness in most cabling applications is dependent on the percent of cable coverage provided by the shield. This is the ratio of metal to total possible shield surface. The angle of the braid wires relative to a plane normal to the cable axis is a parameter that influences percentage shield coverage under cable flexing conditions. It is usually between 10 and 40 degrees. The shield braid angle and percent braid coverage are determined as follows:

$$a = \tan^{-1}[2\pi(D + 2d)P/C]$$

$$K = 100(2F - F^2)$$

where

a = Shield braid angle (angle of braid with axis of cable)

K = Percent coverage

d = Shield strand diameter in inches

C = Number of carriers

D = Diameter of cable under braid, in inches

$F = NPd/ \sin a$

N = Number of strands per carrier

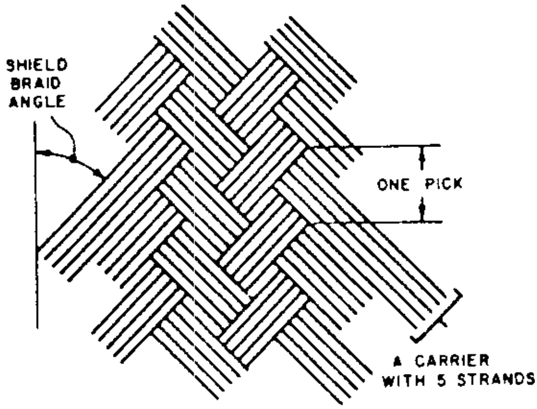
P = Picks per inch of cable length

Note: For 2-conductor cable only

$$D = \frac{(\pi + 2)b}{\pi}$$

where

b = diameter of basic wire



Definitions of Cable Shield Parameters

Much of the previous discussion relates to the shielding of cables against plane wave or high impedance fields. For shielding against magnetic fields, the use of annealed high permeability metal strips wrapped around the cable has already been indicated. Multiple layers of counterspiral-wound nickel-iron or silicon iron alloys, or low carbon steel have proven effective under these circumstances. High permeability tape is available with or without adhesive backing. Also, combination high permeability/high conductivity tape is available to provide both electric and magnetic shielding.

Surface Transfer Impedance. Surface transfer impedance is a shield property that is independent of both shield geometry and the impinging wave. It is given by the following equation:

$$Z_T = \frac{e_i}{I_s} \quad \Omega/\mathrm{m}$$

I_s is a current flow in the shield that is produced in the surface on which a wave impinges (accounting for reflection). It is attenuated by an amount $e^{-\alpha d}$ through the thickness, d, of the shield. In other words, the current on the inside of the shield is only $e^{-\alpha d}$ of its value on the outside surface.

The attenuation rate, α, is equal to ($\sqrt{\omega\mu\sigma/2}$ Np/m,)(1/Np = 8.686dB). Note the reciprocal of α is the skin depth, δ, in a conductor. The skin depth is the distance into the conductor at which currents have been attenuated to $^1/e$ (or 1 Np) of their value at the surface.

The attenuated current, multiplied by the effective resistance per unit length of the shield, results in a voltage per unit length, e_i, along the opposite side of the shield. The better the S.E., the smaller will be e_i for a given I_S, and thus the smaller will be the surface transfer impedance, Z_t. The surface transfer impedance and S.E can be related for electrically short coaxial cables that are circumferentially terminated and above a non-ferrous ground plane.

As an example, a cable shield having ends connected to a ground plane forms a loop or magnetic dipole. Let Z_{loop} be the shield to ground plane loop impedance. Then with respect to the emission and susceptibility of the magnetic dipole:

$$S.E. = 20 \log_{10}(Z_{loop}/Z_T)$$

A similar concept is that of surface transfer admittance, $Y_T = j\omega C_{12}$, where C_{12} is the capacitance between the internal conductor in the shielded cable and the external shield current return path (e.g., ground plane).

For electric dipole emission:

$$S.E. = 20 \log_{10}(Y_{loop}/Y_T)$$

where

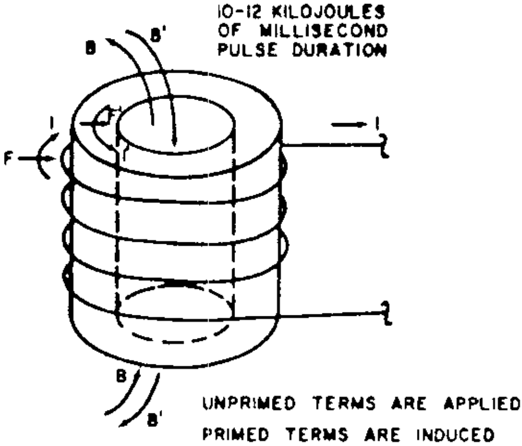
Y_{loop} is the unshielded wire to ground-plane admittance.

4.5.1.7 **Cable Shield Terminations**

If the effectiveness of a shield is to be maintained, the cable shield must be properly terminated. In an otherwise adequately shielded system, RF currents conducted along shields can be coupled to the system wiring from the point of an improper cable termination. This is a particularly important consideration in the case of cables exposed to high power RF fields. In a properly terminated shield, the entire periphery of the shield is grounded to a low impedance reference, minimizing any RF potentials at the surface of the termination.

In high field strength environments, considerable success in terminating both shields and solid cylindrical members has been obtained using the Magnaforming process. Magnaforming is a metal-forming technique that is used to shrink metal tubes and similar shapes around other forms such as collars, sleeves, rods, etc. The process uses a very intense, short duration magnetic field to induce an opposing current in the tubing or sleeve which is to be shrunk. The magnetic field produced by the induced current in the sleeve opposes the field produced by the current in the magnetic coil, and is of equal magnitude.

The resulting force from the magnetic coil field, and the force from the field around the sleeve, combine to produce a uniform compression of the sleeve around the entire sleeve periphery. If the current applied to the magnetic coil is of sufficient amplitude, the combined resultant compressive force on the sleeve will deform the sleeve, reducing its diameter until it conforms to the shape of the underlying material. The basic process is shown below:



Relationship of F, B, and I in
Magnaforming Process

Magnaforming has a limited utility because it requires special equipment to produce high magnetic fields and maintenance problems arise when there is a need for repair; as a result, crimping is the preferred shield termination method.

4.5.1.8 **Cable Shield Connectors**

Another source of RF leakage originates from the connectors of the subsystem. Quick-disconnect connector surfaces represent an impedance discontinuity of the cable shield. Even though there is mechanical contact with the shield through the outer mating section of the connector, a good RF connection is not assured.

To maintain the shield integrity of two interconnecting connectors, it is recommended that spring contacts inside one portion of one connector be placed so that positive contact is made along the circumference of the mating parts. These contacts are extended so that the shell of the connector mates before the pins make contact on assembly and breaks after the pins on disassembly.

A good connector is one in which the shielding effectiveness of the mated connector equals or exceeds that of an equal length of the cable utilized in the circuit. As said before, if the effectiveness of cable shields is to be maintained, the cable shield must be properly terminated. In a properly terminated shield, the entire periphery of the shield is grounded to a low impedance reference, minimizing any RF potentials at the surface of the terminals.

To prevent RF energy from entering a sensitive circuit at connector interfaces, the following features should be considered:

- There should be no break in the shield which would allow RF energy to "leak" into the system's circuits.
- The connector should be able to withstand environmental conditions (vibration, high and low temperatures, corrosion, etc.) without degradation of its shielding characteristics.
- The connector shield at the interface of the two connector halves must make positive contact before any other contacts mate and must maintain contact until after the contacts break.
- The contacts in the connector mating sections should be sufficiently isolated to preclude the possibility of field personnel accidentally getting a shock by touching the socket (mate) contacts, either with their fingers or with the mating connector shell while the connectors are unmated.

- Power and signal circuits should not be routed through the same connector.
- Input and output signal circuits should not be routed through the same connector.

4.5.2 <u>Bonding</u>

Bonding is the process of establishing a low impedance path between two metal surfaces. The purpose of the bond is to make the structure homogenous with respect to the flow of RF currents between metallic conductors. Thus, proper bond design can prevent the development of potentials which may result in EMI.

Good bonding between equipment and a ground reference is essential to minimizing interference. In addition, good bonding enables the design objectives of other methods of EMI suppression, such as shields and filters, to be more nearly achieved. It:

- Minimizes the build-up of RF voltage differences and ground loop currents.
- Deters the build-up of static charges in equipment operation.
- Minimizes damage which might be caused by lightning strikes.
- Protects personnel from the shock hazard that could result if primary power were inadvertently shorted to an enclosure.

4.5.2.1 <u>Surface Treatment</u>

The secret to good bonding is intimate contact between the mating surfaces. The mating surfaces must be smooth and contoured so that the maximum surface area is in actual contact. It is also important that the surfaces are clean and not coated with a nonconductive finish. Immediately prior to bonding, all chips, paint, grease, or other foreign matter must be removed with a proper cleaning solution.

Surfaces should be bonded immediately after protective coatings are removed to avoid oxidation. The method of fastening is very important, and sufficient pressure must be exerted in the presence of deforming stresses, shock, and vibrations associated with the aircraft and its environment. This is important because vibration, expansion, contraction, or relative movement incident to normal service can break or loosen the connection to such an extent that resistance will vary during movement. The most desirable bond is achieved through a continuous butt or lap weld.

After bonding, the exposed areas should be refinished as soon as possible with the original finish. However, if the refinishing paint used is too thin, it may seep under the edges of bonded components and impair the quality of the bond.

4.5.2.2 Corrosion

Corrosion is a process that is active on a 24 hour basis. To effectively combat it, mechanics and technicians must recognize this and treat it on a continuous basis. Corrosion is one of the environmental factors that influences the total product design. Shielding and weight restrictions often dictate the use of particular metals for their electrical and mechanical characteristics. Generally, structural materials such as aluminum or magnesium are highly active electrochemically when in contact with most suitable shielding materials. It is therefore necessary to select shielding materials and finishes which inhibit corrosion, are compatible with the enclosure materials and are highly conductive. Navy aircraft operate in a highly corrosive, all weather environment and can be subject to both electrolytic and galvanic corrosion.

ELECTROLYTIC CORROSION - Corrosion which occurs when a net DC current flows between two metals in the presence of a conducting fluid (electrolyte). The rate of corrosion depends upon the amount of current and the nature of the electrolyte.

GALVANIC CORROSION - Corrosion which occurs between two dissimilar metals in the presence of moisture or some other electrolyte. Under these conditions an electrochemical cell is formed and current will flow from one metal to the other, carrying ions of the metal with it.

Corrosion occurs between dissimilar metals in the presence of an electrolyte. The rate of corrosion depends on the electrochemical potential between the two metals and the conditions under which contact is made. Table 4-4 lists groups of common materials which are compatible. Selection of materials from a single group within this table will provide the least corrosion due to galvanic action when materials are in contact for an extended period of time with the appropriate protective finish. The materials are arranged by decreasing galvanic activity within each group.

Maximum galvanic activity occurs when dissimilar metals are exposed to salt atmosphere, fuels, chemicals and other liquids which may act as electrolytes. To minimize corrosion, all surfaces should be free of moisture.

Table 4-4
Grouping of Metals by Electrochemical Compatibility

(ANODIC)

Group I	Group II	Group III	Group IV
Magnesium	Aluminum	Cadmium Plating	Brass
Magnesium Alloys	Aluminum Alloys	Carbon Steel	Stainless Steel
Aluminum	Beryllium	Iron	Copper & Copper Alloys
Aluminum Alloys	Zinc & Zinc Plating	Nickel & Nickel Plating	Nickel / Copper Alloys
Beryllium	Chromium Plating	Tin & Tin Plating	Monel
Zinc & Zinc Plating	Cadmium Plating	Tin / Lead Solder	Silver
Chromium Plating	Carbon Steel	Lead	Graphite
	Iron	Brass	Rhodium
	Nickel & Nickel Plating	Stainless Steel	Palladium
	Tin & Tin Plating	Copper & Copper Alloys	Titanium
	Tin / Lead Solder	Nickel / Copper Alloys	Platinum
	Lead	Monel	Gold

(CATHODIC)

EMI gasket material making contact with the enclosure material in a corrosive atmosphere must be treated to ensure that materials in contact are compatible from a single group in Table 4-4. For example, an aluminum chassis with a Monel mesh gasket should be tin or cadmium plated for the combination to be compatible. The use of protective finishes on commonly used materials is an excellent way to retard corrosion.

When it is necessary for dissimilar metals to be used, the following practices should be applied to insure compatibility:

- Use a tin or cadmium plated washer between a steel screw in contact with aluminum.
- Use selective plating where it is essential to have reliable electrical contact.
- Design to ensure that the area of the cathodic metal (lower position in a group) is smaller than the area of the anodic metal (higher position in a group).

More information on this subject can be found in various military standards including MIL-STD-454, MIL-STD-889, MIL-STD-1250 and MIL-F-14072 (finishes).

Since most equipment has to operate in a moderately corrosive environment, the metallic surface should be protected with a conductive finish to ensure a low impedance contact. Some finishes which meet this requirement are iridite, nickel and tin for aluminum alloys; tin, cadmium and nickel for carbon steels; and passivation for stainless steel.

4.5.2.3 Bond Straps (Jumpers)

The use of bonding jumpers in indirect bonding is equivalent to the problem of maintaining low impedance paths. At low frequencies, bonding jumpers do not present any special problems other than resistance, and any reasonable length jumper can be used. At higher frequencies, however, the RF impedance of the bond becomes a critical design consideration.

A bonding jumper has the usual electrical parameters of resistance, inductance, and capacitance; of these parameters, resistance is an inherent property of the jumper (depending on the material selected), and capacitance is dependent upon the physical configuration of and separation between the bonded members.

A bonding system must provide minimum impedance to ground within the frequency range of system operation. To reduce the RF impedance of the bond, and thus increase its bonding effectiveness, the case to ground spacing and the length to width ratio of the bond strap must be minimized.

Bond straps should be selected based on material compatibility and removal requirements. Various tests have indicated that the flat, solid bond strap has less inherent ac resistance than other types of straps. However, this advantage is often a minor one, and may not offset the advantages of flexibility (braid) and lower cost (solid wire). It must also be remembered that the bonding strap or direct bond must be sufficient to carry the required currents.

In conclusion, the purpose of bonding is to ensure that the structures of aerospace systems are electrically stable and free from such hazards as lightning, static discharge and electrical shock, and to provide for the suppression of EMI resulting from these hazards. In the next section, grounding will be discussed. Bonding and grounding are complementary in that bonding is the physical implementation of grounding, and good grounding techniques depend on good bonds.

4.5.3 Grounding

Grounding refers to the establishment of an electrically conductive path between the circuit and a chosen reference point. The reference point can be earth, the equipment enclosure, or the aerospace vehicle structure itself.

A uniform grounding philosophy is mandatory to avoid conductive coupling, low impedance ground loops, and hazardous operation conditions. The basis for this interference-free operation is a good, basic ground plane or reference. An ideal ground plane should be a zero-potential, zero-impedance body that can be used as a reference for all signals in the associated circuitry. It should also be a body where any undesirable signal can be transferred for its elimination.

However, due to physical properties and

material characteristics, no ground plane is ideal, and some potential always exists between ground points in a system. The designer's job is to design a ground system that will effectively minimize potentials and reduce ground currents. A poor system, by enabling these spurious voltages and currents to couple into a circuit, subassembly, or equipment, can degrade the shielding effectiveness of well-shielded units. A poor ground system can also result in EMI problems that may be rather difficult to resolve after-the fact.

4.5.3.1 Grounding Systems

The three fundamental grounding methods are floating, single-point, and multiple-point. Each will be discussed in greater detail.

Floating Ground System. The floating ground system is a method to electrically isolate circuits or equipment from a common ground plane, or from any common wiring that might introduce circulating currents. Hazards exist in the use of floating systems, however. Static charges or lightning potentials may accumulate between the floating grounds and other accessible grounds such as the flight deck or other portions of the ship structure. The accumulated charges can cause a destructive or noise-producing discharge current to flow. To correct this, the floating ground method can be compromised with a large bleeder resistor.

The floating ground is most useful at frequencies where capacitive coupling paths are negligible, i.e., usually less than 1 MHz. Isolation techniques can also be used to prevent ground loops from occurring.

Single-Point Ground System. The single-point ground system is a method that uses a single physical point in the circuit as a ground reference; all ground connections are tied to this point. For multiple cabinet configurations, the cabinet and electronic circuit grounds are often kept separate, with the single point grounding concept being used independently for each ground system. This method isolates each cabinet and prevents circulating currents in one ground system from affecting another.

Single-point ground systems are not practical at high frequencies where the wavelengths approach equipment ground plane dimensions or cable lengths. Other upper frequency limits include distributed capacitance and powerline filter capacitive returns to the ground plane. Therefore, it is important for the system designer to have an understanding of the frequency susceptibility of his device. Equally important is an awareness of internal and environmental frequencies which may create EMI before finalizing a grounding system design.

Typically, single-point grounding should be used for circuit or component dimensions less than 0.03 λ but not greater than 0.15 λ. Between 0.03 and 0.15 λ (circuit dimensions), the type of grounding depends on the physical arrangement of the ground leads as well as the conducted emission and susceptibility limits of the circuits being grounded.

Multiple-Point Ground System. For circuit dimensions greater than 0.15 λ, the multiple-point ground method is used. This grounding method uses a ground plane instead of individual return wires for each circuit. The ground plane might be an equipment chassis or a ground wire that is carried throughout the system.

The advantages of using the multiple-point ground system include easier circuit construction, many different paths to ground, and reduced resonance. It is also the only way to avoid standing-wave effects in the ground system at high frequencies. On the other hand, multiple-point grounding creates many ground loops and, if the circuit must handle a broad portion of the frequency spectrum, the presence of ground loops can cause problems when the circuit is operating at low frequencies. To overcome this problem a hybrid ground is used. The hybrid ground contains series capacitors for those points requiring high frequency grounds.

In large circuits or components, grounding should be performed at several locations so that the separation between grounds is never greater than 0.15 λ . The ground plane must be carefully maintained, particularly with reference to corrosion, vibration, and mechanical damage, which can introduce high impedances into the ground system.

4.5.3.2 Circuit Grounding Considerations

In a large ground plane, significant potential differences may exist between various points as a result of the amount of current flow into and out of the plane. To keep these potential differences to a minimum, the circuit components should be physically arranged so that ground currents will be low and isolated.

The potential differences introduced by the ground plane can be canceled by electrically isolating the circuits using a floating ground system. This method works well at audio and low radio frequencies, but at high frequencies capacitive coupling paths appear and bypass the isolation transformers.

Ground circuit interference can be significantly reduced by the use of differential or balanced circuitry. Since a differential circuit responds only to the potential difference between its input leads, the noise voltage at the source may be above ground potential by a considerable amount without degrading circuit performance.

If each input lead has the same impedance to ground, then the interference voltage is balanced out in the input to the device and the device will not respond to the ground circuit signal. This is difficult to achieve since there is always some unbalance in the differential device or associated circuitry. In turn, an interference voltage will appear as a difference voltage across an equivalent resistance. The noise voltage differential results in a reduced output signal-to-noise ratio.

In transistorized digital circuits, the input and output impedances are generally relatively low. This makes the circuits more susceptible to the effects of low impedance (magnetic) fields than to the effects of high impedance (electric) fields. One of the important parameters controlling interference due to a low impedance field is the loop area of the circuits causing and picking up the interference. By minimizing this loop area, much of the interference problem can be eliminated.

4.5.3.3 <u>Power Supply Grounding</u>

Proper power supply grounding is needed to reduce source interference in the electronic circuit. The ideal method would be to give each circuit its own power supply. This would result in complete decoupling of circuits, which is needed for interference-free operation, but would add additional cost, weight, and space requirements. In general, power and signal grounds should be isolated from each other to minimize the possible coupling of signals between these two major path types.

Groups of electronic circuits can be connected to one power supply based on a prearranged logical pattern. If possible, critical (susceptible) circuits should be kept separate and given their own power supply. If this is not feasible then a voltage regulator, such as a zener diode, can be used to act as a decoupling component.

Decoupling components, such as large capacitors or an RC network, are also helpful in reducing the inductive effects of long power supply leads in digital circuits. A problem arises at frequencies where the line and capacitor resonate, producing a "ringing". This condition can be circumvented by shunting the decoupling capacitor with a small RF bypass capacitor.

Physical location must also be considered when deciding which circuits should be connected to which power supplies. If no other factors are involved, all circuits fed by a given power supply should be grouped in the same area. However, in cases where various circuits will have to operate simultaneously (as in synchronous digital systems), some spatial separation may be advantageous to prevent coupling of radiated energy.

Circuits carrying large alternating currents are potential sources of interference coupling to adjacent lines. Twisted lines should be used for ac power circuits and should be kept away from susceptible lines. Also, ac power circuits in which switching transients are expected should use shielding to contain the high frequency components of the transient. Such shielding should cover the entire power wiring bundle and should be grounded at both ends.

Twisting can also be used to minimize the possibility of direct current supply lines coupling interference to other circuits and to protect them from receiving similar interference. Shielding offers little advantage for dc power supply lines because of the low impedance. Also, dc supply lines should be routed away from ac power and control lines, and supply return lines should not be shared with other circuit returns.

4.5.3.4 **Power Returns**

There are two primary concepts behind power returns: ground or structure common return and wired return. In the common concept, all loads use the vehicle frame or structure as the return conductor. Its principal advantage is that it eliminates the need for heavy power return wires; its disadvantage is that it does not distribute the power efficiently.

Current flow through structure produces voltage drops in the structure. These voltages are normally small compared to the operating level of the power system, but are large compared to the operating level of electronic systems. This can create potential interference problems in any electronic system using the structure as a power return. Even systems using structure as a plane for shield grounds are subject to induced voltages in susceptible circuits.

In the wired return concept, all systems are grounded at only one point and have wires for all return circuits. The wired return system eliminates the vehicle structures as an impedance common to all systems and therefore eliminates the complex ground loops associated with the common return system.

4.5.3.5 **Relay Grounding**

A power system that drives electro-mechanical relays should not generally be used as a supply voltage for electronic circuits because of the large amount of noise in the system due to relay operations. However, this power supply can furnish power to indicator lights, small motors, electro-magnetic clutches and brakes. However, these devices, like the relays, may also be sources of noise.

The primary cause of relay interference is the de-energizing of relays. When a relay circuit is opened, the collapsing magnetic field induces a large voltage of the opposite polarity across the coil. This induced voltage initiates an arc across the contacts that are breaking the circuit. The arc contains energy in a wide band of frequencies that may be transmitted by conduction and radiation as interference. There are many standard arc suppression techniques but, even when these are used, a certain amount of noise will be conducted or radiated from the source.

Current changes in the relay power supply buses can also cause conducted interference due to continually changing demands when the equipment is in normal operation. The conducted interference can be reduced by isolation of the relay circuits from the rest of the equipment.

To maintain isolation of the relay circuits and to prevent the system from floating and possibly reaching a high potential above ground, the relay system should preferably be grounded at a single point. Because of the unusually wide distribution of relay circuits, and because it is the point of maximum current, the ground connection should be made at the source. The generation of varying magnetic fields due to the variation of the relay power supply currents must also be considered. The effects of these variations can be minimized by running the supply and return leads as close together as possible throughout the system, thereby reducing the loop areas of the various relay circuits.

4.5.3.6 Cable Shield Grounding

Injudicious application of a grounded shield to a wire may cause coupling problems that otherwise would not exist in a complex electronic system. Grounding of the shields may be accomplished using single or multiple point grounding. Factors that influence this selection include the interference signal frequencies involved, the length of the transmission line, and the relative sensitivity of the circuit to high or low impedance fields.

The impact of cable shield and termination groundings on crosstalk has been explored through various tests. Test performance indicates that, for low-level signals and low-impedance circuits where the distance between input connector and circuit input is small (an inch or two), the use of a twisted-pair wire, to reduce susceptibility, may prove adequate. Single-point grounding is more effective than multiple point grounding only for short shield lengths. For long runs, the use of twisted-pair shielded wire becomes mandatory.

Twisted-pair shielded wire must be used with unbalanced as well as balanced devices. In the balanced case there should be no grounding except for the shield; in the unbalanced case it is often necessary to ground one of the conductors as well. (The shield and conductor should be grounded at the same point.)

High level signals are generally impervious to circuit susceptibility. However, they may be a source of interference to lower level signal lines. For this reason, and dependent on other characteristics of the signal, either a twisted-pair or a shielded lead should be used. Multiple shielding may be required if the signal is of sufficient level. Grounding should be applied at both ends to prevent electrostatic radiation from the cable.

When cable shields are grounded, good electrical contact to the shield must be established. If possible, the shield should be grounded completely around the periphery of the connector shell. The use of pigtail grounding should be avoided on all cables, particularly those carrying signals above 1 MHz. When it becomes necessary to use a pigtail, the length should be minimized.

4.5.4 Concepts of Electromagnetic Topology

The preceding discussions of shielding, bonding and grounding provide the engineer with theoretical and practical methodologies for determining specific parameters. However, due to the complexity of modern electrical systems, it is almost impossible to carry out a rigorous laboratory analysis of how a system would respond to excitation by lightning, EMP, HPM or high density EM fields. In many instances, it is better to estimate the system's response as a basis for designing protective measures or to evaluate the system's vulnerability. A means of obtaining these estimates is to apply a concept of EM shielding topology which had its inception in 1974.

References to the concept of topology were discussed in the IEEE publications EMC in 1978, 1980 and at an EMC symposium in Zurich, Switzerland in 1981. The contents of this section are derived principally from a paper presented in 1986 by Frederick M. Tesche as part of the North Atlantic Treaty Organization (NATO) Advisory Group for Aerospace Research and Development (AGARD) lecture series. The discussions presented herein are only a brief synopsis of the actual content of Mr. Tesche's paper which contains a more rigorous mathematical discussion. The actual paper may be obtained by requesting a copy of AGARD-LS-114 from the National Technical Information Service, Springfield, Virginia, 22161.

Although the referenced paper considers shielding topology from a lightning and nuclear EMP perspective, the information may be readily extrapolated to address all facets of EMI. It is believed that the emerging threat of HPM's make this concept particularly timely and applicable to analysis of very complex weapon systems.

Electromagnetic topology is a description of the configuration and interconnection of conducting surfaces in a system which act as EM shields for the system. With a knowledge of the shielding topology, it is possible to determine all of the points of entry for EM into the system and to concentrate EMI hardening at these points. With this analysis technique, the system's internal configurations lose their importance in that all hardening is focused at the points of entry.

Associated with the topological diagram is a signal flow graph, referred to as an interaction sequence diagram. This represents the major coupling and propagation paths within the system. The interaction sequence diagram yields rough estimates of the system's response to external EM energies. With this knowledge, the system designer may intelligently specify the required hardening in terms of filters and active devices.

In Mr. Tesche's paper, he introduces the concept of electromagnetic topology as follows:

> Consider a very simple example of a shielded system having three separate, nested electromagnetic barriers as shown in Figure 4-3. The volume outside the system is denoted as V_0, with V_1, V_2, and V_3 being the volumes inside, which are bounded by the surfaces $S_{0,1}$, $S_{1,2}$, and $S_{2,3}$.

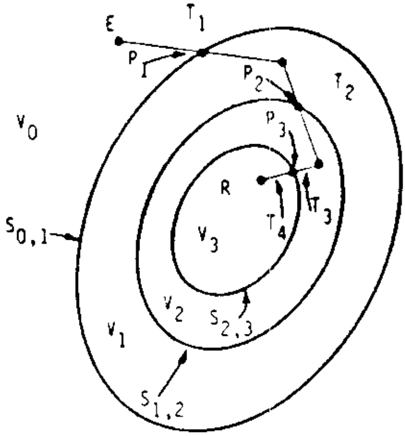


Figure 4-3 Simple electromagnetic topology for a system having three barriers.

Outside the system, it is assumed that there is some form of electromagnetic field excitation, and this is able to penetrate into the system, eventually arriving at the V_3 volume to create an electrical response. Although there may be many different individual paths within the systems by which the external EM field is able to propagate to the response point, these paths are represented schematically in this discussion as a single path from the outside to the inside of the system. In this manner, the various internal responses to the outside EM stress can be viewed as a vector [R] which is related to the excitation fields through a series of matrix transfer functions as:

$$[R] = [T_4][P_{2,3}][T_3][P_{1,2}][T_2][P_{0,1}][T_1][E]$$

In this expression, [E] represents a vector of excitations which account for the electromagnetic field outside the system, $[T_1]$ is a coupling and propagation matrix which provides a knowledge of the local excitation quantities at each of the penetration points on surface $S_{0,1}$, and $[P_{0,1}]$ is a matrix defining the penetration properties of the first barrier, $S_{0,1}$. Thus the product

$$[P_{0,1}][T_1][E]$$

represents the electrical response at all of the points within volume V_1 which are contained on the interaction paths defined for the system.

Generally, the matrices defining the penetration properties of the system's shielding barriers, $[P_{i,j}]$, are sparse and diagonal, since the penetration process is local. However, the matrix defining the coupling and propagation properties of a volume, $[T_i]$ is usually not sparse, due to the wave nature of the electromagnetic field.

Evaluating the response, [R], exactly for anything but the most simple system e.g., a straight wire inside of a spherical shield having an aperture is a very complex task. Consequently, it is desirable to approximate the general matrix equation by considering approximations to this interaction process. This is done by introducing the interaction sequence diagram which is a signal flow diagram associated with the system topological diagram. This diagram shows the major paths of EM energy propagation and penetration within the system.

An actual example of an interaction sequence diagram is considered beyond the scope of this document. Suffice it to note that an interaction sequence diagram is a plot of the field strengths present within each volume and the effects of those field strengths on the system's response.

When constructing a system topology and analyzing the signal flows through it, the critical coupling paths providing the largest excitation at the response point must be identified. In developing an associated interaction sequence diagram, only the most critical coupling paths are considered. The remaining paths, which have minimal influence on the response point, would be ignored. However, as the effects of the critical coupling paths are attenuated through the application of hardening devices, the system topology may change and some of the less critical coupling paths may become critical, making this technique an iterative process.

The topological concept provides a framework for viewing the EM interaction process in a structured manner. System design involves first determining the various shielding surfaces in the system, and then identifying the penetration points. This leads to definition of the major EM coupling paths in the system which transmit the externally produced signals to the critical equipment on the system's interior. With an estimate of the susceptibility levels of system components, it is possible to determine the relative amounts of EM protection required at each penetration point.

It is important to keep in mind that this technique is more qualitative than quantitative. The transfer functions used in the interaction sequence diagram and the approximations used in defining the diagram are such that detailed time domain histories of internal responses cannot be calculated; only rough estimates are possible. Nonetheless, this method of viewing a system provides useful guidance to system designers, many of whom are not accustomed to dealing with EM field problems.

4.5.5 Electrostatic Charging of Aircraft

It is now a well accepted fact that aircraft charge electrically while in flight. But, while so recognized, the frequency and severity of this charging phenomenon is often questioned by pilots, engineers and aircraft manufacturers alike. Electrostatic charging usually cannot be physically experienced, except in extreme cases such as Saint Elmo's Fire or lightning and, with today's digitally tuned and squelched radios, is seldom heard until it reaches magnitudes severe enough to disrupt communications or navigation.

Electrostatic charging of an aircraft's exterior dielectric structure is now the limiting factor in the reliability of LF and VLF navigation and communication systems. Flights in instrumented aircraft have shown that significant (measurable) electrostatic charging may take place during as much as 90% of flights conducted under instrument meteorological conditions.

There are three electrostatic charge operators which may affect aircraft in flight: engine charging, triboelectric charging, and cross field charging.

Engine Charging. Turbine engines often experience engine charging, most frequently at high power settings and during lower altitude climbs. Although the polarity and magnitude of such charging is a function of engine design, it cannot be predicted and can only be determined by an instrumented flight.

Triboelectric Charging. Triboelectric charging is the result of frictional particle contact between dissimilar materials, or flight through charged particles such as electrically charged rain drops. Triboelectric charging is most common and hazardous during flights at or near the freezing level with precipitation, and can become extremely severe over protracted periods of time. Empirically derived figures have been determined for triboelectric charging rates in 95% of the occurrences encountered by various categories of aircraft. For design purposes, a figure of 400 microamperes is used for single engine, general aviation aircraft; a 750 microampere charge rate is assigned to cabin class twins. A figure of 1.5 milliamperes is appropriate for large transports, but a charging rate as high as 5 milliamperes was measured for a short period during a Navy P-3 test flight. Triboelectric charge rates exceeding 40 microamperes per square foot of wetted frontal area appear to be uncommon.

Cross Field Charging. Flight in the vicinity of a thunderstorm is the most obvious example of cross field charging. It has been noted that some electrical aircraft discharge activity, especially from low threshold dischargers, seems to be associated with cumulus type clouds and even with vertical air currents (or "turbulence"). This type of electrostatic charging is characterized by reverse polarity discharges from opposing extremities of the airframe which, although not charging dielectric structures, can be a factor in dielectric streamer current generation, stored potential levels and dielectric punctures.

More than one EMI effect results from the charged state of an aircraft. Fundamentally, these effects include radiated, coupled energy to antennas or unshielded wiring from corona discharges; dielectric surface charge streamer currents; punctures of insulation (sometimes termed as pinholes); and arcing between isolated conductive structures. Each of these RFI generators has a distinctive signature which can be easily identified by a knowledgeable observer, consisting of a pulsed direct current with a rise and decay time having a distinctive interference energy spectrum (Figure 4-4).

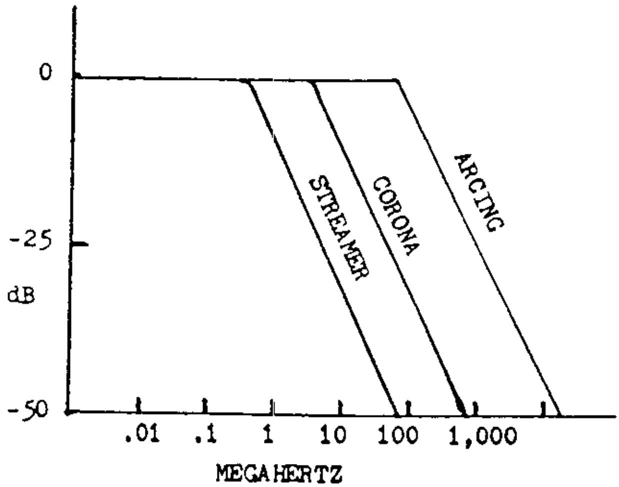


Figure 4-4
Electrostatic EMI Energy Spectrums

The advent of a near all-weather capability for all categories of modern-day aircraft, coupled with the Instrument Flight Rating (IFR) of a quarter million pilots, has resulted in more serious attention being paid to P-Static noise reduction by the airframe manufacturers. There are few manufacturers of IFR qualified aircraft today who do not offer a high quality static discharger installation. Considerable attention is also being given to structural electrical bonding. Most antennas are insulated and installed so that they do not protrude into high intensity electric fields. This has largely been done voluntarily by the airframe companies, without the need and cost of regulatory action. Maintenance of these RFI reduction provisions in the field has been somewhat negligent, however, due to inadequate documentation or ignorance. Neither operators nor maintenance personnel seem to be generally aware of the need for these provisions until severe disruption of communications or navigation results.

Streamer current EMI has received more erratic attention. LF ADF has been largely relegated to short range navigation to the outer compass locator of the ILS, or infrequently used approaches at low traffic density airports. As indicated in Figure 4-4, the energy of the noise spectrum generated by streamer currents is insignificant at frequencies above 1 MHz and, in some aircraft electrostatic surveys, could not even be identified at the 2.2 MHz data frequency.

Nevertheless, dielectric surface electrostatic currents cannot be ignored. Long range navigation aids in the VLF and LF bands, such as Omega and LORAN C/D, are now being used by both military and civilian aircraft electrostatic surveys, and flight reports have shown that during triboelectric charging, signal drop outs and reversion to memory mode operation - even with the proper installation of quality dischargers - is very likely. This reduces the value of such equipment for area IFR navigation purposes, and could eventually prohibit the use of such aids for airport approaches in inclement weather.

Electrically heated windshields are a virtual necessity for flight into known icing conditions. Yet there have been numerous reports of electrostatic charge punctures of electrically heated windshields. This can result in delamination of the windshield and, consequently, at least partial fogging of the windshield. Reports have also indicated that such punctures, or even induced voltages due to streamer currents, have caused failures in heater circuits and other aircraft electrical components.

The charges have also been known to puncture randomes and then attach to interior mounted antennas. Aircraft wiring has proven to be subject to induced potentials, or even direct puncture attachments, when installed within plastic frontal area structures. The result is not only EMI, but often unusual system and component failures.

Some techniques have been developed to drain dielectric surface charges, but they are not always satisfactory. To date, no satisfactory conductive coating is commercially available for plastic windshields. Glass windshields have been coated with angstrom thickness of gold and other elements to drain the charges and retain optical transparency. However, the thin coatings are subject to in-flight precipitation abrasion and abuse from windshield cleaners. A random survey of aircraft on any flight line, with a suitable ohmmeter, will yield coated windshields with isolated sections of coatings and open circuits to the airframes. Each is potentially an energetic arcing EMI generator, having significant RFI spectrums to L-band frequencies and beyond.

Resistive coatings on radomes have similar deficiencies. Many operators dislike the aesthetics of black coatings and when they are overcoated with decorative paint, it is virtually impossible to measure their conductivity to the airframe. Again, arcing is the probable result of inadequate bonding maintenance.

Field maintenance of all such coatings, whether for optical or radio frequency purposes, is difficult, at best, and often impractical. With improper maintenance, transmissivity can be lost.

New materials are becoming available to provide charge conduction where radio or optical transmission is not a factor. Among these are graphite composites, aluminum threads in glass cloth, and metallic flame sprays. For some applications, such approaches have merit. However, there are frequently cost and weight disadvantages.

Recognizing dielectric electrostatic charging to be a problem, there are two steps which must be taken to eradicate it. Namely, economical and maintainable methods of controlling dielectric charges must be developed, and sufficient testing must be accomplished to determine the adequacy of the control method implemented.

F/A-18 Dorsal Longeron

CHAPTER 5
EMI GASKETING

The subject of EMI gasketing is possibly the most discussed subject in the field today. The advent of composite skinned aircraft, advanced concentrated electronic circuits, increased ambient field strengths and the evolution of High Powered Microwaves all have combined to make durable EMI gaskets a necessity. The currently employed gaskets, which provide both RF and environmental seals between composite access panels and the aircraft aluminum structures (F/A-18), are causing severe corrosion problems which lead to significant weakening of the basic airframe. As improved gasketing materials and techniques are discovered, it most likely will fall upon the Navy Depots to install these fixes, develop maintenance techniques and train Fleet personnel in proper maintenance procedures. At a minimum, the depots, as CFA's, will be required to upgrade the maintenance publications ensuring the subject of EMI gasketing is adequately covered.

5.1 Introduction

A recent survey of technical literature produced numerous technical papers on the subject of EMI gasketing, the effects and control of lightning, and P-static. Throughout this review, it was observed that much of today's theoretical technical knowledge was initially published during the 1960's and 1970's. More recent papers on these subjects, presented in the mid 1980's, rely heavily on the concepts and knowledge presented in earlier years. Throughout the literature, it has been consistently recognized that EMI gasketing is a difficult subject to address. The inherent likelihood of corrosion occurring in the joint area and the general difficulties associated with EMI gasketing, have been long recognized and discussed. During the early years of Naval aviation, the best solution was to avoid gasketing of the airframe joints, except for environmental seals. Metallic fasteners were considered sufficient to provide conductivity across the joint. With the all metal airframe, relatively unsophisticated electronics, and relatively low ambient EM field strengths, the aircrews were able to perform their missions with only relatively minor annoyance caused by EMI.

With the advent of the F/A-18, it was no longer possible to avoid the need for a highly conductive EMI gasket that would serve as an environmental seal as well. The original gaskets provided with the F/A-18 were found to cause galvanic corrosion at the aluminum-gasket interface. The problem was so severe that extensive corrosion was found, particularly around the radar bulkhead, the avionic bay access panels and along the dorsal longerons. The severity of the problem was emphasized in that the corrosion was occurring <u>before</u> the aircraft was exposed to the harsh environments associated with carrier deployments.

In 1985, the original gaskets were replaced with a ferrex braid EMI gasket that was spot bonded to an air-sprayed tin zinc base. Unfortunately, this new design did not alleviate the problem. Corrosion continued to plague the dorsal longeron with the discovery of pits having depths of 70 mm (maximum allowable is 10 mm). Recognizing this on-going problem, McDonnell Douglas commenced investigation of a design consisting of fluorosilicon elastomer filled with conductive, silver-plated aluminum particles. Figure 5-1 illustrates the F-18 dorsal longeron problem area.

Figure 5-1 Examination of F-18 Dorsal Longeron EMI Gasket

As an example of the on-going concern relative EMI gaskets, the Naval Research Laboratory (NRL) sponsored a colloquium on EMI Gasketing and Corrosion and the subject is heavily discussed at the semiannual NAVAIR-sponsored E^3 progress reviews. Both the colloquiums and progress reviews have had active participation from industry and government. Minutes to the colloquium may be obtained from Mr. R. Ford at NRL; minutes to the E^3 progress reviews may be obtained from Mr. R. Carstensen, PE at AIR-5161. (See Appendix A for phone numbers).

5.2 **Technical Aspects of EMI Gasketing**

The perfect container for EM sensitive devices is a box made of superconducting metal with no openings. This is, of course, impractical. To be useful, there must be openings and the openings must appear electrically transparent. The degree to which this can be achieved in design is difficult to predict. It will depend upon a myriad of physical and electrical conditions which react with each other in unpredictable manners. The most critical and difficult condition to control is corrosion, namely corrosion between the material used in the gaskets and the airframe materials. Corrosion causes an increase in the resistivity of the joint, which causes larger voltages to be developed across the joint, resulting in higher energy fields being transmitted into the shielded enclosure. Therefore, the effects of corrosion are two-fold: reduced structural strength and reduced shielding effectiveness.

Shielding theory as presented in various EMI design handbooks assumes that EM shields are infinite in size, homogenous and flat. The homogenous assumption nullifies the use of this theory when apertures such as covers and doors are employed in the shield. To circumvent this problem, the super position theorem is utilized whereby the effective penetration of the field is measured utilizing MIL-STD-285 type "shielding effectiveness" tests. Unfortunately, it has been shown that MIL-STD-285 type tests can produce erroneous results of as much as 80 dB. Additionally, errors due to uncontrolled variables render such test results nearly invalid. One of the uncontrolled variables not considered in such testing is degradation of the conductivity of the joint due to corrosion. Basic corrosion effects which are considered in design relate to degradation of the structural strength of the shield and the structure. However, the platings used to protect the base material must also be considered. These platings provide protection by forming an oxide which insulates the plating structure. Most of these oxides are relatively poor conductors. As a result, penetration of EM fields through an aperture as a result of the use of doors and covers will vary as a function of the platings used on the surfaces and the material used in the manufacture of EMI gaskets. Such penetration can significantly increase in time due to oxidation of the EMI gaskets and shielded surface platings.

Figure 5-2 illustrates the mechanism whereby the RF energy incident on an enclosure panel is transmitted inside the enclosure. The illustration clearly shows the effects of varying the conductivity of the EMI gasket and the interface between the gasket and the surfaces. As corrosion is developed at the mating surfaces, impedance is increased, resulting in a higher voltage being developed between the enclosure and the aperture cover and permitting more energy to enter the enclosure.

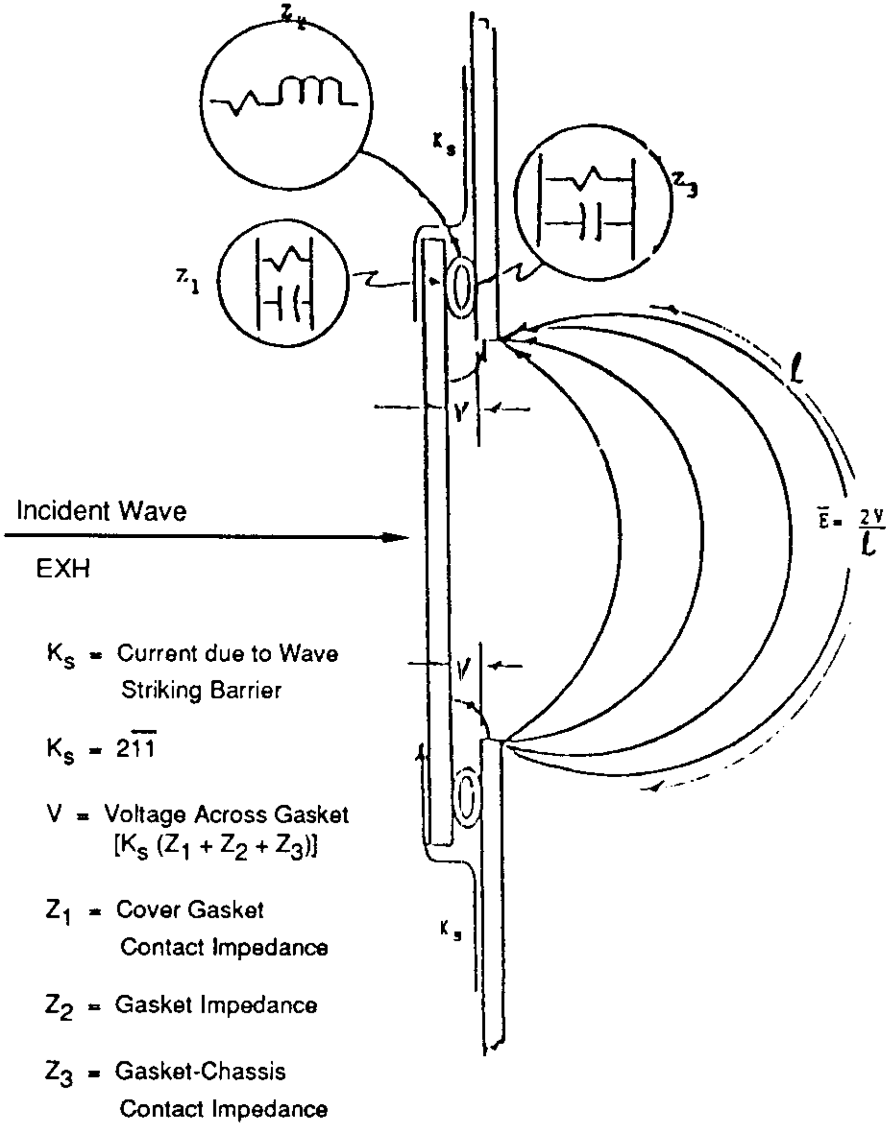


Figure 5-2 Relationships of Current Voltages Associated with EMI Gasket

In reference to Figure 5-2, the ratio of Ks/V is a measure of the transfer impedance of the EMI gasket. In determining the performance of an EMI gasket, the RF transfer impedance and DC resistance of the EMI gasket joint must be determined. Accurate determination of these values through satisfactory tests continues to be a problem. This fact was iterated by Ms. Wendy Lin at the EMI Gasketing and Corrosion Colloquium when she indicated that reliable methods for testing the effects of corrosion on EMI shielding must be developed. She indicated that present test methods produce results which are too variable to allow one to distinguish between conductive gaskets.

To illustrate the magnitudes of resistivity encountered and the effects of salt spray on resistance, the results of selected tests are presented in Tables 5-1 and 5-2. The data presented in these tables should serve as guidance when selecting materials for potential use on EMI gaskets. In addition, Table 5-3 can be used to maximize the compatibility of materials selected.

Table 5-1
Resistance Measurements of Selected Materials

MATERIAL	FINISH	RESISTANCE (MILLIOHMS)		
		INITIAL	AT 400 HR 95% RM	AT 1000 HR 95% RM
ALUM				
2024	CLAD	1.3	1.1	2.0
2024	CLEAN ONLY	0.11	5.0	30.0
6061	CLEAN ONLY	0.02	7.0	13.0
2024	LIGHT CHROMATE CONVERSION	0.40	14.0	51.0
6061	LIGHT CHROMATE CONVERSION	0.55	11.5	12.0
2024	HEAVY CHROMATE CONVERSION	1.0	82.0	100.0
6061	HEAVY CHROMATE CONVERSION	0.42	3.2	5.8
STEEL				
1010	CADMIUM	1.8	2.8	3.0
1010	CADMIUM-CHROMATE	0.7	1.2	2.5
1010	SILVER	0.05	1.2	1.2
1010	TIN	0.01	0.01	0.01
COPPER	CLEAN ONLY	0.05	1.9	8.1
COPPER	CADMIUM	1.4	3.1	2.7
COPPER	CADMIUM-CHROMATE	0.02	0.4	2.0
COPPER	SILVER	0.01	0.8	1.3
COPPER	TIN	0.01	0.01	0.01

Table 5-2
DC Resistance Test Results on Gasketed Joints

GASKET MATERIAL	JOINT SURFACES									
	2024 ALUMINUM		IRIDITE PLATED 2024 ALUMINUM		NICKLE PLATED 2024 ALUMINUM		CADMIUM PLATED 2024 ALUMINUM		TIN PLATED 2024 ALUMINUM	
	RESISTANCE (MILLIOHMS)		RESISTANCE (MILLIOHMS)		RESISTANCE (MILLIOHMS)		RESISTANCE (MILLIOHMS)		RESISTANCE (MILLIOHMS)	
	BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER
	TEMPERATURE-HUMIDITY SOAK PER MIL-STD-202E (240 HRS @ 95% RELATIVE HUMIDITY)									
TIN SPIRA	2.0	35.0	3.5	90.0	0.9	4.8	0.5	45.0	0.3	2.4
S-TIN SPIRA	0.6	50.0	1.7	60.0	0.9	6.8	0.2	2.4	0.1	0.2
S-TIN SPIRA	0.2	7.5	2.9	190.0	0.7	4.1	1.0	1.5	0.15	0.3
SS SPIRA	35.0	1000.0	370.0	370.0	10.0	20.0	40.0	2000.0	40.0	180.0
SS SPIRA	60.0	190.0	250.0	2500.0	2.7	3.0	200.0	2000.0	15.0	1000.0
	SALT SPRAY TEST PER MIL-STD-810B (96 HOURS @ 5% SALT SOLUTION)									
TIN SPIRA	1.00	70.0	3.6	90.0	0.5	1.9	0.2	30	0.2	4
S-TIN SPIRA	0.40	17.0	1.3	90.0	0.8	1.0	0.15	0.3	0.1	0.3
S-TIN SPIRA*	0.25	60.0	3.3	25.0	0.6	3.4	0.8	10	0.15	0.2
SS SPIRA	50.0	2500.0	90.0	1600.0	8.0	28.0	20	290	19	270
SS SPIRA	20.0	2000.0	250.0	2200.0	2.7	600.0	150	1200	12	20

* Secured to one of the joint surfaces with copper-filled conductive epoxy.

Table 5-3
Dissimilar Materials

Gasket Materials: Aluminum	Tin Plated	Monel	Silverelastomer	Stainless Steel	Beryllium Copper	Finishes	Materials
A	A	C	E	C	C	None	Aluminum
A	A	D	C	C	C	MIL-C-5541 Class 1A	Clad, 1000,
A	A	D	C	C	C	MIL-C-5541 Class 3	3000, 5000,
D	D	A	D	A	D	Electroless Nickel	6000 Series
A	A	D	C	C	C	Cadmium Plated Bare	Casting 356
A	A	D	C	A	C	Cadmium Colored Chromate	
A	A	D	C	A	C	Cadmium Clear Chromate	
A	A	A	A	A	D	Chromium	
A	A	D	C	D	C	MIL-C-5541 Class 1A	Aluminum
A	A	D	C	C	C	MIL-C-5541 Class 3	2000, 7000
D	D	A	D	A	D	Electroless Nickel	Series
D	A	D	E	D	C	Cadmium Bare	
A	A	D	C	A	C	Cadmium Colored Chromate	
A	A	D	C	A	C	Cadmium Clear Chromate	
A	A	A	A	A	D	Chromium	
A	A	D	A	A	C	Tin	
A	A	D	C	C	C	Cadmium Bare	Carbon and
A	A	D	C	A	C	Cadmium Colored Chromate	Alloy Steel
A	A	D	C	A	D	Cadmium Clear Chromate	
D	D	A	D	A	D	Nickel	AISI-410
D	D	A	D	A	D	Electroless Nickel	
A	A	A	A	A	C	Chromium	
A	A	A	A	A	C	Tin	
D	A	D	X	D	D	Lead	
X	A	A	A	A	D	Silver	
C	A	A	D	A	C	Passivated	Corrosion
A	A	D	E	D	C	Cadmium (Passivated)	Resistant
A	A	A	D	A	D	Tin	Steels
C	A	A	D	A	C	Passivated	High Nickel
A	A	D	E	D	C	Cadmium (Passivated)	and FH Steels
A	A	A	D	A	C	Tin	
A	A	A	D	A	C	Tin	Copper Alloys
X	A	D	A	A	C	Silver	
X	A	D	A	A	C	Gold	
A	A	A	D	A	C	Solder (Lead-Tin)	
X	D	D	A	A	D	Silver Paint	Miscellaneous
X	A	D	X	X	C	Zinc Paint	
D	D	D	A	A	C	Silver Adhesive	
D	D	D	A	D	C	Carbon Adhesive	
D	D	A	D	A	C	None	Titanium
D	D	A	D	A	C	Nickel	

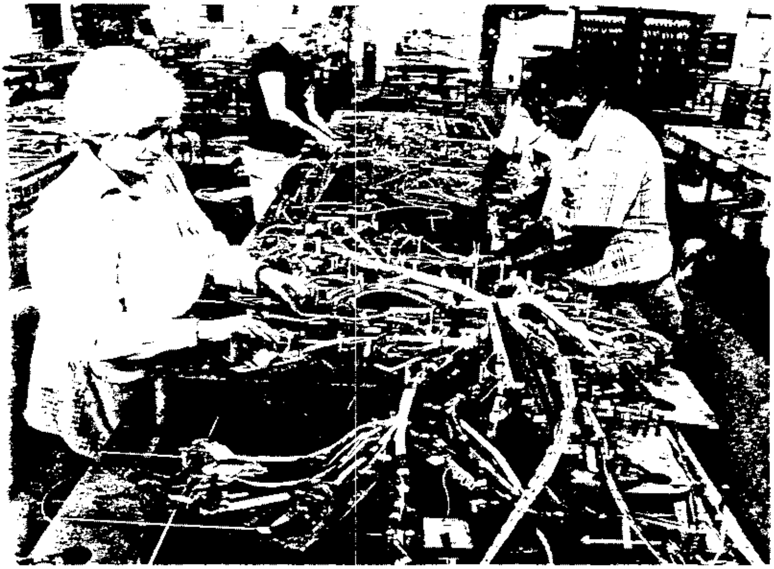
Legend/Notes

A - Compatible.
B - Requires sealing only if exposed to salt atmosphere or high humidity. Edge priming may be satisfactory.
C - Requires sealing if exposed to humid environment.
D - Compatible in environment of controlled temperature and humidity.
E - Requires sealing regardless of exposure.
X - Not useable.

5.3 Conclusion

As discussed in the preceding paragraphs, attainment of quality EMI gaskets in Naval aviation is an ongoing problem. Much research is being conducted by private industry and Navy field activities such as the Naval Air Development Center and NRL. As new concepts are developed and proven, the information will be made available to the aviation community. As a minimum, the NAVAIR E^3 community will be kept appraised of current efforts via presentations at the periodic NAVAIR E^3 progress reviews.

Avionic Test Facility



Fabrication of Wiring Harnesses

CHAPTER 6
PRACTICAL APPLICATIONS

In the preceding chapters, the business aspects of the Naval aviation depots were presented with discussions on depot organization, the role and responsibilities of the organization entities, and an introduction to the tools and techniques available to manage and control EMI. Chapter 4 presented theoretical considerations applicable to controlling EMI and attaining EMC, and Chapter 5 discussed the specific problems associated with EMI gaskets.

In this chapter, emphasis is placed on the practical application of theory. The areas of shielding and bonding are addressed as is a suggested methodology for identifying and marking E^3 related components, specifically wiring. The information presented in this chapter has been submitted for possible inclusion in a revised NAVAIR-01-505 Manual.

The control of EMI is an increasingly complex problem, made more difficult by broader use of the frequency spectrum, higher power level transmitters and more sensitive circuitry. At the present time, intensive research is being performed to perfect methods of achieving quality RF gasketing and find better methods of attaining individual circuit protection. In the area of RF gasketing, the Naval Research Laboratory has initiated colloquiums to bring together the leaders of industry to address the problem. In the area of improved circuit protection, Deutsch has developed a conductive-coated composite connector that is lighter, more durable and less prone to corrosion than existing connectors (the DG-123 Connector). These are but two examples of people working to solve the EMI problem. It is hoped that the materials presented in this chapter will stimulate the reader to help make the attainment of EMC an achievable goal.

6.1 Shielding

6.1.1 Introduction

The effectiveness of cable shielding for the control of Electromagnetic Interference (EMI) depends largely upon proper termination of the shield. RF currents that are conducted along cable shields will be coupled into a system at the point of improper cable termination and reduce the effectiveness of an otherwise adequately shielded system. In a properly terminated shield, the entire periphery of the shield is grounded to a low impedance reference, minimizing any RF potentials at the surface of the termination.

Shield terminations and grounding which may be suitable for low frequency applications (audio and below 50 KHz) are generally not suitable or adequate for prevention of EMI problems at high frequencies. Improper grounding schemes are more apt to cause EMI control problems than cure them. Grounding cable shields often leads to severe compromise of the shield system. Attempts to solve ground loop problems may interrupt the shield, when it is the shield current that should be interrupted. Similarly, poorly conceived grounding can virtually nullify the common-mode rejection benefit from a shielded twisted pair, and a ground wire that penetrates a shield can reduce shielding effectiveness to 0 dB. A prudent interference control analysis will be wary of grounds and their claimed benefits for interference control.

The cable shield is an important element of the EM barrier that protects the enclosed circuits from extraneous sources of interference. A shield works best when it is closed; whether or not it is grounded is irrelevant. The general rule for grounding is that grounding conductors should never penetrate barrier surfaces. Since there is no way for grounding to be an effective element of the barrier, grounding is not properly an interference control mechanism, although inappropriate grounding can aggravate the interference control problem.

Shielded wires are often terminated in connectors as shown in Figure 6-1.

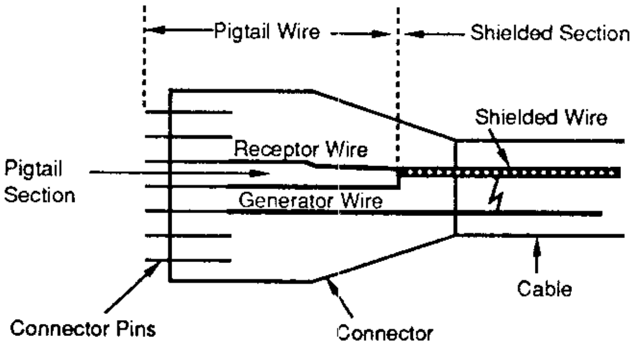
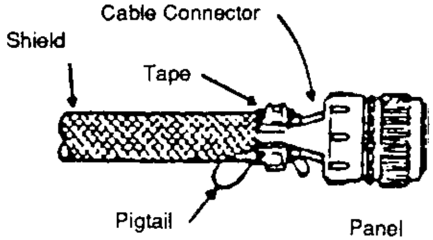


Figure 6-1. Termination of Shielded Wires

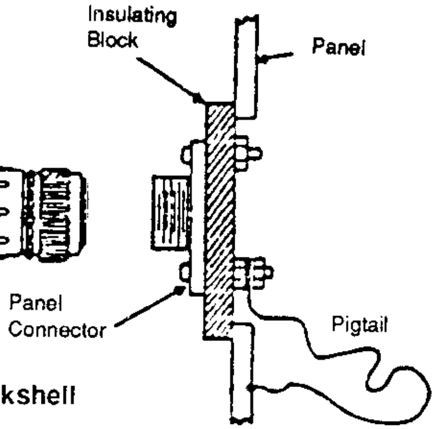
The braided shield is stripped back and the interior wire is connected to a connector pin. If a shield must be carried through the connector, a separate wire (the pigtail wire) should connect the shield braid to an additional pin. When using this type of connection, however, problems can arise within the connector because the pigtail section of the shielded wire is directly exposed to coupling from adjacent wires or other pigtail sections within the connector. Above 100 KHz, the predominant interference coupling in this type of shield termination will be inductive via the pigtail. The pigtail will degrade a shield's ability to reduce crosstalk, so it is important to eliminate pigtails within connectors to realize the full effectiveness of the shield for EMI control.

Another common treatment of a shield at a connector is to insulate the shield with tape and connect it to the back shell through a pigtail. Such treatment is shown in Figure 6-2(a). An equally common practice is to insulate a panel connector from a panel with an insulating block and ground the panel connector either to the panel through a pigtail or, more commonly, to an internal ground bus as shown in Figure 6-2(b). Another common treatment of a shield at a connector, shown in Figure 6-2(c), is to connect the shield to one of the connector pins and ground it internally through a pigtail, either to the panel or to an internal ground bus.

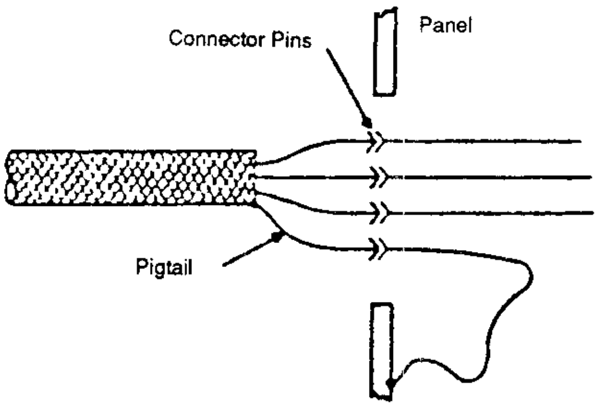
Problems associated with pigtail grounds can best be illustrated with the following example. Assume a shield is carried, as in Figure 6-2(c), through a panel on a pigtail and a set of connector pins. Assume the total length of the pigtail-pin combination is 7 cm, the spacing between the pigtail and a signal connector averages 0.05 cm, and the pigtail will be made from number 22AWG wire



(a) Pigtail connection to a backshell



(b) Pigtail grounding to a panel connector



(c) Shield carried on a connector pin

Figure 6-2(a) to 6-2(c). Common Treatment of Shields at Connectors

having a radius of 0.0323 cm. The self-inductance of the pigtail would then be 7.45 nH, the mutual inductance between the two would be 65.0 nH, and the difference, the factor equivalent to the transfer inductance for the shielding cable, would be 9.5 nH/m. A rather mediocre shielded braid would have an inductance on the order of 1 nH/m; a large-diameter, tightly woven braid might have an inductance on the order of 0.25 nH/m. Therefore, the amount of voltage injected into a signal circuit by the current flowing through this one relatively short pigtail would be as much as that coupled onto a signal conductor of a shielded cable 10 to 40m in length.

6.1.2 Protection Against EMI

The outside shield of cable bundles should be circumferentially bonded to the circuit enclosure at both ends, even if this creates a ground loop, because high-frequency leakage at the shield break is almost always greater than the ground-loop effect. The shield should be terminated on the backshell of a connector, and the connector shell itself should be designed to have low dc resistance to its mating panel connector. Most commonly, such low-resistance mating requires the use of grounding fingers or other special bonding configuration within the connector shell. The shell of the panel connector should provide a 360-degree peripheral connection to the metal equipment case. Providing such a connection frequently requires that paint or other coatings on the case of the equipment be removed and the bare metal exposed. Corrosion protection should be added after the bonding is complete.

If circumferential bonding cannot be used, a wide pigtail connection should be made, although that is usually ineffective at frequencies above about 10 MHz. In addition, multiple shield bonding can be used to minimize antenna-type pickup. This requires bonding to a continuous conducting surface at about every one-eighth of a wavelength of the highest frequency of interest, but with aperiodic spacing. In the absence of a 360-degree connector, an external pigtail is often used for grounding the shield, as shown in Figure 6-2(b). Such pigtails are definitely inferior to the 360-degree connector because they force an interfering current on the shield to be concentrated through the pigtail and, hence, provide a much greater degree of coupling to the core conductors than does the distributed current flow on a properly designed connector backshell. If a pigtail is used, it should be as short as possible and should terminate on the outside of the equipment case. A pigtail of only a few inches may introduce more leakage from the shield to the inner conductors that does a several-foot section of the shield itself.

An open shield that is not bonded at one end can result in two serious effects. First, the potential of the shield relative to the adjacent case or other nearby conductive surface can become great enough to cause arcing. In addition to being damaging, arcs can radiate a broad spectrum of high-frequency RF energy that can be coupled to signal lines. Second, an open shield can propagate high frequencies internally by coaxial propagation.

While shields bonded at one end may provide better shielding to interior wires for low-frequency magnetic fields, that advantage is lost at frequencies above 1 MHz. For electric fields, coupling is less at low frequencies for shields bonded at both ends.

The practice of grounding an overall shield to the inside of an equipment case through a pigtail and a set of contacts in the connector is less effective than the use of an external pigtail, partly because it brings currents directly inside the case. Such grounding of an overall shield should be avoided wherever possible and must be avoided whenever the shield runs through a region where it will intercept a significant amount of energy from an external EM field.

Braided wire shield is the most attractive shield mechanically and can be made electrically sound with proper design. Specific guides are to achieve 85% to 90% optical coverage and weave angles between 30 and 45 deg (measured from the cable axis). Optical coverage greater than 85% increases shielding effectiveness by about 0.5 dB. However, cable flexibility usually limits the combination of optical coverage and weave angle. In practice, it is possible to get only about 85% optical coverage for a 30 deg weave angle, 93% for a 40 deg weave angle, and 96% for a 45 deg weave angle. Shielding effectiveness for these combinations is almost equivalent since the effects of optical coverage and weave angle nearly compensate over the range quoted. Other tests have shown that double and triple shielding can increase shielding effectiveness by approximately 15 dB per layer for weave angles close to 30 deg. Less improvement is obtained for larger weave angles.

Good connector-backshell configurations for shield terminations, especially in the presence of vibration and other environment extremes, are important. Locking connectors are generally not vulnerable to vibration environments, and large improvements in shielding effectiveness can be obtained by using specially designed shielded receptacles.

Figure 6-3(a) through 6-3(e) shows good and bad methods of grounding a shield when it is placed over a group of conductors being brought into an equipment enclosure. Note that the overall shield should never be connected to a signal ground bus. Figure 6-4 illustrates cable-shield-to-conductor termination and connector-to-bulkhead terminations.

Figure 6-5 illustrates the method of preserving individual shields when more than one shielded conductor must be routed through a single cable and connector. The shield should never be pulled back, twisted and bonded to the connector in pigtail fashion. No portion of the shield should be broken before it is bonded to the connector shell. Individual shields for conductors that are routed through multi-coaxial connectors should be terminated individually in the manner described previously. When cable tension or vibration discourages such a termination, rigidly supported connectors should be used. It should be noted that there are situations in which an improper shield can actually increase the hazard to an Electro Explosive Device (EED). A fairly common EED configuration is one having unshielded leads. Since there is no provision for completing a shield to the case of the EED, the weapons designer faces a situation in which the effort to provide a shield may create a problem. If a shield is placed over

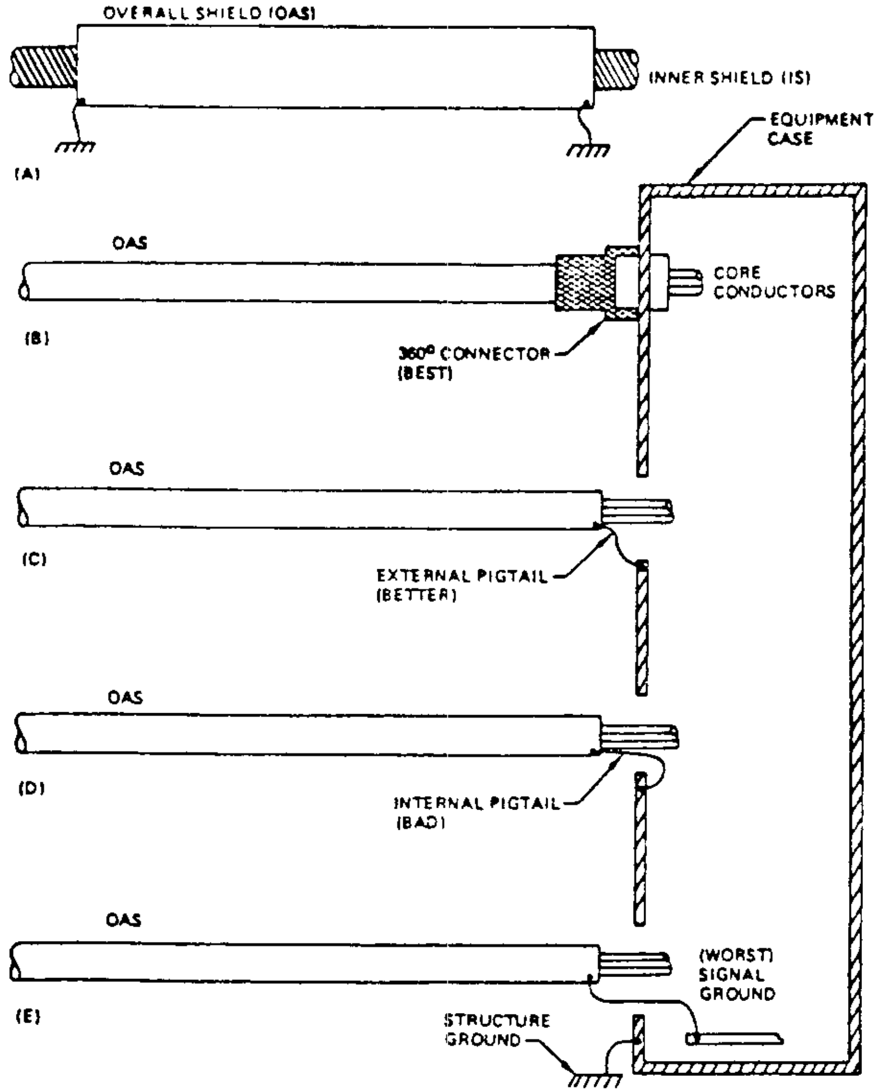


Figure 6-3(a) to 6-3(e). Types of Grounding for Shields

Preferred: Fillet Weld around entire periphery of female connector housing

Alternative: Bolt and Tooth type lock-washer connection as shown by dotted outline

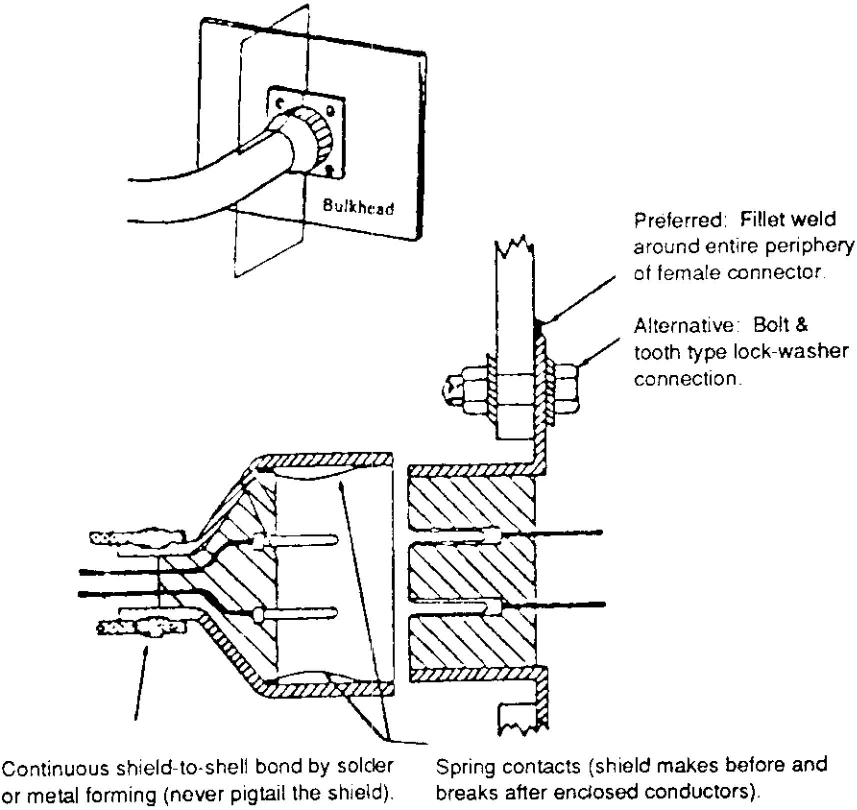


Figure 6-4. Shield Termination for Electrical Connectors

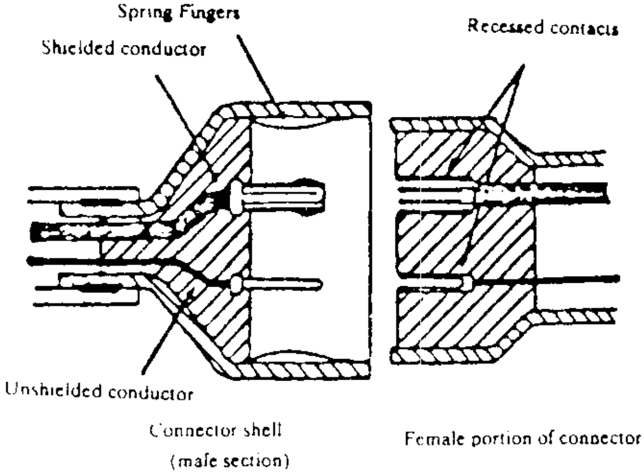


Figure 6-5. Multi-Coaxial Connector Design

NOTES:

1. There should be no breaks in the shield though the connector and cable which would allow EM energy to "leak" into the firing circuit.

2. The connector should be able to withstand environmental conditions (vibration, high and low temperatures, corrosion, etc.) without degradation of shielding characteristics.

3. The connector shield at the interface of the two connector halves must make positive contact before the two power contacts make and must maintain contact until after the power contacts break.

4. The firing system contacts in the connector mating sections should be sufficiently isolated to preclude the possibility of field personnel accidently touching the socket contacts, either with their fingers or with the mating connector shell, while the connectors are unmated.

the lead wires and allowed to be ungrounded at the EED, the shield discontinuity will support the generation of high voltages directly at the EED. Consequently, the shield would contribute to the hazard. In such situations it is better not to attempt to shield the EED. If the shield must be extended to the EED, then the EED should be specified and purchased with shielded leads installed in the manufacturing process.

6.1.3 <u>Use of Solder for Shield Bonding in RF Coaxial Cables</u>

In a properly terminated shield, the entire periphery of the shield is grounded to a low impedance reference, minimizing any RF potentials at the surface of the termination. Solder is undesirable in terminating RF coaxial cables because:

(1) Too much solder increases the center conductor diameter, thus increasing shunt capacitance.

(2) Too little solder increases the current path, thus increasing series inductance.

(3) The use of silver epoxy or other synthetic conducting material has been found to be unacceptable for shield bonding because of lack of mechanical strength necessary for this application.

6.1.4 Shield Termination by Crimping

A frequently used method of shield termination is shown in Figure 6-6(a). In this arrangement, the cable shield is flared so that it extends over the rear portion of the sleeve and the crimp ring is slid into place over the sleeve. A crimping tool is then used to crimp the ring onto the sleeve.

An alternative to crimping is shown in Figure 6-6(b). The shield is placed through the ground ring and flared over and around the ring, and may be secured to the ring with a spot tie. The ground ring is then slid into the rear of the sleeve, which has a tapered base. Tightening the cable clamp onto the end of the sleeve assures positive 360° grounding of the shield, and provides a strain relief for the cable.

6.1.5 Shield Termination by the Magnaforming Process

For cabling that must operate in high field strength environments, both shields and solid cylindrical members have been terminated using the Magnaforming process. Magnaforming is a metal-forming technique that is used to shrink metal tubes and similar shapes around other forms such as collars, sleeves and rods. The process uses a very intense, short duration magnetic field to induce an opposing current in the tubing or sleeve which is

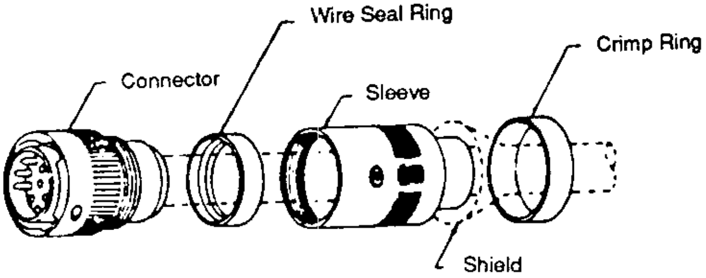
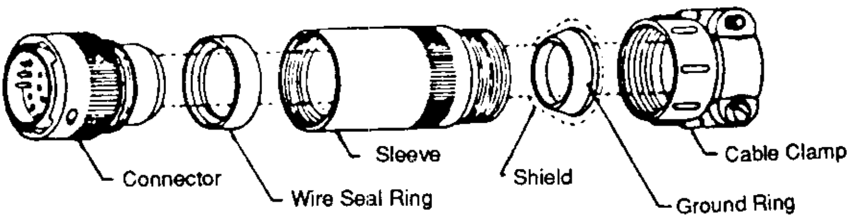


Figure 6-6(a). Shield Termination Using Crimping



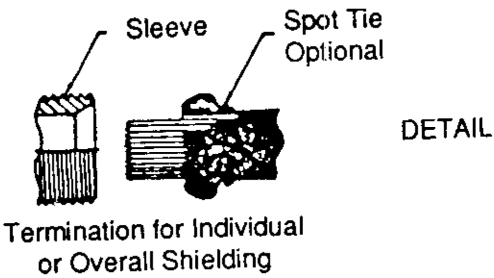


Figure 6-6(b). Shield Termination Using Threaded Assembly

to be shrunk. The magnetic field produced by the induced current in the sleeve opposes the field produced by the current in the magnetic coil, and is of equal magnitude. The resulting force from the magnetic coil field and the field around the sleeve combine to produce uniform compression of the sleeve around the entire sleeve periphery. If the current applied to the magnetic coil is of sufficient amplitude, the combined resultant compressive force on the sleeve will deform the sleeve, reducing its diameter until it conforms to the shape of the underlying material. The basic process is shown in Figure 6-7(a).

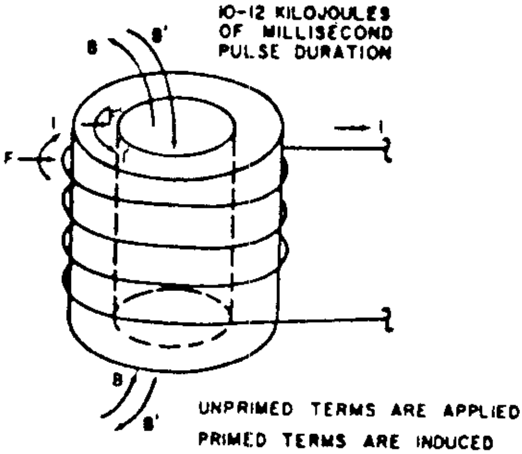


Figure 6-7(a). Relationship of F, B & I in Magnaforming Process

A cross-section of a fixture in which a workpiece is to be shrunk around a cable sleeve and connector is shown in Figure 6-7(b). An insulating "former" is normally used between the magnetic coil assembly and the workpiece, but the insulator does not directly enter into the forming operation. A cut-away photograph of two connectors terminating opposite ends of a short length of cabling in conduit is shown in Figure 6-7(c). The Magnaforming process was used to make the terminations at the points identified in the figure.

When maintaining the shielding integrity of a connector pair (i.e., two interconnecting connectors), a good method to employ is to place spring contacts inside one portion of one connector so that positive contact is made along the circumference of the mating parts, as in Figure 6-7(d). These contacts are extended so that the shell of the connector mates before the pins make contact on assembly of the connector and breaks after the pins on disassembly. A connector which meets these requirements is available under MIL-D-27599 and is the preferred type for use in RF-proof designs. The advantages of circumferential spring fingers over bayonet coupling is dramatically illustrated in Figure 6-7(e). In this case, the spring contacts were of silver-plated beryllium copper.

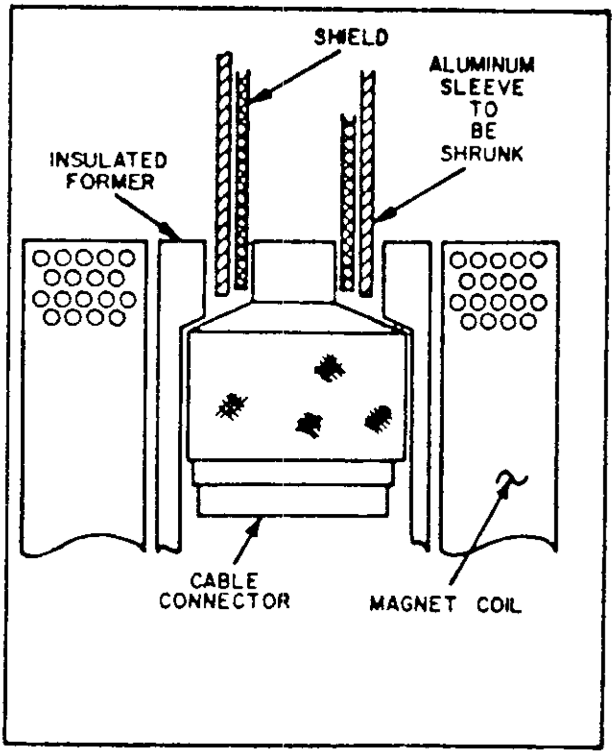


Figure 6-7(b). Typical Magnaforming Process

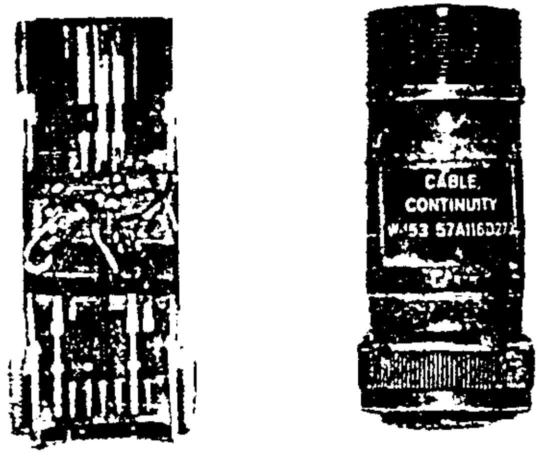


Figure 6-7(c). Cut-Away View of Magnaformed Cable Transition

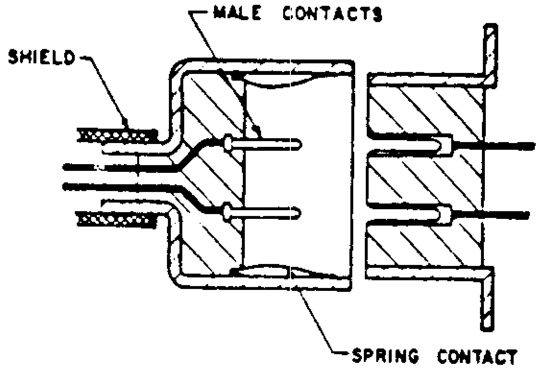
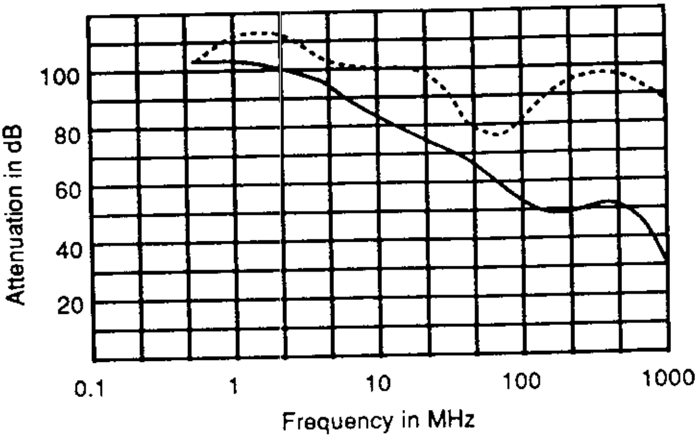


Figure 6-7(d). RF-Proof Connector



.... MIL-C-26482 connector with cadmium RFI modifications

——— MIL-C-26482 standard olive drab finish (bayonet coupling)

Comparison of the RFI shielding at the interface coupling of a MIL-C-26482 connector having standard olive drab finish with the same connector using peripheral spring contact fingers over cadmium plating (RFI type).

Figure 6-7(e). Comparison of RFI Shielding

Figure 6-7(f) illustrates the type of connector that should be used when a shielded cable assembly contains individual shielded wires. The practice of pigtailing shields and connecting them to one of the pins is not recommended. The individual shields should be connected to coaxial pins specifically adapted for this purpose, with the shields of the mating surfaces making contact before the pins.

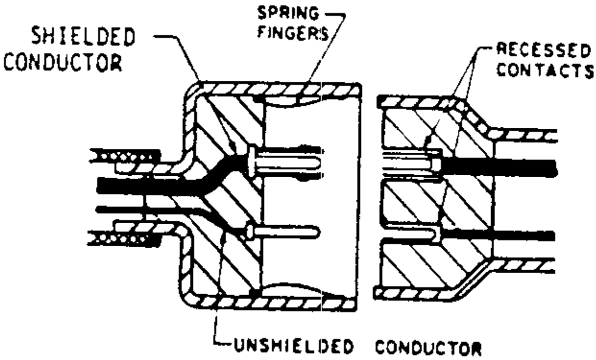


Figure 6-7(f). Connector for Shield within a Shield

An alternative method of terminating individually shielded wires (if the shields can be tied together) is shown in Figure 6-8. A pick is used to strip the shield from each of the wires involved. The shields are then laid over a grounding ring and the entire assembly is secured by screwing items 1 and 4 together.

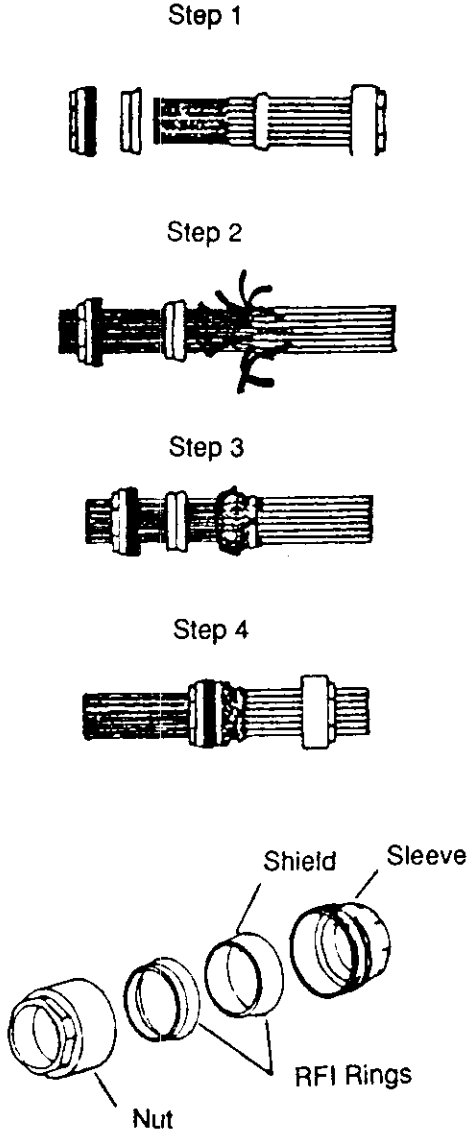
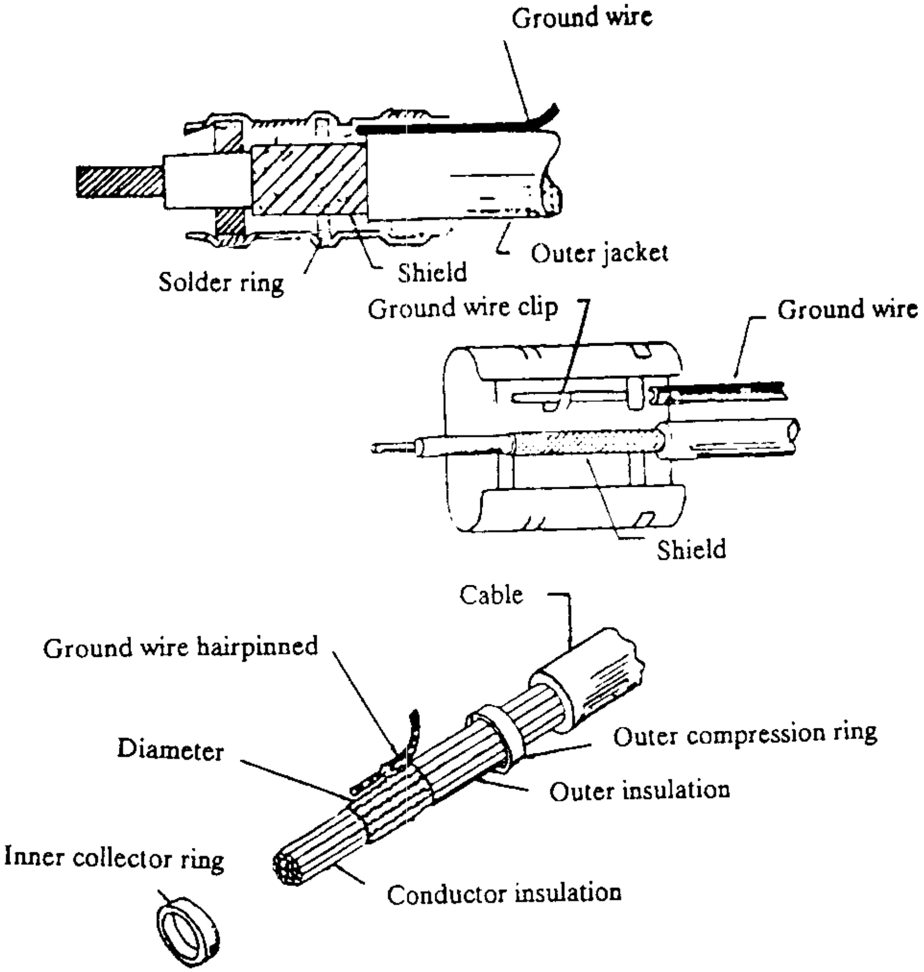


Figure 6-8. Shield Termination of Multiple Shielded Wires

RF arcing problems can occur in a shield that is adequate at audio frequencies. Induced RF currents can be conducted along cable shields and coupled to the system wiring at points of incorrect cable shield termination. RF potentials at the termination can be minimized by grounding the entire periphery to a low-impedance reference.

6.1.6 Wiring and Cabling

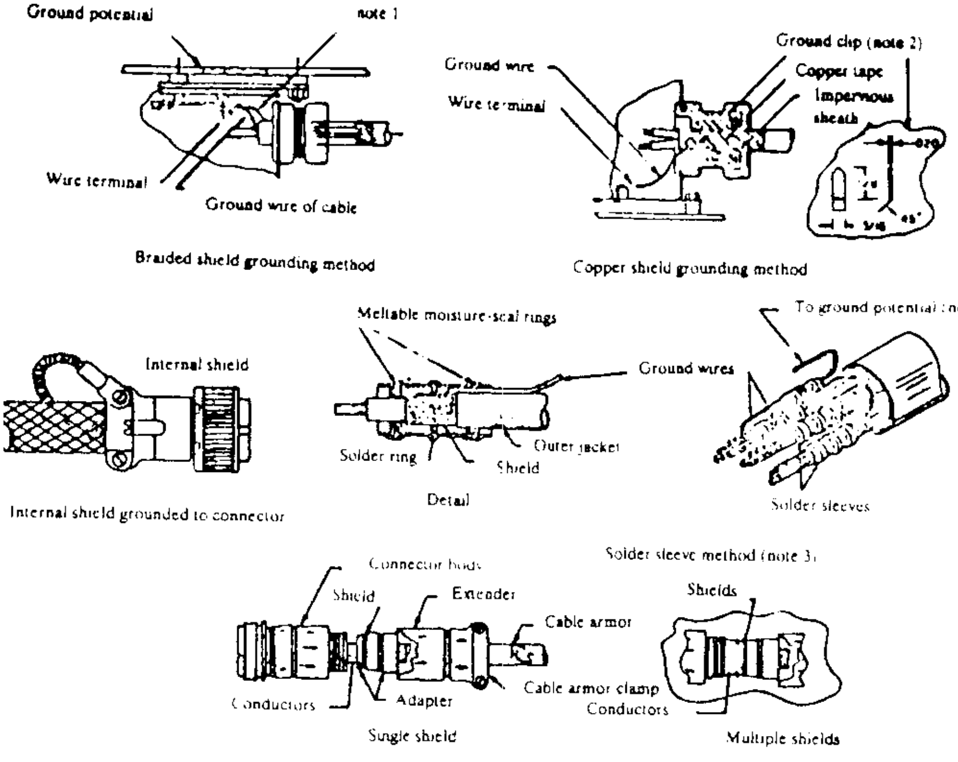
Wiring and cabling should be designed to minimize coupling and obtain optimum separation and use of available wiring space. Cable design should include provisions for adequate termination of shielded wires. Unless otherwise specified, connectors used to carry shielded wires must not use a nonconductive finish but have a back shell that provides for peripheral bonding of shields. Procedures must be established to categorize each wire or cable according to its interference and susceptibility characteristics. Wires and cables should be marked in such a manner that personnel can visually identify the EMC category for each wire or cable. Figure 6-9 shows cable shield grounding methods and materials for Thomas and Betts Company or Raychem Corporation, or equal. Figure 6-10 shows additional cable shields grounding methods. Figure 6-11 shows method of cable armor bonding to connectors.



NOTES:

1. Cable shield grounding methods and materials shall be Thomas and Betts Company or Raychem Corporation, or equal. Other approved shield grounding methods are by Backshells MS3189 and Kerm Engineering & MFG, Co., "IRIS CONCEPT" or equal.

Figure 6-9. Cable Shields Grounding Methods; Thomas and Betts Company/Raychem Corporation



NOTES:

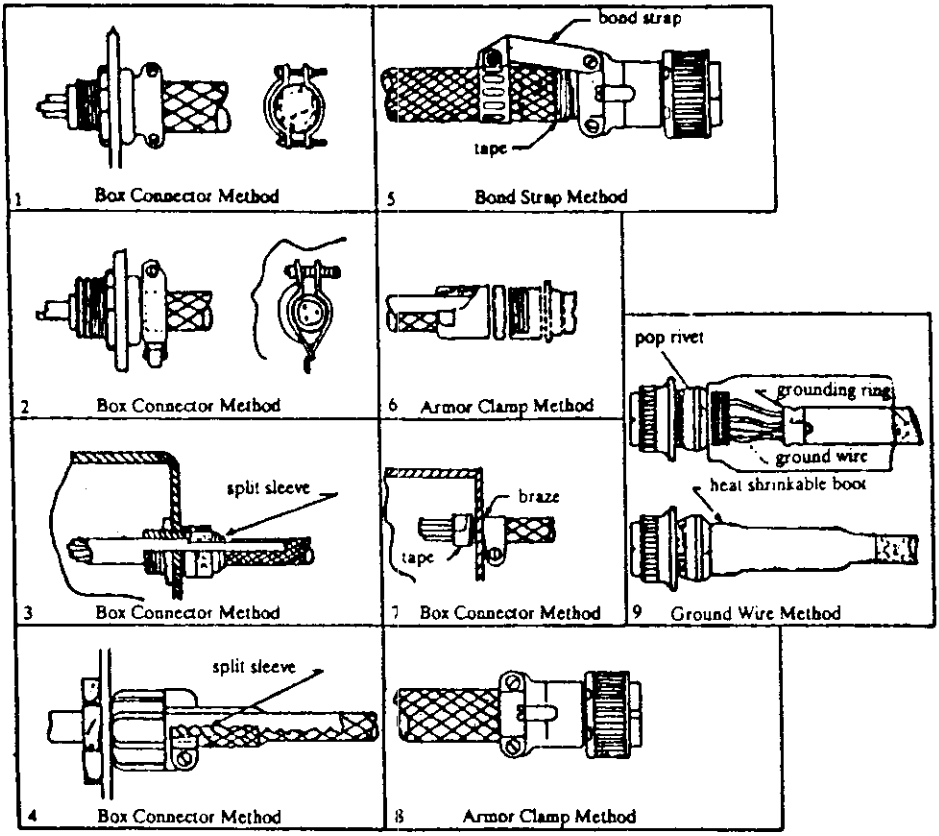
1. The cable is formed into a grounding strap. The strap and ground wire of cable are then connected to a ground screw by solder loops or wire terminals. A flat steel washer (size to suit) is installed on the ground screw.

2. The grounding clip is fabricated with a slit cut crosswise in the impervious sheath. The clip will then be inserted between sheath and copper tape.

3. One end of the ground wire is soldered to the ground clip. The other end has a terminal affixed to attach to an existing bolt.

4. When grounding shields of multi-conductor cables, the size of the ground wire between the solder sleeve & ground potential should be equal in size to the total number of ground wires connected between the solder sleeve and the wire shields.

Figure 6-10. Cable Shields Grounding Methods



NOTES:

1. That area of the cable armor where bonding is accomplished shall be thoroughly cleared of all paint, film, grease or other coating which would prevent metal-to-metal contact. The bonding device shall then be securely tightened around the cable armor.

Figure 6-11. Cable Armor Bonding to Connectors

6.1.7 Shielded Conductors

Shields must not be used for signal returns except in the case of coaxial cables. All terminations should be made through a collectively crimped peripheral ring or equivalent, as illustrated in Figure 6-12, for all shields exclusive of coaxial cables and shielded leads classified as RF susceptible only. The collective crimping ring or equivalent utilizes two ground wires, one from the ring to the connector shell (where connector design permits) and one to be carried through a connector pin.

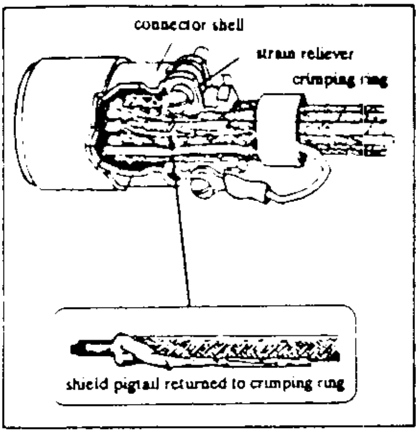
NOTE: If an EMI type connector with grounding fingers is used, do not use the ground wire carried through the connector pin.

6.1.8 Shield Terminations Using Glenair Tag Rings and Adapters

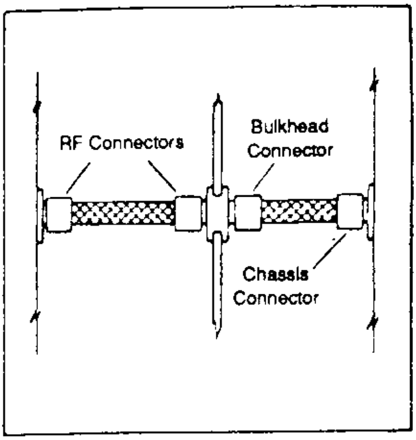
Although Glenair Tag Rings are no longer used in new production, the following discussion is provided for background understanding.

Typical Glenair Tag Rings are illustrated in Figure 6-13. Tag Rings are two-piece devices used for terminating groups of individually shielded wires. The principle of assembly is that shield braids are pigtailed and then captivated in slots of the tag ring body. The tag ring nut holds them in place.

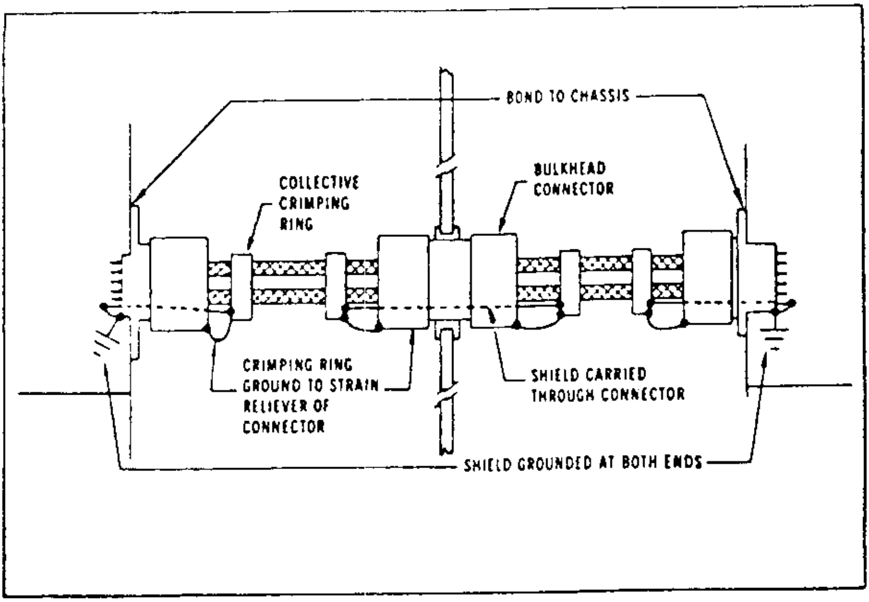
Collective Crimping
Termination of Shields in Connector Shell



Termination of
Coaxial Cable Shields (Class VII Circuits)



Termination of Shielded Wires (Class V and VI Circuits)



NOTE: If critical, make grounding pins as leaderless as possible to prevent any re-entering through loop.

Figure 6-12. Termination of Shielded Wires

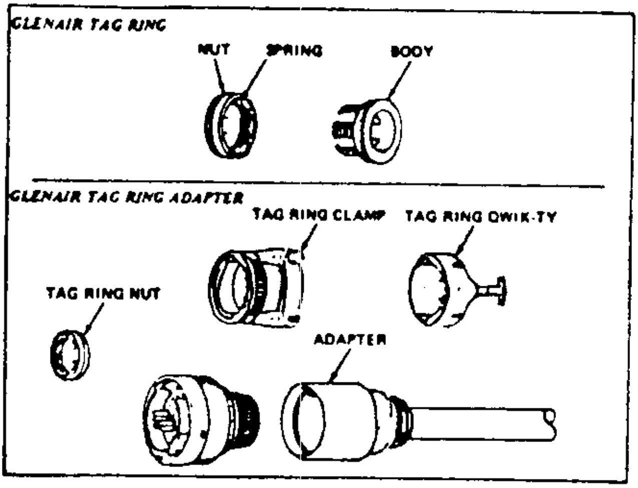


Figure 6-13. Typical Glenair Tag Rings & Adapters

Tag Ring Adapters are devices used to adapt tag rings to a connector shell. When the tag ring is supplied as part of the adapter, the connector shell may be used as a ground point or a ground wire may be connected from the tag ring to some other point. The adapters may also contain strain relief devices such as a clamp or the Glenair Quick-Ty. Assembly of tag ring adapters is similar to the basic tag ring procedure.

6.1.9 <u>Shield Termination Using EMI or RFI Adapters</u>

EMI or Radio Frequency Interference (RFI) adapters are devices typically found on shielded or jacketed cables and are used for overall shield termination. With this type of adapter, the shield braid is captivated between two or three tapered ferrules (or rings). These adapters may be environmental, as in Figure 6-14, or non-environmental, as in Figures 6-15 and 6-16, and can be supplied with or without strain relief clamps. This section discusses three typical adapters and general assembly procedures.

(1) Assembly procedures for typical RFI environmental adapter (Glenair shown) are referred to in Figure 6-14.

(2) Assembly procedures for typical RFI non-environmental adapter (Glenair shown) are referred to in Figure 6-15.

(3) Assembly procedure for non-environmental adapter (Sunbank) is referred to in Figure 6-16. Assembly of Sunbank adapter is similar to the Glenair non-environmental adapter shown in Figure 6-15.

6.2 Bonding

Bonding is the process of establishing a low impedance path between two metal surfaces. The purpose of the bond is to make the structure homogenous with respect to the flow of RF currents between metallic conductors. Thus, proper design of a bond can avoid the development of potentials which may result in EMI.

Good bonding between equipment and a ground reference is essential to minimizing interference. It minimizes the buildup of RF voltage differences

ASSEMBLY PROCEDURE FOR TYPICAL RFI ENVIRONMENTAL ADAPTER (GLENAIR)

1 Temporarily assemble adapter 1 to connector

2 Place remaining adapter assembly components 2 through 5 on cable in sequence shown Keep these components at a convenient distance from end of cable so they will not interfere with subsequent assembly steps.

3. Insert cable into adapter 1 and bottom against connector Hold cable jacket at rear end of adapter 1.

CAUTION

If cable conductors are to have service loops, or if conductors will have crossovers, etc., allow sufficient added length to cable to compensate for these factors

4. Remove adapter 1 from connector and place on cable with components in step (2) above

5 Trim cable jacket and shield at mark made in step (3) above allowing for service loops and crossovers

6. Strip jacket 1/4 inch back from trim point in step (5).

7. Prepare and terminate cable conductors in accordance with established practices.

8. Assemble adapter 1 to connector and tighten securely.

9 Flare shield over tapered end on assembler 1 and slice RFI ferrule 2 into place over shield. Hold ferrule in position and trim any exposed shield strands adjacent to rear threads on adapter.

10 Slide grommet 3, grommet ferrule 4, and washer 5 against RFI ferrule 2

11. Engage clamp 6 with adapter and tighten securely Tighten clamp saddles on cable jacket.

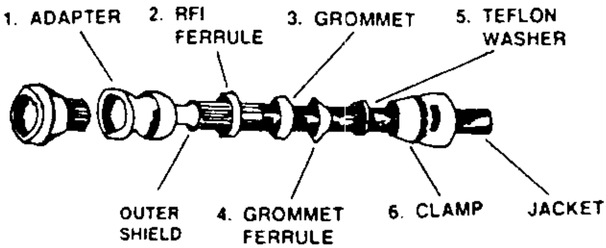


Figure 6-14. RFI Environmental Adapter (Glenair shown)

ASSEMBLY PROCEDURE FOR TYPICAL RFI NON-ENVIRONMENTAL ADAPTER (GLENAIR SHOWN)

1. Temporarily assemble adapter ① to connector.
2. Place RFI ferrule ② and clamp ③ on cable or harness in sequence shown. Keep these components at a convenient distance from end of cable so they will not interfere with subsequent assembly steps.
3. Insert cable into adapter ① at bottom against connector. Hold cable in position and mark outer shield at rear end of adapter ①.
4. Remove adapter from connector and place on cable with items in step (2) above.
5. Trim outer shielding at mark made in step (3) above.
6. Prepare and terminate individual conductors in accordance with established practices.
7. Assemble adapter ① to connector and tighten securely. (Hand plus 1/4 - 1/2 turn)
8. Flare shield over tapered end of adapter ① and slide RFI ferrule ② into place over shield. Hold ferrule in position and trim any exposed shield strands adjacent to rear threads on adapter.
9. Engage clamp ③ with elbow and tighten securely. Tighten clamp saddles on cable or harness. (Hand plus 1/4 - 1/2 turn)

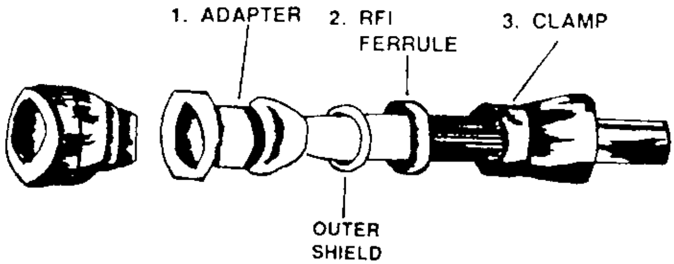


Figure 6-15. RFI Non-Environmental Adapter (Glenair shown)

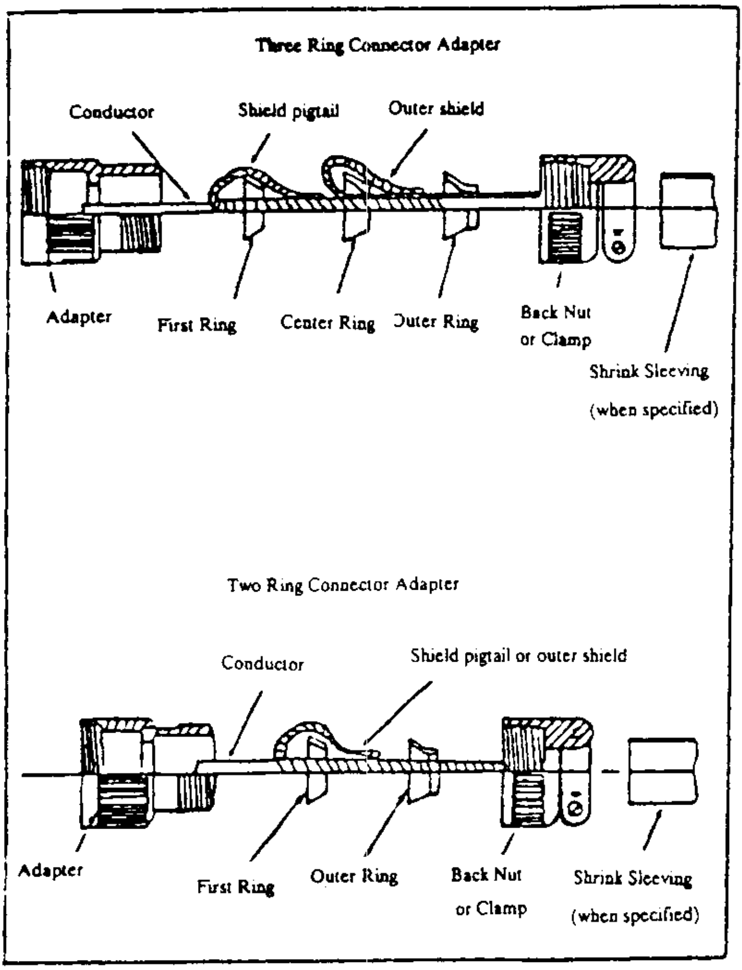


Figure 6-16. RFI Non-Environmental Adapter (Sunbank shown)

involvement. (Bond straps have significant impedance at frequencies above 10 MHz.) Use of indirect bonds is unavoidable when equipment must be removable or when items are subject to shock and vibration.

The effectiveness of a bond also depends on its application, frequency range, magnitude of current and environmental conditions such as vibration, temperature, humidity, fungus and salt content in the ambient.

6.3 Grounding

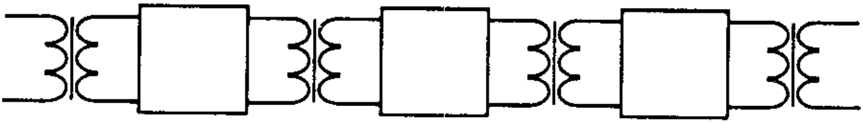
Grounding refers to the establishment of an electrical conductive path between the circuit to some reference point. The reference point can be earth, the equipment enclosure or the aerospace vehicle structure itself. A uniform grounding philosophy is mandatory to avoid conductive coupling, low impedance ground loops or hazardous operation conditions. The basis for this interference-free operation is a good, basic ground plane or reference. The ideal ground plane should be a zero-potential, zero-impedance body that can be used as a reference for all signals in the associated circuitry and can transfer any undesirable signal for its elimination. Due to physical properties and material characteristics, however, no ground plane is ideal, and some potential always exists between ground points in a system. The designer's job is to create a ground system that will effectively minimize potentials and reduce ground currents. A poor ground system, by enabling spurious voltages and currents to couple into a circuit, subassembly or equipment, can degrade the shielding effectiveness of even well-shielded units and result in EMI problems that may be difficult to resolve in later operations.

Various ground systems must meet requirements for personnel safety as related to the electrical power system, for lightning protection of personnel and property and for providing a signal ground bus as a common electronic circuit return. Emphasis in this addendum is placed on the establishment of good signal grounds, since this aspect of grounding will be of the most concern to users. It is also important to note that ground systems must be compatible under the interfaced condition.

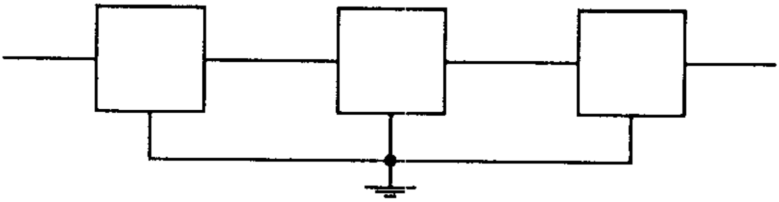
6.3.1 Grounding Techniques

There are three fundamental grounding concepts that can be employed, as illustrated in Figures 6-17(a), (b) and (c). The approaches can be used separately or in combination in any given equipment of system.

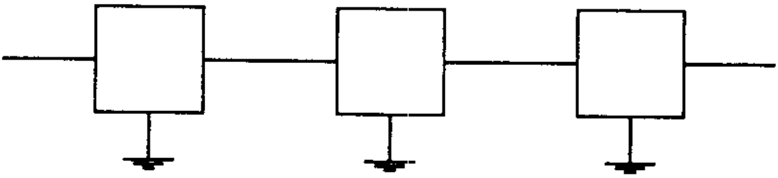
Figure 6-17(a) shows the Floating Ground System. This method electrically isolates circuits or equipment from a common ground plane, or from any common wiring that might introduce circulating



(a) Floating Ground



(b) Single-Point Ground



(c) Multiple-Point Ground

Figure 6-17(a) to 6-17(c). Grounding Methods

currents. Floating grounds depend, for their effectiveness, on truly "floating." For many situations, this complete isolation may be very difficult to achieve. Certain hazards also exist in the use of floating systems, in that static charges or lightning potentials may accumulate between the floating grounds and other accessible grounds such as the skin or other portions of the aircraft structure, power line neutrals, or the skin of the weapon system. Examples of isolation techniques are shown in Figures 6-18 and 6-19. Figure 6-18 employs transformer isolation, while Figure 6-19 obtains isolation by optical means.

Figure 6-17(b) shows a Single Point Grounding System. A single physical point in the circuitry is defined as a ground reference point, and all ground connections are tied to this point. For multiple cabinet configurations, the cabinet and electronic circuit grounds are often kept separate, with the single point grounding concept being used independently for each ground system. The interconnection between ground systems is then made only at the reference point. This isolates the rack or cabinets, and prevents circulating currents in one ground system from affecting another.

At frequencies whose wavelengths approach equipment ground plane dimensions or cable lengths, single-point ground systems are not practical.

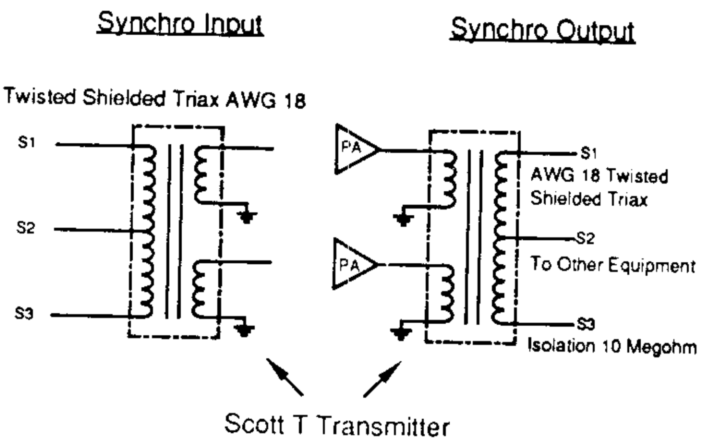
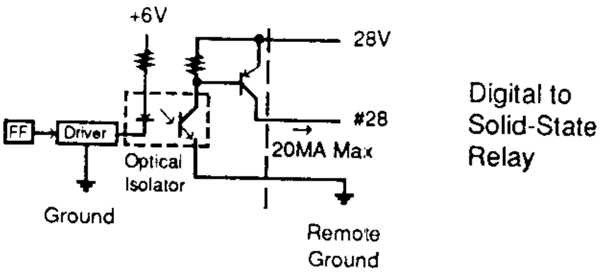


Figure 6-18. Typical Synchro Input & Output Isolation Circuitry



Isolation: 1KV Breakdown

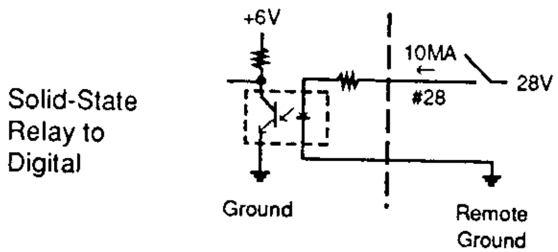


Figure 6-19. Digital to Solid-State & Solid-State to Digital Isolation Circuitry

Therefore, it is important for the equipment/system user to have an understanding of the frequency-susceptibility of the device, as well as the internal environmental frequencies that may create EMI, before finalizing grounding system design.

The Multipoint Grounding System, illustrated in Figure 6-17(c) shows how a ground plane is used. The ground plane might be an equipment chassis, a ground wire that is carried throughout a system, or the aircraft structure.

6.3.2 Circuit Grounding

If the ground plane is fairly large, significant potential differences may exist between two points. These voltages must be considered when defining the permissible ambient interference level in the system and when determining the expected signal-to-interference ratio of the signal transmission circuits.

The simplest and most direct approach to keeping potential differences introduced by the circuit ground plane to a minimum is to physically arrange circuit components so that ground return paths are short and direct, and to cross these paths as little as possible. In this way, the intercircuit coupling of the ground currents will be low and isolated.

The effect of ground potential can be cancelled by electrically isolating the circuits using a floating ground system. This method is especially effective at audio and low radio frequencies. Above these frequencies, its effectiveness progressively diminishes because as the frequency of equipment operation increases, coupling paths appear that bypass the isolation transformers.

Band pass filters are another method of obtaining circuit isolation. These filters are only effective when the frequency of the interference energy is outside of the frequency band of the desired signal. Then the band pass filter will reject the interference signal across the load, causing the voltage drop to occur elsewhere in the circuit and not at the load. When using band pass filters, care must be taken to insure that "ringing" is not initiated by the undesired signal when it is processed by the filter.

Differential or balanced circuitry can help reduce the effects of ground circuit interference. Since a differential circuit responds only to the potential difference between its input leads, the noise voltage at the source may be above ground potential by a considerable amount without degrading circuit performance. Figure 6-20 illustrates a differential circuit. The input voltage, V_g, is the voltage to which the device responds. The interference voltage, V_n, is simultaneously impressed on both input leads but is balanced out in the input to the device because each input lead has the same impedance to ground. Thus, the device does not respond to the ground circuit signal. In theory, the ambient noise voltage is cancelled out, assuming the impedance of V_g is zero ohms. In practice, there is always some unbalance in the differential device or associated circuitry, and some part of V_n will appear as a difference voltage across an equivalent resistance R. The noise voltage differential results in a reduced output signal-to-noise ratio. Figure 6-21 shows how the unbalance causes a portion of V_n, $V_g + \Delta V_n$, to appear across the input terminals of the device.

Figure 6-22 summarizes the situation just discussed by showing the ground circuit voltage, V_n, introducing an incremental voltage, $V_g + \Delta V_n$, at the input to the differential circuit.

Where modular type construction is used, one method of minimizing the loop area of grounded circuits is to mount modules on a sheet of good conducting material, such as copper or aluminum, that is connected to the circuit ground as directly

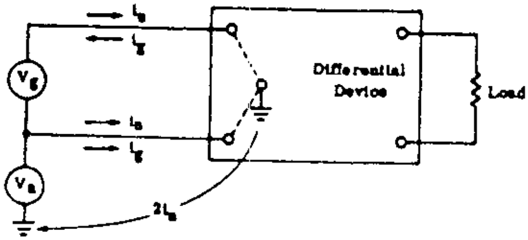


Figure 6-20. Schematic Diagram of a Differential or Balanced Circuit

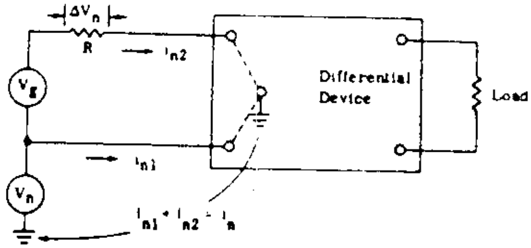


Figure 6-21. Effect of Unbalance in a Differential Circuit

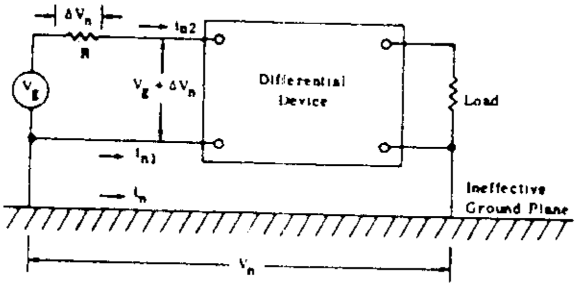


Figure 6-22. Common-Mode Voltage Generated by Flowing Finitely Conducting Ground Plane

as possible. The technique of running all intra-module wiring as close to this sheet as possible can reduce the loop area of these circuits to a miniscule value but will, at the same time, increase the capacitive coupling of the circuits. The effect of this increase on circuit operation should be considered when this technique is used.

The use of high impedance input or output circuit impedances when signals must be transmitted over even a few inches should, in general, be scrupulously avoided. Where the use of such signals cannot be avoided, the interconnecting lead must be shielded and the shield grounded at each end.

6.4 P-Static

There are basically two types of static dischargers: active and passive.

- The active discharger uses electronic circuitry to dissipate static charge on an aerospace vehicle. One type uses the thermionic emission principle to boil off excess electrons. Since active dischargers are independent of airflow, they are particularly adaptable to spacecraft applications.
- Passive dischargers, on the other hand, depend on airflow to bleed off the charge on an aircraft. The passive discharger is

attached to the trailing edge of surfaces and is electrically grounded to the metallic structure. Detailed descriptions of passive dischargers appear in specification MIL-D-9129D. A tabular synopsis of this specification is shown in Table 6-1.

A procedure and test set have been developed to simulate P-Static conditions similar to that encountered during flight. This "Electrostatic Diagnostic Test Set", developed by the Dayton-Granger Company, is currently being tested and validated by NATC, Patuxent River, for possible use by Navy maintenance activities. These test sets are being used by some aircraft manufacturers during the production and flight tests of new aircraft. Utilizing this test set:

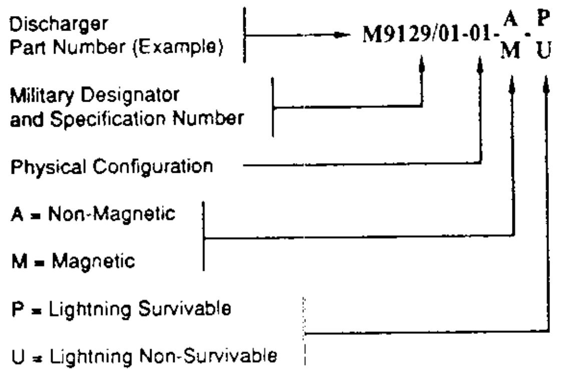
- The integrity of the dischargers and their mounting bases may be ascertained.
- Aircraft outside skin finishes may be tested for uniformity.
- Radome antistatic properties may be determined.
- The effects of ion streamering on windshields may be measured.
- Composite surfaces may be tested to assure a discharge path.

Table 6-1
Selection of Electrostatic Dischargers According to MIL-D-9129D

Discharger Part Number M9129/	Base I = Integral N = Non-Integral	Application TE = Trailing Edge WT = Wing Tip	Speed (Knots)	Holder Part Number ② M9129/09-
01-01	I	TE	<300	N/A
01-02	I	TE	<300	N/A
01-03	I	TE	<300	N/A
02-01	N	TE	<300	N/A
02-02	N	TE	<300	02, 07, 08
02-03	N	TE	<300	03, 04, 05, 06
03-01	I	TE	<600	N/A
03-02	I	TE	<600	N/A
04-01	I	WT	<600	N/A
05-01	N	TE	<600	01
05-02	N	TE	<600	02, 07, 08
05-03	N	TE	<600	03, 04, 05, 06
05-04	N	TE	<600	N/A
06-01	N	WT	<600	10①
06-02	N	WT	<600	02, 07, 08
06-03	N	WT	<600	09
06-04	N	WT	<600	N/A
07-01	N	TE	>600	11
07-02	N	TE	>600	N/A
07-03	N	TE	>600	03, 04, 05, 06
08-01	N	WT	>600	10①
08-02	N	WT	>600	N/A
08-03	N	WT	>600	09

① -10 () will include a letter designating radius

② Only 01, 03, 07, 10, & 11 are lightning survivable for use with P-Type dischargers



- Access panels, antennas, wheels, landing gear and deicing boots may be tested as to their contribution to P-Static generation.

These evolving P-Static test procedures are conducted with a physically dry aircraft in a hangar with the aircraft securely grounded. The time required to perform the tests, with problems identified, is less than eight hours. The potential use of this test set by the NADEP's during the aircraft induction phase could result in more comprehensive EMI evaluation of the airframe.

Until a P-Static test set similar to the one discussed above becomes available at the depots, it is suggested that P-Static evaluations commence with a visual inspection. While observing the static dischargers:

- Look for broken or missing elements;
- In the case of orthodecoupled dischargers, look for dull points;
- Observe discharger mounts for corrosion;
- Inspect windshields for obvious delamination, erosion or hairline cracks in the conductive coating;
- Inspect radomes for cracks in conductive coatings or loose or missing bonding straps;
- When observing dischargers, ensure that they are the correct ones for the

aircraft, i.e., low speed dischargers on a high performance aircraft, or a rigid type for a flexible type on a low wing aircraft where they would be susceptible to damage or could cause personal injury due to accidental contact.

After the visual examination, electrical resistance tests of the passive discharging system should be conducted. Note, the required continuity tests cannot be conducted with a conventional VOM (Volt Ohm Meter). The high resistance of dischargers should be measured with a "Megger", and the very low bonding resistances with a milliohmmeter.

- The resistance of a trailing edge discharger from the extremity to the base is 8 to 200 megohms and 6-120 megohms for a wing tip discharger. Measured values between 1 and 200 megohms indicate that the discharger is probably still functional.
- The installed resistance from discharger mounting base to the airframe is generally 3 to 5 milliohms; for lightning diverter types, any resistance exceeding 10 milliohms must be reworked to provide an acceptable (survivable) lightning discharge path, since the mount to airframe

attachment should be capable of surviving a 100 KA lightning strike.

If the aircraft mission or avionics has changed, in that equipment more susceptible to precipitation static has been installed, it may be necessary to recalculate the number of dischargers required.

Studies have shown that five dischargers per trailing edge reduce static accumulation to an acceptable level. Using this level as a base, the approximate number of required dischargers can be estimated by determining the relative total discharge capacity and applying it to the graph in Figure 6-23. Electrostatic charging results from the collision of airborne particles with the leading edges of the aircraft or as it passes through the crossfield gradients. The relative total discharge capacity of an aircraft =

$$\frac{\text{velocity} * \text{span} * 1.75}{K}$$

Where:

K = 75 046 for mi/h and span in feet, or

K = 65 100 for knots and span in feet, or

K = 36 760 for km/h and span in meters.

Velocity = maximum cruising velocity (subsonic).

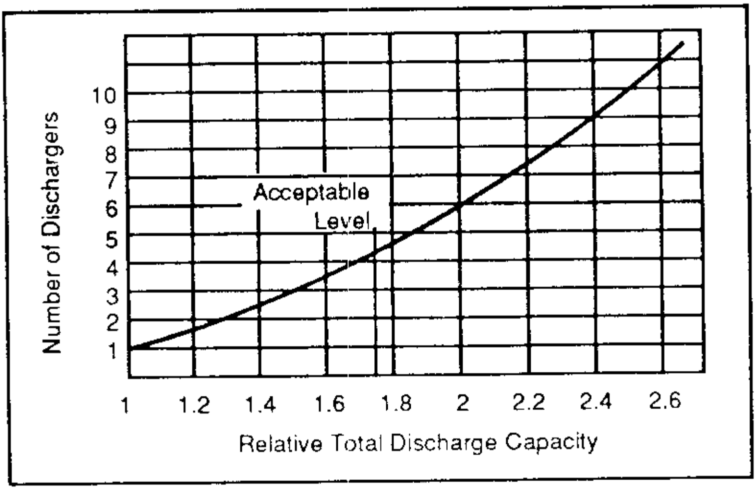


Figure 6-23. Number Dischargers vs Discharge Capacity

6.5 Lightning

Lightning on aircraft can be categorized as producing direct and indirect effects, either of which may occur as the result of a single lightning strike. Direct effects include the physical damage produced at the point of arc attachment and by current flow between arc attachment points. Direct effects of lightning may also include high voltage and current on externally mounted electrical hardware and installed avionics equipment (lightning effects to fuel systems are also recognized, but are beyond the scope of this document). Indirect effects are electromagnetically induced by field coupling to wires or avionics equipment. They are of principal concern to avionics and electrical systems.

Lightning also produces temporary physiological effects on aircraft crew, such as flash blindness and loss of consciousness from electrical or acoustical shock. In addition, effects such as fuel vapor ignition or engine outages may be caused by either direct or indirect effects.

For the purpose of studying lightning effects, aircraft are typically divided into three major lightning attachment zones. Zone 1 is located in the high field regions such as wing tips, vertical fin, and nose, where the probability of direct attachment is high. Zone 2 is aft of zone 1 and includes those areas where lightning attachments may only sweep. Zone 3 encompasses all other regions of the aircraft where there is low probability of arc attachment but through which lightning currents may possibly pass enroute between zone 1 or zone 2 attachment points.

6.5.1 Direct Effects

The direct effects of lightning are the burning, eroding, blasting and structural deformations caused by lightning arc attachment to an aircraft, as well as damage produced by the high-pressure shock waves and magnetic forces produced by the high currents. Since current density is highest at the point of contact, structural damage effects are typically localized to the immediate area of the arc attachment point or points. As the current enters a conductive structure, it rapidly spreads and current density is quickly reduced to harmless levels. This localization effect is particularly true for the lower level, continuing current phases of a strike.

There are three types of nonmetallic materials now being utilized in aircraft. These are glass or polymer fiber reinforced epoxies (fiberglass or Kevlar), boron or graphite-reinforced plastics, and polycarbonates such as Lexan and Plexiglass.

Fiberglass and Kevlar are used most commonly to achieve light weight in wing tips, fin caps, access doors, and in other applications where high mechanical strength is not required. Graphite reinforced composites, on the other hand, are capable of sustaining very high tensile and shear loads, making them suitable for primary structural applications. The general class of fiber reinforced materials are referred to as "advanced composites." Homogenous materials such as Lexan or Plexiglass are used for windshields or canopies.

Fiberglass and Kevlar reinforced plastics have essentially no electrical conductivity. Moreover, they are usually incapable of withstanding the high-voltage stresses created by the approaching lightning leader and frequently will undergo dielectric breakdown, allowing the flash to puncture them and terminate on some conducting object inside. The ensuing return stroke current can blast a large hole in the fiberglass or Kevlar skins. A diverter must usually be placed on the outside surface of such a skin to provide a place to which lightning flashes can attach or to guide flashes to a nearby metallic structure.

Damage may be far more extensive if current dispersion is prevented or if there is limited current-carrying capacity in the path taken by the lightning currents. For example, if the lightning arc attaches to a nose radome mounted pitot mast, the only current path to the main structure may be through the heater wires attached to the pitot probe. These wires would not typically be able to carry a heavy lightning current without explosively vaporizing. The resulting vaporization pressure could rupture the radome causing extensive damage and possible serious aerodynamic effects. The lightning currents could also find their way into the heater power supply and from there into the main electrical distribution system, causing widespread electrical problems.

Other examples of inadequate current-carrying capacity might include bonding straps, adhesively bonded structures, or high resistance coatings of the type designed to prevent static charge build-up.

When an electric current passes through a material, a certain amount of energy is converted to heat because of the electrical resistance of the conducting material. When the material heats, its resistance also changes. Complicating the matter still further is the fact that the current is transient in nature.

When the electric current is introduced into the conducting material (assume a flat metal plate) by means of an electric arc, an even more complex situation arises. Heat is generated in the material due to normal Joule heating and to heating at the arc/metal interface. If the current is fast rising, the initial current will essentially remain on the surface of the metal (skin effect) but, as the current continues, the current and the heat will diffuse and spread into the material. This can be compared to an arc weld except that electrical currents are several orders of magnitude greater for lightning and the time can be several orders of magnitude shorter.

The nature of localized structural damage to electrical hardware is dependent upon the construction and geometry of the part, and the type of lightning current flowing. The high peak current surge exerts shock and mechanical bending forces because of the intense magnetic fields and the explosive channel. However, on sturdy conductors such as thick aluminum, very little effect is noted, typically just small pits or etch marks on the surface. Conversely, the continuing current phase is capable of melting sizable holes through relatively thick, metal parts if allowed to deposit its energy at one point for a few tenths of a second.

The shock and blast effects of the high peak current phase may shatter light coverings or lenses, allowing the current direct access to the electrical system. The high peak currents tend to flow in straight lines so conductors with sharp bends will either be magnetically distorted or the lightning may flash across the corner or find an alternate path. Magnetic forces are proportional to the square of the current producing them and the damage produced relates both to the magnetic forces and to the response time of the affected system.

In areas where the current density is high, such as the attachment of protective bonding jumpers or at an arc root, the magnetic forces can become extremely large. It has been determined that an arc rising in a few microseconds to a peak current of 200 kA will have a diameter of about 2 mm; hence, its maximum magnetic field will be about

40 Tesla, producing a magnetic force approaching 150,000 lbs/in.^{2}.

Externally mounted electrical components which most frequently experience the direct effects of lightning include various types of lights, antennas, probes, windshield heaters and radomes. Radomes are frequently located in prime lightning attachment points (nose or wing tips). Therefore, particular attention should be paid to the mechanisms of high voltage breakdown and high current damage which they may experience.

6.5.2 <u>Bonding</u>

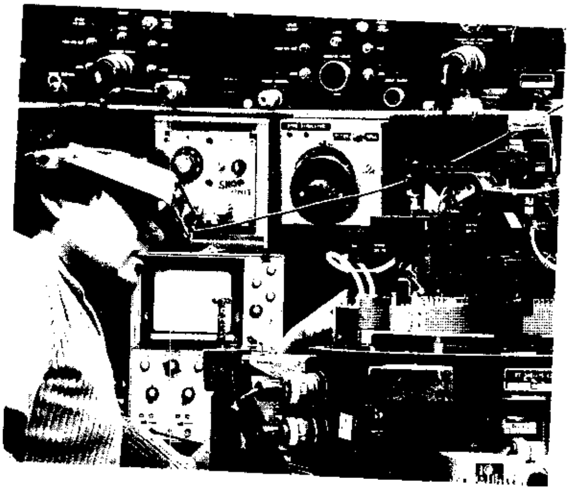
Several equipment procurement specifications have contained a lightning protection or test requirement. The principal specification governing the design and test of lightning protection for aircraft and other military systems is MIL-B-5087B, which concerns electrical bonding and lightning protection for aerospace systems. Paragraph 3.3.4, entitled "Class L bonding (lightning protection) (except for antenna systems)," addresses the lightning protection and testing requirement. It is quoted in its entirety as follows.

"Protection can be provided at all possible points of lightning entry into the aircraft. All of these forms of protection should be proven by test before installation.

- navigation lights,
- fuel filler caps,
- fuel gauge covers,
- refueling booms,
- fuel vents,
- antennas,
- radomes,
- canopies,
- pitot-static booms and
- wiring not protected by metal or body structure.

The following bonding requirements are designed to achieve protection against lightning discharge current carried between the extremities of an airborne vehicle without risk of damaging flight controls or producing sparkling or voltages within the vehicle in excess of 500 volts. These requirements are based upon a lightning current waveform of 200,000 amperes peak, a width of 5 to 10 microseconds at the 90-percent point, not less than 20 microseconds width at the 50-percent point, and a rate of rise of at least 100,000

Calibration Facility



Avionic Test Bench

CHAPTER 7
WIRE AND CABLE INSTALLATION TECHNIQUES

7.1 Identification Marking Scheme

It is proposed that the following procedures be established to catagorize each wire or cable according to its interference or susceptibility characteristics. Wires and cables are to be marked in such a manner that personnel can visually identify the E^3 category for each wire or cable. Wires and cables will also be identified, in order of E^3 priority, as listed in Table 7-1.

TABLE 7-1 E^3 CLASSIFICATION CATEGORY

E^3 Classification Letter	E^3 Category
X	Wires and cables which are used for special purposes such as pulsed circuits,

low level signal circuits or RF-power circuits, where interference may vitally affect operation.

E	Wires and cables which emit interference.
P	Wires and cables which carry electrical power.
S	Wires and cables which may be susceptible to interference.
Y	Wires and cables which are passive with respect to EMC, i.e., they do not emit and are not susceptible to interference.

It is further proposed that the existing wire and cable identification code be modified to include the E^3 classification category letter. These changes are depicted in Figures 7-1 and 7-2 as illustrated on the following pages.

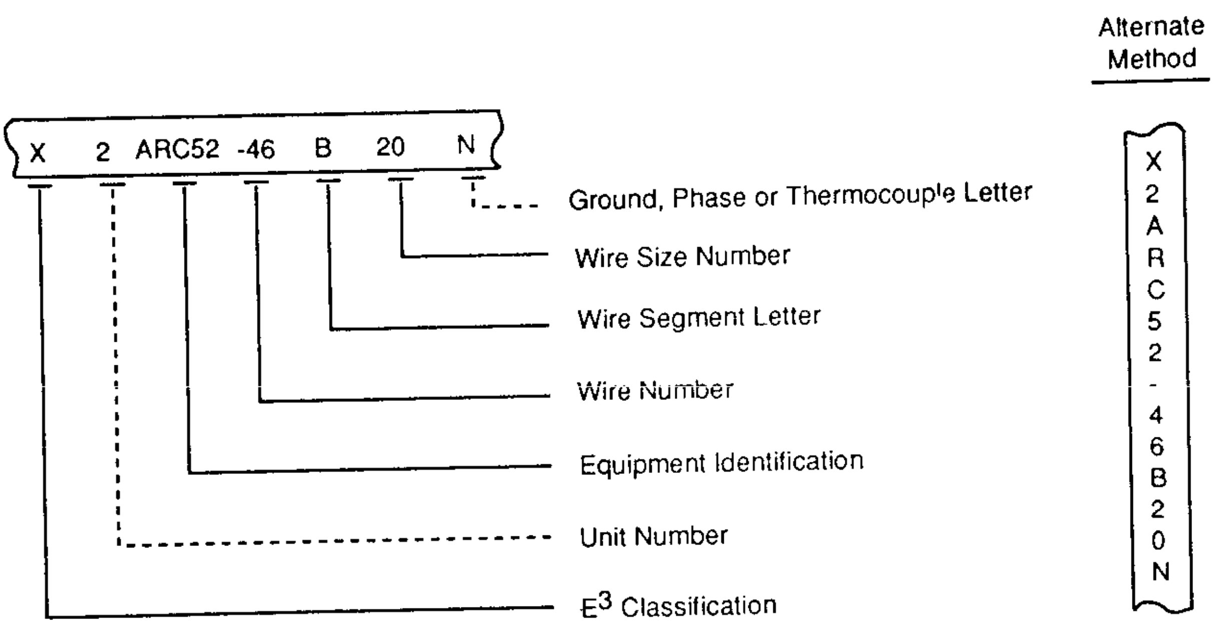


Figure 7-1. Wire Identification Coding of Circuit Function Letters R, S, T & Y

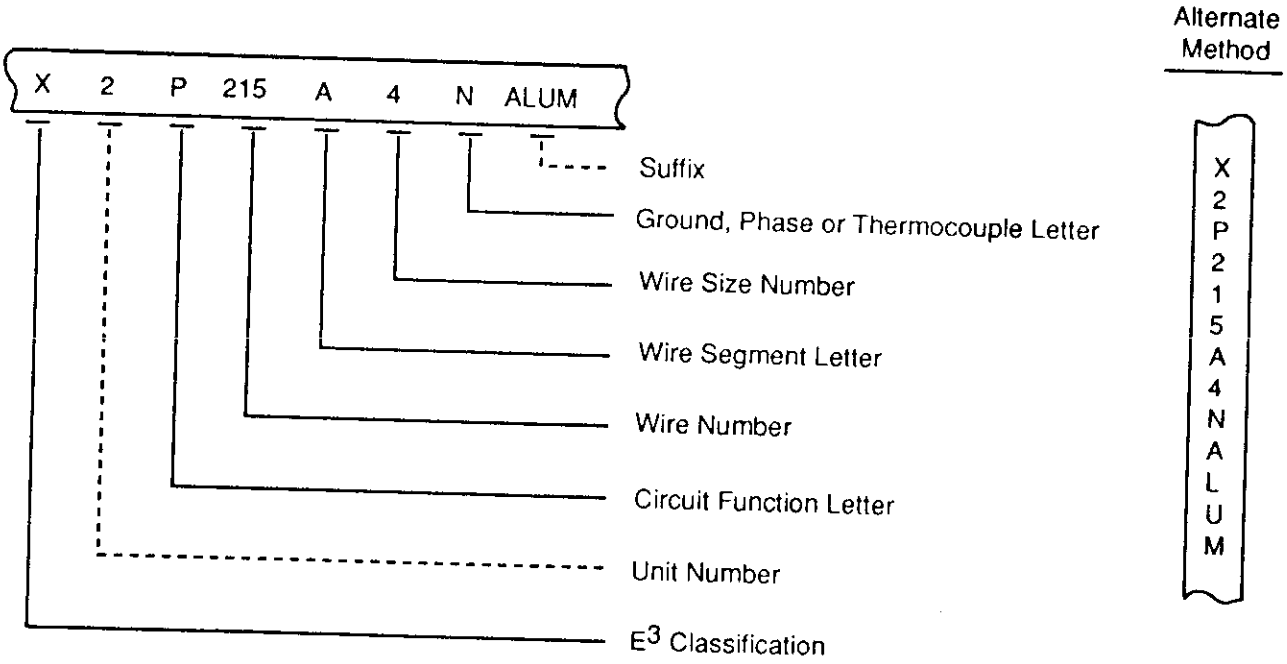


Figure 7-2. Wire Identification Coding Excluding Function Letters R, S, T & Y

7.2 Installation Method

Wiring, including RF and antenna cables, shall be routed so as to minimize EMI in accordance with the segregation scheme depicted in Table 7-2. This segregation scheme shall be utilized to minimize the possibility of interactions between the E^3 classes of wire and cabling listed in Table 7-1.

TABLE 7-2

Cable or wire E^3 Classification		Separation (in cm) from E^3 Classification Cables					
		X	E	P1	P2	S	Y
X	Specific purpose	-	10	15	10	10	7
E	Emitters	10	-	10	7	7	-
P1	Primary power feeders	15	10	-	10	15	7
P2	Secondary power feeders and distribution wiring	10	7	10	-	7	7
S	Susceptible	10	7	15	7	-	-
Y	Passive	7	-	7	7	-	-

NOTE: Table 7-2 specifies the recommended minimum separation distances between the different E^3 classes of wires and cables. Additionally, transmitter and transceiver cables which are coaxial in nature should be at least 30 centimeters from all other cables.

7.3 Coaxial Cable Selection Guide

Most engineers are quite familiar with the use of 75 ohm coax cable used in LF and baseband telephone transmission installations, and the universal use of the same cable for broadcast and cable TV. More recently, with the rapid growth of commercial computer data distribution, coax and twinax cables are being used for local dedicated installations. Even newer are the non-dedicated commercial coax data bus systems, such as Ethernet and Z Net, where many terminals are tied to one high bit rate trunk cable. Military aircraft systems are now being designed calling for 78 ohm twinax data bus distribution for main functions of guidance and control, navigation, communications, etc., per MIL-STD-1553B using the TRS and TRB series connectors.

Twinax cable (Figure 7-3) is a two-conductor twisted balanced wire line having a specific impedance with a shielding braid around both wires. Twisting the two balanced signal carrying wires provides cancellation of any random induced noise voltage pickup, thereby giving protection against magnetic noise fields of the low-frequency variety that pass through the copper braid. Twinax cable also lowers cable losses by adding two dielectric fillers under the braid. The fillers separate the braid from the signal pair, thereby lowering the leakage capacitance to ground. Additionally, by using more copper wire in the braid and weaving it tighter, the coverage is improved to 90%. This cable also provides protection against ground loops and capacitive fields, as does triax cable. Twinax cable usefulness, however, is limited to approximately 15 MHz since it has rather high transmission losses above this frequency. Twinax cable and concentric connectors are available for low frequency, digital and video distribution systems.

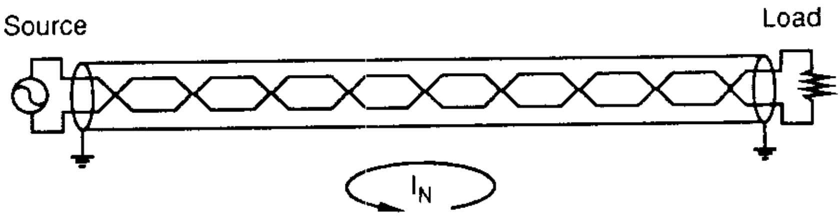


Figure 7-3 Twinax Cable

Twinax cable provides a shield, insulated from the twisted pair signal carrying conductors.

7.3.1 General Considerations

Flexible coaxial cables are the simplest, most versatile and popular means of transmission of RF and microwave energy. Since 1942, they have been improved continually with regard to temperature range, attenuation stability, and operating voltage. Their extensive use has also been a major incentive for the development of new high-frequency dielectric materials and new production techniques.

Coaxial cables have been made in a wide range of sizes and electrical characteristics, but most consist of the same basic elements - a center conductor, a low-loss solid or semisolid dielectric and one or more braided outer conductors followed by a waterproof covering. Over the covering, medium and large size cables may also have armor, a lead sheath or both. Other types of RF cables are the twin-conductor or shielded pair and dual-coaxial cables. The shielded pair consists of two parallel conductors separated from each other and surrounded by an insulating dielectric material. The conductors are contained within a copper-braid tubing which acts as a shield. This assembly is covered with a rubber or flexible-composition coating to protect the line against moisture and friction. The outstanding advantage of the shielded pair is that the two conductors are balanced to ground. The dual coaxial consists of two coaxial cables with individual shields covered by a common shield and jacket. Many compromises are involved when choosing materials and constructional features of each of these elements to attain good overall electrical and mechanical performance under a wide range of environments.

7.3.2 Center Conductor

To increase flexibility, solid copper is used for conductors above approximately 0.100 inch in diameter and for concentric stranded conductors (7, 19, or 27 strands) below 0.100 inch; with certain miniature cables, however, adequate flexibility can be achieved with a solid conductor. In these small size cables, the majority of the flexing stress is absorbed by the dielectric and jacketing materials whose strength exceeds that of the conductor. As a result, the conductor does not, in general, limit the flex life of the completed cable.

Single copper-clad steel conductors also provide good flexibility and add mechanical strength in the small and miniature sizes and in the airspaced cables. Silver or nickel coatings are necessary on high-temperature cables to prevent rapid oxidation of the copper during processing and use. Tin coatings are used to facilitate soldering of cables to fittings.

Tin and nickel-plated conductors should be limited to low frequency applications where the thickness of the coating will not increase the conductor attenuation significantly.

7.3.3 Dielectric

Polyethylene is used almost exclusively where the maximum temperature will not exceed 85 degrees centigrade. It is extruded directly over the center conductor in either a solid or airspaced form. Polytetrafluoroethylene (Teflon) is required when temperatures from 85 to 250 degrees centigrade are encountered in the vicinity of the dielectric. It may be extruded and sintered in solid form or built up from layers of tape to achieve greater flexibility. A high temperature sealing compound is sometimes used to fill the voids in a taped cable, thereby raising its corona level or maximum operating voltage. In the miniature sizes, unsintered tapes are sometimes used since they can be heat fused after application. This also tends to minimize the number of voids in the dielectric.

The Helical Membrane cable uses a thin flat ribbon of either polyethylene or Teflon to support the inner conductor. This membrane is obtained by cutting a spiral in a hollow dielectric tube of precise size, and drawing an aluminum sheath tightly over the open spiral. This construction results in slightly lower permittivity, attenuation, and cost than Styroflex, but is not as rugged; it is feasible over the size range from

0.475 to 3.125 inches. Greater care must be taken during installation to assure that slippage of the center conductor does not occur due to bends, thermal expansion or both.

Heliax cables are air dielectric, semi-flexible coaxial cables that require no pressurization. A helical ribbon of Teflon supports the inner conductor within a corrugated high conductivity copper outer conductor. These cables are available jacketed or unjacketed in 3/8 through 5 inch diameter sizes. Jacketed cables include a special weatherproof flooding compound and black polyethylene jacket. No straightening or bending tools are required for field installation and connectors may be applied with ordinary tools. The ability of the outer conductor to withstand flexure (50-100 times) about a radius ten times its overall diameter permits reasonable reuse of the cable.

The dielectric of a semiflexible line may be either an airspaced structure or a continuous form of solid insulation. In the former, a continuous ribbon or rod of dielectric material is spiraled openly with a uniform pitch around the center conductor to support it and maintain low effective permittivity. Some semiflexible cables are manufactured with a continuous laminated helix composed of thin flexible-oriented polystyrene tapes. The high tensile and compressive strengths of this type of film (10,000 to 13,000 psi) and the wrapping technique permits the finished cable to withstand high tensile forces and crushing load. Another type of semiflexible cable uses dielectrics of compressed high density polyethylene tubes which eliminate a direct air path between the center and outer conductor and provide individual air cells. Strength is added to the cable by the continuous radial web support of the dielectric tube. Overall dimensions range from 3/8 to 6-1/8 inches and closely follow rigid line practice.

The latter category of semiflexible cable uses a solid or continuous form of dielectric in the size range from 0.080 to 0.750 inch. One of the early types (RG-81 & 82/U) uses a highly purified, compacted magnesium oxide insulation, with soft copper conductors. The attenuation of these Pyrotenax cables is somewhat high, particularly at the higher frequencies, and the insulation is very hydroscopic when exposed to the atmosphere. More recent designs use polyethylene or foamed polyethylene with an aluminum sheath. The introduction of a solid dielectric increases the peak operating voltage and the attenuation, but lowers the thermal resistance sufficiently to retain the equivalent power handling capacity of an airspaced line. Semiflexible lines without a jacket have a smaller volume and improved power rating in comparison to flexible cables of the same diameter over the dielectric. The solid outer conductor also has a lower attenuation than does braided cable. The solid dielectric semiflexible cables can be permanently sealed for high altitude or for submarine use without the need for auxiliary pressuring equipment.

The electrical properties of these airspaced cables are very similar to rigid lines below 100 MHz. In this region, the aluminum outer conductor increases the attenuation by about 6 percent. Above 100 MHz, this difference gradually increases with frequency to an ultimate value of 35 to 45 percent above the equivalent size rigid line at cutoff. The impedance variation with frequency is also slightly larger, but still below VSWR of 1.08 as a result of minor irregularities in the dielectric structure and dimensions of the outer conductor. However, close to the upper frequency limit, a marked lowering of the impedance has been observed due to an increased concentration of the electric field in the dielectric. These cables should be installed with sealed fittings and maintained with a positive dry gas pressure.

7.3.4 **Outer Conductor**

A single close-fitting braid of fine copper wire (0.010 to 0.004 inch) is most frequently used as an outer conductor. Tin or silver-coating is used for the same reasons as in the center conductor; these coatings also reduce the apparent RF resistance of the braid. A second braid of either copper or steel is used to improve shielding. This second braid has only a secondary effect on attenuation and is designed primarily for shielding.

7.3.5 Jacket

Black vinyl resins are extruded or tubed over the outer conductor of all polyethylene dielectric cables. Cables with PFTE dielectric have a close wrap of PFTE tape, or an extruded FEP jacket, followed by one or more glass braids impregnated with a silicone varnish, although the latter may be omitted. An extruded rubber sleeve with a Dacron braid impregnated with a flourocarbon lacquer can be used to improve the poor abrasion resistance of the glass braids. For miniature cables, a wide variety of jacket materials is available with different upper temperature limits, such as extruded PFTE (FEP) (200°C); heat-fused tapes or PFTE-impregnated glass (260°C); extruded monocloro-trifluorethylene (H Kel-F, Fluorothene, or Poly-fluron) (135°C to 150°C); extruded nylon over vinyl or heat fused or lacquered nylon braid (105° to 125°C). High molecular weight polyethylene with black pigment is also being used where the temperature will be kept below 85°C.

7.3.6 Protective Coverings

A close braid of aluminum armor and paint is applied over the jacket for shipboard installations. This armor protects the jacket against cuts and tears in hazardous locations or during burial in rocky terrain. Cables for permanent burial in wet locations have a lead sheath over the jacket for added long-time moisture resistance. A treatment of heavy-duty galvanized steel armor wire, embedded in layers of asphalted jute, is necessary for the installation and recovery of these heavy leaded cables.

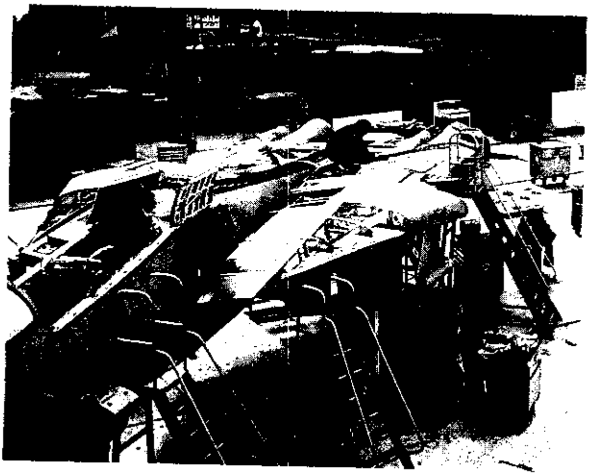
There are many constructional variations between the rigid coaxial lines and flexible cables which fall in the broad category of semiflexible lines. These lines can be fabricated and shipped in continuous lengths to 2000 feet, which can be formed into moderate bends during installation. The outer conductor is a smooth-drawn or corrogated tubing of a ductile metal. Additional protective coverings may be added for greater abrasion and corrosion resistance.

Precautions should be taken to prevent "work hardening" and eventual cracking of the sheath from continual vibration. Copper sheath is better than aluminum in items of vibration resistance. These cables can withstand short-time operation in the presence of open flames. Sustained use above their rated temperature will cause damage to the cable sheath due to the relatively large thermal coefficient of expansion of the dielectric. However, mineral-insulated types can be used up to 250°C for limited operation of up to about 100 hours, and close to the softening point of copper under emergency conditions.

Unprotected copper or aluminum can be used outdoors in dry locations or in serial installations where there is no danger of electrolytic action. In wet locations, or in the presence of corrosive vapors, the sheath should be protected with asphalt coated tapes, or a jacket of black polyethylene or vinyl. A metallic armor is recommended for additional mechanical protection when underground or underwater burial is required.

The cable should not be dragged across rough terrain that may cut, fracture or in any way damage the cable; nor should the cable be allowed to lay unprotected on the ground where it is subject to heavy vehicle traffic.

F-14 Awaiting Depot Processing



F-14 Undergoing Major Disassembly

CHAPTER 8
APPLICABLE DOCUMENTS

During the preparation of this manual, most, if not all, of the existing government instructions relating to aircraft EMI were reviewed. The more important documents, categorized as specifications, standards and handbooks, are listed in the following paragraphs. In addition to the Government publications, EM textbooks and numerous technical papers dealing with various aspects of EMI were reviewed. These documents are also listed in the following paragraphs.

8.1 Official Publications

8.1.1 Specifications

MIL-B-5087	Bonding, Electrical, and Lightning Protection, for Aerospace Systems
MIL-W-5088	Wiring, Aerospace Vehicle

MIL-E-6051	Electromagnetic Compatibility Requirements, Systems
MIL-D-9129	Dischargers, Electrostatic, General Specification for
MIL-F-15733	Filters, Radio Interference, General Specifications for
MIL-F-18327	Filters, High Pass, Low Pass, Band Pass: Band Suppression, and Dual Functioning, General Specifications for
MIL-I-83456	Installation of Segmented Lightning Diverter Strips on Aircraft Radomes, General Specification for

8.1.2 <u>Standards</u>

MIL-STD-202	Test Methods for Electronic and Electrical Component Parts
MIL-STD-220	Method of Insertion Loss Measurement

MIL-STD-285	Attenuation Measurements for Enclosures, Electromagnetic Shielding, for Electronic Test Purposes, Method of
MIL-STD-449	Radio Frequency Spectrum Characteristics, Measurement of
MIL-STD-454	Standard General Requirements for Electronic Equipment
MIL-STD-461	Electromagnetic Interference Characteristics, Requirements for Equipment
MIL-STD-462	Electromagnetic Interference Characteristics, Measurement of
MIL-STD-463	Definitions and System of Units, Electromagnetic Interference Technology
MIL-STD-469	Radar Engineering Design Requirements, Electromagnetic Compatibility
MIL-STD-470	Maintainability Program Requirements

MIL-STD-471	Maintainability Verification/ Demonstration/Evaluation
MIL-STD-480	Configuration Control - Engineering Changes, Deviations, and Waivers
MIL-STD-704	Electric Power, Aircraft, Characteristics and Utilization of
MIL-STD-889	Dissimilar Metals
MIL-STD-1250	Corrosion Prevention and Deterioration Control in Electric Component and Assemblies
MIL-STD-1310	Shipboard Bonding, Grounding, and Other Techniques for Electromagnetic Compatibility Safety
MIL-STD-1364	Standard General Purpose Electronic Test Equipment

MIL-STD-1377	Effectiveness of Cable, Connector, and Weapon Enclosure Shielding and Filters in Precluding Hazards of Electromagnetic Radiation to Ordnance; Measurement of
MIL-STD-1379	Training Operations and Training Data
MIL-STD-1385	Preclusion of Ordnance Hazards In Electromagnetic Fields, General Requirements for
MIL-STD-1399	Interface Standard for Shipboard Systems
MIL-STD-1605	Procedures for Conducting a Shipboard Electromagnetic Interference (EMI) Survey (Surface Ships)
DOD-STD-1686	Electrostatic Discharge Control Program for Protection of Electrical and Electronic Parts, Assemblies and Equipment (Excluding Electrically Initiated Explosive Devices)

MIL-STD-1757	Lightning Qualification Test Techniques for Aerospace Vehicles and Hardware
DOD-STD-1795	Lightning Protection of Aerospace Vehicles and Hardware

8.1.3 <u>Handbooks</u>

MIL-HDBK-216	RF Transmission Lines and Fittings
MIL-HDBK-235	Electromagnetic Radiated Environment Considerations For Design and Procurement of Electrical and Electronic Equipment (Part I, II, and III)
MIL-HDBK-237	Electromagnetic Compatibility/Interference Program Requirements
MIL-HDBK-238	Electromagnetic Radiation Hazards
MIL-HDBK-253	Guidance for the Design and Test of Systems Protected Against the Effects of Electromagnetic Energy

AFSC DH1-4	Design Handbook - Electro-magnetic Compatibility
NAVAIR AD 1115	Electromagnetic Compatibility Design Guide for Avionics and Related Ground Support Equipment
NAVAIR 01-1A-505	Installation Practices, Aircraft Electric and Electronic Wiring

8.2 General References and Technical Papers

Keises, B: "Principles of Electromagnetic Compatibility," ARTECH House Inc., Norwood, MA, 1987

Plonus, M.A.: "Applied Electromagnetics," McGraw-Hill Book Company, New York, 1978

Tocci, R.J.,: "Fundamentals of Electronic Devices," Charles E. Merrill Publishing Co., Columbus, OH, 1975

Jordan, E.C. "Reference Data for Engineers: Radio, Electronics, Computer, and Communications, Seventh Edition," Howard W. Sams & Co., Inc., Indianapolis, IN, 1985

AGARD Lecture Series No. 144 "Interaction between EMP, Lightning and Static Electricity with Aircraft and Missile Avionics Systems," AD-A171 298

AGARD Lecture Series No. 110 "Atmospheric Electricity - Aircraft Interaction," AD-A087976

"Practical EMI Fixes" Syllabus Don White Consultants, Inc., Gainesville, VA 1986

ITEM (Interface Technology Engineering Master), Robar Industries, West Conshohocken, PA (1987) (Issued Annually)

R. L. Truax "Electrostatic Charging and Noise Quieting," SAE 700926

R. L. Truax "Dielectric Electrostatic Charge Reduction," SAE 810571

"Instruction and Servicing Manual, Null Field Dischargers and Retainers," Dayton-Granger, Ft. Lauderdale, FL

"Operation and Maintenance Manual for Electrostatic Diagnostic Test Set," Dayton-Granger, Ft. Lauderdale, FL

R. L. Tanner and J. E. Nanevicz "An Analysis of Corona Generated Interference in Aircraft," Proceedings of IEEE, Jan 1964

J. E. Nanevicz and R. L. Tanner "Some Techniques for the Elimination of Corona Discharge Noise in Aircraft Antennas," Proceedings of IEEE, Jan 1964

TERMS AND DEFINITIONS

Absorption

a. Loss of energy, due to conversion into heat or other forms, in the transmission of waves over radio or wire paths.

b. The term is usually applied, in wire transmission, only to loss of energy in extraneous media.

Absorption loss

That part of the transmission loss due to the dissipation or conversion of either sound energy or electromagnetic energy into other forms of energy, either within the medium or attendant upon a reflection.

Aperture

That portion of a plane surface, in a unidirectional antenna, near the antenna that is perpendicular to the direction of maximum radiation through which the major part of the radiation passes.

Arrester

Protective device used to provide a bypass path directly to ground for lightning discharges that strike an antenna or other conductor.

Atmospheric Interference

Interference from sources such as precipitation static, fractional charging, and thunderstorms.

Background Noise

Total system noise independent of whether or not a signal is present. The signal is not included as part of the noise.

Balanced Wire Circuit

A circuit whose two sides are electrically alike and symmetrical with respect to ground and other conductors. The term is commonly used to indicate a circuit whose two sides differ only by chance.

Bonding

In electrical engineering, the process of connecting metal parts so that they make low resistance electrical contact for direct current and lower frequency alternating current.

Broadband Interferences

Includes impulse noise, thermal noise, shot noise, and other nonsinusoidal interference whose energy is distributed over a spectrum of frequencies that is wide when compared with the band width of the interference measuring equipment. The response of an interference measuring set to broadband interference is a function of the effective bandwidth of the receiver.

Capacitive Coupling

The association of two or more circuits with one another by means of capacitance mutual to the circuits.

Conduit

A sheet metal enclosure normally of rectangular or circular construction used to provide electromagnetic shielding/grounding protection to cables, and electrical shock protection to personnel.

Coupling

Association of two circuits so that electrical energy may be transferred from one to another.

Decibel (dB)

Dimensionless unit for expressing the ratio of two values, the number of decibels being 10 times the logarithm to the base 10 of a power ratio, or 20 times the logarithm to the base 10 of a voltage or current ratio.

Distortion

An undesired change in waveform. The principal sources of distortion are: a nonlinear relation between input and output of a component at a given frequency; nonuniform transmission at different frequencies; and phase shift not proportional to frequency.

Earthing

The process of making a satisfactory electrical connection between the structure, including the metal skin, of an object or vehicle, and the mass of the earth, to ensure a common potential with the earth.

Electrical Noise

Noise generated by electrical devices, for example, motors, engine ignition, power lines, etc., and propagated to the receiving antenna direct from the noise source.

Electroexplosive Device (EED)

Any electrically initiated explosive device within an electroexplosive subsystem having an explosive or pyrotechnic output, and actuated by an electroexplosive initiator.

Electroexplosive Initiator (EEI)

The first device in a pyrotechnic or explosive train which is designed to transform an electrical, mechanical, or heat input into an explosive or pyrotechnic reaction. Detonators, electrical match, and squibs are examples of initiators.

Electroexplosive Subsystem (EES)

The term EES is intended to include all components required to perform control, monitor and initiation of an electrically initiated ordnance/pyrotechnic function.

Electromagnetic Compatibility (EMC)

Capability of electronic equipment or systems to be operated with a defined margin of safety in the intended environment at desired levels of efficiency without degradation due to interference.

Electromagnetic Interference (EMI)

Electromagnetic energy which interrupts, obstructs, or otherwise degrades or limits the effective performance of telecommunications equipment or subsystems.

Electromagnetic Pulse (EMP)

The electromagnetic radiation from a nuclear explosion caused by Compton-recoil electrons and photoelectrons from photons scattered in the materials of the nuclear device or in a surrounding medium. The resulting electric and magnetic fields may couple with electrical/electronic systems to produce damaging current and voltage surges.

Emission

Any electromagnetic signal, conducted or radiated, which causes EMI.

Enclosure

A housing such as a console, cabinet, or case designed to protect and support mechanisms, electronic parts and subassemblies.

Equipment

Any electrical, electronic, or electromechanical device or collection of items intended to operate as an individual unit and perform a singular function. As used herein, equipments include, but are not limited to, receivers, transmitters, transceivers, transponders, power supplies, electrical office machines, hand tools, processors, test apparatus and instruments and material handling equipment.

Ferrite

Magnetic material made of a wide variety of ceramic ferro-magnetic materials.

Filter

A four-terminal network designed to freely transmit currents or voltages of certain frequencies while attenuating all others.

Galvanic Corrosion

Galvanic corrosion is the the acceleration of corrosive action due to dissimilar metals in contact in the presence of moisture. The action is that of a galvanic cell, in which the metals act as electrodes, with the metal that is corroded acting as an anode with respect to the other metal.

Grounding

The bonding of an equipment case, frame, or chassis to an object or vehicle structure to ensure a common potential.

Ground-Return Circuit

A circuit which has a conductor (or two or more in parallel) between two points and is completed through the ground to earth.

Harmonic

A sinusoidal component of a periodic wave or quantity having a frequency which is an integral multiple of the fundamental frequency. For example, a component whose frequency is twice the fundamental frequency is called the second harmonic.

Harmonic Distortion

Nonlinear distortion characterized by the appearance in the output of harmonics other than the fundamental component when the input is sinusoidal.

Hum

In audio frequency systems, a low-pitched droning noise, usually composed of several harmonically related frequencies, resulting from an alternating-current power supply or from induction due to exposure to a power system. By extension, the term is applied in visual systems to interference resulting from similar sources.

Impulse Noises

Noise due to disturbances having abrupt changes and of short duration. (NOTE: These noise impulses may or may not have systematic phase relationships. Noise is characterized by overlapping transient disturbance. The same source may produce impulse noise in one system and random noise in a different system.)

Inductive Coupling

a. Association of one circuit with another by means of inductance common or mutual to both. (NOTE: This term, when used without modifying words, is commonly used for coupling by means of mutual inductance, whereas coupling by means of self-inductance common to both circuits is called direct inductive coupling.)

b. In inductive coordination practice, the interrelation of neighboring electrical supply and communications circuits by electric and/or magnetic induction.

Inductive Interference

Effect arising from the characteristics and inductive relations of electrical supply and communications systems of such character and magnitude as would prevent the communications circuits from rendering service satisfactorily and economically if methods of inductive coordination were not applied.

Insertion Loss

a. At a given frequency, the insertion loss of a feed-through suppression capacitor or a filter connected into a given transmission system is defined as the ratio of voltages appearing across the line immediately beyond the point of insertion, before and after insertion. As measured herein, insertion loss is represented as the ratio of input voltage required to obtain constant output voltage, with and without the component, in the specified 50-ohm system. This ratio is expressed in decibels (dB) as follows:

$$\text{insertion loss} = 20 \log E_1/E_2$$

WHERE:

E_1 = The output voltage of the signal generator with the component in the circuit.

E_2 = The output voltage of the signal generator with the component not in the circuit.

b. The ratio in dB of the power in the load when the filter is out of the circuit to the power in the load when the filter is in the circuit (with a constant source voltage).

c. The ratio of received powers before and after the insertion of shielding between a source and a receiver of electromagnetic energy.

Interface

Common boundary between two components, systems, or phases.

Interference

a. Electrical disturbance that causes undesirable responses in electronic equipment.

b. Disturbance in radio reception caused by undesired signals, stray currents from electrical apparatus, etc. A current from a foreign source or a second communications line that in some way produces a degraded performance. Interference is sometimes spoken of as the current or power that causes noise in the telephone.

c. In a signal transmission system, either extraneous power that interferes with the reception of the desired signals or the disturbance of signals that results.

Intermodulation

Mixing of two or more signals in a nonlinear element, producing signals at frequencies equal to the sums and differences of integral multiples of the original signals.

Intermodulation Interference

Interference that occurs as the result of mixing two undesired signals in a nonlinear element such as the first stage of a receiver or the final stage of a transmitter. The nonlinear element may even be external to the communications equipment as in the case of a corroded metal-to-metal joint. This mixing may result in the generation of a new signal or signals of sufficient amplitude to be detected as interference.

Intersystem Interference

Interference between systems. A lack of system-to-system EMC.

Intrasystem Interference

Interference and resultant performance degradation confined within the physical and EM bounds of a single system.

Lossy Line

a. Cable used in test measurements which has a large attenuation per unit length.

b. Transmission line designed to have a high degree of attenuation.

Magnetic Shield

Sheet or core of iron enclosing instruments or radio parts to protect them from stray magnetic fields by providing a convenient path for the magnetic lines of force.

Magnetic Susceptibility

Ratio of the magnetic intensity produced in a substance to the applied magnetizing force.

It is the reciprocal of permeability.

Man-made Interference

Any EMI due to the operation of electrical or electronic equipment, but particularly harmonic or spurious signals from radio frequency devices, as opposed to noise.

Man-made Noise

High-frequency noise signals created by sparking in an electric circuit. When picked up by a radio receiver, these signals cause buzzing and crashing sounds and may seriously interfere with radio communications.

Metrication

Act of developing metric standardization documents or converting current standardization documents to metric units of measurement.

Metric Units

Units defined by the International System of Units based on "Le System International d'Unites (SI)" of the International Bureau of Weights and Measures. These units are described in ANSI/ASTEM E 380-79 or successor documents as listed in the DOD Index of Specifications and Standards.

Noise

a. An unwanted receiver response other than another signal (interference). Noise may be audible in voice communications equipment, or visible in equipment such as radar. In the latter case, it is also known as snow.

b. Unwanted energy (or the voltage produced), usually of random character, present in a transmission system due to any cause.

Nonlinear Distortion

Distortion caused by a deviation from a linear relationship between specified measures of the input and output of a system or transducer.

Optical Coupling

Coupling between two circuits by a light beam or a light pipe, having transducers at opposite ends, to isolate circuits electrically. One application is to interconnect microcircuits.

Precipitation Static

Static interference due to the discharge of large charges built up on aircraft or other object by rain, sleet, snow or electrically charged clouds.

Pulse

A variation of a quantity whose value is normally constant but not necessarily zero. This variation is characterized by a rise and decay and has a finite duration.

Reflection Loss

The loss in transmission due to reflection of energy at a point of discontinuity or change of impedance, usually expressed as a ratio in decibels of difference between the incident power and the power absorbed by the load.

Return Wire

Ground wire common wire, or the negative wire in a dc circuit.

Secondary Power Lead

Any lead conducting ac or dc power which is regulated, rectified, filtered, isolated, transformed, converted or modified in any way within a unit of an equipment or subsystem.

susceptible circuit from being affected by interfering signals.

b. In cables, a metallic layer placed around a conductor or group of conductors to prevent electrostatic or electromagnetic interference between the enclosed wires and external fields.

Shielding Effectiveness

The ratio (usually expressed in decibels) of noise induced current or voltage in a system element when a source of shielding is present to the corresponding quantity when the shielding is absent.

Signal-to-Noise Ratio

The ratio of the value of the signal to that of the noise. The ratio is usually in terms of peak values in the case of impulse noise and in terms of root-mean-square values in the case of random noise.

Soft Conversion

The process of changing a measurement language to mathematically equivalent metric units without changing the physical configuration.

and ground loop currents, deters the buildup of static charges during equipment operation, minimizes damage which might be caused by lightning strikes, and protects personnel from the shock hazard that could result if primary power were inadvertently shorted to an enclosure. Most importantly, good bonding enables the design objectives of other methods of EMI suppression, such as shields and filters, to be more nearly achieved.

MIL-B-5087B classifies bonds for aerospace systems by the purpose of the bond. For each class of bond, MIL-B-5087B specifies the unique parameters that must be considered. Typical parameters are impedance, type of return paths, current requirements, voltage drop, size of conductor, soldering; riveting, and corrosion control. The specified classes are:

Class	**Application**
A	Antenna Installation
C	Current return path
H	Shock hazard
L	Lightning protection
R	RF potentials
S	Static charge

Use of direct bonds is preferred over indirect bonds because of the minimum bond impedance achievable and the scope of maintenance

Soft Conversion

The process of changing a measurement language to mathematically equivalent metric units without changing the physical configuration.

Spike

A transient of short duration, comprising part of a pulse, during which the amplitude considerably exceeds the average amplitude of the pulse.

Spurious Emission

Any electromagnetic emission from the intended output terminal of an electronic device, outside of the designed emission bandwidth. Spurious emissions include harmonics, parasitic emissions and intermodulation products, but exclude unnecessary modulation sidebands of the fundamental frequency.

Spurious Response

Any response of an electronic device to energy outside its designed reception bandwidth through its intended input terminal.

amperes per microsecond. When flight safety is not a factor, 100,000 amperes peak with a rate-of-rise of 50,000 amperes per microsecond may be used at the discretion of the procuring activity."

Other paragraphs in MIL-B-5087B deal briefly with lightning protection design considerations, but the paragraph quoted above has been the governing criterion for lightning testing of aerospace systems, in conjunction with the specifications for particular subsystems mentioned earlier.

Static

a. Interference caused by natural electrical disturbances in the atmosphere or EM phenomena capable of causing such interference.

b. Noise heard in a radio receiver caused by electrical disturbances in the atmosphere such as lightning and northern lights.

Subsystem

A major functional element of a system, usually consisting of several equipment essential to the operational completeness of the subsystem or system. Examples are airframe, propulsion, guidance, navigation and communication.

Susceptibility

A characteristic of electronic equipment that permits undesirable responses when subjected to electromagnetic energy.

System

A composite of equipment, sub-systems, skills and techniques capable of performing or supporting an operational role. A complete system includes related facilities, equipment, software, subsystems, materials, services and personnel required for its operation to the degree that it can be considered self-sufficient within its operational or support environment.

Telecommunications Equipment

Any equipment which transmits, emits or receives signs, signals, writing, images, sounds or information of any nature by wire, radio, visual or other electromagnetic means.

Thermal Noise

a. Noise voltage generated in resistors due to minute currents caused by thermal motions of the conduction electrons.

b. Random noise in a circuit associated with the thermodynamic interchange of energy necessary to maintain equilibrium between the circuit and its surroundings. Also called resistance noise.

Transient

a. An intermediate physical disturbance to two steady state conditions.

b. Pertaining to rapid change.

c. A buildup or breakdown in the intensity of a phenomenon until a steady-state is reached.

d. A momentary surge of signal or power line. May produce fake signals or triggering impulses.

APPENDIX A

POINTS OF CONTACT

This appendix presents a compilation of significant organizations and associated points of contact. The organizations and personnel identified are actively working to improve the EMC of Naval aircraft and may be of assistance in answering E^3 questions and providing technical support.

Chief of Naval Operations (OP-941F)
Washington, DC 20350

Haislmaier, Dr. Robert (202) 695-2710
Electromagnetic Spectrum
Management Branch

ERC International, Inc.
Applied Engineering Division
5510 Morehouse Drive
San Diego, CA 92121

Trimmer, Thomas (619) 535-1255
West Coast E^3 Technical Support

J.F. Taylor, Inc.
Route 235 and Maple Road
Lexington Park, MD 20653

Fowler, Richard C. (301) 862-4744
East Coast E^3 Technical Support

National Bureau of Standards
Gaithersburg, MD 20889

Horlich, Jeffrey (301) 975-4020
Navy Laboratory Accreditation
Program (NVLAP)

Naval Air Development Center (NADC)
Warminster, PA 18974-5000

Kozol, Joseph (215) 441-7606
EMI Gasketing
Lane, Ronald (7053) (215) 441-1881
EMI Branch Head
Lin, Wendy (6064) (215) 441-7149
EMI Gasketing
Reilly, John (215) 441-1924
Conductive Composites
Walker, William (7053) (215) 441-2906
Lightning

Naval Air Engineering Center
Lakehurst, NJ 08733

Snedaker, David (5452) Aviation Support Equipment	(201) 323-7052

Naval Air Forces Atlantic (COMNAVAIRLANT)
NAS, Norfolk, VA 23511

McGrath, Howard EMC Coordination	(804) 444-3414

Naval Air Forces Pacific (COMNAVAIRPAC)
NAS, North Island
San Diego, CA 92135

Patterson, Louis	(619) 437-5901
Rigsby, Thomas	(619) 437-5901
Shipley, W. L. (Code 7276)	(619) 437-5901

Naval Air Systems Command (NASC)
Washington, DC 29361-5160

Carstensen, Russell AIR 5161 E^3 Branch Head	(202) 692-8600/1
Davis, Mike V-22	(202) 692-8600/1
Fellin, David HPM/HERO	(202) 692-8600/1
Hammett, Raymond (AIR-5161) Rotary Wing	(202) 692-8600/1
Iacono, Anthony (AIR-5161) Fixed Wing	(202) 692-8600/1
Lockhart, Eugene E^3 Data Base, ES-3A, AIEMC, F/A-18, AV-8	(202) 692-8600/1

Naval Air Test Center (NATC)
Patuxent River, MD 20670-5304

Nahaj, Mike (SY-82) E^3 Section Head	(301) 863-4681
Thompson, Tommy (SY-83) TEMPEST Section Head	(301) 863-4591

Naval Air Weapons Center (NWC)
China Lake, CA 93555-6001

Covino, Josephine (Code 3891) (619) 939-3381
ESD Test Section (Propellants)
Southworth, David (Code 36254) (619) 939-2948
E^3 Section Head

Naval Aviation Depot
Naval Air Station
Alameda, CA 94501

Romano, Dennis (415) 869-4472
Chairman, Naval Wiring Action Group

Naval Aviation Depot
Marine Corps Air Station
Cherry Point, NC 28533-5030

Bach, Wayne (Code 840) (919) 466-7531
EMC Coordinator

Naval Aviation Depot
Naval Air Station
Jacksonville, FL 32212

Beaman, Brian — (904) 772-2737
E^3 Coordinator

Naval Aviation Depot
Norfolk, VA 23511

Cole, John (Code 311) — (804) 444-8500
E^3 Coordinator

Naval Aviation Depot
Naval Air Station
Pensacola, FL 32508

Johnson, Maurice (Code 323) — (904) 452-3588
E^3 Coordinator

Naval Aviation Depot
Naval Air Station
North Island, Bldg. 6
San Diego, CA 92135-5112

Schmidt, Mary Jane (619) 437-5636
E^3 Coordinator

Naval Avionics Center (NAC)
6000 E. 21st Street
Indianapolis, IN 46219-2189

Swift, William (317) 353-7405
E^3 Coordinator

Naval Ocean Systems Center (NOSC)
271 Catalina Blvd.
San Diego, CA 92117

Bossart, Lou (619) 225-7213
E^3 Data Base & Training

Naval Research Laboratory (NRL)
Washington, DC 20375

Cohen, Lawrence	
E^3 Program Coordinator	(202) 767-6947
Cooper, Dr. J.	
Ford, Richard	(202) 767-3115
E^3 Consultant	(202) 767-3440

Naval Safety Center
Naval Air Station
Norfolk, VA 23511

Valdillez, CWO3 Ramon	
Avionics Branch Head	(804) 444-3494

Naval Surface Warfare Center (NSWC)
Dahlgren, VA 22448

Guthrie, Mitchell (H12)	
E^3 Risk Assessment	(703) 663-7550
Lenzi, William (H22)	
Electromagnetic Vulnerability	(703) 663-8594
HERO	

Naval Surface Weapons Center
Silver Spring, MD 20903-5000

Bechtold, George (202) 394-1746

Oak Ridge National Laboratory
P.O. Box X, Bldg. 3500
Oak Ridge, TN 37831-6007

Hess, Richard (615) 574-4544

Pacific Missile Test Center
Point Mugu, CA 93042-5000

Boone, Jerry (805) 989-8941
E^3 Test Laboratory

Space and Warfare Systems Command
Department of Navy
Washington, DC 20363

Caine, Stephen (Code 3214)	(202) 692-0559
Head E^3 Branch	692-4396
(BF E^3)	692-4430
Tedder, James (Code 3214)	(202) 692-0559
EMC Engineering Programs	

Manual Review Form

It is requested that Government or contractor users of this manual complete this form when comments on the applicability and suitability of the manual can be provided. This action will materially assist in updating the publication, and in keeping designers informed of techniques that can assist them in their undertakings. Mail the form to:

Naval Air Systems Command
Attn: Code 5161
Washington, DC 29361-5160

Electromagnetic Compatibiity Theory and Practice Manual for Aviation Depots, NAVAIR 5161/653-1988

Organization of Submittee	City, State & ZIP

Equipment to which the Manual was Applied:

Errors or Deficiencies in the Manual:

Recommendations for Correcting the Deficiencies:

Additional Comments:

Submitted by: (Printed or typed name & activity)	Date:

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