This is
AFSC DESIGN HANDBOOK 1-4
FOURTH EDITION, REVISION 1
31 JANUARY 1991

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS AERONAUTICAL SYSTEMS DIVISION (AFSC)
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-6503

REPLY TO ATTN OF: ENES (P. Marth) — 31 January 1991

SUBJECT: AFSC DH 1-4, Electromagnetic Compatibility, Fourth Edition, Revision 1

TO: AFSC DH 1-4 Distribution List

1. The attached pages constitute the Fourth Edition, Revision 1, of the Air Force Systems Command (AFSC) Design Handbook (DH) 1-4, Electromagnetic Compatibility.

2. Retain this letter in the front of your handbook until a revision is issued, then replace it with the new letter of transmittal.

3. Notice this transmittal has 19 punched holes rather than the 18 of the previous transmittals. This change is made to accommodate the new standard size ($8^1/_2 \times 11$) paper. If you have an 18-ring binder, place the bottom hole of the pages in the bottom binder ring. This helps to prevent bottom edges from fraying.

4. Your comments on this handbook are desired. All comments may not be incorporated in the handbook, but each will be given careful consideration. You are encouraged to use the "Reader's Service Letter" for making recommendations, reporting address changes, requesting changes in quantity, etc. You may use AFSC Form 2614 or AFSC Form 2615a, as appropriate, to request handbooks. Direct all communications concerning this handbook to:

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Wright-Patterson AFB OH 45433-6503
(513) 255-6291
AUTOVON: 785-6291.

JAY B. FREE
Chief, Engineering Documents Division
Directorate of Support Systems Engineering

4 Atch
1. AFSC Form 2614
2. AFSC Form 2615a
3. Reader's Service Letter
4. AFSC DH 1-4, Fourth Edition, Revision 1, 31 January 1991

AFSC DESIGN HANDBOOK 1-4
ELECTROMAGNETIC COMPATIBILITY
FOURTH EDITION, REVISION 1

This handbook provides system designers with electromagnetic compatibility design principles, information, guidance, and criteria; and establishes a central source of electromagnetic compatibility design data (any type of factual information that can be used as a basis for design decisions). This handbook partially implements AFSCR 8-4.

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2. **RESPONSIBILITY.** The responsibility for preparing, revising, and distributing this handbook is delegated to the Directorate of Support Systems Engineering of Aeronautical Systems Division. The Responsible Engineering Offices (REOs) for the technical content of this handbook are identified at the bottom of the first page of each Design Note. The addresses for the REOs are contained in *Design Note 1A3*.

3. **DISTRIBUTION.** Handbooks are provided without charge to qualified agencies supporting USAF technical interests and objectives. Government organizations will justify requests based on need for the handbook in carrying out assigned missions and functions. Requests by non-Government organizations should either reference a Government contract which requires their compliance with this handbook or show how their having it will benefit the Government. Direct requests to ASD/ENES, Wright-Patterson AFB OH 45433-6503. Requesters may use AFSC Form 2614 or AFSC Form 2615a, as appropriate.

4. **RECOMMENDATIONS.** Users are invited to submit recommendations to ASD/ENES, Wright-Patterson AFB OH 45433-6503, to correct inaccuracies, provide additional information, or otherwise improve the handbook. The Reader's Service Letter (AFSC Form 2363) may be used for this purpose.

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TRANSMITTALS ISSUED TO DATE

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UNCLASSIFIED AFSC DESIGN HANDBOOK (DH) REQUEST

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I. JUSTIFICATION

State required application(s) of handbook(s).

REQUIRED ON CONTRACT NO.	REQUIRED TO RESPOND TO RFP NO.
OTHER (Specify)	EXPLAIN USE

II. FOREIGN DISCLOSURE

All Foreign Nationals must obtain official diplomatic clearance to use the AFSC Design Handbooks.

POLICY AGREEMENT

(For release of AFSC design handbooks to US business and potential contractors)

1. I request that the designated AFSC Design Handbook(s) be released to me under the terms set below.

2. I understand that:

   a. The requested information is subject to the Export Control Laws and Regulations.

   b. Export of such information, or of items made using such information, without obtaining export licenses is subject to substantial criminal penalties.

   c Willfully making any false statement in connection with the Export Control Laws and Regulations, or omitting any material fact necessary to make the statements not misleading, is subject to the same penalties.

   d. Export includes release within the United States to foreign nationals including publications or release to US companies controlled by foreign nationals.

   e. Most of the handbooks contain copyrighted material. Permission for using copyrighted material was granted in accordance with *AFR 110-8, Inventions Patents, Copyright*, and *Trademarks*, and with the understanding that the material would not be offered for sale.

3. I agree that:

   a. Any information in these handbooks which is marked as subject to export control shall not be released or to any foreign national within the organization who is not admitted to permanent residence within the United States.

   b. I will notify ASD/ENES of any application for licenses to export the information.

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   c. No copyrighted material shall be reproduced without first obtaining permission from the original author.

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CITY		TITLE	
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Contact the address below to obtain a description and the scope of each Design Handbook.
Mail all unclassified requests directly to:

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PHONE: Area Code 513, 255-6281
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2-7	SECRET - RESTRICTED DATA				

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☐ Approved – I certify the need-to-know until ______ (DATE) ☐ Disapproved (Return to Requester)	SIGNATURE TYPED NAME TITLE
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II. CERTIFICATION OF RESPONSIBLE ENGINEERING OFFICE (Government Requesters Only)

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READER'S SERVICE LETTER

Instructions: Use to submit comments, recommendations, and address changes. Use AFSC Form 2614 to request unclassified AFSC Design Handbooks and AFSC Form 2615 to request classified AFSC Design Handbooks.

AFSC DESIGN HANDBOOK NO.	DESIGN NOTE	PARA OR SUB-NOTE

REMARKS *(If more space is required, attach additional sheets)*

OLD ADDRESS *(As shown on envelope)*	NEW ADDRESS

SIGNATURE	DATE

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CHAP 1 GENERAL INFORMATION

CHAPTER 1 GENERAL INFORMATION

SECT 1A THE AFSC DESIGN HANDBOOK PROGRAM

SECTION 1A THE AFSC DESIGN HANDBOOK PROGRAM

DESIGN NOTE 1A1 INTRODUCTION

1. PURPOSE

The primary purpose of the AFSC Design Handbooks is to document Air Force technical knowledge for use in support of acquisition programs. They are intended to reduce duplication of technical effort and to increase application of technical knowledge.

1.1 CONTRACT APPLICATION

Design Handbooks are usually applied by (1) directly incorporating their requirements into a contract or by (2) translating handbook data into specific standards or specifications called out in a contract.

2. SCOPE

Design Handbooks are a principal source of design criteria and guidance in technical areas of Air Force systems and equipment design. They contain both mandatory and nonmandatory statements.

2.1 MANDATORY STATEMENTS

Unless otherwise specified, imperative statements (e.g., Use the equipment.) are mandatory when applied to a contract. Waivers to them should be obtained through established management procedures.

2.2 NONMANDATORY STATEMENTS

Design information of a nonmandatory nature is provided to increase understanding of technical problems and to facilitate their solution. Nonmandatory statements are for guidance and may be deviated from without a formal request.

REO ASD/ENES

DESIGN NOTE 1A2 HANDBOOK ORGANIZATION AND MANAGEMENT

1. TEXT

The Chapter is the main division within each AFSC Design Handbook. Chapters are broken down into Sections. Each Section contains Design Notes (DN) which are a reasonably complete, self-contained coverage of a specific topic. For easy reference, the Design Note consists of numbered paragraphs, subparagraphs, and occasionally sub-subparagraphs.

2. UNITS OF MEASUREMENT

Measurements contained in the Handbooks are normally given in metric units. When a metric unit of measurement is followed by its equivalent US customary unit contained in parentheses, the measurement was originally given in US customary units and has been "soft converted" into metric units. When a measurement is given in metric units only, the metric unit is the original unit of measurement and has not been converted from US customary units. (See *App A* for definitions of metric terms.)

3. ILLUSTRATIVE MATERIAL

Tables, drawings, and other illustrative material are called Sub-Notes (SN) within a Design Note. They are identified by the number of the paragraph in which they are first referenced followed by a number in parentheses (e.g., the first Sub-Note in *Para 1.2* would be designated *SN 1.2(1)*; the second *SN 1.2(2)*; etc.).

4. NUMBERING

Paragraphs and pages are numbered consecutively within each Design Note. Design Notes are numbered consecutively within each Section. Sections are lettered alphabetically within each Chapter. Chapters are numbered consecutively within the Handbook. The Handbook and Design Note are identified at the top of each page (see above).

5. PAGE DATING

Each Handbook page has the publication date at the bottom inner edge. A list of current pages immediately follows the title page in the front of each Handbook.

6. TABLES OF CONTENTS

Tables of Contents appear at the beginning of each Chapter and Section.

7. REFERENCES

Each Handbook contains two types of references: (1) cross-references to paragraphs in that or in other Handbooks, and (2) references to other documents.

7.1 CROSS-REFERENCES

Wherever possible, cross-references are used within and between Handbooks to avoid duplicating information.

7.2 REFERENCE DOCUMENTS

Documents referenced in Handbooks consist of (1) specifications, standards, and related documents and (2) technical reports and copyrighted publications.

7.2.1 SPECIFICATIONS, STANDARDS, AND RELATED DOCUMENTS. Specifications, standards, drawings, technical orders, handbooks, bulletins, manuals, regulations, and pamphlets are referenced as shown in *SN 7.2.1(1)*. The effective date of these references shall be the date listed in the latest issue of the *Department of Defense Index of Specifications and Standards (DODISS)* and supplements thereto, unless otherwise specified in the individual contract or work statement.

REO: ASD/ENES

SUB-NOTE 7.2.1(1) Methods of Referencing Documents in Handbooks* (Sheet 1 of 2)

TYPE OF DOCUMENT	SAMPLE TEXT REFERENCE
SPECIFICATIONS	
Aerospace Material Specifications	AMS 999
Federal Specifications	Fed Spec QQ-Q-1111
Military Specifications	MIL-A-1111
National Aeronautics and Space Administration Specifications	KSC-C-123
STANDARDS AND DRAWINGS	
Air Force-Navy Aeronautical Design Standards	AND 10070
Air Force-Navy Aeronautical Standards	AN1111
American National Standards Institute Standards	ANSI A24.10
American Society for Testing and Materials Standards	ASTM D86
American Welding Society Standards	AWS A2.2-66
Federal Standards	Fed Std 595
International Electrotechnical Commission Recommendations	IEC 184(1965)
International Standards	STANAG, ABC, etc.
Military Standards (Book Form)	MIL-STD-111
Military Standards (Sheet Form)	MS21348
National Aeronautics and Space Administration Standards	KSC-STD-E-0001
National Aerospace Standards	NAS2115
National Fire Protection Association Standards	NFPA 11-1970
Society of Automotive Engineers (SAE) Aerospace Standards	SAE AS 219
SAE Aerospace Information Reports	SAE AIR 720
SAE Aerospace Recommended Practices	SAE ARP 321
USAF Standard Drawings	Dwg 721111
HANDBOOKS	
AFSC Design Handbooks	DH 1-3
Department of Defense Handbooks	DOD 5010.8-H
Federal Handbooks	Fed Hdbk H-28
Military Handbooks	MIL-BUL-130
Cataloging Handbooks	H2-6
BULLETINS AND LISTS	
Air Force-Navy Aeronautical Bulletins	ANA Bul 111
Data Item Descriptions (indexed in *DOD 5000.19-L, Vol II*)	DI-R-3531
Military Bulletins	MIL-BUL-400
USAF Specification Bulletins	USAF Spec Bul 111
MANUALS	
Air Force Flight Test Center Manuals	AFFTCM 55-2
Air Force Test Range Manuals	WTRM/ETRM 127-1
Air Force Manuals	AFM 86-1
Air Force Logistics Command Manuals	AFLCM 86-1
Air Force Systems Command Manuals	AFSCM 86-1
1st Strategic Aerospace Division Manuals	1STRADM 127-200
Department of Defense Manuals	DOD 4120.3-M
Navy Manuals	NAVAIR 01-1A-509
Space and Missile Systems Organization Manuals	SAMSOM 127-1
Space and Missile Test Organization Manuals	SAMTOM 127-1
Federal Manuals for Supply Cataloging	M1-2
*For sources of Design Handbook references, see *App B*.	

SUB-NOTE 7.2.1(1) Methods of Referencing Documents in Handbooks (Sheet 2 of 2)

TYPE OF DOCUMENT	SAMPLE TEXT REFERENCE
REGULATIONS	
Air Force Flight Test Center Regulations	*AFFTCR 55-15*
Air Force Regulations	*AFR 86-1*
AFSC Regulations	*AFSCR 8-4*
Federal Aviation Administration Regulations	*FAR 25*
Armed Services Procurement Regulations[1]	*ASPR 3-100*
Defense Acquisition Regulations[2]	*DAR 3-100*
PAMPHLETS	
Aeronautical Systems Division Pamphlets	*ASDP 127-1*
Air Force Pamphlets	*AFP 88-27*
Air Force Systems Command Pamphlets	*AFSCP 80-5*
Federal Aviation Administration Advisory Circulars	*AC 20-53*
National Aeronautics and Space Administration Procedures	*MSFC-PROC-151*
TECHNICAL DOCUMENTS	
Technical Reports (TR), Journal Articles, Manuals, Books, Bulletins, Symposium Proceedings	*Ref 126*
Copyrighted Publications	*Ref 525©*
TECHNICAL ORDERS	
USAF Technical Orders	*TO 11-1-1*

[1]Have been replaced by Defense Acquisition Regulations (DAR) or Federal Acquisition Regulations (FAR).

[2]Have been replaced by Federal Acquisition Regulations (FAR).

7.2.2 TECHNICAL REPORTS AND COPYRIGHTED PUBLICATIONS. Technical reports, journal articles, book, etc., are assigned numbers in sequence from a consolidated master list and referenced by number only (e.g., "See *Ref 112*" or "Extracted in part from *Ref 25*"). Material extracted verbatim from copyrighted publications is identified by the symbol © following the reference number. Such material may not be reproduced in any manner without permission of the copyright owner. Numbered references used in each Handbook are listed in *App C*.

8. INDEX

At the back of each Handbook is a detailed index of subject matter keyed to paragraph numbers. A general subject index for all Design Handbooks is contained in *AFSC DH 1-1*.

9. GLOSSARY

Each Handbook contains a glossary in *App A*. The glossary consists of terms applying to specialized areas. If a term appears only once (or infrequently) in the Handbook, it is explained where it occurs.

10. CHECKLISTS

Checklists are used in establishing design requirements and in verifying that the requirements have been met. Checklists for each Handbook are contained in the DH-X series (*DH 1-X, DH 2-X*, as applicable).

11. HANDBOOK REVISIONS

Each handbook is scheduled for a semiannual revision.

11.1 SPECIAL SAFETY ITEMS

Information on a critical or extremely hazardous design situation may be issued at any time in the form of a "Design Bulletin." This type of publication will be limited in size not to exceed one complete Design Note.

11.2 IDENTIFYING REVISED MATERIAL

A black line to the left of the text or title shows that a technical or significant nontechnical change has been made at that place. A black line beside the date on a page (bottom inside corner) indicates editorial changes only have been made on the page. An asterisk (*) beside the number in a Design Note title or after the title of a paragraph shows that either new material of considerable length has been added or extensive changes have been made in the text or illustrations. An appropriate footnote informs the use of the extent of the changes. For other needed reference marks on the page, single character symbols used in sequence are dagger (†), double dagger (‡), section mark (§), and parallel (//). Then, if more symbols are needed, these may be doubled or tripled. The date of the page is the effective date of all marked changes.

11.3 LIST OF CURRENT PAGES

Each handbook includes a "List of Current Pages" showing the latest date of each page; in revisions an asterisk (*) indicates a new or replacement page. The symbol (#) denotes pages to be deleted without replacement. Treat any classified pages being replaced as classified material until destroyed.

12. STANDARDIZATION

Detailed information on standardization programs is covered in *DN 1A4*.

12.1 IMPLEMENTATION OF INTERNATIONAL AGREEMENTS

Some international agreements are implemented by Design Handbook requirements. Where a handbook implements an international standard, it will do so by specifying the applicable data from the international agreement together with the international standard document number (STANAG, ABC, ASCC, etc.) and title. When a deviation from such a requirement is sought, the requester must state that the deviation involves an international agreement.

13. HANDBOOK ACQUISITION

Design Handbooks are supplied without charge to qualified organizations furnishing technical support to the US Air Force. Use AFSC Form 2614 (for unclassified) and AFSC Form 2615a (for classified) to request Design Handbooks. (See *Para 16*, below, for obtaining a description of the contents of each Design Handbook.) The Design Handbooks are not considered "records" according to *AFR 12-30*; therefore, they are not subject to the requirements of the *Freedom of Information Act*.

13.1 UNCLASSIFIED HANDBOOKS

All US Government organizations must justify handbook requests based on specific needs to carry out assigned missions. Non-Government organizations requesting handbooks must meet at least one of the following requirements:

a. The specific handbook is cited in an active US Air Force contract or current Invitation for Bid (IFB) or Request for Proposal (RFP).

b. The specific handbook is needed in private or educational technical assignments which will result in direct technical benefits to the US Air Force.

These requests must (1) identify the handbook(s) needed, (2) identify contract, IFB, or RFP number, and (3) explain use to be made of the handbook by giving the requesting organization's specific assignment and stating the expected benefits to the US Air Force.

13.2 CLASSIFIED HANDBOOKS

Automatic distribution of classified handbooks in the AFSC DH-series will be restricted to those organizations having a known continuing need.

Also, quantities requested will be closely controlled. A separate decision will be made on each request as to whether a classified Design Handbook will be required and released to prospective bidders. Justification for continued need for classified handbook(s) is required at least every 3 years.

13.2.1 JUSTIFICATION AND ORDERING PROCEDURES. To order any classified Design Handbook, complete AFSC Form 2615a. The "Verification of Need-To-Know" section will be completed by the organizations indicated on the form. Requesters must furnish the following information: contract number(s) and termination dates, and their facility security clearance. Classified handbook, *AFSC DH 2-9*, is no longer an approved document for distribution. (See also, *Para 14.*)

13.3 FOREIGN DISTRIBUTION

Design Handbook requests from foreign governments or foreign nationals must be cleared through that nation's Embassy in Washington DC, then through AFSC/DLXI, Andrews AFB DC 20334. United States citizens or industries wishing to take Design Handbooks into a foreign country must submit a request (with justification) directly to AFSC/DLXI, Andrews AFB DC 20334, for approval.

13.4 GENERAL DISTRIBUTION

Approved handbook users are placed on automatic distribution for all revisions and handbook changes. If their requirements change, users must submit a new request and justification using AFSC Form 2614 or AFSC Form 2615a, as appropriate. Because of copyright limitations, Design Handbooks cannot be legally sold. Copies of the handbooks are available in many technical libraries.

14. HANDBOOK DISPOSITION

All handbooks (including binder and contents) remain the property of the US Government. They are loaned without charge for as long as a need exists. When the user can no longer satisfy the requirements in *Para 13.1* or *Para 13.2* above, the binders are to be returned to: 2750ABW/IMP, Wright-Patterson AFB OH 45433. The contents are to be destroyed in an approved manner. Classified handbook *AFSC DH 2-9* has been withdrawn from circulation. All copies of this document (contents and binders) are to be returned to: 2750ABW/IMP (VAULT), Wright-Patterson AFB OH 45433.

15. COMMENTS AND RECOMMENDATIONS

A Reader's Service Letter is provided with each handbook for comments, recommendations, or change of address. Comments and recommendations are encouraged from all users so that the information in the Design Handbooks will continue to be current and useful to designers.

16. COMMUNICATIONS

Direct all communications concerning AFSC Design Handbooks to:

ASD/ENES
Wright-Patterson AFB OH 45433-6503
Tel: (513) 255-6281
AUTOVON: 785-6281.

DESIGN NOTE 1A3 ELECTROMAGNETIC COMPATIBILITY HANDBOOK

1. PURPOSE

The Electromagnetic Compatibility (EMC) design handbook is devoted to promoting overall system compatibility with emphasis on reducing the problems generated by the interference of overlapping electromagnetic fields. Each part of the system must be studied for possible deleterious effects. This study program determines test equipment used to evaluate the functional performance of the system prior to combat or mission readiness; equipment that supplies power or signals to the system during test, checkout, alignment, or launch preparation; the characteristics of the site on which the system is deployed; and any industrial, commercial, military, or natural phenomena which may affect the system by conduction, induction, or radiation of electrical energy.

2. SCOPE

Electromagnetic compatibility includes the procedures utilized by the operational unit; the amount and nature of energy in the aerospace region through which the vehicle travels; the physical characteristics of the operational environment; the amount of rain, snow, moisture, heat, impurities, salt spray, and other environmental factors to which the system is subjected; and the telephone, communication, and power lines of the operations area which may be a source of propagation of interference and interaction. Electromagnetic compatibility means that all electrical components of the system must function as intended. No degradation caused by the surrounding environment or by the conditions and procedures involved in operational use will be permitted to continue unchecked. The definitions and system units used in EMC are contained in *MIL-STD-463*.

3. RESPONSIBLE ENGINEERING OFFICE(S) (REO)

The REO is the activity assigned the final engineering or technical surveillance function for a specific discipline. *Sub-Note 3(1)* contains the mailing addresses and telephone numbers for all REOs contained in this handbook.

SUB-NOTE 3(1) Responsible Engineering Office(s) (REO) List (Sheet 1 of 2)

ADDRESS AND TELEPHONE NUMBER	AREA OF RESPONSIBILITY
AERONAUTICAL SYSTEMS DIVISION	
ASD/ENACE Wright-Patterson AFB OH 45433-6503 (513) 255-5986 AUTOVON 785-5986	**Electromagnetic Effects Branch**—Engineering developments in avionics subsystems principally for determination of electromagnetic interference and compatibility.
ASD/ENES Wright-Patterson AFB OH 45433-6503 (513) 255-6295 AUTOVON 785-6295	**Engineering Documents Division**—DoD, Air Force, and local engineering standardization programs in support of ASD and the AFSC laboratories at Wright-Patterson AFB; Air Force Characteristics Guides; the AFSC Design Handbook (DH) series; DoD and Air Force control for type designation of military aircraft, rockets, and guided missiles.
ASD/ENFEF Wright-Patterson AFB OH 45433-6503 (513) 255-3451 AUTOVON 785-3451	**Fuels and Hazards Branch**—Fuel systems, aerial refueling systems, tank inerting, passive defense, hazards detection, and extinguishing systems.

REO: ASD/ENES

SUB-NOTE 3(1) Responsible Engineering Office(s) (REO) List (Sheet 2 of 2)

ADDRESS AND TELEPHONE NUMBER	AREA OF RESPONSIBILITY
AIR FORCE CRYPTOLOGIC SUPPORT CENTER	
AFCSC/SRVT San Antonio TX 78243-5000 (512) 977-2511 AUTOVON 969-3149	**Engineering Division**—Focal point for engineering assistance and testing in the area of TEMPEST and communication security.
WRIGHT RESEARCH AND DEVELOPMENT CENTER	
WRDC/AAAI Wright-Patterson AFB OH 45433-6543 (513) 255-4947 AUTOVON 785-4947	**Information Transmission Branch**—Accomplishes exploratory and advanced development programs which will provide and demonstrate the technology base for secure, jam-resistant, and reliable links for the effective transfer of information to, from, and between aerospace vehicles. Conducts investigations ranging from basic research to advanced development, as assigned, in the areas of coding, signal processing image bandwidth reduction, radio system design and related areas germane to avionic communications.
WRDC/MLSA Wright-Patterson AFB OH 45433-6533 (513) 255-5117 AUTOVON 785-5117	**Materials Integrity Branch**—Develops programs to solve problems relating to detection, control and prevention of corrosion or deterioration.
WRDC/MTEM Wright-Patterson AFB OH 45433-6533 (513) 255-2461 AUTOVON 785-2461	**Electronics Branch**—Formulates programs for the production of new electronic materials and full scale components as a result of technical analyses of current research and projected requirements in the areas of electronic circuit design, thermionics, heat transfer, chemistry, solid-state physics, crystallography, thermodynamics, and light and electron optics.
ROME AIR DEVELOPMENT CENTER	
RADC/RBCT Griffiss AFB NY 13441-5000 (315) 330-2519 AUTOVON 587-2519	**Compatibility and Measurements Branch**—Development of techniques, components, and equipment to predict, measure, control, and minimize electromagnetic interference.

DESIGN NOTE 1A4 STANDARDIZATION

1. INTRODUCTION

Although the Design Handbooks are not an integral part of the Defense Standardization Program, they are frequently applied as an additional medium for achieving standardization objectives.

2. INTERNATIONAL MILITARY STANDARDIZATION

The United States participates in International Military Standardization programs which involve allied nations. The Air Standardization Coordinating Committee (ASCC) consists of the United States, Great Britain, Canada, New Zealand, and Australia. Prior to the inclusion of Australia and New Zealand, the ASCC was referred to as the "ABC Standardization Committee." The North Atlantic Treaty Organization (NATO) Standardization Program results in NATO Standardization Agreements (STANAG). The Military Agency for Standardization (MAS) fosters NATO military standardization within the policy established by the Standing Group. The MAS is composed of a chairman and three Service Boards (Army, Navy, and Air Force). Each board consists of service members from Canada, France, the United Kingdom, and the United States. Accredited representatives are provided to each of the Service Boards from the remaining NATO countries. The nations which have entered into these standardization programs have agreed to conform with the adopted standards, and many of these standards are implemented through Design Handbook requirements. International military standardization is effected through the actions of combined commanders and staffs, various agencies and activities, and formally established programs. The broad objectives are:

a. To ensure that in future war or emergency action there will be a minimum of logistical, technical, procedural, and operational obstacles to combined operations.

b. To realize the economy in combined effort and in the use of combined resources.

3. DEPARTMENT OF DEFENSE STANDARDIZATION

In this era of rapidly changing technology associated with the development of complex systems, standardization should be applied from conception through acquisition. Wherever practicable, standard parts, components, and subsystems should be used in a system, and the number of unique component items and design prerogatives in system development and production should be reduced. It is important that Government and industry coordinate their efforts toward this achievement. These efforts include: (1) standardization of materials, components, equipment, and processes, and (2) standardization of engineering practices and procedures essential to the design, procurement, inspection, application, preservation, and preparation for delivery of items of military supply. There is a Congressional mandate to standardize the Federal Supply System, applicable to all areas where specific benefits can be seen. The objectives of the Defense Standardization Program are:

a. To improve the efficiency and effectiveness of logistical support and operational readiness of the Army, Navy, and Air Force.

b. To conserve money, manpower, time, production facilities, and natural resources by: (1) adopting the minimum number of sizes, kinds, and types of items and services essential to military operations, (2) gaining the greatest practical degree of component interchangeability, (3) developing standard terminology, codes, and drawing practices, (4) preparing engineering and purchase documents which provide for the design, purchase, and delivery of items consistent with the objectives of the Department of Defense Standardization Program, and (5) supplying the military departments with the most reliable equipment possible by adoption of materiel which has been evaluated according to established Government specifications and standards.

4. CONTRACTOR STANDARDIZATION

Wherever possible and practicable, standardization of contractor-furnished parts, components, assemblies, and subsystems within a system is required. Maximum application of the principle of using the minimum number of different items will greatly affect maintainability, reliability, supply, and cost. Where identical or similar functions are performed in more than one application within a system, contractors must strive to use only one design for all applications. Requirements to use standard items of proven design and known availability are called out in various parts of the Design Handbooks. The prime contractor for a system should use the handbooks in monitoring the efforts of subcontractors to achieve the same standardization objectives.

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SECT 1B ELECTROMAGNETIC SPECTRUM

SECTION 1B ELECTROMAGNETIC SPECTRUM

DESIGN NOTE 1B1 ELECTROMAGNETIC SPECTRUM

1. RELATIONSHIP BETWEEN FREQUENCY AND WAVELENGTH

Electromagnetic radiation can be considered a wave phenomenon, having a frequency of oscillation and a wavelength. As with any oscillation, the relation between frequency (F) and wavelength (λ) can be expressed by the formula

$$F = \frac{V}{\lambda} \text{ or } \lambda = \frac{V}{F} \qquad \text{(Eq 1)}$$

where V is the velocity of the wave. For electromagnetic radiation, this velocity is C, the velocity of light.

2. ELECTROMAGNETIC SPECTRUM

Historically, radio waves, X rays and gamma rays were discovered at different times and were first treated as independent phenomena, but it was eventually realized that they differed from visible light only in wavelength and could be arranged in sequence along an expanded version of the familiar color spectrum. The chart in *SN 2(1)* juxtaposes several wave phenomena for comparison. The top scale gives wavelength and the bottom scale gives the corresponding frequency for electromagnetic radiation (EMR). At the left end, the chart approaches infinite wavelength, which is direct current, and at the right end it approaches zero wavelength. Other wave phenomena shown are sound waves through air, sound waves through water (SONAR), water surface waves, seismic waves, and atomic and subatomic vibration. The frequencies shown vary from 5×10^{-4} Hz to 6×10^{22} Hz; the wavelengths vary from the diameter of an electron to the diameter of the largest star, which is about four times the distance from Earth to the Sun. Off the frequency scale to the left would be lunar and solar ocean tides and radio waves generated by rotating stars (10^{-5} Hz). Off the chart to the right would be the most energetic known cosmic rays (10^{37} Hz).

2.1 SONIC SPECTRUM

The sonic spectrum is divided according to the normal frequency range of the human ear, 20 to 20 000 Hz. The upper frequency limits for ultrasonic waves approach the relaxation frequencies of metals, around 10^{12} Hz, beyond which materials can no longer respond to the input of mechanical wave energy.

2.2 RADIO WAVES

The term radio waves is used for electromagnetic radiation longer than infrared waves and includes radio, television, and radar waves.

2.3 INFRARED

In the infrared region the energy is generated by oscillations within the molecular and atomic structures.

2.4 LIGHT

In the visible region, the transition of energized or "excited" electrons to lower energy levels results in the emission of photons whose frequencies excite the naked eye as visible light. This one octave visible band is a "window" into space.

2.5 ULTRAVIOLET

The increased energy of the electromagnetic (EM) waves in this region excites the valence (bonding) electrons in the molecules causing chemical reactions to take place. Ultraviolet rays actually drive electrons out of the molecules resulting in their ionization. All EM waves above approximately 10 electron volts are very energetic ionizing waves and can be harmful to life. Mutations can result from irradiation. The atmosphere gives protection from the ionizing rays of the sun by absorbing them.

2.6 X RAYS

X rays are produced when highly accelerated electrons bombard the atoms of a metal such as tungsten. The impact of the charged particles causes the electrons in the inner orbit of the atoms to be ejected. X rays are produced when electrons from the outer orbits of the atom fall into the vacated inner orbits. The higher the anode voltage, the harder the X rays become and the greater their penetrating power. X rays have the same fundamental nature as gamma rays, differing only in the means of production.

2.7 GAMMA RAYS

Gamma rays are produced during the disintegration occurring in radioactive materials. They are also produced when an extremely high-energy particle, measured in millions of electron volts, penetrates the nucleus of an atom. Secondary cosmic rays are considered high-energy gamma rays and are produced when very high-energy particles (usually positive charged

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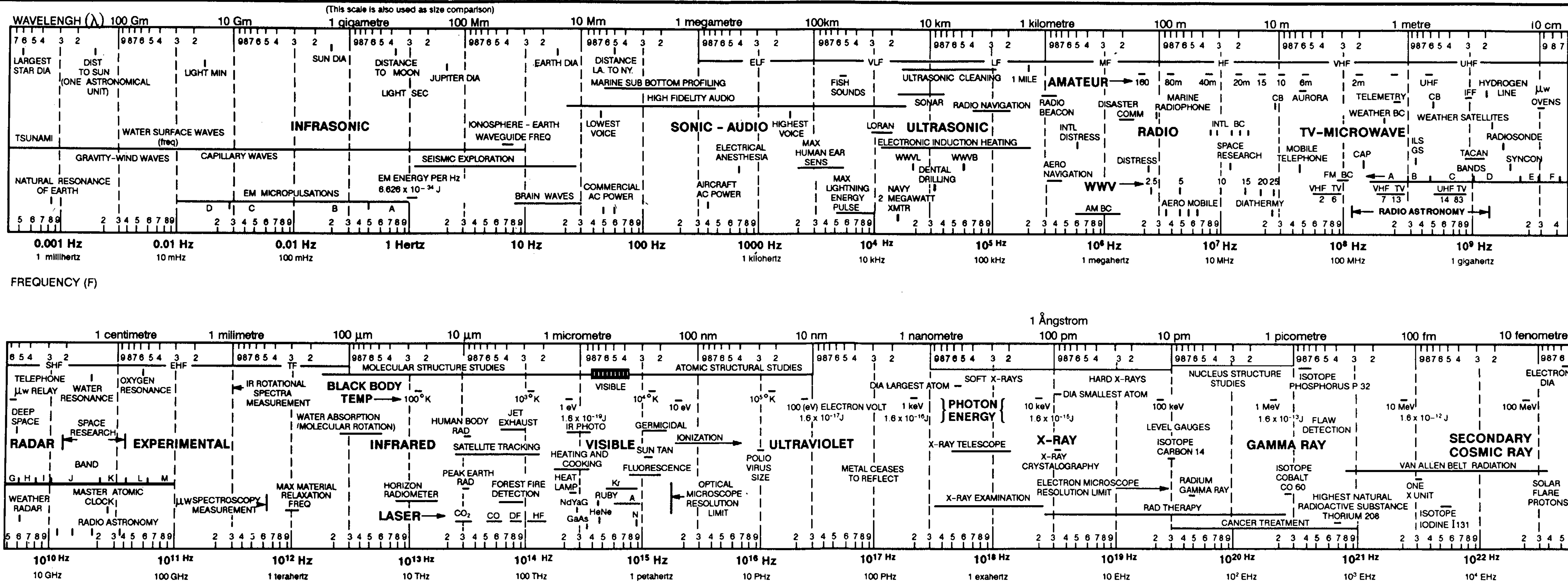
atomic nuclei) arrive from outer cosmic space and bombard the atoms and molecules in our atmosphere.

2.8 COSMIC RAYS

Primary cosmic rays are electrically charged particles, largely protons, that travel in space at speeds nearly equal to that of light. They are generated in solar flares, novas and supernovas, certain red giant stars, galactic magnetic fields, the galactic halo, and some other places. When one of these particles collides with atoms in the air, it produces a "shower" of secondary radiation which may include any of the known elementary particles. A very high-energy primary cosmic ray has been recorded as producing 10 billion photons, electrons, and positrons in a single shower. Cosmic rays from solar flares can cause storms in the earth's magnetic field, resulting in disruption of high-frequency radio communications. (See also *DN 3E3, SN 1(1)*.)

SUB-NOTE 2(1) Frequency Spectrum Chart



LEGEND:

The frequencies shown on this chart vary from 5×10^{-4} to 6×10^{22} cycles per second (now called Hertz Hz) and the wavelengths vary in length from the diameter of an electron to the diameter of our largest star, this dimension being equal to four times the distance to our sun. To show this tremendous range, advantage is taken of the compressibility offered by the logarithmic scale. Not shown is Light Years = 9.5×10^{15}m.

The wavelength or frequency of electromagnetic radiation is determined by the amount of energy carried by that radiation. As the energy content increases the frequency increases, while the corresponding wavelengh decreases. Gamma rays are examples of high energy-radiation while radio waves may be considered to have low energy radiation.

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DESIGN NOTE 1B2 MAN'S USE OF THE SPECTRUM

1. HISTORICAL

Early use of radio began in the radio frequency part of the spectrum and provided maritime communications and navigational aids. In the early 1920's amateurs pioneered the use of middle and high frequency bands for long-distance communication. Single sideband dates from 1927. The 1930's saw the extension of spectrum use to include VHF, UHF, and SHF, a result of continuing improvements in oscillators. Radar was invented in the early 1940's, transistors and experiments in the EHF band began in the 1950's, and the first laser dates from 1960. The National Bureau of Standards operates radio stations (WWV, WWVB, WWVL) giving precise frequency and time signals. Electromagnetic (EM) waves begin to penetrate the ionosphere at about 30 MHz. Commercial broadcasting in this area is limited to line-of-sight broadcasts such as television. However, this penetration makes possible space communications and radio astronomy. Much of radio astronomy centers around the hydrogen line at 1420 MHz, which is the radio frequency emitted by atomic hydrogen in interstellar space.

2. FREQUENCY ALLOCATION

2.1 WORLD AND UNITED STATES

Increasing use of radio for all forms of communication has made it necessary to assign frequencies to various users. Worldwide, frequency allocation is handled by the International Telecommunications Union (ITU). The ITU meets irregularly. The chief issues before the 1979 meeting are the demands of the developing countries for a greater share of frequencies, their practice of broadcasting on frequencies presently assigned to other countries, and the use of communications satellites. *Sub-Note 2.1(1)* is a frequency spectrum chart showing the commonly used telecommunication frequency range (3 MHz to 300 GHz) as a function of frequency. The chart shows man's use and the natural phenomena of EM energy as a function of frequency. An attempt has been made to place activities in their proper frequency relationships. The assigned frequencies shown are current allocations used in the United States. Broadband interference indicates the frequency ranges at which there is generation of spurious or unwanted EM energy resulting from man's use of electric and electronic products. Radiated and conducted signals are also included in the broadband range. The listing of an item in the "biological effects" column indicates the frequency at which experiments have been performed but does not imply evidence that the effect is unique to that frequency, nor does it indicate the intensity and duration of exposure necessary to induce the effect. See also *DN 3E4, Para 5.4*.

2.2 US TELECOMMUNICATIONS POLICY

Knowledge of Department of Commerce, National Telecommunication and Information Administration (NTIA), (formerly Office of Telecommunication Policy, OTP) is important to all EMC engineers as NTIA standards and criteria become national policy, and they automatically take precedence over documents published by individual Government agencies (i.e., DoD, FCC, etc). The following documents are not intended to be used for procurement; however, they are essential for those engineers who write specifications for equipment that use the frequency spectrum:

a. "*Manual of Regulations and Procedures for Federal Radio Frequency Management*." NTIA, Department of Commerce. Available from Superintendent of Documents, U.S. Government Printing Office, Wash DC 20402.

b. "*Frequency Spectrum Policy Concerning the Development and/or Procurement of Communication-Electronic Systems*." Available from NTIA, Department of Commerce, Wash DC 20230.

c. "*Planning Guide for the Review of Telecommunication Systems for Frequency Availability and Electromagnetic Compatibility*." NTIA Report 84-141, Department of Commerce, Wash DC 20230.

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2.3 FEDERAL COMMUNICATIONS COMMISSION

The present Federal Communications Commission (FCC) standard band designations are listed in *SN 2.3(1)*. Symbols and frequency spectrum designations are contained in *MIL-STD-463*.

2.4 USAF FREQUENCY MANAGEMENT

2.4.1 AIR FORCE REGULATION 700-14. *Air Force Regulation 700-14, Radio Frequency Spectrum Management*, contains literature, graphs, and charts in the field of frequency management as it is related to electromagnetic compatibility.

2.4.2 VOICE COMMUNICATIONS. Communication subsystems now used by Air Force aircraft, commercial aircraft, and spacecraft are of the following types:

a. HF radio (3 to 30 MHz) normally is used for voice communications over medium distances but can be extended by skywave propagation.

b. VHF radio (30 to 300 MHz) is used exclusively in commercial aircraft and in some USAF aircraft. It is used for line-of-sight distances.

c. UHF radio (300 MHz to 3 GHz) has been standardized as the equipment used in all USAF aircraft and is for line-of-sight transmission.

3. INTERFERENCE

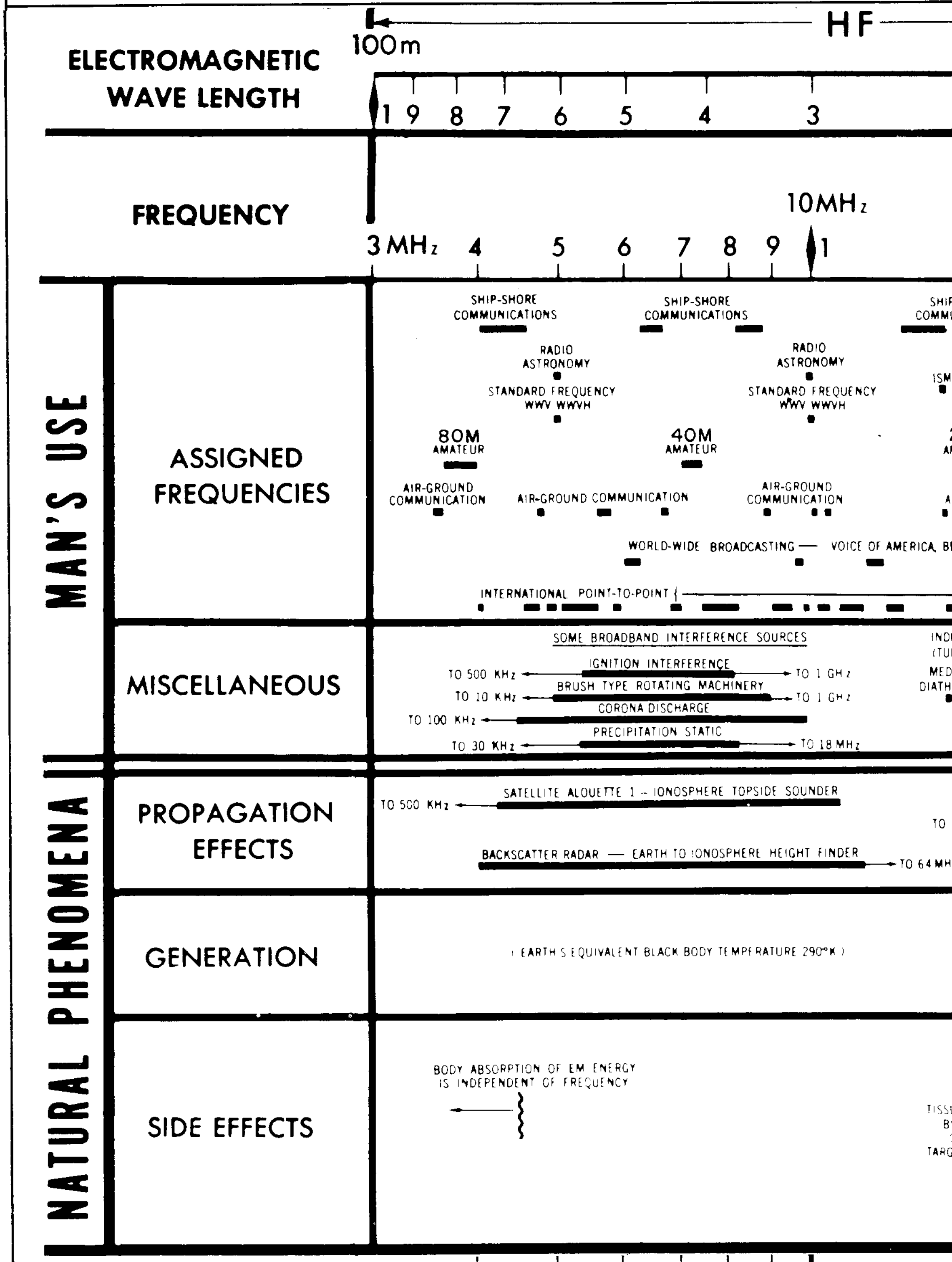
Interference is any electromagnetic (1) disturbance, (2) phenomenon, (3) signal, or (4) emission, man-made or natural, which causes or can cause undesired response, malfunctioning, or degradation of performance of electrical and electronic equipment. Interference is caused by the radiation or conduction of undesired transient or steady disturbances and steady-state susceptibility to such disturbances. From a military point of view, interference can cause premature and undesired location, detection, or discovery by enemy forces. The ways in which electromagnetic interference (EMI) can be generated and the ways it can affect equipment performance are discussed in *Chap 3* and *Chap 7*. Techniques for counteracting interference are discussed in *Chaps 3* through *7*.

SUB-NOTE 2.3(1) Frequency Spectrum Designations

BAND NUMBER*	FREQUENCY RANGE (LOWER LIMIT EXCLUSIVE UPPER LIMIT INCLUSIVE)	CORRESPONDING METRIC SUBDIVISION	ADJECTIVAL BAND DESIGNATIONS
4	3 to 30 kHz	Myriametric waves	VLF (very low frequency)
5	30 to 300 kHz	Kilometric waves	LF (low frequency)
6	300 kHz to 3 MHz	Hectometric waves	MF (medium frequency)
7	3 to 30 MHz	Dekametric waves	HF (high frequency)
8	30 to 300 MHz	Metric waves	VHF (very high frequency)
9	300 MHz to 3 GHz	Decimetric waves	UHF (ultrahigh frequency)
10	3 to 30 GHz	Centimetric waves	SHF (superhigh frequency)
11	30 to 300 GHz	Millimetric waves	EHF (extremely high frequency)
12	300 GHz to 3 THz	Decimillimetric waves	TF (transition frequency)

*Band number "n" extends from 0.3×10^n to 3×10^n Hz.

SUB-NOTE 2.1(1) Man's Use of the Electromagnetic Spectrum*



*Contributed by Luther Moneil, North American Rockwell Corp. Copywrighted by IEEE. *Ref 11.*©

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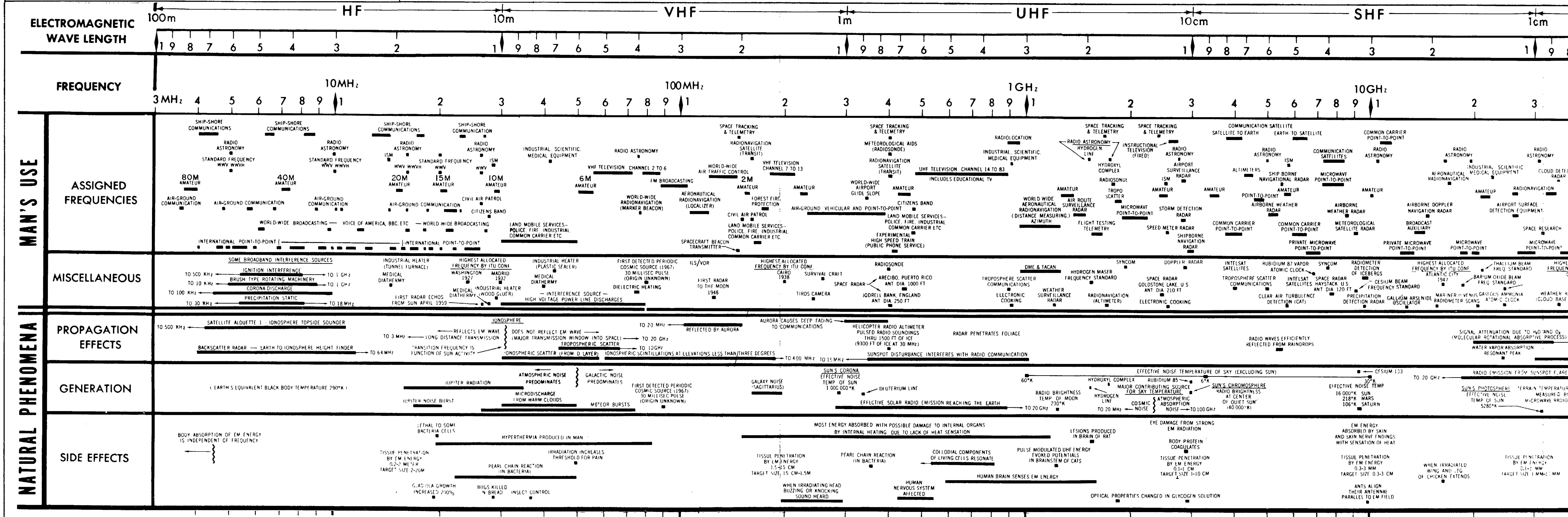
SUB-NOTE 2.1(1) Man's Use of the Electromagnetic Spectrum*



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DESIGN NOTE 1B3 HARMONICS

1. GENERAL

Oscillating bodies, including circuits, may oscillate at more than one frequency at a time. These frequencies are called harmonics. The lowest is called the first harmonic, or fundamental. The frequencies of harmonics are always an integral multiple of the fundamental.

1.1 CALCULATIONS

To calculate the harmonic frequencies (f_h) of a given fundamental frequency (f_0), use the formula

$$f_0 n = f_h, \qquad \text{(Eq 1)}$$

where n = the number of the harmonic.

To find the frequencies that a harmonic may emanate from, use

$$\frac{f_h}{n} = f_0. \qquad \text{(Eq 2)}$$

2. HARMONIC INTERFERENCE

The harmonics of a lower-frequency EM signal can cause distortion of a higher-frequency signal if the higher frequency is an integral multiple of the lower. The interfering harmonics are known as spurious emission and the two frequencies are said to have a harmonic relationship. *Sub-Note 2(1)* charts a segment of the harmonic relationships of the 200- to 400-MHz band. The three lower scales show frequencies whose 2nd, 3rd, or 4th harmonics may interfere with the 200- to 400-MHz band. The three upper scales show bands that may be distorted by harmonics from the 200- to 400-MHz band. The harmonic relationships of a given frequency may be found by placing a straight-edge at right angles to the scales through the point representing that frequency and reading from the other scales. See *DN 3B2, Para 4.3* and *4.4*, for more information on harmonic interference.

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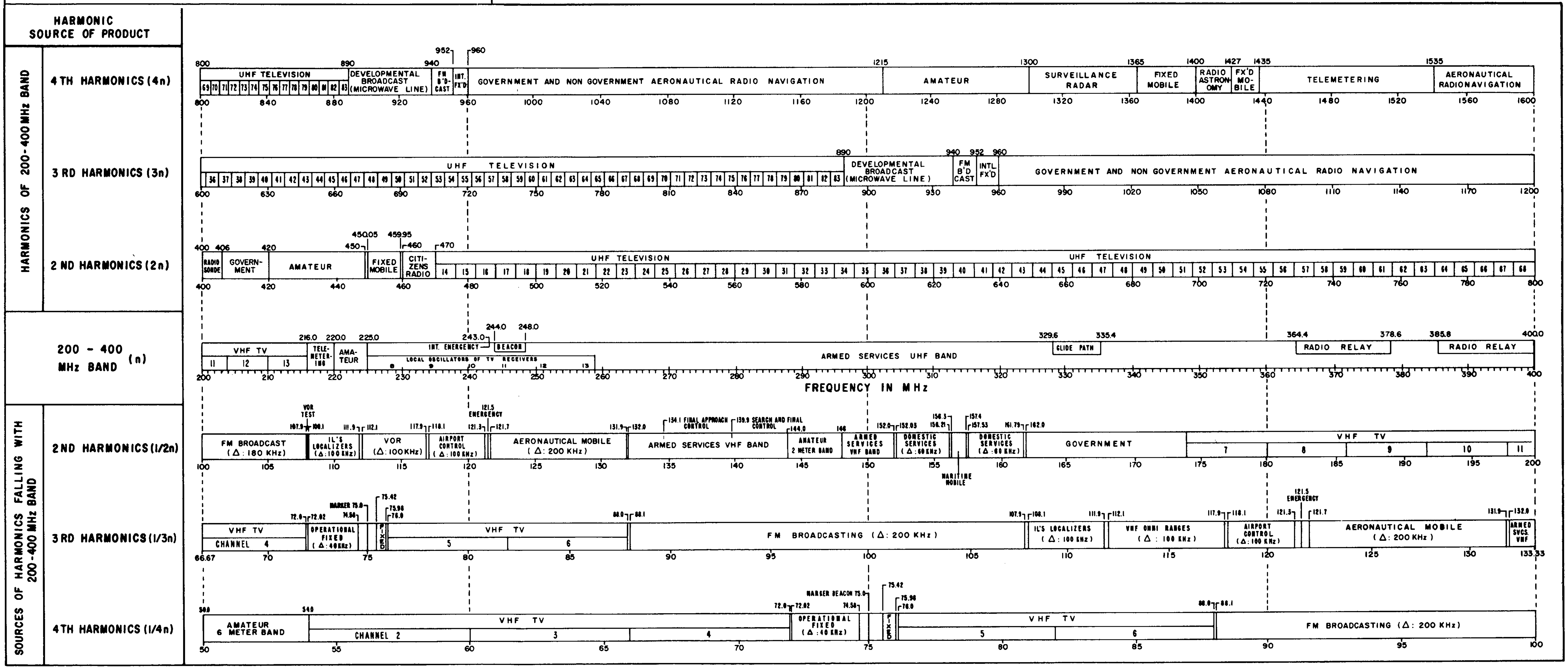
SUB-NOTE 2(1) Harmonic Relationships



CHAP 2 PLANNING THE EMC DESIGN PROCESS

CHAPTER 2 PLANNING THE EMC DESIGN PROCESS

SECT 2A SYSTEM EMC PROGRAM

SECTION 2A SYSTEM EMC PROGRAM

DESIGN NOTE 2A1 INCORPORATING EMC DURING SYSTEM LIFE CYCLE

1. INTRODUCTION

Management and engineering personnel must establish and implement a procedure for integrating EMC into the various phases of the life cycle of systems and equipment. This approach is required to assure early consideration of EMC as well as to provide the necessary continuity for achieving and maintaining the required EMC. The approach, in the case of a complex system, usually includes modeling, analyzing, simulating and testing to determine emission and susceptibility characteristics and operational constraints. Final requirements are postulated by tailoring of general standards to the peculiar characteristics and operational requirements of the item in its individual specification. See *MIL-HDBK-237* for additional information.

2. ELECTROMAGNETIC ENVIRONMENT

The electromagnetic (EM) environment in which military systems and equipments must operate is created by a multitude of sources. Primary contributors are intentional and unintentional, friendly and hostile emitters, electromagnetic pulses, atmospheric, solar and galactic emissions, lightning, etc. See *MIL-HDBK-235*. The contribution of each emitter may be described in terms of its technical characteristics, such as power, modulation, frequency, bandwidth, etc. Effects depend on the receiver's characteristics, relative locations of emitters and receptors, operational concepts, etc. However, it can be concluded that the EM environment can adversely affect all electronic, electrooptical, electrical and electromechanical equipment and systems, personnel, fuels, and weapons. Various terms have been used to describe the programs established to reduce or prevent adverse effects from electromagnetic energy. These terms include: EMC, EMI, EMV, EMP, ECCM, EM-power, P-static, HERO, EME, E^3, HERF, LIGHTNING, HERP, and RADHAZ. To avoid confusion, the term EMC will be used in this Design Note to describe the condition which prevails when equipment and systems operate in their intended operational electromagnetic environment without causing or suffering unacceptable degradation or other adverse effects due to electromagnetic energy to or from other equipment or systems in that environment. EMC is concerned with any source of electromagnetic energy and any type of potential victim. EM interactions between elements of a system is termed intrasystem EMC whereas EM interactions between systems is intersystem EMC.

REO ASD/ENACE

3. SYSTEM LIFE CYCLE AND EMC

The principal phases in the life cycle of a major system are generally delineated as:

- Concept Development
- Concept Validation
- Full Scale Engineering Development
- Production
- Deployment

A flow diagram depicting the approach which should be taken to integrate an EMC program into the overall acquisition process for major defense systems is shown in *SN 3(1)*. The relationship between these activities and specific actions required by the manager is presented in other sections of this handbook. The EMC documents which may be used to assist in carrying out these actions are listed in *App B*.

3.1 CONCEPT DEVELOPMENT

During this phase, technical and financial baselines for a development and acquisition program are established. Included are definitions of required operational capability, doctrines, and specific material requirements. Critical technical and operational issues will be identified for study and resolution in subsequent phases, whereas performance characteristics are established only in general terms. Outputs of this phase are alternate concepts, estimated operational schedules, and estimated procurement costs. During this phase, proper consideration of EMC will have a significant impact throughout the life cycle. For example, preliminary selection of operating frequency band modulation and other technical parameters must be consistent with established international and national frequency management policies. Also, an assessment of the ability of a system to perform its function during its life cycle must include a threat analysis using both the friendly and hostile EM environment which may be encountered. These factors must be addressed not only in performing trade-off studies and risk assessments, but also in estimating total program costs. The culmination of these activities will be the first major design review DSARC I, the program initiation decision.

3.1.1 EMC TASKS DURING CONCEPT DEVELOPMENT. A list of EMC tasks which should be addressed during this phase of the program is provided in a. through h. On large programs, it is recommended that the program manager either consult with the EMC authority within his activity or designate an EMC Task Manager to support him on EMC matters throughout the program.

a. Prepare EMC Plan.

b. Budget for EMC effort during program.

c. Establish an EMCAB (see *Para 4.2*).

d. Determine spectrum requirements and submit request for frequency allocation (see *Para 4.1*).

e. Define EM environment which may be encountered during life cycle (see *Para 4.3* and *DN 2A2*).

f. Perform an analysis to determine if proposed system can operate in the anticipated EM environment (see *Para 4.5* and *Chap 4*).

g. Establish initial EMC requirements for system (see *Para 4.5* and *DN 2A2*).

h. Update EMCP and refine schedules and cost estimates.

3.2 CONCEPT VALIDATION

The primary objective of this phase is the selection of the single concept which will be carried out through full scale development. To accomplish this, the estimates made in the concept development phase must be refined. Areas of risk must be reassessed to assure that they have been adequately defined and can be resolved or minimized. Frequently, this phase includes the construction of prototypes to evaluate operational, technical and environmental factors as well as to refine costs. The studies, analyses and testing are culminated in the second design review DSARC II where a decision is made as to whether to proceed to full scale development.

3.2.1 EMC TASKS DURING CONCEPT VALIDATION. A list of EMC tasks which should be addressed where applicable during this phase of the program is provided in a. through j.

a. Continuation of EMCAB (see *Para 4.2*).

b. Review/update anticipated EM environment (see *Para 4.3* and *DN 2A2*).

c. Refine analyses to determine if proposed system will satisfactorily operate in the latest estimated EM environment.

d. Define acceptable performance criteria.

e. Evaluate EMC standards and criteria, EM environment and acceptable performance criteria to determine if system will meet general EMC criteria (see *Para 4.5*).

f. Develop tailored EMC requirements for acquisition and corresponding statement of work (SOW) for preparation and submission of contract data items (see *Paras 4.4, 4.4.1, 4.4.2* and *DN 2A2*).

g. Submit request for developmental frequency allocation (see *Para 4.1*).

h. Specify operability analyses and testing requirements for inclusion in TEMP (see *Para 4.4.1*).

i. Refine cost estimate for EMC effort, including testing.

j. Update EMCP.

3.3 FULL SCALE DEVELOPMENT

The primary objective of this phase is the design and fabrication of a system in accordance with requirements tailored to the specific procurement, mission, environmental factors, etc. The system must be fully evaluated and tested to verify that the design not only meets its specifications, but that the system satisfactorily performs its stated missions in the operating environment. This phase must also provide the documentation, including testing and analysis reports, to enable a decision to be made as to whether to proceed to production. Approval for service must be obtained prior to proceeding to production.

3.3.1 EMC TASKS DURING FULL SCALE DEVELOPMENT. A list of EMC tasks which should be addressed during this phase of the program is provided in a. through j.

a. Continue EMCAB (see *Para 4.2*).

b. Finalize EMC requirements and SOW for acquisition of preproduction model. This includes requiring the preparation and delivery of contract data items, such as EMC control plans, test plans and test reports (see *Para 4.4, 4.4.1, 4.4.2,* and *DN 2A2*).

c. Review and comment on contractor's data items.

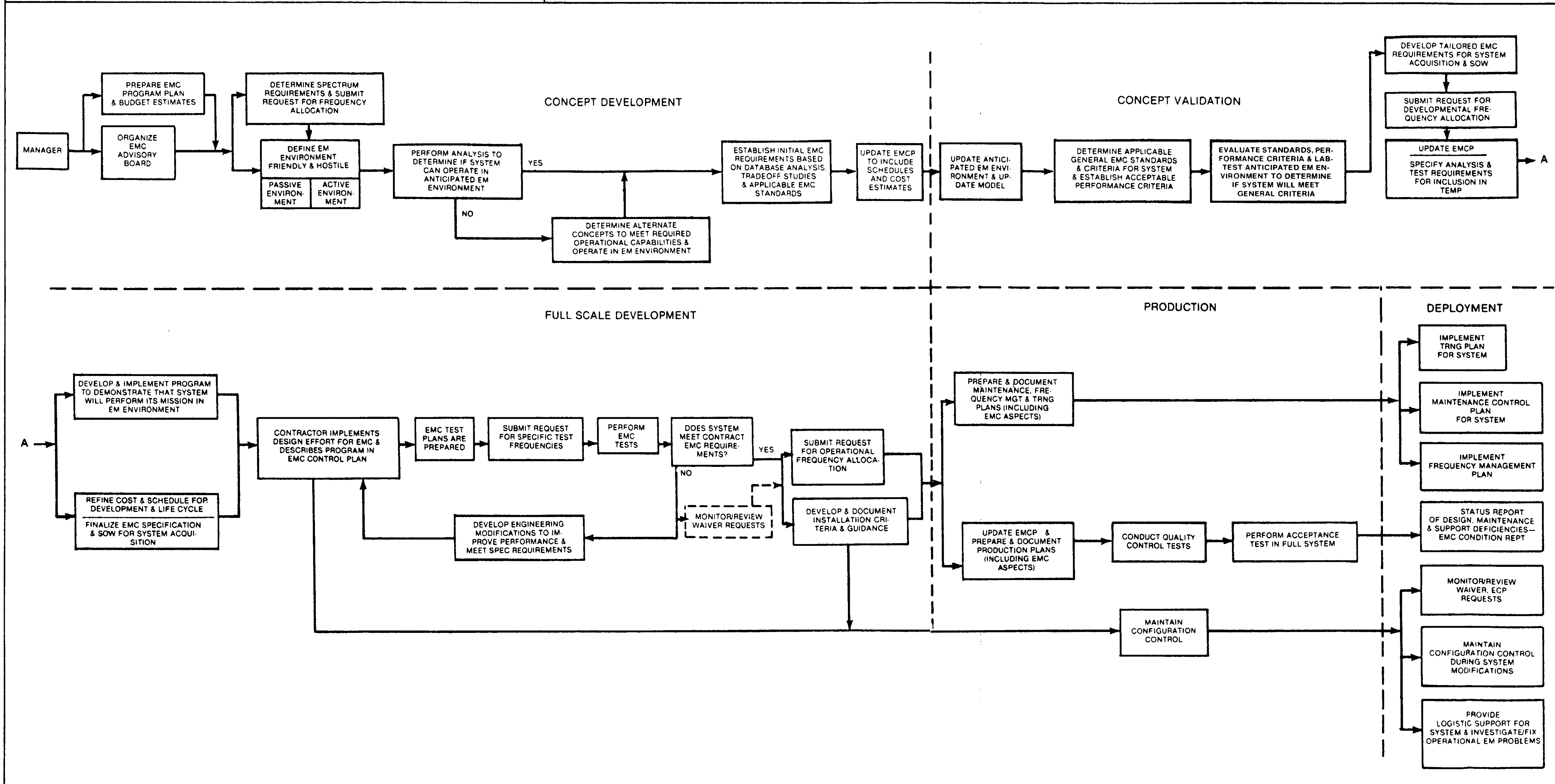
d. Monitor and review ECPs and requests for waivers to contract EMC requirements.

e. Develop and implement comprehensive program to demonstrate by simulation, analysis and test that the system will perform its mission in the operational EM environment. The testing program will be described in the TEMP or TEP.

f. Submit request for assignment of specific frequencies for testing (see *Para 4.1*).

g. Document EMC aspects of maintenance, production and training plans.

SUB-NOTE 3(1) Sample of EMC Activities During System Life Cycle



h. Develop EMC specification requirements for inclusion in production contract (see *Para 4.3* and *DN 2A2*).

i. Develop installation criteria and guidance to preclude EM problems.

j. Submit request for operational frequency allocation (see *Para 4.1*).

3.4 PRODUCTION

This phase encompasses the program from approval for production to delivery and acceptance of the last item being procured. Acceptance tests will be performed to demonstrate conformance to the requirements in the production specification as well as to assure satisfactory performance when the item is in operational use. Strict quality control methods are required to ensure that proposed changes to the configuration do not degrade the performance of the item. When acquisition is complete, responsibility to support the system is turned over to the logistics manager.

3.4.1 EMC TASKS DURING PRODUCTION. A list of EMC tasks which should be addressed during this phase of the program is provided in a. through g.

a. Review contractor's EMC test plan and report for acceptance tests.

b. Perform special EMC acceptance tests.

c. Finalize EMC aspects of maintenance and training plans.

d. Develop and document frequency management/usage plan (see *Para 4.1*).

e. Update EMCP and turn it over to the logistics manager.

f. Ensure ECPs are reviewed for EMC impact.

g. Include EMC condition report in status report of design, maintenance and support deficiencies.

3.5 DEPLOYMENT

This phase begins with the acceptance of the first operational system and extends until all are phased out of the inventory. There is usually an overlap with the production phase. In-service performance must be monitored by a reliable, established feedback system to detect, report and correct operational problems. Any modifications, ECPs and overhaul plans must be reviewed in accordance with the program configuration control system.

3.5.1 EMC TASKS DURING DEPLOYMENT. EMC tasks which should be addressed during this period are:

a. Implement maintenance, training and frequency management/usage plans.

b. Maintain configuration control during systems modifications. ECPs must be reviewed for EMC impact.

c. Investigate and fix reported EM problems.

4. PROGRAM MILESTONES AND TASKS

The following tasks are essential for preventing EM problems:

- Frequency Management
- EMC Plan (EMCP)
- EMC Advisory Board (EMCAB)
- Tailoring General EMC Standards
- Data Items
- Analyses and Simulation
- Approval for Service Use
- Training
- Configuration Management and Control

The depths to which all the efforts are pursued will depend on the program costs, schedules, and goals. The proper application of the management controls, electromagnetic compatibility controls, and practices are the responsibility of the Program Manager.

4.1 FREQUENCY MANAGEMENT

The first action required of the Program Manager is to initiate a request, where applicable, for experimental frequency allocation. The Program or Acquisition Manager is responsible for submitting the completed frequency allocation request (DD Form 1494). Data on DD Forms 1494 are reviewed for conformance to national and international criteria. Failure to comply could result in denial of frequency allocation request. Frequency allocation approval is required before a contract can be let. Approval of frequency allocation requests (DD Form 1494) provide an authorization to utilize defined frequency bands or frequencies for the accommodation of a specific electronic function. However, such allocations do not, per se, provide authorization to operate equipment on specific frequencies, (i.e., frequency assignment) within the tuning range of the equipment.

4.1.1 CONTRACTOR FREQUENCY ASSIGNMENT APPLICATIONS. An allocation does not give authority to operate on a specific frequency. Following allocation, the Military Departments may assign frequencies for use by a contractor having a valid contract, if contractor operations are to be conducted:

a. On a military installation, or

b. At a contractor's plant

under control of the installation commander or a Military Department representative, respectively. Requests for Military Department frequency support should be through appropriate channels. If neither a. nor b. above is the case, the contractor should request frequency support from the Federal Communications Commission (FCC) by filing an FCC form for a station license. Coordination between contractors and cognizant procuring activities is recommended before action is taken.

4.2 EMC ADVISORY BOARD (EMCAB)

An EMC Advisory Board (EMCAB) should be established within the EMC program by the Program Manager (or contractor if required by contract) for the design and procurement of all platforms. The EMCAB constitutes a major resource for control, review, advice, technical consultation, and other assistance to the Program Manager.

4.2.1 OBJECTIVE The objective of the EMCAB is to assist the Program Manager in controlling the system EMC Program, and to provide means of expediting solution of problems. In fulfilling the objective, the EMCAB can:

a. Assist in generating the EMCP.

b. Assist in identifying and resolving EM problems that may arise during the life cycle of the procurement.

c. Act in an advisory capacity in all EM aspects of a program.

d. Serve as a formal adjutant to the procuring activity change control process concerning EMC matters.

e. Review predicted and reported EM problems to determine their applicability as potential problems in the specific procurement.

f. Direct required tasks and analyses, and report findings via appropriate channels for action.

4.2.2 RESPONSIBILITIES. The Board's responsibilities include, but are not limited to:

a. Reviewing, coordinating and monitoring all EMC requirements.

b. Providing EMC design requirements, which shall be available for the contract design phase.

c. Providing an effective method of monitoring EMC efforts and programs.

d. Scheduling periodic EMC program design reviews.

e. Identifying deficiencies and making recommendations.

4.3 TAILORING OF EMC SPECIFICATIONS

The complexity of EM problems requires a full scale EMC Program tailored specifically to mission and mission requirements, including the intended EM operational environment. Compliance with general military EMC standards, by itself, can result, in some cases, in unnecessarily costly design to requirements, and in others, requirements that are inadequate for a particular operational environment. EMC requirements must be tailored to specific needs with program risks and costs considered and trade-offs established. The application and tailoring of EMC standards and requirements is to be based on adequate analysis and should be initiated in the conceptual phase of system acquisition and updated as required during the acquisition process. In tailoring, factors such as the intended operational environment, the program risks, interference characteristics, cost, etc., should be considered and trade-offs established. Tailoring of EMC requirements by Program Managers is reflected in the preparation of solicitation documents. Tailoring takes the form of deletion, alteration, or addition of EMC requirements. In tailoring the requirements, the depth of detail and level of effort required, and the intermediate and output data expected should be defined. Subsequent tailoring of EMC requirements may be recommended by the contractor but is subject to approval by Government during contract negotiations. The agreement reached on the engineering effort will be reflected in the resultant contract. Additional factors to be considered when tailoring are described in *DN 2A2*. Subsequent to contract award, the contractor should be required to perform other analyses and predictions for critical items, including a simulation of their functioning in the intended operational EM environment. Effective use of EMC analysis and modeling techniques can provide the necessary EM data and obviate many specific tests which are usually called out for EMC Programs.

4.4 DATA ITEMS

EMC Plans are required by *MIL-STD-461* for equipment and *MIL-E-6051* for aerospace and associated weapons systems. Content requirements for these control plans are specified in existing Data Item Descriptions (DIDs), DD Form 1664, in these documents. The EMCP will not be prepared, delivered or updated, unless specifically required by Contract Data Requirements List (CDRL), DD Form 1423. When required by the contract, the EMC Plan is prepared by the contractor, submitted for review, and approved by the Program Manager and EMCAB. See *DN 2B1*. The Plan is a document that identifies how all EMC requirements will be implemented. It contains summaries of parts of the EMCP, where applicable, but also emphasizes the specific techniques to be employed in the system of interest. It basically is a detailed, yet comprehensive, account of all those things which will be done in the EMC Program to ensure meeting contractual EMC requirements in the end product. The Plan describes in detail the contractor's effort used for controlling electromagnetic environmental effects, beginning with program initiation, through final design and production, and throughout the operational life of the system being procured.

4.4.1 EMC TEST PLAN. The content of the EMC test plan (procedures) for demonstrating compliance with contract requirements should be in accordance with applicable DIDs and the CDRL. See *DN 2B2.*

- Test plans are required by the various EMC standards, i.e., *MIL-E-6051, MIL-STD-462, MIL-STD-469,* and *MIL-STD-449,* to verify compliance with the contractual EMC requirements. In general, the plans indicate measurement objectives, test configurations, test points, detailed measurement procedures, and the formats for recording data. The specific test techniques should be based on procedures in the EMC standards and specifications referenced in the contract. The test procedures should be described in sufficient detail to enable the procuring activity to duplicate the proposed methods.
- The contractor should be required to submit an EMC test plan conforming to its content requirements to the procuring activity for approval.
- Specific details regarding intersystem and intrasystem EMC testing, and emission and susceptibility testing of equipment and subsystems provided by subcontractors must be considered and included by the overall system contractor in his test plan.

4.4.2 EMI TEST REPORT. The results of all EMC tests must be presented to the procuring activity for evaluation before acceptance of the equipment or system. The EMC standards and corresponding DIDs specify the content requirements for completely certified test reports. When required by the contract, the contractor will forward the test reports to the procuring activity for approval. The formats for recording and reporting test results have been established to aid in the analyses that follow. The EMI test report format should be in accordance with the DID. Omissions of apparently minor facts can render data worthless. See *DN 2B3.*

4.5 EMC ANALYSIS

One of the most vital elements of the EMC program is prediction of electromagnetic problems. It is far less costly to analyze, predict, and prevent problems at the outset than to be overtaken by problems late in the schedule—problems whose solution will probably be extensive, time-consuming and costly. In some cases, EMC analysis will show that the entire system is infeasible. An EMC analysis should include the following:

- Intended operational EM environments
- System design concepts
- Mission requirements
- EM characteristics of interfacing equipment and systems
- Signal flow, power distribution and installation diagrams
- Equipment EM characteristics
- See also *Chap 4.*

The Program Manager will define the initial or baseline EMC requirements that will be included in the request for proposal (RFP) or invitation for bid (IFB) including anticipated uses for the item. It should specify the tailored EMC requirements which the equipment or system will be required to meet. Subsequent to RFP or IFB, the bidder may determine the adequacy of the baseline requirements. If they are not considered feasible, the bidder may propose alternate requirements. The mission objectives, operational electromagnetic environment, minimum acceptable system functional requirements, desired technical performance and system figures of merit for EMC effectiveness as stipulated in the RFP or IFB should be examined for consistency and attainability.

DESIGN NOTE 2A2 TAILORING GENERAL EMC STANDARDS TO EM OPERATIONAL REQUIREMENTS

1. INTRODUCTION

The basic step in any engineering effort is to define what the end product is intended to accomplish in as complete and exact form as possible. The definitive statement is updated as often as more precise statements become possible. The engineer will thus be working with the system developer from general conceptual statements toward increasingly precise technical specifications "tailored" to operational requirements to provide cost-effective EMC design. Closely associated with the statement of operational requirements is a statement of preliminary system design—the technological features that should make the system operate as required. The systems engineer can provide invaluable guidance to the Program Manager early in the conceptual phase of system development by determining the feasibility of meeting various electromagnetic requirements and presenting alternative means to achieve the desired results. Early feasibility and trade-off studies with EMC in mind can save considerable effort later.

2. EM OPERATIONAL ENVIRONMENT

While "operational environment" properly includes the entire EM situation in which a system is to be placed, such a definition would be prohibitively expensive to acquire and would be too voluminous to handle. It is adequate and much more practical to restrict the gathering of the data to all those systems and equipments which there is some reason to believe could interfere with intended operations and performance.

3. SYSTEM EM ENVIRONMENT

The system EM environment is composed of the EM characteristics of the total parts of all the subsystems and equipment within the system. The definition of the environment is dependent upon the detailed subsystem and equipment information supplied to the EM analysis group. An initial gross analysis will indicate where further detailed analysis is required. Refer to *MIL-HDBK-235* for general information on maximum EM environment characteristics.

4. DEFINITION OF EM OPERATIONAL REQUIREMENTS

Early in the conceptual phase of system development, the Program Manager should require the users, engineers and system developers (1) to provide information which can impact on EM considerations, and (2) to include this information in the definition of system development, whenever more precise information is available. The following is a typical checklist which may be used (with modifications when necessary) for gathering the kind of information needed for defining EM operational requirements and environment:

(1) What is the system intended to do?

(2) Is it to be a tactical, mobile system; transportable; fixed plant, point-to-point, or repeater-dependent?

(3) Does it stand alone, or is it part of a larger system?

(4) What are the inputs and outputs, and their range of frequency and power?

(5) What are the frequency constraints and requirements?

(6) What are the basic power requirements?

(7) What are the range and power requirements?

(8) What is the sensitivity requirement for the receiving equipment?

(9) Where will the system be used?

(10) What will the system EM environment be?

(11) Is the system required to operate continuously or intermittently?

(12) Are there any location, size, or weight restrictions?

(13) When is the system to be operative?

(14) Who will maintain and operate the system?

(15) To what extent is the system manned during operation?

(16) What are the classification aspects of the system and its application?

(17) Will classified information be accessible in clear-text form at any point?

(18) Is the system critical to some military operation; and if so, what?

(19) Are there critical sequences of operations involving this system?

(20) To what extent will malfunction affect mission success or personnel safety?

(21) What is the medium of the transmission?

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(22) How is the system matched and/or coupled to the medium?

(23) If antennas are involved, what special characteristics should be considered?

(24) Is the system active or passive (that is, does it transmit, receive, or both)?

(25) Is signal processing equipment required?

(26) With what equipment does the system interface directly?

(27) What modulation system will be used?

(28) What waveforms are involved?

(29) What are the frequency and spectrum requirements?

(30) What sensitivity and resolution are required?

(31) What are the minimum threshold responses, both amplitude and duration?

(32) What are the accuracy requirements?

(33) Is this an analog or digital operation?

(34) Are there any special remote control requirements?

(35) In what type of facility is the equipment to be installed?

(36) What other equipment will be in the same installation?

(37) Are there any inherent, definable problems expected as a result of grounding systems used?

(38) Are there space-available problems to be anticipated?

(39) Are there any special cosite problems anticipated?

(40) What are the inherent shielding characteristics of the installation?

DESIGN NOTE 2A3* EMC PROGRAM CONTROLS

1. EMC PROGRAM CONTROLS

Use the guidelines in *SN 1(1)* through *1(5)* for setting up electromagnetic compatibility program controls.

SUB-NOTE 1(1) EMC Requirements Analysis Controls

- Establish system EMC requirements and EMC resource allocations.
- Establish EMC team in accordance with *MIL–E–6051.*
- Review all system requirements and guidelines.
- Establish operational compatibility, mission and time compatibility, interference definition, and minimum acceptable degradation for the mission.
- Perform spectrum studies to evaluate frequency allocation.
- Develop alternate methods to perform the same function.
- Develop the necessary information studies and guidelines for achieving compatibility and stability.
- Use trade-off studies to optimize EMC and cost.
- Translate meaningful equipment EMC requirements into specific design, manufacturing, and operational criteria.
- Prepare EMC specifications for subcontractors.
- Prepare lists of hardware types with EMC requirements.
- Establish the depth and scope of repair at different repair levels.
- Specify training for the various supply and maintenance personnel with respect to proper handling, storage, and care.
- Determine training needs in the broad sense and in the specialized areas.
- Analyze skills and abilities needed by field engineers, maintenance, and operating personnel.

SUB-NOTE 1(2) EMC Environmental Determination Controls

- Determine and establish the specifications that define the environments to which the items will be subjected.
- Promulgate and maintain environmental criteria for handling, storage, ground operations, and the definitions of environmental test limits.

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*Extracted in part from *Ref 108*

SUB-NOTE 1(3) EMC Prediction Controls
• Develop EMI susceptibility predictions of flight-critical equipment.
• Generate performance specification requirements and tolerances.
• Observe out-of-tolerance effects of EMI generators and flight-critical equipment.
• Provide information that would allow logical test point selection.
• Formulate an EMC demonstration plan.
• Evaluate prototype demonstration tests.
• Use test results and design analyses to demonstrate EMC tests.
• Collect and analyze parts characteristic data to develop and revise specifications.
• Measure attained electromagnetic compatibility.

SUB-NOTE 1(4) EMC Specification and Drawing Review Controls
• Review preliminary specifications and procedures to determine feasibility and adequacy.
• Make certain that operating procedures and hardware are compatible.

SUB-NOTE 1(5) EMC Parts Control
• Develop test methods to simulate environment and establish EMC criteria.
• Define test conducted criteria.
• Design the experiments.
• Write the test plans and procedures.
• Prepare the item for test.
• Conduct and monitor test and test results.
• Negotiate production environmental test plans with the procuring activity.
• Prepare the EMC demonstration plans and the integration of the demonstration provision in specifications.

2. DATA REPORTING CONTROL

Use the lists given in *SN 2(1)* through *2(6)* to set up an EMC reporting system integrated with the reliability reporting system.

SUB-NOTE 2(1) Data System and Process Control Requirements
• Integrate the EMC data into the established data center to receive, compile, and analyze EMC information.
• Integrate pertinent EMC information into the data processing system.
• Prepare significant summaries of EMC data, such as EMC trends, spectrum signatures, and possible troublesome areas.
• Provide for interchange of pertinent EMC information with Government agencies.

SUB-NOTE 2(2) EMI Analysis Control

- Formulate the detailed plan and the writing of the operating procedure for the interference and susceptibility characteristics of parts.
- Conduct EMI analyses to determine criticality, system identification of potential interference, and susceptibility.
- Analyze operating procedures and instructions to ensure that interference and susceptibility modes are not introduced.

SUB-NOTE 2(3) Control Change Requirements

- Review and approve changes in manufacturing processes, specifications, and procedures.
- Provide for rebuilding or reworking of returned components to a higher EMC configuration.
- Provide for spares that satisfy the system requirements and necessary checks.

SUB-NOTE 2(4) Corrective Action Control

- Prepare operating procedures delineating responsibilities for corrective action.
- Prepare follow-up action reports when data indicates a problem is present.
- Assure the compatibility analyses and corrective action through document review.
- Monitor vendor and subcontractor interference and susceptibility analyses and subcontractor compatibility analyses and corrective action for adequacy.
- Assure the vendor and subcontractor of corrective action on EMC problems.

SUB-NOTE 2(5) Controls for EMC Improvement Studies

- Initiate and prepare detailed plans for parts improvement when information indicates the allocated EMC requirements will not be attained.
- Conduct EMC improvement studies to predict the compatibility of potential interference and susceptibility modes.
- Conduct studies and research in design improvement, costs, EMC methods, procedures, and manufacturing techniques.
- Coordinate advanced EMC techniques to all program EMC effort.

SUB-NOTE 2(6) Vendor Control

- Establish and maintain a supplier selection program based on facilities, past experience, and EMC, reliability, and quality efforts.
- Assure that suppliers conform with EMC and other performance requirements.
- Provide the vendor with test, receiving, and other applicable data on the product
- Evaluate the subcontractor's proposed EMC program.
- Prepare and include qualitative and quantitative EMC and test requirements.
- Monitor vendor's preparation and release of procedures and specifications with periodic design reviews.

3. PRACTICES AND STANDARDS

The practices and standards of design, manufacturing, quality assurance, and system test and operation are the cornerstones to program success. Follow those given in *SN 3(1)* through *SN 3(4)*.

4. EMC ENGINEER'S APPROACH

Many of the EMC controls are already built into the reliability program. The reliability function and the electromagnetic function are closely related in this respect. There are other similarities, such as those of starting the program in the concept stages, prediction, optimum design, and environmental and acceptance testing requirements. The big differences are in the approaches used and the highly specialized skills required to resolve their respective problems. The EMC engineer approaches his problems from the standpoint of degradation due to interference rather than that of part failure as does the reliability engineer (although parts failure can also be a factor in EMC control). In addition to the environmental tests required in the reliability program (most of which are also required for the compatibility function), interference and susceptibility tests must be conducted in the EMC program. Through careful consideration of the various functions of these programs, it is evident that some can be integrated, while others must be performed separately for an effective and efficient overall approach.

SUB-NOTE 3(1) Practices and Standards—Design

- Prepare a standard design manual.
- Prepare a standard parts manual.
- Prepare a drafting practice and drawing specifications.
- Use safety margins judiciously.
- Apply spectrum signatures based on critical review of application.
- Use standard parts.
- Devise rules to be followed when nonstandard parts are used.

SUB-NOTE 3(2) Practices and Standards—Manufacturing

- Establish production tooling controls to ensure that tooling is within tolerance and that out-of-tolerance tooling is not used.
- Establish manufacturing processing procedures and inspection checks.
- Furnish special equipment when handling, storing, or installing delicate items.
- Require that critical items be conveyed by protective means.
- Prepare and evaluate process specifications and procedures for manufacturing activities with respect to lessening the degradation of the design EMC.
- Participate in vendor selection surveys.
- Develop training aids, equipment, and standards to be used in manufacture.
- Formulate and implement training programs for manufacturing personnel.
- Clearly mark identification on external packages.
- Furnish the correct packaging to protect equipment during handling, transportation, storage, and field use.

SUB-NOTE 3(3) Practices and Standards—Quality Assurance

- Establish detailed inspection and acceptance testing documentation plus instructions for the care and use of the test equipment.
- Develop a qualification test program for parts.
- Formulate and implement a production test plan.
- Establish acceptance test parameters (including time) for maximum screening effectiveness and minimum life expenditure.
- Participate in establishing and monitoring a vendor control program to ensure fully qualified parts.
- Develop acceptance criteria to assure compliance with specifications.
- Establish methods, processes, and procedures for inspecting equipment.
- Operate an electrical standard laboratory to calibrate and maintain electrical measurement equipment.
- Operate a mechanical laboratory to calibrate and maintain gages and mechanical measurement equipment.
- Establish classification of characteristics for selected items.
- Perform recurring inspection on all incoming material.
- Participate in materials review board.
- Perform inspections at specified check points on various assembly lines.
- Inspect packaging of outgoing items.
- Establish and implement controls to assure that the required physical and performance variations fall within the desired distribution set for the production process.
- Furnish management with the necessary documentation in the areas of receiving, inspection, fabrication, assembly, and functional testing.

SUB-NOTE 3(4) Practices and Standards—System Test and Operation

- Make available field manuals and technical orders which fully describe the proper methods and procedures for setting up, checking, adjusting, aligning, calibrating, and operating equipment prior to test or operational use.
- Establish policies and procedures for repair and maintenance for the various phases in the field.
- Assure availability of procedures to isolate interference to the level required in the field.
- Develop testing procedures to determine degradation from storage or use.
- Establish policies and procedures for disposition of unacceptable or rejected test items.

DESIGN NOTE 2A4 TEMPEST

1. INTRODUCTION

TEMPEST is an unclassified short name referring to investigations and studies of compromising emanations. When designing new equipment, TEMPEST should be considered. Compromising emanations are unintentional, data-related or intelligence-bearing signals which if intercepted and analyzed disclose the classified information transmitted, received, handled, or otherwise processed by an information-processing equipment.

2. TEMPEST DOCUMENTS

The following documents should provide designers and engineers with guidance for controlling TEMPEST:

a. *Air Force Regulation 56-16, CONTROL OF COMPROMISING EMANATIONS (TEMPEST)* (U). This regulation prescribes responsibilities of Air Force organizations and overall guidance to the user on controlling compromising emanations (TEMPEST) of electrically operated equipment and facilities which process national security information. It implements the effective edition of *DOD Directive 5200.19R* and affects development, procurement, installation, and operation. This regulation applies to all Air Force personnel including Air Force Reserves, Air National Guard, and contractors who do business with the Air Force.

b. *NACSIM 5100A, COMPROMISING EMANATIONS LABORATORY TEST REQUIREMENTS, ELECTROMAGNETICS* (U), contains the laboratory TEMPEST test limits used to evaluate equipment that processes national security information.

c. *NACSEM 5201, TEMPEST GUIDELINES FOR EQUIPMENT/SYSTEM DESIGN* (U), provides circuit-level guidelines for designing TEMPEST compliant equipment.

d. *NACSIM 5203, GUIDELINES FOR FACILITY DESIGN AND RED/BLACK INSTALLATION* (U), provides TEMPEST guidance for the installation of classified information processing equipment on a system/facility level.

The documents cited above are Confidential Nonforeign. The Air Force (and all Air Force contractors) will not impose any TEMPEST requirements without first contacting the supporting MAJCOM TEMPEST Officer (IAW *AFR 56-16*).

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SECT 2B EMC DOCUMENTATION

SECTION 2B EMC DOCUMENTATION

DESIGN NOTE 2B1 — EMC PLAN (EMCP)

1. INTRODUCTION

One significant phase of the Electromagnetic Compatibility Program, whether it is a complete aerospace system or subsystem/equipment, is the Electromagnetic Compatibility Plan (EMCP). The Air Force's interference and compatibility program requires the contractor to be responsible for submitting an Electromagnetic Compatibility Plan. This plan is a detailed description of the contractor's overall approach for assuring electromagnetic compatibility. It relates the nature and magnitude of the effort to be implemented, the organization responsibilities for implementation, and the milestones to be used for status indication of the effort. The plan is the basis for all program EMC requirements. Without it, all subsequent EMC documentation, requirements, specifications, etc., are without foundation and cannot be enforced. Details of the EMC plan are contained in *DOD 5000.19L, Vol II, Acquisition Management Systems and Requirement Control List*. It is recommended that *Chapters 2* and *3* of NASA's EMC handbook, (*Ref 108*) be used for guidance in the role of EMC in the system engineering process. *Chapter 2* of the NASA handbook covers the organization of an EMC group, responibilities for design reviews, and qualification of personnel. *Chapter 3* covers consideration of cost effectiveness, controls for the systems engineering process, use of systems documentation, and the relation of the EMC task to the overall program.

2. PURPOSE

The EMC plan is one that will place into effect the methods to allow the contractor to meet the commitments of the bid proposal and the contract. It is the document that will communicate to each engineer, each department head, each subcontractor, and the procuring agency the work effort, the emphasis, and design guides to be utilized to avoid practices that may cause serious interference problems at a time when delays can be ill afforded. It is the document that will establish the engineering and management milestones. This document also assures the Air Force of the eventual achievement of a compatible system.

3. CONTENT

Present the EMC plan in detail, specifying the interference and susceptibility control, prediction and analysis program, proposed engineering design procedures, and the techniques that will be used to achieve conformance with contractual requirements. Such conformance will enable the subsystem/equipment to perform its operational function within its specified parameters without adversely affecting or being affected by collocated subsystems/equipments. Approval of design procedures and techniques does not relieve the contractor of the responsibility of meeting the requirements specified in the procurement documentation. Deliver the EMCP to the procuring activity for approval prior to the start of the acquisition phase. Update the EMCP when necessary at intervals specified in the procurement documentation including all changes, deletions, improvements, and new information on the emission and susceptibility characteristics of the equipment or subsystem. Update the original EMCP documentation when new information is obtained and submit to the procuring activity for approval. Include the following in the control plan.

3.1 TECHNICAL GUIDANCE

Include in the EMCP, the specific organizational responsibilities, lines of authority and control, the implementation plan, and milestones and schedules. Also include the detailed requirements to be imposed on suppliers and subcontractors for vendor items, test requirements to be placed on independent testing laboratories, a complete listing of all EMI/EMC requirements in supplier's procurement documentation, and enumerate additional requirements for support equipment. Include a description of the subsystem/equipment and its characteristics, where known.

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3.2 SPECTRUM CONSERVATION

Define the program to be employed to minimize emission spectrum and receiver bandwidths and to control oscillator frequencies, pulse rise times, harmonics, side bands, and duty cycles within the specified design constraints of the equipment or subsystem. Include a completed copy of "Application for Frequency Allocation Date," (DD Form 1491).

3.3 ELECTROMAGNETIC INTERFERENCE (EMI) MECHANICAL DESIGN

In the control plan, describe the material and construction to be used to provide the inherent attenuation to electromagnetic emissions and susceptibilities while still meeting the contract end item specification requirements. Include specific data on the following. Expand as necessary.

a. Types of metals, castings, finishes, and hardware employed in the design.

b. Types of construction, such as compartmentizing, filter mounting, and isolation of other parts; types and characteristics of filtering used on openings including ventilation parts, access hatches, windows, meter faces, and control shafts; and types of attenuation characteristics of RF gaskets used on all internal and external mating surfaces.

c. Shielding and design practices employed for determining shielding effectiveness.

d. Corrosion control procedures.

3.4 ELECTRICAL/ELECTRONIC WIRING DESIGN

Describe in accordance with the classification procedures in *DN 5B5* the proposed electrical/electronic wiring design, cable separation, and routing to minimize emision and susceptibilities. Fully describe modifications to the applicable categories. Describe in detail the grounding philosophy and enumerate methods of shielding and routing of cables. Supply interconnecting cabling diagrams for equipment or subsystems, consisting of a number of black boxes.

3.5 ELECTRICAL/ELECTRONIC CIRCUIT DESIGN

Describe fully the EMI control and suppression techniques which will be applied to all parts and circuitry, whether capable of generating undesirable emanations or suspected of being susceptible. Include, as a minimum, the following specifically required design data:

a. Choice of parts and circuitry, criteria for use of standard parts and circuitry, and bonding and grounding techniques.

b. Justification of selected filter characteristics, including types and attenuation, and technical reasons for selecting types of filters.

c. Part location and separation based on orientation of electromagnetic fields for reduction of emissions, susceptibility, or both.

d. Discussion indicating valid technical reasons for selection of pulse shape. Use pulse shapes to minimize the electromagnetic spectrum employed consistent with achieving design performance.

e. Location of critical circuits and decoupling techniques employed for each.

f. Shielding and isolation of critical circuits.

3.6 ANALYSIS

Include prediction or analysis techniques employed to determine adequacy of supplier's conclusions. Include specific aspects of the mechanical, electrical, and electronic design as follows:

a. Adequacy of mechanical construction, and an analysis of the shielding afforded by the proposed designs over the specified frequency range and energy level.

b. Complete frequency matrix of all frequencies associated with receivers and transmitters, expected spurious responses of receivers at input signal levels and at frequency range(s) specified in *MIL-STD-461*, and expected spurious output of items such as transmitters, local oscillators, and frequency synthesizers. Some spurious responses will be determined by use of the following equation:

$$f_{sp} = \frac{pf_{lo} \pm f_{if}}{q} \qquad \text{(Eq 1)}$$

Where:

f_{sp} = Received spurious frequency, hertz

p = All integers, including zero, represent harmonics of the local oscillator, hertz

q = All integers, except zero, represent harmonics of the spurious signal, hertz

f_{lo} = Local oscillator frequency, hertz

f_{if} = Intermediate frequency, hertz

Use the frequency matrix to formulate a subsystem test matrix in the subsystem test plan.

c. Worst-case analysis of multivibrators, switching (single and repetitive) and logic circuits, clock signals and strobe signals.

d. Analysis of circuitry, subassemblies, and total equipment or subsystem, including cabling and loads for: (1) the prediction of susceptibility to internally and externally generated fields and voltages, whether below or above the limits specified in the contract, and probability of occurrence, and (2) the prediction of emissions, whether below or above the limits specified in the contract, and probabilities of occurrence.

e. Subsystem EMC analysis for mobile or fixed installations with two or more antennas, including descriptions of fundamental and spurious radiation characteristics from antennas and discussions on how to minimize antenna coupling and obtain isolation by the placement and location of antennas.

f. Recommended tailored requirements and justification, including assumptions, and sufficient information to verify analyses.

3.7 PROBLEM AREAS

Discuss plans for potential EMI problems, including the procedure for defining problems, formulating solutions, implementing and testing the solutions, and documentation procedures.

3.8 UPDATING

Discuss the method of updating the control plan.

DESIGN NOTE 2B2 SUBSYSTEM/EQUIPMENT ELECTROMAGNETIC INTERFERENCE AND SUSCEPTIBILITY (EMI&S) TEST PLAN

1. INTRODUCTION

This Design Note details the means of implementation and application of *MIL-STD-462* test procedures to be used to verify compliance with contractual requirements. Do not begin formal testing without approval of the test plan by the procuring activity. The procuring activity will review test plans or procedures prepared by the prime supplier for use by independent testing laboratories to determine accuracy of requirements and consistency with the contractual requirements. When a number of subsystem equipment are involved, the plan may be divided into appendices or sections for each subsystem/equipment.

2. CONTENT

The following paragraphs describe the EMI&S test plan.

2.1 SCOPE

Include the following introduction or scope:

a. An opening statement indicating the purpose of the plan and its relationship to the overall EMC program for the subsystem equipment.

b. A table listing all the tests to be performed, the paragraph number of the plan, and corresponding test method of the basic standard.

2.2 APPLICABLE DOCUMENTS

List the following applicable documents:

a. Military (standards, specifications, etc.).

b. Company (any in-house documents for calibration or quality assurance).

c. Other Government or industry standards, specifications, or documents.

2.3 TEST SITE

Include the following data regarding the test site:

a. Description of test facility, shielded enclosure, or anechoic chamber (size, power availability, filters, attenuation characteristics of room to electric, magnetic, and plane waves).

b. Description of ground plane (size and type) and methods of grounding or bonding test sample to the ground plane in order to simulate actual equipment installation.

c. Spot-check measurements of the ambient electromagnetic emission profile of the test facility, both radiated and conducted, to determine ambient suitability.

2.4 TEST INSTRUMENTATION

Describe the following test instrumentation to be used:

a. When matching transformers or band-reject filters are used, describe their characteristics.

b. Specify the bandwidth of the measurement instrumentation.

c. List all test equipment.

d. Identify scanning speed used to drive EMI measuring equipment.

e. Describe monitoring equipment utilized during measurements.

f. Describe antenna factors of specified antennas, transfer impedances of current probes, impedance of line impedance stabilization network (LISN), and insertion losses and impedance curves of 10-microfarad (μF) capacitors.

2.5 TEST SAMPLE SETUP

The test sample includes actual physical layout of equipment under test, depicting positions of test sample and feed-through capacitors or line impedance stabilization networks on the ground plane; lead dress; bond straps; real or simulated loads, electrical or mechanical; and any test sets employed in the test. (Notes may be used to indicate height above ground plane for leads.)

2.6 TEST SAMPLE OPERATION

Include the following test sample operation description:

a. Modes of operation for each test and operation frequency.

b. List of control settings on the test sample.

c. List of control settings on any test sets employed or characteristics of input signals.

d. Test frequencies at which oscillators, clocks, etc., may be expected to approach test limits.

e. Performance checks initiated to designate the equipment as meeting minimal working standard requirements.

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f. Enumerate circuits, output, or displays to be monitored during susceptibility testing as well as the criteria for monitoring degradation of performance.

g. Describe malfunction and degradation of performance criteria (that is, change in output spectrum, change in (S+N)/N ratio, loss of synchronization, and changes in output waveform for susceptibility testing).

2.7 TEST PROCEDURE

Fully describe test procedures to be employed to demonstrate compliance with the contractual requirements. As a minimum, include the following:

a. Block diagram depicting test setup for each test method.

b. Test equipment used in performance of the test and methods of grounding, bonding, or achieving isolation for the measurement instrumentation.

c. Detailed step-by-step procedures enumerating probing of the test sample, placement and orientation of probes and antennas, frequency range of test, selection of measurement frequencies, detector functions used, data to be recorded, frequency of recording data, and the units of recorded data.

d. During susceptibility testing, specify the actual modulation characteristics of the interfering signal (amplitude, type, degree, waveform, etc.).

2.8 SUBSYSTEM TEST

Include a test matrix similar to *SN 2.8(1)* in subsystem test plans and enumerate potential for the following:

a. Receiver to receiver interactions.

b. Transmitter to receiver interactions.

c. Transmitter to active and passive devices (magnetic device).

d. Active devices to receiver interactions.

e. Active devices to passive devices (magnetic devices).

2.9 RECORDED DATA

Outline the data to be recorded as follows:

a. Sample data sheet.

b. Sample test log.

c. Sample graphs.

SUB-NOTE 2.8(1) Sample Test Matrix

I. RECEIVER-TO-RECEIVER INTERACTION:

Source receiver	Victim receiver	Source receiver frequency (MHz)	Victim receiver frequency (MHz)	Test frequency (MHz)	Interaction
AN/ARC-100BX	AN/ARC-1000	230.00	17.1	17.1	1st LO of source with victim
AN/ARC-100BX	AN/ARC-1000	238.80	25.1	25.1	1st LO of source with victim

II. TRANSMITTER-TO-RECEIVER INTERACTION:

Source receiver	Victim receiver	Source transmitter frequency (MHz)	Victim receiver frequency (MHz)	Test frequency (MHz)	Interaction
AN/ARC-1000	AN/ARC-100BX	3.85	225.95	3.85	Source frequency with 2nd IF of victim
AN/ARC-1000	AN/ARC-100BX	22.50	232.50	22.50	Source frequency with IF of victim
AN/ARC-1000	AN/ARN-115E	22.00	110.00	110.00	5x source frequency with victim
AN/ARC-1000	AN/ARN-115E	29 00	116.00	116.00	4x source frequency with victim

DESIGN NOTE 2B3 SUBSYSTEM/EQUIPMENT EMI AND SUSCEPTIBILITY (EMI&S) TEST REPORTS

1. INTRODUCTION

In the EMI&S test report, detail the results of the test performed to determine compliance with the contractual EMI&S requirements. Submit test reports in accordance with contract. *Paragraph 3* gives the test report content requirements which are forwarded to the procuring activity for evaluation prior to acceptance of the subsystem/equipment.

2. QUICK-LOOK REPORTS

If required by the contract, prepare a "quick-look" report in Teletypewriter Exchange Service (TWX) form announcing the accomplishment or occurrence of a significant test event. Identify the specific events along with prevalent test conditions and important results or happenings affecting program objectives. Identify problems requiring immediate attention by the procuring activity. Provide the complete details of the test in the formal test report.

3. EMI&S TEST REPORTS

Include the following in the subsystem/equipment EMI and susceptibility (EMI&S) test report:

3.1 FORMAT

Use the test report format specified in *MIL-STD-831* with the following supplements:

a. A cover page is required.

b. Include the following administrative data which may be supplemented: (1) test performed by prime supplier or independent testing laboratory, (2) contract number, (3) authentication by the supplier personnel responsible for performance of the test and required inspection or witnessing organization, (4) disposition of the test specimen, (5) description of test specimen, function, and intended use and installation, if known, (6) list of individual tests performed and changes in limits or test frequencies previously authorized.

c. Use a separate appendix for each test. Include the applicable test procedure, data sheets, graphs, illustrations, and photographs in each appendix. Include the log sheets as a separate appendix which will be last. In another appendix, include definitions of specialized terms or word usage.

3.2 CONTENT

Assure that the test report contains the following factual data:

a. Nomenclature and serial numbers of interference measuring equipment.

b. Data of last calibration of interference measuring equipment, procedures used, and their traceability to National Bureau of Standards (NBS).

c. Photographs or diagrams of test setup and test sample with identification.

d. Transfer impedance of current probes.

e. Antenna factors of specified antennas, impedance of Line Impedance Stabilization Network (LISN), and insertion loss and impedance curve of 10-f capacitor.

f. Measured levels of emission of each frequency (before and after the application of suppression devices), including data specified in *SN 3.2(1)*.

g. Graphs or X-Y recordings of applicable contractual limits and measured data in units specified in *MIL-STD-461* for that limit.

h. Data to show compliance with susceptibility requirements and thresholds of susceptibility or limitations of test equipment, including data specified in *SN 3.2(2)*.

i. If suppression devices are employed to meet the contractual requirements, identify them using schematics, performance data, and drawings, except where these data are in other documents required by the contract.

j. Sample calculations, if any.

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SUB-NOTE 3.2(1) Sample Data Sheet—Emission Tests

Technician: **Date:**

Equipment Nomenclature: **Serial:**

Test Method:

Type of Measurement:
(Check as applicable)
Radiated: NB ☐ BB ☐
Conducted: NB ☐ BB ☐

Measurement Point:

Frequency Range of Test:

Measurement Technique:
Calibrated volt ☐
Slideback ☐
Substitution ☐
Automatic ☐

Mode of Operation:

Test Equipment Used:

Test Frequency	Meter Indication	Attenuator Setting	Correction Factors Ⓐ Ⓑ Ⓒ Ⓓ	Corrected Reading	Limit	Remarks

Ⓐ Current Probe Ⓑ Bandwidth Ⓒ Cable Losses Ⓓ Antenna Factor

SUB-NOTE 3.2(2) Sample Data Sheet—Susceptibility Tests

Technician: **Date:**

Equipment Nomenclature: **Serial:**

Test Method:

Type of Measurement: (Check)
Radiated ☐
Conducted ☐

Measurement Point:

Frequency Range of Test: **Mode of Operation:**

Test Equipment Used: **Description of Test Signal:**

Test Frequency	Meets Limits? Yes	No	Susceptibility Threshold Level	Description of Degradation	Maximum Test Signal Applied If Not Susceptible	Remarks

3.3 RECOMMENDATIONS AND CONCLUSIONS

Include in the recommendations and conclusions a brief narrative form of test results, a discussion of remedial actions already initiated, and proposed corrective measures which will be implemented to assure compliance of the equipment or subsystem with the contractual EMI requirements. In addition, discuss any test sample characteristics which may influence the equipment's ability to meet the contractual EMI requirements. These characteristics may include: power consumption, shock hazard, weight, water-tightness, and utilization of nonferrous materials.

CHAP 3 EMI CHARACTERISTICS AND EFFECTS

CHAPTER 3 EMI CHARACTERISTICS AND EFFECTS

SECTION 3A SYSTEMS

DN 3A1 - AEROSPACE SYSTEMS

DESIGN NOTE 3A1 AEROSPACE SYSTEMS

1. INTRODUCTION

Electromagnetic interference (EMI) suppression measures are general requirements for the design of all aerospace 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. Interference is defined as any electromagnetic (1) disturbance, (2) phenomenon, (3) signal, or (4) emission (man-made or natural), which causes or can cause undesired response, malfunctioning, or degradation of performance of electrical and electronic equipment. Interference can also cause premature and undesired location, detection or discovery by enemy forces. Interference is caused by the radiation or conduction of undesired transient and steady-state susceptibility to such disturbances. Design aerospace systems and equipment installations to ensure that electrical and electromagnetic compatibility exists between equipments in the system. See *Ref 27* and *208* for interference prediction techniques. Also see *Ref 325* for additional information on interference. A system includes:

a. Equipment installed in aircraft or missiles.

b. Combinations of aircraft, missiles, or weapons which must operate together to fulfill a military requirement.

c. Combination of airborne and ground equipment which must operate together to fulfill a military requirement.

1.1 ELECTROMAGNETIC INTERFERENCE ENVIRONMENT

The electromagnetic interference (EMI) environment existing within an aerospace system is a function of: (1) the external couplings between subsystem antennas, (2) the manner in which the subsystem components are installed, (3) the interconnected, spurious outputs of all subsystem components, and (4) the susceptibility characteristics of low circuit level subsystem components. The environment is not uniform at all places in the aircraft. The local environment may be determined by empirical or analytical methods. Analytical methods are required if electromagnetic compatibility is to be controlled (in design) before prototype articles are available.

1.2 COMPATIBILITY ENVIRONMENT

The compatibility of systems to the electromagnetic environment should take into account both conducted and radiated interference. Design systems for minimum interference and susceptibility according to *MIL-STD-461*. Provide additional design factors (as necessary) to meet susceptibility requirements. The responsibility for obtaining systems compatibility divides equally between the installation design engineer and the systems and equipment design engineers. Ideally, an investigation of all equipment in the aircraft to determine the interference and susceptibility characteristics is required for full compatibility determination.

1.3 OTHER ENVIRONMENTAL EFFECTS

Heat, vibration, and moisture can also cause EMC problems. Sockets and connectors can become loose or undone by vibration. Solder joints can break or debond on printed circuit boards (PCBs) due to a combination of heat and vibration. Moisture can cause corrosion in equipment, and leakage paths on PCBs. Even though electronic boxes may be airtight, water vapors may still enter that compartment. See *Refs 655* and *656* for more detailed information on how to prevent these problems.

1.4 SUBSYSTEM AND EQUIPMENT COMPATIBILITY

The operational integrity of electrical and electronic subsystems requires that information bearing signals, conveyed by subsystems and equipment, be free of extraneous electromagnetic energies. The introduction of interference (including transients and harmonics to such signals conveying electrical intelligence) (1) may cause errors in computer outputs; (2) may result in adverse reaction of flight control and ECM subsystems; (3) may introduce errors and false targets in fire-control subsystems; and (4) could degrade the performance of bombing-navigational and communication subsystems. The same suppression principles that apply to

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system also apply to subsystems and equipment. Design all subsystems and equipment to meet the minimum interference control requirements of *MIL-STD-461*. Provide additional design factors and installation techniques (as required) to obtain low susceptibility, particularly to low frequency transients and 400 Hz induction fields. See *Ref 54* for techniques to effect interference control during design and *Ref 209* for general approaches to interference control in aerospace systems.

2. INTERFERENCE CONTROL

The following paragraphs give some basic system design considerations for EMI control. (See *Chap 5* of this handbook for more extensive coverage of this subject.)

2.1 BONDING

Design and execute bonding to achieve the following results:

a. Protect the aircraft and personnel from hazards associated with lightning discharges (see *Chap 7* of this handbook and *Ref 89, 147, 211, 212,* and *213*).

b. Provide power-current and (where applicable) fault-current return paths.

c. Provide sufficient homogeneity and stability of conductivity for RF currents affecting radio transmission and reception.

d. Prevent the development of RF potentials on conducting frames and enclosures of electrical and electronic equipment and conducting objects adjacent to unshielded, transmitting antenna lead-ins.

e. Protect personnel from shock hazards caused by internally power-faulted equipment. Shock hazards may be nonexistent for system voltages of less than 50 volts. This in no way obviates the other requirements for bonding (if and when applicable).

f. Prevent the accumulation of static charge which produce (by periodic spark discharge) (1) radio interference, (2) explosion hazard, or (3) a shock hazard.

2.2 SHIELDING

Shielding is used to prevent the coupling of undesired radiated electromagnetic energy into susceptible equipment. In aircraft, structural shielding effects can range from 20 to 100 dB. This degree of shielding attenuation is generally not sufficient to protect external antennas from electromagnetic energy generated within the aircraft.

a. Equipment shielding enclosures are also required to prevent intrasystem and intersystem radiated couplings within the aircraft. A shielded enclosure can seldom be constructed of one continuous sheet, because openings are necessary for (1) control and power leads, (2) ventilation, (3) doors and covers, (4) control shafts, (5) seams, and (6) other mechanical features that will introduce discontinuities in the shield. Keep mechanical discontinuities to a minimum. All joints and flat metal seams must be electrically continuous across the interface.

b. Hold leakage due to seams, doors, removable panels, and holes to a minimum by (1) welding, brazing, or soldering the seams, (2) removing the finish around doors, (3) using RF conducting gaskets on removable panels, and (4) keeping holes as small as possible. Grounding sleeves on metallic control shafts or using nonconducting control shafts reduces or eliminates shielding leakage from control shafts.

2.2.1 EXTENT OF CABLE SHIELDING. Shield all audiofrequency (af) signal circuits and ground the shield at the signal source end only. Carry the shield through a pin of the connector and bond internally to the equipment enclosure. Multiple circuits from the same signal source may have common shields and be carried through a pin of the connector and bonded internally to the equipment. Shield each RF signal circuit by grounding the outer braid of a coaxial cable at both ends. Do not shield power leads between a power supply and a subsystem, or between units of a subsystem.

2.2.2 ELECTRICAL CONTINUITY. Maintain electrical continuity and isolation of signal circuit electrical shields through connectors, equipment, and junction boxes intermediate between the signal source and the signal load. Shield any intermediate terminal strip or block by a metallic enclosure properly bonded to the structure.

2.2.3 ISOLATION. Ensure each cable shield is electrically isolated from other cable shields within a harness.

2.2.4 BREAKOUTS. Position shield breakouts for all shielded wires so that not less than 12.7 mm ($^1/_2$ in.) nor more than 25.4 mm (1 in.) of unshielded insulated wire shows aft of each connector solder pot.

2.3 WIRE ROUTING

Do not route wires carrying af signals at levels less than 10 mW with electrical control, pyrotechnic circuits, and RF circuit wiring. Maintain a minimum separation of 50 mm (2 in.) between af signal wires and such wiring. Do not route or group antenna lead-ins with other electrical wiring. Install electrical and electronic wiring according to *MIL-W-8160* (modified as necessary) to meet the compatibility and interference control requirements of *MIL-E-6051*. Comply with wiring requirements outlined in *DN 5B5* of this handbook.

2.4 GROUND LOOPS

Analyze each subsystem and each interface between subsystems, to determine the magnitude of dc and ac paths, and to detect the existence of loops of nominally zero ohms impedance (commonly known as ground loops). These ground loops will result in undesirable dc and ac magnetic fields and generate interference currents in signal or control circuits due to magnetic field coupling.

2.5 SINGLE POINT VERSUS MULTIPOINT GROUNDING

The technical merits of single point versus multipoint grounding have never been fully resolved. Strong technical support can be generated for each type of grounding. Engineering agreement has been reached, however, that when major subsystems are to be mated together, full consideration must be given to the type of grounding, bonding, and shielding each subsystem uses, so that groundings are compatible.

2.6 LOW SIGNAL LEVEL CIRCUITS

Apply existing *MIL-STD-461* requirements for minimum susceptibility. Design and maintain signal levels above the predicted noise level. Restrain the response of signal paths to the required frequency band and apply filtering and isolation of auxiliary input leads as required.

SECT 3B SUBSYSTEMS

SECTION 3B SUBSYSTEMS

DN 3B4 - Contd

DN 3B5 - ELECTRICAL IGNITION OF COMBUSTIBLE MIXTURES

DESIGN NOTE 3B1 FLIGHT CONTROL, INERTIAL GUIDANCE AND INFRARED SUBSYSTEMS

1. FLIGHT-CONTROL SUBSYSTEMS

The great increase in airplane performance has been accompanied by a continual decrease in airframe inherent stability. Increased speeds require hydraulic power to aid the pilot in moving the control surfaces.

a. The hydraulic boost subsystem is increased to the point that almost 100% of the surface hinge moment is supplied by the hydraulic subsystem. It is necessary to include stability devices to fly the aircraft safely. For compatibility considerations, no demarcation need be made between unmanned and manned vehicle flight-control subsystems.

b. Automatic control devices for improving vehicle stability have been labeled in the past as (1) stabilizers, (2) autopilots, (3) stability augmenters, (4) dampers, etc. The term "stability augmenter" will be used for the generic description of all of these. This type of subsystem senses one or more airframe motion and moves a control surface to oppose this motion.

c. Imagine a block diagram of the airframe control loop which uses a stability augmenter to increase the damping of the airframe yaw mode of oscillation. In practice, yaw rate is a mode of oscillation and is sensed by a rate gyro that produces an output voltage proportional to the rate of yaw. This signal is amplified and equalized (as required) from servomechanism considerations. The resulting signal is used to operate the servo actuator which (in turn) produces the appropriate rudder motion. This is proportional to the control unit output signal and is phased in such a manner as to oppose the yaw rate. Besides the function of damping, a stability augmenter can perform most of the flight functions.

d. The flight-control subsystem has elements throughout the entire vehicle. Information is thus transmitted over long cables into which signals may be conducted or radiated. Transients that result when (1) switches close, (2) heaters turn on, (3) power subsystem loads change, etc., can be propagated into the flight-control subsystem and appear as a signal. Such a transient actuates the subsystem just as a signal from a gyro or an accelerometer would. A spurious motion of the control surfaces can result in an uncoordinated maneuver of the vehicle. Use extreme caution to avoid such errors. Consider the problems of bonding, shielding, and grounding (see *Sect 5D* and *5F* of this handbook).

2. INERTIAL GUIDANCE SUBSYSTEMS

Inertial guidance subsystems offer completely self-contained attitude reference and distance measurement outputs. The heart of such a subsystem is a gyro-stabilized platform which may be carrying the rectangular coordinate system. The axes are kept aligned at all times to true North, East, and the local Earth's gravity vector, respectively. The position of the airframe, relative to this coordinate system, is made available in the form of synchro voltages or other means of data transmission. The output is made available in the form of voltages which are proportional to the distance traveled along each of the three axes.

a. The stable platform is suspended within three or more servo-driven gimbals which serve to isolate the inertial instruments from accelerations and motions of the vehicle carrying the guidance subsystems. To maintain proper control of the platform, it is necessary to pass the output of the roll and pitch gyros through a resolver which sends the appropriate signals to the correct servos.

b. Also, it is necessary to add isolation amplifiers to prevent the resolver from loading the outputs of the gyros. The resolver performs a coordinate rotation when receiving the output of the gyros, giving error signals which have appropriate magnitude and polarity to the servo motors.

c. Ensure that the electrical power required to operate an inertial guidance subsystem is obtained from a transient and interference-voltage-free supply. Because of the accuracy required, it is usually not possible to simply filter the power from the main source. In some cases, complete isolation (as provided by a motor generator set) is required. The motor is driven from the main power source and the generator supplies the electrical power. This is especially necessary when the navigational computer is digital in nature, because any transients on the power source supplying the computer appear as additional pulses and can cause error in the output.

3. INFRARED SUBSYSTEMS

Interference is less of a problem to infrared subsystems than to radar subsystems. Ground clutter and sea return has a much smaller effect on the infrared detector.

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Auxiliary infrared trackers have been used to assist radars operating against ground targets. Infrared detection capabilities are limited by noise and simulation the same as radar subsystems. Noise is a random fluctuation that interferes with the transmission of the signal. These fluctuations may be electrical or thermal. The term noise may include anything that interferes with the detection of the target. Infrared subsystems are susceptible to the following types of noise:

a. Thermal noise is caused by fluctuation of electrons in resistors. This noise is flat (or white), which means that the spectrum is flat for all frequencies.

b. Shot noise is an electrical noise arising from the random manner in which electrons are emitted from vacuum tubes or through active elements. This limits the sensitivity of amplifiers and photoconductive devices. The spectrum of shot noise is flat and can be considered a white noise.

c. Photon noise or radiation noise is caused by the fluctuation in the rate at which photons fall on the detector. The spectrum of this energy is flat and follows the response curve of the infrared detector.

d. Temperature noise is caused by the temperature variations of the thermal detector which is a function of the interchange of heat energy between the infrared cell and its environment. This noise also has a flat power spectrum density.

e. Current noise is produced by the current load through a resistor. It is not as fundamental as the other types, and can be a contact noise somewhat like that generated between carbon grains in a carbon pile. The power spectrum may be inversely proportional to the frequency and directly proportional to the square of the current.

f. Scintillation noise comes from objects in the area being scanned. Clouds and thermal gradients are potential false targets for scanning subsystems. These can be considered noise, since their presence decreases the effectiveness of the infrared subsystem. Sea and land backgrounds produce additional interference which can cause some degradation of the infrared subsystem.

DESIGN NOTE 3B2 COMMUNICATIONS

1. INTRODUCTION

This design note (DN) discusses interference and susceptibility characteristics of communication subsystems. This includes (1) telemetry, (2) receivers, (3) transmitters, and (4) radar. For additional information on communication subsystems, see *Ref 721*.

1.1 CONSERVATION OF SPECTRUM AND SYSTEM COMPATIBILITY

To conserve the spectrum and improve system compatibility, restrict intentional signal generators to the minimum bandwidth required to contain the useful information and restrict the amplitude to the minimum level required for satisfactory information transfer.

a. Use pulse shapes with the slowest rise time practicable and minimum amplitude. Generate them at the location where they are required and do not transmit them over long lines.

b. In system design, consider filtering sideband components, using subsystems which do not transmit unnecessary signals (such as carriers), or reducing carriers to an acceptable level.

c. Carefully review antenna directivity, reduction of side lobe gain, and development of increased frequency stability.

d. Enclose broadband generation devices properly. Shield and/or decouple their leads.

e. Carefully review all interface connections to avoid redundant filtering at both ends and to assure proper routing and grounding of wires and shields.

1.2 SUSCEPTIBILITY BANDWIDTH

Conservation of the frequency spectrum is as important for the design of the receiver as for the design of the transmitter. Acceptance of unwanted signals is the reciprocal problem to spurious emission. Thus, it is important to restrict bandwidth to that which is necessary for information acquisition. Where feasible, store information known in advance at the receiver location instead of transmitting it over a communication channel.

a. Calculate rejection of signals outside the desired band to be consistent with the levels anticipated in the environment. Do this not only for signals appearing at the input circuitry, but also for signals on interconnecting leads and power supply wires.

b. Avoid spurious responses at image frequencies or intermediate frequencies and avoid spurious modulation of the desired signal. To maintain minimum acceptance bandwidth, design the local oscillator in heterodyne receiving equipment to have adequate stability.

c. Carefully consider the dynamic range of receiving equipment to avoid subjecting signals to nonlinear regions of operation which will result in the production of interference frequencies internal to receiving equipment. The problem of dynamic range is particularly important in receiving equipment which may be subjected to high level impulse interference.

d. Also take acceptance bandwidth problems into account when designing amplifiers and other assemblies which respond to relatively low power levels.

2. TELEMETRY SUBSYSTEMS

Interference in telemetry subsystems falls into these two categories: (1) interference due to extraneous signals received by the ground station (both man-made and atmospheric) and (2) self-generated interference occurring as an undesired byproduct of the normal transmitter and receiver operation. Such interference may exhibit its effects in the subtle form of residual errors in the decommutated data or may contribute to actual malfunctioning of the equipment whose performance is being monitored. The telemetry standard is *MIL-STD-1572* and test methods for telemetry systems and subsystems are in *MIL-STD-1573*.

2.1 INDUCTIVE TRANSDUCERS

Inductive transducers are used to vary the frequency of the subcarrier oscillator by acting as a portion of a frequency-determining resonant circuit. Conequently, they are subject to thermal variations, and in order to improve stability, a heater element should be incorporated. The thermostatic heater contacts produce broadband interference which may be conducted into the power lines.

2.2 COMMUTATOR AND DRIVE MOTOR

The commutator consists of a switching device used to sample information from dc circuits or slowly varying ac sources. Any abrupt change of current may result in the generation of interference because the typical mechanical commutator is a prolific source of broadband noise. This interference results from two primary sources: arcing at the drive motor brushes and at the commutator brushes. A Fourier analysis of the output spectrum shows a dc component in the output, plus harmonics at the rate the information is sampled. These harmonic components exist in the form of noise in the audiofrequency range, but are readily removed by the low-pass filters employed in telemetry. The high frequency components, exhibiting high orders of magnitude insofar as radio-frequency potentials are concerned, are significant up to 10 or 20 MHz. In this range, the usual low-pass filter applications are not effective over the radio-frequency spectrum, due to coupling between the input and output circuits and inherent inductance of the capacitors employed therein. The usual commutator employs a governor-controlled dc motor, which exhibits all the attendant interference of a conventional dc machine.

2.3 SUBCARRIER OSCILLATOR

To prevent overloading, the commutated output passes through an amplitude limiter to a subcarrier oscillator. In many subsystems, an appreciable signal may be found on the oscillator grid, capable of being transferred back to the commutator and induced or conducted into other circuits. The subcarrier oscillator frequencies range from audio through radio frequencies and may produce harmonics extending into the megahertz region.

2.4 TRANSMITTER APPLICATIONS

Transmitters for telemetry applications consist of a crystal-stabilized, modulated oscillator, followed by one or more frequency multiplier stages and a power amplifier. The final stage operates as a Class C amplifier, with the resultant harmonic output. Coupling between the power supply leads and the transmitter tank circuit may result in transfer of RF energy to other equipments operating from the same power source. Radiation of energy may occur from openings in the transmitter housing and from the cables entering or leaving the enclosure.

3. RECEIVERS

Receivers are designed to offer extreme sensitivity to signals at their desired or resonant frequency and to present a high attenuation to off-frequency undesired signals. Unfortunately, this is not always the case due to a number of degrading factors. See *DN 4A1* of this handbook for the mathematical approach to nonlinear devices.

3.1 IMAGE RESPONSE FREQUENCIES

In general, image rejection is improved if the frequency of the local oscillator is above the desired signal frequency for low-frequency receivers and below the desired signal in high-frequency receivers. Therefore, the following equation can be used to relate the three variables if the proper sign is chosen:

$$f_{lo} \pm f_{if} = f_o \qquad \text{(Eq 1)}$$

Where:

f_0 = receiver tuned frequency

f_{if} = receiver intermediate frequency

f_{lo} = local oscillator frequency.

3.2 LOCAL OSCILLATOR HARMONICS

Sound design practice requires a large local oscillator drive to the mixer tube or crystal to obtain good sensitivity, so the mixer is driven into the nonlinear region. A general result can be written since a large number of harmonics will be generated in the mixer:

$$pf_{lo} \pm f_{if} = f_{sp} \qquad \text{(Eq 2)}$$

Where:

f_{sp} = spurious frequency

$p = 0, 1, 2, \ldots$

The value $p = 0$ is included because the intermediate frequency itself is also a special spurious response.

3.3 RESPONSES BELOW THE TUNED FREQUENCY

If the local oscillator frequency is below the signal frequency, all the preceding spurious responses except two (the IF and the image) are above the receiver-tuned frequency. However, an additional set of responses exists below the tuned frequency due to nonlinearities in the RF mixer stages generating harmonics of the interfering signal. These are defined by:

$$f_{lo} \pm f_{if} = qf_{sp} \qquad \text{(Eq 3)}$$

Where:

$q = 1,2,3,\ldots$

These responses are located at submultiples of the tuned frequency. Additional responses are generated by a combination of the results of Eq 3 which may be expressed by:

$$pf_{lo} \pm f_{if} = qf_{sp} \qquad \text{(Eq 4)}$$

or

$$f_{sp} = \frac{pf_{lo} \pm f_{if}}{q} \qquad \text{(Eq 5)}$$

This is the spurious-response equation so often used in interference frequency calculations. Up to this point, only the first local oscillator has been considered, but the above equations also apply to the second and third conversion stages in a triple conversion receiver. Not many responses are attributed to the second and third mixers except in special cases. In some receivers, strong signals applied to the antenna terminals leak around the selective circuits and arrive at the third detector in sufficient amplitude to create a considerable number of spurious response frequencies.

3.4 CROSS MODULATION

A change in the notation is necessary when cross modulation, as opposed to intermodulation, is being examined. Cross modulation involves only two signals: one is the signal of the desired channel and the other is the signal of one undesired interfering channel. All even orders of cross modulation are mathematically nonexistent. Therefore, the output signal of an amplifier having input signals at the desired and one undesired frequency and having sufficient selectivity after the nonlinearity to reject all signals except those at the desired frequencies will be:

$$i = C_i e_d \sin \omega_d t + \frac{3}{2} C_3 e_n^2 e_d \sin \omega_d t + \ldots \qquad \text{(Eq 6)}$$

The first term represents the desired output, while the second and remaining terms represent the cross-modulation output. The various orders of cross modulation are difficult, if not impossible, to separate entirely from each other by direct measurements. If cross-modulation data are to be of practical use in quantitative equipment analysis, separation of the contributions made by each order of cross modulation would be desirable.

4. TRANSMITTERS

Transmitters can be a source of EMI because they have a Class C output stage which produces high harmonic content. The oscillator, multiplier, and modulator stages can also cause spurious signals because they involve nonlinear elements. Ensure that proper shielding, filtering, bonding, and grounding are used so spurious signals will not emanate outside the transmitter enclosure and that the output waveform to the antenna is relatively free of harmonics or spurious signals.

4.1 SOURCES OF SPURIOUS VOLTAGE

From data taken on various transmitters, it is apparent that the spurious voltages generated in a particular stage, such as a multiplier or power amplifier, are primarily dependent on (1) the nonlinear operation of the tubes (the fact that current flows for only a part of a cycle), (2) the impedance presented to the plate of the tube by passive circuitry, and (3) the input voltages to the grid of the tube which includes all of the spurious voltages from the previous stage. It is possible to analyze active circuitry to show the effect of each of these factors. Furthermore, such an analysis provides a basis for predicting the frequency and magnitude of spurious signals that will be generated in a particular stage, and it offers a means of evaluating possible remedial techniques.

4.2 DESIGN TO ELIMINATE SPURIOUS VOLTAGES

One result of such an analysis shows that an ideal parallel tuned circuit is not sufficiently selective to reduce spurious signals close to the carrier. The remedy requires either a more elaborate output circuit or external filters to bolster the tank circuit. In the latter case, there is usually an undesired loss of carrier power. The surest method is designing to eliminate the unwanted signals at their source. The design of RF circuitry can include RFI control for frequency ranges beyond that in which the equipment is intended to operate. A series of studies made to determine the significant parameters in spurious signal generation disclosed several practical approaches to the choice of components. One of these involved the selection of coils and capacitors for use in tuned circuits. It is known that the impedance of a coil is a function of frequency and that the distributed capacitance of the coil can cause multiple resonances. The coil's reactance, therefore, alternates from inductive to capacitive and back. If such a component is used with a capacitor to form a tuned circuit, there will be as many resonances as there are frequencies at which the inductive reactance is equal to the capacitive reactance. The solution to this problem is to choose an inductor whose reactance undulations remain greater than the reactance of the capacitor at all frequencies greater than the operating frequency. In general, this means using high quality components, keeping lead lengths short, and using good judgment in component placement.

4.3 SPURIOUS AND HARMONIC EMISSIONS

The most common off-frequency signals which give rise to radio frequency interference are the spurious outputs from transmitters. While one may consider all outputs but the carrier and its required sidebands as being spurious, the usual practice is to identify spurious outputs with frequencies reasonably well-removed from the carrier. Generally, these will be harmonics of the basic oscillator frequency. Frequencies which are multiples of the carrier frequency are distinguished with the name "harmonic."

4.4 SPURIOUS SIGNALS

It is beneficial to follow the course of the spurious signals through at least one transmitter to develop an appreciation of the mechanisms involved and to understand the importance of rigid control at the final stage of the transmitter. For this purpose, neither the vintage nor the exact circuitry of the transmitter is important.

4.4.1 OSCILLATOR HARMONICS. It may be shown that the oscillator harmonics behave as a function of frequency. For example, the fundamental at 1.2 MHz is greater than 100 V. Harmonics of this fundamental diminish in amplitude with increased frequency, but remain significant at 180 MHz. The level does not decrease uniformly, but rather rises and falls in an undulating manner.

a. First Multiplier Stage. Consider the spurious outputs from the first multiplier stage. The dominant frequency is now given as 3.6 MHz. The original 1.2-MHz signal is present and many signals that were not measurable in the oscillator spectrum now become significant.

b. Second Multiplier Stage. Consider the output from the second multiplier whose dominant frequency is at 10.8 MHz. The basic oscillator frequency (1.2 MHz) is still present and is one of the larger spurious signals.

4.4.2 OUTPUT MEASUREMENT. Consider the transmitter output as measured across a 50-ohm dummy load. All the basic oscillator harmonics will still be present even though they are no longer called "harmonics." Experience proves that there are many signals larger in amplitude than some of the harmonics of the transmitter frequency.

4.4.3 EFFECT OF CIRCUIT IMPEDANCE. The effect of the impedance of the various circuits on the modulations of the spurious signal spectra was investigated and from the results a rough idea of the magnitudes of the currents flowing through the stage can be derived. The general nature of the impedance spectra suggests a correlation with the spurious signal spectra. Measurements performed on a different transmitter verified these observations.

4.5 RF INTERMODULATION

Having observed the abundance of spurious signals at each stage of a transmitter, it appears that these signals could be eliminated at their source in each stage but, in actuality, each nonlinear element in succeeding stages would add back the signals that were eliminated. Whenever a nonlinear element is subjected to a signal, harmonics of the signal frequency will be produced. The frequencies of those products are simple to calculate (see *DN 4A1*). The magnitudes are quite difficult to predict and can best be determined by measurement.

4.6 ELECTRONIC COUNTERMEASURES

Electronic countermeasures (ECM) can have a severe impact on electromagnetic compatibility in overall systems. A comprehensive systems analysis of the overall mission requirements and subsystems characteristics is necessary to achieve compatibility. Consider the harmonics of all transmitters and the measured spurious responses of receivers. Equipment which must operate at the same time as ECM equipment must be carefully designed to ensure proper operation. In some cases, it may be necessary to impose more stringent requirements than those in *MIL-STD-461*. (See *DH 2-4* for more information on ECM.)

5. RADARS

It has been estimated that over 12 000 radars are currently operating in the continental United States. Many of these radars are situated in congested areas and because of real estate considerations are frequently collocated at specific sites such as airport, military bases, and missile launching sites. In addition, there has been and will be in the future, an ever-increasing use of radar in (1) airborne systems, (2) navigational aids, (3) weather observation, and (4) satellites and space probes. The trend toward greater spectrum usage and congestion has resulted in a mutual interference problem which is becoming increasingly complex.

5.1 INTERFERENCE

A common form of radar interference is the appearance of interfering dots or spirals on the scope presentation of the radar caused by pulse interference from other radars. This type of interference is usually moving continuously and may cover a large portion of the scope face, making targets difficult to detect. Interference of this type is annoying to the operator and (over a period of time) causes fatigue which reduces effectiveness. If the interference sector contains a target, delayed detection is likely to result. If the interference is extreme, false target reports become likely.

5.1.1 TRACKING RADARS. Pulse interference to tracking type radars is possible especially during the acquisition or lock-on phase. Once the tracking radar has locked on, it is relatively difficult for interference to cause a break because EMC design considerations tend to make the system invulnerable to jamming. However, interference signals could cause acquisition difficulties by presenting the tracking radar with strong returns which may be compatible with its tracking circuits. In such a case, the tracking radar might be decoyed and fail to acquire the true target.

5.1.2 MICROWAVE RELAY. Radar interference to microwave radio relay is also a problem. Radar interference appears (1) as a rough buzzing noise in telephone circuits; (2) as moving, almost randomly located, white dashes in a television picture; and (3) as errors in data signals. The first two cases are commercially objectionable, but the latter is intolerable especially in circuits carrying data signals for defense systems. Experiments show that as the peak value of the interference approaches the peak value of the desired signal, the interfering noise in telephone circuits rises rapidly. The noise is negligible when the ratio of peak signal to peak interference is more than 5 dB, but it is intolerable when the ratio is unity. Similar tests have indicated data signals are not seriously affected by radar interference when the circuits do not have much interference for ordinary telephone usage. On the other hand, television signals are somewhat more sensitive to radar pulse interference. A ratio of peak signal to peak interference of more than 15 dB is required to avoid degraded television pictures (signal power = 32 × interference power).

5.2 DESENSITIZATION

Desensitization is not quite as obvious as pulse interference, but the phenomenon is important in radar. A pulsed radar operating in the vicinity of a powerful continuous wave (CW) transmitter can be rendered completely inoperative, if the CW power level is sufficient to fire the transmit-receiver (TR) tube continuously. In fact, lower levels of CW power may be sufficient to maintain a TR tube arc once the tube has been fired by its own transmitter. Some tubes have been found to remain in conduction when the CW power was reduced to 20 mW. If the CW power level is not high enough to maintain the TR tube arc, desensitization can still occur. The presence of the CW power at the radar mixer can change the bias level of the mixer crystal, thereby changing the noise level and reducing maximum range performance. Degradation of 1 dB in receiver response has been noted for CW power levels of 0.15 mW. Stronger signal levels tend to change bias levels in both the mixer and IF stages to a point where noise and desired signals disappear entirely due to receiver overload.

5.2.1 CRYSTAL DETERIORATION. Desensitization also occurs as the result of crystal deterioration or burnout. The most common causes of crystal burnout in microwave receivers are:

a. Inadequate shielding of output leads from the crystal. These leads can pick up large extraneous voltages and consequently produce crystal burnout.

b. Reception of strong signals by receivers protected by transmit-receiver (TR) switches.

c. Failure of the duplexers and TR tube to protect the crystals for one or more of the following reasons:

(1) The TR tube has deteriorated

(2) Keep-alive does not function

(3) Frequencies outside the design band of the duplexer have passed directly to the crystal with very low loss.

5.2.2 AUTOMATIC FREQUENCY CONTROL CAPTURE. In circuits employing automatic frequency control (AFC), a sufficiently strong undesired signal relatively close to the desired signal may cause the AFC circuits to lock on the undesired signal. The resulting shift in receiver frequency may be sufficient to lose the desired signal altogether.

5.2.3 OVERINTERROGATION. Identification friend or foe (IFF) systems used in conjunction with radars are generally susceptible to this type of interference. The basic function of IFF has been to establish the identity of an aircraft from a remote point. This subsystem usually consists of a ground-based interrogator-responder and an airborne transponder, used in conjunction with a surveillance radar. When the target is detected on the radar display, the interrogator is activated and transmits a series of coded pulses. The airborne transponder (if properly adjusted) replies with another series of pulses, which are received by the responder and displayed in the vicinity of the target on the radar scope. In a heavily congested area, the airborne transponder may be interrogated simultaneously by many IFF subsystems, resulting in a subsystem overload. Subsystem overload results in unsynchronized replies, erroneous range data, and other subsystem errors. Part of the difficulty lies in the fact that many subsystem antennas in use have poor main-lobe to side-lobe ratios; therefore, interrogations by side lobes are possible. This results in needless interrogations, which contribute to eventual transponder overload and increased clutter on the scope display, by showing one aircraft in many different places on the plan position indicator (PPI) scope. The problem is complicated by the appearance (on the PPI scope) of transponder replies to interrogation by other radars. These replies are unsynchronized and appear at random positions on the scope display causing scope clutter.

5.3 RADAR TRANSMITTERS

In theory, a radar transmitter is required to radiate energy only over the band of frequencies necessary to convey the intelligence which it is processing. However, the practical transmitter may emit energy at a great number of spurious frequencies. These extraneous signals exist because the general system design incorporates techniques involving application of signals to, or generation of signals by, nonlinear elements. This results in an output which may contain the signal fundamentals and many harmonics. In addition, spurious resonances frequently produce spurious signals not related harmonically to the fundamental. From its contribution to the total environment, the transmitter parameters affecting the environment are (1) frequency, (2) tunability, (3) type of modulation, (4) output power, (5) stability, and (6) spurious emissions produced.

5.3.1 OPERATING FREQUENCY. The operating frequency (fundamental) determines the location of the transmitter's primary contribution to the frequency spectrum. The operating frequency for radars is normally specified as the frequency in the center of the fundamental emission bandwidth having the highest output power. Therefore, a powerful transmitter operating at a given frequency denies spectrum occupancy at this frequency to other adjacent systems in the geographical area during its time on the air.

5.3.2 EQUIPMENT TUNABILITY. The ability to tune most radar equipment permits an operator to select a clear frequency in a congested area, and thus serves to ease the interference problem. However, many radar equipment operate on fixed frequencies and conflicts are inevitable. This situation is made more complex because manufacturers of radar tubes tend to make more tubes for the center of an allotted band to minimize out-of-band rejects. Thus, an uneven distribution of frequencies occurs which leads to an uneven use of the spectrum.

5.3.3 GENERATION OF SIDEBANDS. Radar transmitters are the primary sources of interference to other radar subsystems. This is due to the radiation at the fundamental frequency and harmonics, and to the number of sidebands which are generated. Radar receivers are normally designed so they use only the power contained in the main lobe. The sideband lobes are not used and actually reduce the effective power of the radar. Moreover, these sidebands can cause an appreciable degree of interference to other equipment. As an example, the third side lobe, on one side of the carrier, contains 0.43% of the total radiated energy. Assuming a radar with 1-MW peak power, this sideband contains approximately 4.3 kW. The sensitivity of an average radar receiver is 10^{-13} watts. Thus, the transmission path between the radar receiver tuned to this ideband and the transmitter must provide at least 167 dB of attenuation. Several factors which can influence the amplitude and number of sidebands are described in the following paragraphs:

a. Pulse Shape. The shape of the modulated pulse can influence the amplitude and number of sidebands generated. Rather than being an ideal rectangle, it is often trapezoidal in nature and this modifies the RF output spectrum. Recent studies have indicated that the number of sidebands and their amplitudes can be reduced by using modified pulse shapes. For example, cosine squared and gaussian shape pulses have been proposed. Although the gaussian pulse envelope is difficult to achieve in practice, some other pulses which can be produced closely approximate the gaussian.

b. Frequency Shift. A second important deviation from the ideal is the tendency of the average magnetron or klystron to shift frequencies during modulation. The periodic shift in frequency introduces frequency modulation in the RF output spectrum. Usually both effects are present.

c. Short Duration Pulse. Since many modulated pulses are extremely short (2 μs or less), their spectrums can extend well into the HF or even VHF regions. Thus, they can produce a major source of interference to communications systems operating in these bands and located a few hundred yards away from the radar. Primary sources of this type of interference are the modulator case and pulse cable and other modulator power control cables.

5.3.4 OUTPUT POWER. As equipment output power increases, the amplitudes of the sidebands and the power in harmonic and spurious emissions are usually increased. Higher power thus denies a larger portion of the spectrum to other users.

5.3.5 SPURIOUS EMISSIONS. Spurious resonances can result in output signals unrelated to the fundamental signal. For example, magnetron moding may cause spurious outputs at frequencies adjacent to, as well as some distance from, the desired frequency. There are inherent nonlinearities in microwave tubes which cannot be reduced without sacrificing desirable operating characteristics of the device.

5.4 RADAR RECEIVERS

Radar receivers, if not adequately shielded, also contribute to the active environment. Local oscillations can produce milliwatts of power that can affect nearby receivers. Receivers with poor RF hreselection and inadequate shielding are chief offenders. The major factors in radar receivers pertaining to interference include (1) frequency and tunability, (2) sensitivity and selectivity, (3) spurious response, (4) intermodulation, (5) desensitization, and (6) signal recognition features.

5.4.1 TUNABILITY. Tunability is an asset in seeking clear channels, even though in many radars, the tuning procedure is slightly more complex and time-consuming than merely turning a dial as on communication-type receivers.

5.4.2 SENSITIVITY AND SELECTIVITY. The sensitivity of a receiver is a measure of its ability to receive low-level signals. In most receivers, the lower limit of this level is determined by the noise generated in the input stage. While the operational advantages of sensitive receivers are obvious, it is known that an increase in sensitivity at the desired frequency also increases the sensitivity of the receiver to noise. Selectivity of a receiver refers to the ability of the receiver to discriminate against signals at undesired frequencies. In radars, transmitter drift can be compensated by broadening the receiver selectivity curve and providing automatic frequency control of the local oscillator. Some missile beacons use a very broadband selectivity to allow the tracking radar to tune at will to any frequency in the band. This makes the beacon highly susceptible to interference from other transmitters occupying the band. The crystal video receiver, however, has a low sensitivity and many of the weaker signals are not received.

5.4.3 SPURIOUS RESPONSES. When an RF voltage is applied to the antenna terminals of a receiver, and varied over a wide range of frequencies, a number of receiver responses may be noted. In general, a spurious response is caused by the mixing of the spurious signals with the local oscillator signals, all of which are generated in the mixer stage, to produce a signal at the first intermediate frequency (see *DN 4A1*).

5.4.4 DESENSITIZATION. Desensitization is the effect of an undesired signal in the passband of the receiver, which causes reduction of the desired signal level. The gain reduction is due to overload of some portion of the receiver, resulting in desired signal suppression, because the receiver will no longer respond to incremental input voltages. The degree of desensitization experienced depends upon the dynamic range (linearity) and overload characteristics of the receiver. If the receiver has good linearity, the ratio of the signal-to-noise ratio in decibels to an increase in undesired signal in decibels, is approximately 1 to 1.

a. Effects of Strong CW Signal. In pulse receivers, the sensitivity reduction, due to a stronger CW signal, is on the order of 2 or 3 dB if overloading is avoided. To prevent defocusing on strong signals, intensity-modulated displays are generally used in radar receivers. Video overload can occur in the presence of CW signals due to the limiting device used with this type of display. To preclude this possibility, use a high-pass filter between the second detector and the video amplifier.

b. IF Amplifier Saturation. Intermediate frequency (IF) amplifier saturation can also result, due to the presence of a strong CW signal. If the amplifier is inadequately shielded and decoupled, IF oscillations may result. A significant test of radar receiver stability and saturation effects in the presence of CW interference is a plot of receiver sensitivity as a function of on-frequency CW interference. A stable receiver will exhibit relatively little reduction of sensitivity, with increase in interference power up to a point where the receiver noise is no longer visible on the radar scope. Above this point, the curve displays a linear relationship between the interference power and sensitivity. The slope of the curve is such that for a 1-dB increase in interference power, the sensitivity of the receiver is decreased 1 dB. Any erratic departure from this linearity indicates an unstable receiver.

5.5 INTERFERENCE REDUCTION METHODS

Causes of interference may be classified as (1) spectrum congestion and (2) subsystem incompatibility. Both of these categories are complex and they overlap in many respects. Spectrum congestion results when too many equipment in one geographical area uses the same portion of the frequency spectrum. Subsystem incompatibility may result from as few as two subsystems, one of which interferes with the other. Each specific cause of interference tends to contribute to an increase in spectrum congestion or to a decrease in system compatibility, or both. While there are hundreds of problems and appropriate fixes, only a few easily understood principles of interference reduction are applicable to all electronic systems. See *Ref 634* and *AFM 100-31* for more details on this subject.

DESIGN NOTE 3B3 COMPUTERS/DATA PROCESSING

1. INTRODUCTION

Many time computers are located near radar installations and other similar interference producing devices where they are exposed to a high degree of radiation and interference. Computer malfunction from radiation will occur when the following general conditions exist:

a. There is a coincidence of computer pulses with external interference pulses.

b. The level of the external interference pulse is large enough in amplitude to sufficiently deteriorate the computer pulse.

c. External noise source simulates computer pulses.

2. DIGITAL COMPUTERS

A digital computer uses a binary number system to perform its required functions. Information is in the form of 1s and 0s. A binary 1 may be represented by a positive voltage level or a pulse with a defined amplitude, shape, and phase; a binary 0 may be represented by a negative voltage level, or the absence of a level, or the absence of a pulse, or with a pulse of the 1 type, but at a different phase. In computer operation, timing is also a determining factor. A gate tube is normally strobed at a defined time to sense a 1 or 0 bit. The gate tube is normally opened by a level or pulse which represents a 1 bit and is closed by the absence of a level or pulse, which represents the 0 bit. For a computer to malfunction from external radiation, an interference pulse must be of sufficient amplitude to either subtract from or deteriorate the computer information pulse, or simulate a computer pulse and at the same time be in coincidence with the strobing pulse.

2.1 ERRONEOUS ZERO BIT

Consider an interference pulse producing an erroneous 0 bit; i.e., a 1 output was changed to a 0 output. When the strobing pulse is in coincidence with a 1 output of the ferrite core the interference pulse from a simulator produces no erroneous effects if it was not present at the sample time. However, the same 1-bit pulse will be deteriorated if the interference pulse is at sample time. Deterioration occurs because of interaction of the computer and the interference pulses. The result is a 0 output instead of a 1 output.

2.2 ERRONEOUS ONE BIT

Consider a waveform which represents the output of a sense amplifier, a circuit which senses and amplifies the output of a ferrite core. The ferrite core, heart of the memory subsystem, is able to store 1 and 0 bits. Strobing pulses appear at sample time. If, at sample time there is no core output (0 bit), and the interference pulse appears some time before the sample time, the circuit does not see the effects of the interference pulse, although the field intensity is greater than normally required to produce an erroneous bit. However, if the same interference pulse is in coincidence with the strobing pulse there is a computer malfunction because where there should have been a 0 output, a 1 bit is induced.

2.3 SUSCEPTIBILITY

Overall computer susceptibility is determined by utilizing a unit-by-unit test procedure. In a typical computer many circuits of the computer do not malfunction under intense electromagnetic field radiation. Circuits in this category are high-level circuits such as flip-flops, AND and OR gates, pulse amplifiers, relay drivers, level inverters and cathode followers. Low-level circuits of the computer, whose normal input is within the range of 50 mV to 2 V peak to peak, do malfunction when subjected to moderate field intensities. Sense amplifiers of the memory element malfunction at a field intensity in the region of 15 V/m peak; the tuning fork oscillator of the output section will malfunction near 40 V/m peak. Data conversion receivers of the input section malfunction at 50 V/m peak. The flux amplifier of the output section fails at 100 V/m peak. In actual usage, the susceptibility data levels of malfunction must be identified with the specific parameters which characterize the radar.

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2.4 SUSCEPTIBLE CIRCUITS

A few circuits are most susceptible. They represent a comparatively small number of the total computer circuits. In the remaining group, which represents most of the computer circuits, malfunction does not occur at field intensity levels as high as 400 V/m peak. Generally, when susceptible circuits are subjected to radiation near the low end of the 450–2900 MHz band, they are more susceptible than when subjected to the higher frequencies in this band. Variations in susceptibility due to variations in pulsed width and PRF are slight. Polarization of the signal is significant, but varies widely by computer unit. Generally, the computer is more susceptible to vertically polarized signals. Resetting and clearing the circuits of computer subsystems are particularly important to prevent susceptibility problems that could result in loss of, or more errors in, stored data.

2.5 INTERFERENCE REDUCTION

The effects of radiation on the equipment can be reduced by shielding the susceptible circuits or by redesigning the susceptible circuits. Changes to the circuit include RF filtering of the interference at the circuit input, reducing the circuit rectification characteristics, and audiofrequency (af) filtering of the rectified interference pulses. Shielding techniques are discussed in *Sect 5F* of this handbook.

3. ANALOG COMPUTERS

The many electronic parts of an analog computer installation make it susceptible to interference generated within the subsystem. Therefore, consider the following:

3.1 DC POWER SUPPLIES

Power supplies are an integral part of any dc analog computer and usually consist of a transformer-rectifier and a regulator unit. The regulator unit keeps the supply voltage constant, within specified limits, in order to minimize dc amplifier drift. It also keeps the power supply output incremental impedance below a specified minimum value, not only throughout the range of expected computer signal frequencies, but also throughout a range of higher frequencies. This is necessary to avoid undesirable coupling between different amplifier stages and computing elements. Feedback effects due to such coupling might otherwise lead to errors in the computation or cause uncontrolled oscillations.

3.2 AC AMPLIFIERS

In repetitive analyzers using ac amplifiers, power supply regulation is not an essential requirement. Eliminate interaction between computing elements through the power supplies of repetitive computers by the use of conventional decoupling filters. Alternating current amplifiers used for controlling two-phase motors require a high-voltage dc supply which may or may not be self-contained in each servo amplifier. If servo motors are operated at high power levels, thyratron or SCR control of ac motors can be used, but careful shielding and isolation of the control device is necessary to prevent their interaction with other computing elements.

3.3 AMPLIFIER OSCILLATION

Another source of interference is the typing of a large number of trunk lines onto the output of an amplifier. This may yield a large enough capacitance to throw the amplifier into oscillation. Under certain operating conditions electronic multipliers can also cause oscillations. If the multipliers are set in a common chassis there may be coupling from one unit to another. Eliminate this problem by proper shielding.

3.4 INTEGRATORS AS INTERFERENCE SOURCES

Integrators in analog computers can produce errors due to conducted interference. In dc analog computers, the output of each amplifier is balanced to zero by some biasing arrangement before computation. Ideally, only the desired signal voltages should act on the integrator input terminals. Actually, certain stray voltages occur due to noise pickup and unbalances in the dc amplifier resulting from grid current and drift.

They are integrated and may lead to errors in the integrator output voltages. Direct current integrators are fairly susceptible to errors resulting from pickup of 60-Hz ac hum. Keep hum voltages out of the equipment by reasonable shielding and placement of leads and power supplies which carry alternating currents.

4. COMPUTER COMPATIBILITY

4.1 WIRING INTERFERENCE

Inter-unit wiring is a potential source of interference in any complex computer installation. Consider the following general recommendations:

a. Use common ground straps for all units. Do not rely on chassis ground.

b. High-voltage power-supply wiring in common to more than one amplifier should have an impedance of less than 2 ohms to minimize coupling between amplifiers.

c. Patch cords may be of the ordinary telephone variety, but it is desirable to have the shielded typed to prevent crosstalk between adjacent cords. Give careful attention to shielding to avoid crosstalk if frequencies in excess of 3 Hz are involved in the computation. Patch panels and plugboards made of polystyrene minimize leakage effects. Also, the higher frequencies used with repetitive computers make the shielding of computing elements and interconnecting leads more critical than in the case of "slow" do analog computers.

4.2 USE OF ENCLOSURES

In larger computers it is good practice to place power supplies, dc amplifiers, and servomechanisms in enclosed cabinets or racks separate from the computing elements proper to avoid hum due to the magnetic fields of their components. Locate feedback networks inside the control console where they are not affected by heat generated in the amplifiers and power supplies. Interconnect the various units with well-insulated cables.

4.3 INPUT DATA

The input data is smoothed by filtering random noise from the input data before being processed by the impact prediction subsystem. The digital input to the subsystem is recorded, usually on magnetic tape, for later evaluation or simulation. There are three main sources of noise in magnetic recording: (1) inhomogeneity in the recording medium, (2) variations in contact between the medium and the recording heads, and (3) variation in the cross section of the track. Strong electromagnetic fields near the recording instrument may also affect the quality of the recorded data if shielding precautions are not observed.

4.4 OUTPUT DATA

The digital output of the computer is converted to analog form and transmitted to the Range Safety Officer. Television (TV) monitors and plotters display the necessary information in useable form. These may also be sources of interference. The major sources of electric field interference from TV monitors are (1) sweep output tube elements and associated circuits, (2) high-voltage circuits including the picture tube, (3) components of the video amplifier, and (4) miscellaneous components such as sweep transformers, deflection yokes, etc. The major sources of magnetic field interference are due to deflection yokes, sweep transformers, and miscellaneous sources due to connection of the other components to the sweep circuits. For example, for the external fields, incorporate a principal mode of coupling into the power line. The following will occur:

a. The magnetic field created is a result of all magnetic fields due to the mentioned sources.

b. An external electric field results where there is capacitance between "hot" components and ground. The displacement currents flowing through these capacitances return through the chassis-to-ground impedance consisting of the chassis-to-ground capacitance shunted by the power line impedance. An external electric field may also result from a potential difference between chassis and power line.

c. There is also the possibility of push-pull currents flowing in the power line as a result of coupling with the receiver.

4.5 POWER LINE INTERFERENCE

The highest levels of RF energy in many data processing machines appear as conducted interference on the power lines. This type of interference is suppressed quite effectively with an L-type filter properly installed in series with the main supply lines. Often, this filter is all that is required to reduce the interference levels to comply with the specification limits. For machines which still require additional suppression after the installation of such a filter, it usually suffices to locate the offending component and either adjust the circuitry or apply some simple inductance-capacitance (LC) network to filter out the interference. Avoid shielded wiring as much as possible, except in cases of absolute necessity, due to its high cost as well as the possible detrimental effects produced by the added capacitance. The usual method of protecting digital information channels against interfering noise involves the insertion of redundant digits. Various coding systems are used, including parity check, fixed count coding, recurrent burst correcting codes, and interlaced parity checks. These methods attempt to compensate for rather than reduce the interfering noise levels, and from a compatibility viewpoint do not provide the ideal solution. If the source of interference, both internal and external to the equipment, can be suppressed or confined, a more satisfactory solution to the interference problem is obtained. Included within these machines are such interference generating devices as DC motors, commutators, emitters, clutch magnets, solenoids, relays, switches, tubes, transmitters, amplifiers and associated electronic circuitry; as well as fluorescent and mercury arc lamps, functional corona, and high voltage supplies. Each of these devices presents varied interference problems.

4.6 BONDING OF COVERS

A very important part of developing interference-free data processing equipment lies in the retention of energy inside the unit. It is necessary to enclose the interfering unit in a well grounded, electrically tight enclosure, but an electrically tight enclosure is not always feasible with this type of equipment. Some modifications to existing covers and the screening of some functional open areas can result in a reduction of interference. Provide good electrical bonding between the covers and the machine frame, which is at ground potential, to reduce the RF energy present on the covers and the leakage through the seams and openings. Cover-screws with star washers under the screw heads must be tight to ensure good contact with the metal base. Electrically conducting glass and plastic panels could be used where it is necessary to have visual indication but these make the problem of confining radiated interference more difficult. A material is desired which will compensate for the natural shielding that is lost with the removal of steel covers. Shielding effectiveness of various metals is listed in *SN 1(1)* of *DN 5F5* of this handbook. The shielding effectiveness to the electric field using reinforced plastic covers sprayed with 10 mils of copper averages 25 dB between 0.015-20.0 MHz, and averages 8 dB to the magnetic field between 30.0-1000 MHz. The one big drawback for most of these covers, excepting the sprayed covers, is the difficulty of effecting a practical means of electrical bonding. To be most effective, it is necessary to design covers with as few open seams and with as few joints as physically possible. It is also necessary to provide good metal-to-metal contact over the entire contact surface. This becomes a perplexing problem when machines must be opened periodically for servicing. If the cover is removed it is unlikely that as good a bond will be made when it is replaced, unless costly devices such as electrically conductive gaskets or serrated spring-type fingers are available.

DESIGN NOTE 3B4 — ELECTRICAL SUBSYSTEMS

1. INTRODUCTION

One principal producer of electromagnetic interference is the electrical generation and distribution subsystem. Without careful design and application of noise suppression, this interference could be carried throughout the entire system. Improved mechanical design (including shielding and bonding) is an important step in interference suppression. Filtering and shielding at junction boxes and proper routing of interconnecting wires of each subsystem are also important. Do not bundle interference-free leads with leads that could carry noise or spurious signals. Also, avoid routing them near leads carrying large power pulses or harmonics. (See *Chap 5* of this handbook for further guidance in this area.) The characteristics of electric power supplied to airborne equipment at the equipment terminals and the requirements for the utilization of such power by the airborne equipment are delineated in *MIL-STD-704*.

2. AC GENERATORS—ALTERNATORS

For ac power generation subsystems, the alternator, which comprises a wound stator and a permanent magnet or dc field, is the main source of power. A good alternator will produce a "pure" sine wave with a small percentage of harmonics. Although other interference phenomena exist, harmonic generation is most significant. Reduce the generation of harmonics by careful consideration of the following items:

a. Ideally, if the alternator were completely symmetrical, no even harmonics would be present in the output. To achieve this objective, give careful attention to producing a uniform armature winding, constructing identical pole pieces, and avoiding any dissymmetry in the machine.

b. Since the voltage waveform generated depends upon the shape of the magnetic flux around the armature, sinusoidal flux distribution is an essential factor. Achieve sinusoidal flux distribution (1) by having many slots per hole per phase, (2) by proper shaping of the pole tips, (3) by avoiding saturation in the magnetic structure, and (4) by skewing the pole faces.

c. Harmonics are greatly reduced by a suitable choice of chord factor. The chord factor for the nth harmonic is cos $n\theta/2$ where θ is the electrical angle between the pole pitch and coil pitch. A typical value of 30° is taken for θ, because this greatly reduces the fifth and seventh harmonics, without appreciably affecting the fundamental.

d. With a three-phase alternator, the third harmonic and its multiples can be eliminated when the machine is delta-connected. Avoid a wye-connected machine with a grounded neutral because (with this connection), third harmonics are present in the phase-to-neutral voltage. Because of the advantage of grounding the neutral, it may be necessary to use special wiring techniques to eliminate these harmonics.

e. Reduce harmonics by distributing the winding over several slots per pole per phase. The distribution factor (D_h) for the nth harmonic is

$$D_h = \frac{\sin(mn\phi/2)}{m \sin(n\phi/2)} \qquad \text{(Eq 1)}$$

where ϕ is the slot pitch in electrical degrees and m is the number of slots per hole per phase. Choose the factor to eliminate the lowest harmonic which is not eliminated by one of these techniques.

f. Reduce tooth ripple generation by skewing through one slot pitch either the pole shoes or the armature slots.

These design considerations can produce a machine which generates a minimum of interference and reduces the amount of filtering required. If filters are required, use low-pass types with a cutoff frequency of one-half times the fundamental power frequency. One filter is required in each phase. Although all the indicated precautions have been taken, a well-designed alternator can radiate interference from the housing. Take care to obtain a good shield around the machine and to maintain a good bond to the airframe. A perfect shield is difficult to obtain because of the need for adequate ventilation. Often ventilation can be provided through tubular air vents, which also serve as wave guide attenuators to reduce the interference.

3. DC GENERATORS

Although many system power sources use an alternator, others make use of a dc generator. Comments on ac generators are also applicable to dc generators (see *Para 2*). The delineations such as winding symmetry, mechanical and electrical balance, close tolerances, and accuracy of machined parts are important. In addition, dc generators are subject to other interference problems, and without careful design can be the largest contributors to interference generation.

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3.1 BRUSH INTERFERENCE

The most significant source of interference is that which is generated by brushes. In most rotating equipment, electrical contact is made between the stator and the rotating armature. This contact is made by brushes sliding along continuous (slip rings) or discontinuous (commutator) metal surfaces. The transfer of electrical energy across such a sliding contact is accompanied by noise generation which is termed "brush interference." Reduce this interference by careful design and consideration of the factors in the following paragraphs.

3.2 CURRENT DENSITY

The interference generated will increase with increased current density. With increased current density, more heat is generated in the contact resistance. With increased temperature an oxide film is formed on the metal surface along the path where the brushes ride. Irregularities in this oxide film cause variations in the contact resistance as the machine rotates, and the unidirectional voltage is modulated with an alternating voltage which gives rise to interference. Provide larger brush surface area to reduce this problem. Too low a current density, however, develops nonuniform grooves which frequently cause brush chatter. As a guide, use contact current density of 77 to 93 kA/m^2 (50 to 60 A/in.^{2}) at full load for electrographite carbon brushes, and 108 to 140 kA/m^2 (70 to 90 A/in.^{2}) for metal graphite brushes.

3.3 BRUSH PRESSURE

The amount of noise generated reduces markedly as the brush pressure is increased. The effect occurs at all frequencies. The contact between the brush face and the metal surface becomes more uniform and constant as brush pressure is increased. This reduces the variation in contact resistance and hence reduces surface contact noise. In addition, arcing and severe transients caused by brush bounce and chatter are greatly reduced as brush pressure is increased. In general, increase brush pressure as the revolutions per minute of the machine is increased. Select the specific pressure depending on the revolutions per minute of the particular application. As the brush pressure is increased, the rate of wear increases, and the replacements are more frequent. For many missile applications, this may be insignificant because the life of the machine is relatively short. For manned vehicles, the increased replacement rate and cost are normally justified by a reduction in generated interference.

3.4 SURFACE FRICTION REDUCTION

By properly treating the metal surface with a graphite substance, the mechanical friction, the voltage drop, and hence the generated interference can be greatly decreased. Because of wear and high temperature, give special consideration to the metal surface upon which the brush rides. A copper surface quickly becomes covered with copper oxide, mixed with carbon particles, which result from brush wear. The resulting layer displays a non-bilateral effect not unlike a copper oxide rectifier. This results in a greater resistance drop at the negative terminal than at the positive terminal. This dissymmetry can result in considerable generation of interference. Improved performance results from plating the copper surface with a harder and less corrosive material, such as chromium. Although the resistivity is higher, the I^2R loss is not appreciable and the interference generated is greatly reduced. In addition, the chromium surface avoids grooving and shows greater resistance to wear.

3.5 BRUSH RESISTANCE

The generated interference is reduced for brushes with lower resistivity. Use graphite carbon brushes with specific resistance of 0.002 ohm for voltage applications greater than 30 volts. Use metal graphite brushes for machines which generate less than 30 volts. Although the design is a compromise, the brush with the lowest resistivity will generate the least interference. In slip-ring applications, where no switching action occurs, the brush design is far less critical. The brush can be composed of copper or precious metal contacts sliding on a chrome or precious-metal-plated slip ring. Such contacts are relatively free of interference. Brushes and slip rings operating in high altitudes present design problems. The lack of moisture in the air at high altitudes retards oxide formation. Although this oxide is the cause of interference, its presence does serve as a lubricant. Without this lubricant, severe wear results, considerable interference is generated, and the life of this rotating electrical device is seriously limited. Brushes which contain a lubricant, or which contain the materials to form the oxide, can be used in this application.

4. ELECTRIC MOTORS

Electric motors are capable of generating electromagnetic energy which may interfere with nearby electronic equipment. The levels of interference generated by similar motors vary by a factor as great as one thousand to one. Factors influencing the generation of this interference are as follows:

a. Arcing at the brushes.

b. Capacitance and inductance of the field and armature coils from local resonating circuits for multiples of line and commutator frequencies.

c. Discharge of electrostatic energy built up between moving parts. This is particularly true of high speed parts, such as the inner and outer races of ball bearings, where the grease or oil film acts as the dielectric through which the discharge takes place.

d. Poor concentricity between the commutator and bearings, causing brush bounce.

e. Commutator segments that are too free.

f. Too little or too much brush spring tension.

g. Poor mechanical balance of the armature resulting in armature shaft "whipping." This causes the brushes to bounce on the commutator which results in arcing.

h. Armature shaft of too small diameter resulting in shaft whipping, particularly under load.

i. Radiation of interference through air vents adjacent to the commutator and from the plastic covers of brush holders. Fine mesh wire screen over the air vents can confine the interference, and metal caps over the brush holders would prevent radiation of interference.

5. COMMUTATOR INTERFERENCE

Commutators, which are used on many dc machines, produce serious transients which propagate throughout the system. The combined effect of brush noise and commutator transients causes a noise voltage commonly termed "hash." Machines which have commutators are most difficult from an interference point of view. Avoid use of dc machines whenever possible. If their use is unavoidable, use the following techniques to reduce the interference:

a. Precision Design. If the designer maintains careful machining and symmetry in the design, the transients generated can be greatly reduced.

b. Interpoles. Interpoles reduce the voltage induced in the armature coils resulting from the leakage flux from the poles during commutation. They also cancel the self-inductance of the armature coils during the commutation period. On larger machines, it is possible to improve commutation and reduce transients by adding interpoles, but they are not used on small machines due to lack of space and increased weight.

c. Compensating Windings. Additional windings (known as compensating windings) on the pole pieces, produce an effect similar to interpoles. Although these windings add to the expense of the machine, it is usually justified by the decrease in interference generation.

d. Special Brushes. Fabricate the brush from several layers of laminated material to obtain unique characteristics. Make the leading edge of the brush from a low resistance material and increase the resistance through the lamination so that the trailing edge is a high resistance material. With this configuration, the current is reduced on the trailing edge and the commutator is required to break less current. Less arcing and transients result and interference is reduced.

6. POWER DISTRIBUTION

The power distribution subsystem for an aerospace system includes the (1) cables, (2) connectors, (3) switches, (4) relays, (5) disconnect switches, and (6) plugs. The distribution subsystem is critical in interference because it runs throughout the entire aerospace system. For this reason, it can conduct transients and noise voltages into the numerous subsystems which make up an aerospace system.

6.1 TRANSFORMERS

In ac subsystems, iron-cored transformers are often used. These devices exhibit nonlinear characteristics between the voltage and current, or between the flux and magnetizing force. Hence, a transformer produces numerous harmonics in both higher and lower frequency regions. In addition, because the permeability of the iron core is not constant, the inductance varies and the input impedance of the transformer varies in a nonlinear fashion. This nonlinearity results in additional generation of harmonics in the power distribution subsystem. Transformers are frequently used with a transmission line and the generation of higher harmonics is particularly difficult, because these higher frequencies tend to resonate with the transmission line parameters. Because of its high frequency components, the energy developed by these resonant circuits is readily coupled into many other portions of the system. In order to minimize the generation of harmonics and interference, high permeability material must be used as a core for power transformers. Less harmonic generation exists when using mu metal and other high-alloyed magnetic irons rather than silicon steel.

6.2 RELAYS

Switching circuits which employ electromechanical relays can be a great source of interference. Take considerable precaution to develop an interference-free system. The following points are important in the consideration of such relays.

6.2.1 MECHANICAL BOUNCE AND CHATTER. With the possible exception of mercury switches, most electromechanical relays show a tendency to bounce and chatter. This causes repetitive opening and closing of the contacts, and transients are generated. These transient disturbances can be of large magnitude and long duration with the result that interference is propagated throughout the system. Mechanical bounce and chatter can be the result of a relay's own closing action, or can result because of vibration and acceleration of the vehicle carrying the relay. Shock mounting the relay and careful designs of the closing mechanism are required to reduce bounce and chatter.

6.2.2 CIRCUIT INTERRUPTIONS AND CLOSURES. During normal operations, some arcing results as the contacts are opened and closed. This arcing can cause spitting and sputtering with the result that additional arcing occurs on subsequent openings and closings. Arcing produces a large amount of interference voltage over a wide frequency spectrum. Reduce this interference by enclosing the relay and its associated circuitry in a metallic shielded can. It is usually necessary to use multiple shields in order to sufficiently reduce this wide frequency response interference. Low-pass filters also provide a method of reducing or eliminating the interference developed by relays and other switching devices, which produce wave shapes with steep rise times and high frequencies. Low-pass filters use an inductance that has the least possible distributed capacitance together with feed-through type capacitors. Another method of noise suppression is simply to connect a series resistance and capacitance across the terminals of the relay. It is important to use a resistor of a few ohms in series with the capacitor, so that the discharge current can be reduced when the contacts of the relay are closed (see *DN 3C4*).

6.3 SWITCHING DEVICES

Switching devices can cause transients similar to relays, so consider them as potential interference sources. Whenever a large current is interrupted by the changing of a switch, an arc will develop and considerable radiated and conducted interference can result. The problem is increased when energy storage components (such as inductors and capacitors) are in the circuit. Use resistance capacitance diode suppression networks to reduce noise that is the result of switch action. Occasionally, it may be necessary to shield the switch unit, but use this technique only as a last resort due to the weight and space increases involved.

6.4 LIGHTNING SURGES

Lightning constitutes a major hazard to electronic ground equipment having data transmission and power lines (either overhead or underground). Lightning surges can occur frequently on transmission lines, causing semiconductor damage, contact burning, and rectifier damage. In addition to damage caused by direct strikes of lightning, damage also results from the side effects due to susceptibility of underground lines to resulting earth-potential gradients, potential rise of associated grounds, and induction in nonshielded lines. One study of lightning surges, during 10 thunderstorms, revealed 249 surges on one cable pair in a metallic sheath. For lightning protection, see *Chap 7* of this handbook.

7. DC POWER SUPPLIES

The electronically regulated dc power supply is universally employed to furnish the stable low voltages required by radar and other type receivers. The basic electrical circuit arrangement of such a power supply may be described in the following terms. The regulating element consists of a variable series impedance, furnished in the form of an electron tube and resistance combination. The magnitude can be controlled electrically from an error signal associated with the output voltage of the power supply and a reference voltage. The degree of regulation obtainable is a function of the loop gain provided, and the absolute stability of the output voltage is determined primarily by the constancy of the reference voltage by the use of the gas-discharge tube. By incorporating wide frequency band characteristics to the loop gain elements, the maximum rate of change of regulation can be extended, and this circuit becomes effective in reducing the fundamental frequency and harmonics of the primary supply voltage.

7.1 RECTIFIERS AND FILTERS

Use single-phase half-wave rectifiers only when the low average value of load voltage and the presence of large variations in this voltage are permissible. The chief advantage of this type of rectifier is its simplicity. A method of overcoming both disadvantages is to place a capacitor across the load so that it will behave as a shunt. By using the proper capacitor, it is often possible to increase the value of E_{dc} to within a few percent of the peak voltage E_{pk}.

a. The principal disadvantage of this method of filtering is the large current drawn by the capacitor during the charging interval. This current is limited only by transformer and rectifier regulation; yet it must not be so large as to cause damage to the rectifier. The higher the value of E_{dc} with respect to E_{ac}, the larger the charging current taken by the capacitor.

b. Therefore, if a smooth current wave is desired, some other method of filtering must be used. To obtain less voltage variation or ripple amplitude, after the limiting capacitor size has been reached, an inductive reactor may be employed. It may be placed on either the rectifier or the load side of the capacitor, depending on whether the load resistance (R) is high or low. In the former, the voltage E_{dc} has less than the average value 0.45 E_{ac}, because the inductor delays the buildup of current during the positive half-cycle of voltage. The inductor in this case should have a high value of reactance (X_L) compared to the capacitive reactance (X_C) in order to filter effectively.

When R is low, reactance (X_L) should be high compared to R. When the load resistance R is high (inductive reactor placed on the rectifier side of the capacitor), the ripple amplitude across R is $-X_C/(X_L - X_C)$ times the amplitude generated by the rectifier, if R is high compared to X_C. When the load resistance is low (inductive reactor placed on the load side of the capacitor), the ripple amplitude across R is R/X_L times the ripple obtained with capacitor only. R here is small compared to X_L.

c. Large values of inductance are required to cause continuous current flow when the inductor is on the rectifier side of the capacitor in a half-wave rectifier circuit. Since current tends to flow only half the time, the rectified output is reduced accordingly. This difficulty is eliminated by the use of the full-wave rectifier. The alternating components of the output voltage have a fundamental frequency double that of the supply and the amplitudes of these components are much less than for the half-wave rectifier. The higher ripple frequency causes L and C to be doubly effective; the smaller amplitude results in smaller percentage of ripple input to the filter. Current flow is continuous and E_{dc} has double the value that it had in the half-wave rectifier. For these reasons, this type of rectifier is widely used.

7.2 POLYPHASE RECTIFICATION

The effect of rectifying more than one phase is to superpose more voltages of the same peak value, but in different time relation to each other. Increasing the number of phases increases the value of E_{dc} and the frequency of the alternating components, and decreases the amplitude of these components. Ripple frequency is p times that of the unrectified alternating voltage, p being 1, 2, 3, and 6 for the respective waves. Generally, p may be taken to represent the number of phases, provided that due allowance is made for the type of circuit. Rectifiers with p = 3 or 6 are derived from three-phase supply lines and, by special connections, rectifiers with p = 9, 12 or more are obtained. The frequency of any ripple harmonic is mp, where m is the order of the harmonic. Ripple voltage for any of these rectifiers can be found by the Fourier relation

$$A_n = \frac{2}{T}\int_{-T/2}^{T/2} f(t)\cos(n\omega t)\,dt \qquad \text{(Eq 2)}$$

Where:

A_n = amplitude of the nth ripple harmonic

T = ripple fundamental period

t = time (with peak of rectified wave as t = 0)

ω = $2\pi/T_p$ = $2\pi \times$ supply line frequency

f(t) = ripple as a function of time = $E_{pk}\cos\omega t$, $T/2 > \omega t > -T/2$.

The voltage peak is chosen as t = 0 to obtain a symmetrical function f(t) and eliminate a second set of harmonic terms (which will develop) but with $\sin(n\omega t)$ under the integral. In a typical situation, a ripple amplitude will develop for the ripple fundamental and (in turn) will produce the second and third harmonics with reactor-input filters. If a curve, the ratio P_A of ripple amplitude to direct output voltage, is plotted against the number of phases (p), it will follow that P_A diminishes by a considerable amount for the second and third harmonics. In general, if a filter effectively reduces the percentage of fundamental ripple across the load, the harmonics may be considered negligible.

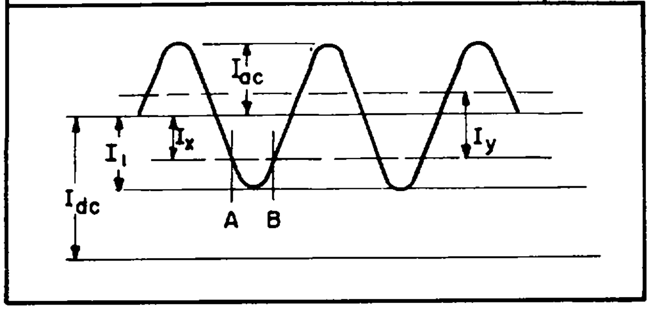
7.3 FILTER CAPACITOR

Consider the rectifier circuit which delivers single-phase, full-wave rectifier output to an inductor input filter and then to a variable load (see *Para 7.1*). In such a circuit, the filter inductor keeps the capacitor from charging to a value greater than the average E_{dc} of the rectified voltage wave at heavy loads. At low loads, the dc output voltage rises above the average of the rectified wave, as shown by a typical regulation curve. Starting at zero load, the dc output voltage (E_O) is 1.57 times the average of the rectified wave. As the load increases, the output voltage falls rapidly to E_1 as the current I_1 is reached. For any load greater than I_1, the regulation is composed only of the two components IR and IX. It is good practice to use a bleeder load I_1 so that the rectifier operates between I_1 and I_2.

a. Filter elements X_I and X_C determine the load I_1 below which voltage rises rapidly. The filter attenuates the ac ripple voltage so that there exists across the load a dc voltage with a small ripple voltage superposed. A chock-input filter attenuates the harmonic voltages much more than the fundamental and, since the harmonics are smaller, the main function of the filter is to take out the fundamental ripple voltage. This has a peak value of 66.7% of the average rectified dc voltage for a single-phase full-wave rectifier. Since this ripple is purely ac it encounters ac impedances in its circuit. If the choke impedance is designated X_L and the condenser impedance X_C (both at the fundamental ripple frequency) the impedance to the fundamental component is $X_L - X_C$, the load resistance being negligibly high compared to X_C in an effective filter.

b Conversely, the dc voltage produces a current limited mainly by the load resistance, provided the choke IR drop is small. Alternate current and dc components are shown in *SN 7.3(1)* with the ripple current (I_{ac}) superposed on

SUB-NOTE 7.3(1) AC and DC Components



the load direct current (I_{dc}.) If the direct current is made smaller by increased load resistance, the ac component is not affected because load resistance has practically no influence in determining its value. Hence, a point will be reached, as the dc load current is diminished, where the peak value of ripple current just equals the load direct current. Such a condition is given by dc load (I_1) which is equal to I_{ac}. If the dc load is reduced further (e.g., to the value I_x) no current flows from the rectifier in the interval A-B of each ripple cycle. The ripple current is not a sine wave, but is cut off on the lower halves (see the heavy line of *SN 7.3(2)*). Now the average value of this current is not I_x, but a somewhat higher current I_y. That is, the load dc is higher than the average value of the rectified sine-wave voltage divided by the load resistance. This increased current is caused by the tendency of the capacitor to charge up to the peak of the voltage wave between such intervals as A-B; hence the term capacitor effect which is applied to the voltage increase. The limiting value of voltage is the peak value of the rectified voltage, which is 1.57 times the sine-wave average, at zero load current.

c. To prevent capacitor effect, the choke must be large enough so that I_{ac} is equal to or less than the bleeder current I_1. This consideration leads directly to the value of choke inductance. The bleeder current (I_1) is E_1/R_1, where R_1 is the value of bleeder resistance. The ripple current is the fundamental ripple voltage divided by the ripple circuit impedance, or

$$I_{ac} = \frac{0.667E_1}{X_1 - X_C} \qquad \text{(Eq 3)}$$

Equating I_1 and I_{ac} for a single-phase full-wave rectifier

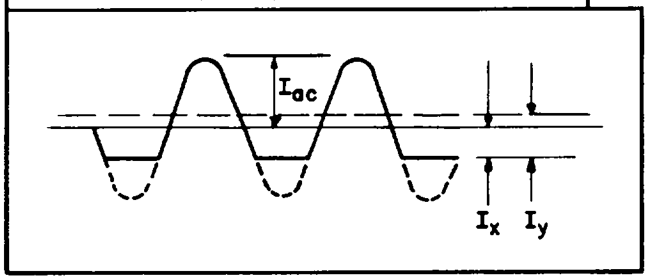
$$R_1 = \frac{X_L - X_C}{0.667} \qquad \text{(Eq 4)}$$

Here, the value of capacitance also has an effect, but is minor, relative to that of the choke. In a well-designed filter, the choke reactance (X_L) is high compared to X_C. Therefore, the predominant element in fixing the value of R_1 (and of I_1) is the filter reactor. Polyphase rectifiers have similar effects, but the rise in voltage is not so great because of the smaller difference between peak and average dc output. In general, the bleeder resistor for eliminating capacitor effect can be found from

$$R_1 = \frac{X_L - X_C}{A_1} \qquad \text{(Eq 5)}$$

where A_1 is the fundamental ripple peak amplitude that occurs in polyphase rectifiers, and X_L and X_C are the filter reactances at fundamental ripple frequency (see *Para 7.2).*

SUB-NOTE 7.3(2) Capacitor Effect at Light Load

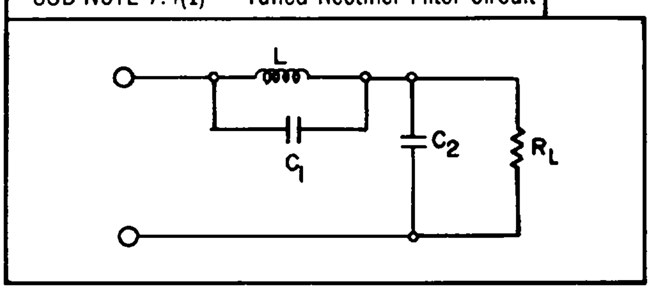


7.4 TUNED RECTIFIER FILTERS

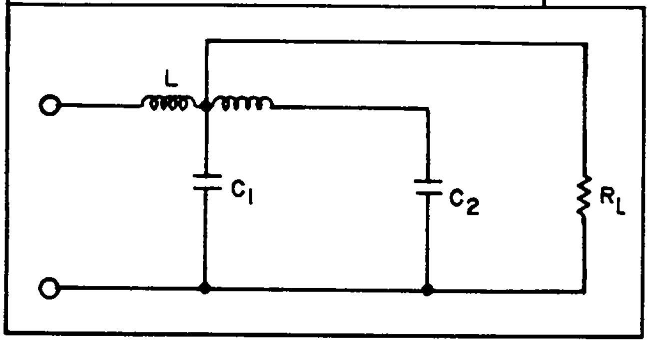
Sometimes an inductor-input filter is tuned as in *SN 7.4(1)*. The addition of capacitor C_1 increases the effective reactance of the inductor to the fundamental ripple frequency. Both regulation and ripple of this type of filter are improved. The filter is not tuned for the ripple harmonics, so the use of high Q filter inductors is unnecessary. An increase in effectiveness of the filter inductor of about 3:1 can be realized in a single-phase full-wave rectifier circuit.

a. Tuned filters are less effective with three-phase rectifiers because slight phase unbalance introduces low frequency ripple which the filter does not attenuate. Filters may be tuned as in *SN 7.4(2)* where the filter capacitor (C_1) is connected to a tap near the right end of inductor (L), and the other filter capacitor (C_2) is chosen to give series resonance and hence zero reactance across the load at the fundamental ripple frequency.

SUB-NOTE 7.4(1) Tuned Rectifier Filter Circuit



SUB-NOTE 7.4(2) Alternate Tuned Rectifier Filter Circuit



b. Because of choke losses, the impedance across R_L is not zero, but the resulting ripple across load resistor R_L can be made lower than without the use of capacitor C_1. Ripple is attenuated more than in the usual inductor-input filter, but regulation is not substantially different.

c. In a shunt-tuned power supply filter, as shown in *SN 7.4(1)*, the current drawn from the rectifier is likely to be peaked because two capacitors C_1 and C_2 are in series, without intervening resistance or inductance. This peak quickly subsides because of the influence of the inductor L, but an oscillation may take place on top of the current wave. The rectifier tube must be rated to withstand this peak current. At the end of commutation the voltage jumps suddenly from zero to V. Peak rectifier current may be as much as

$$I_{pk} = \frac{V}{\omega L_s} \qquad \text{(Eq 6)}$$

L_s is half the transformer leakage inductance and $\omega = 2\pi$ X_L frequency of oscillation determined by L_s in series with C_1 and C_2. This peak current is superposed on I_{dc}. It flows through the anode transformer and tube, but the current in choke L is determined by ripple voltage amplitude and choke reactance. Series resistance (R_s) reduces this peak current to the value $-\pi R_s/4\omega L_s$

$$I_{pk} = \frac{V}{\omega L_s} e \qquad \text{(Eq 7)}$$

It is obtained by applying a step function voltage to the series R_sL_sC circuit. The criterion for oscillation is

$$R_s < \sqrt{\frac{L_s}{C}} \qquad \text{(Eq 8)}$$

where C is the capacitance of C_1 and C_2 in series. Many rectifier tubes have peak current ratings which must not be exceeded by such currents.

7.5 GRID-CONTROLLED RECTIFIERS

Smooth control of rectifier dc voltage under load conditions is possible through the use of thyratrons or ignitrons with phase shift control of the grid or igniter. Stable control or filtered output is possible only with choke input filters. With grid control, if the filter choke inductance is great enough, the tube conducts even after the anode reaches zero. The tendency of current to stop at voltage zero builds up voltage across the filter choke in such a direction that cathode potential is less than zero after the anode reaches zero. This conduction in the tube is maintained until the next tube fires. If the choke inductance is less than critical, tube current wave is discontinuous, regulation is poor, transient surges and oscillations in the output voltage occur, and control is unstable.

7.6 RECTIFIER TRANSIENTS

The shunt-tuned filter currents mentioned in the preceding paragraphs are transient. Since the tube current is cut off during each cycle, a transient current may occur in each cycle. When power is first applied to the rectifier, another transient occurs, which may be smaller or larger than the cyclic transient, depending on the filter elements. In reactor-input filters approximate the transient current by Eq 6 for a step function applied to the series circuit comprising filter L and C plus R_s. This circuit is valid because the shunting effect of the load is slight in a well-proportioned filter. In capacitor-input filters the same method can be used, but the inductance is the leakage inductance of the anode transformer. Therefore, Eq 7 applies, except that the maximum step function voltage is E_{pk}.

7.6.1 SPASMODIC-TYPE TRANSIENTS. Transients which occur when power is first applied differ from cyclic transients in that they are spasmodic. Power may be applied at any instant of the alternating voltage cycle, and the suddenly impressed rectifier voltage ranges from zero to E_{pk}. Spasmodic transients are difficult to observe on an oscilloscope because of their random character. It is necessary to start the rectifier several times for one observation of maximum amplitude, and the trace is faint because it appears for a very brief time. Excessive current inrush, which occurs when a power transformer is connected to a supply line, plagues rectifier design. The phenomenon is associated with core saturation. For example, assume that the core induction is at the top of the hysteresis loop at the instant when power is removed from the rectifier, and that it decreases to the remnant value (B_r) for $H = 0$. Suppose that the next application of power is at such a point in the voltage cycle that the normal induction would be B_2 This added to B_r requires a total induction far above saturation value; therefore, heavy initial magnetizing current is drawn from the line, limited only by primary winding resistance and leakage inductance. This heavy current has a peaked waveform which may induce momentary high voltages by internal resonance in the secondary coils and damage the rectifier tubes. Or it may trip ac overload relays. The problem is especially acute in large transformers with low regulation. A common remedy is to start the rectifier with external resistors in the primary circuit and short-circuit them a few cycles later. Some rectifiers are equipped with voltage regulators which reduce the primary voltage to a low value before restarting. In some applications the load is varied or removed periodically. Examples of this are keyed or modulated amplifiers. Transients occur when the load is applied (key down) or removed (key up), causing respectively a momentary drop or rise in plate voltage. If the load is a device which transmits intelligence, the variation in filter output voltage produced by these transients results in the following undesirable effects:

a. Modulation of the transmitted signal.

b. Frequency variation in oscillators, if they are connected to the same plate supply.

c. Greater tendency for key clicks, especially if the transient initial dip is sharp.

d. Loss of signal power.

7.6.2 INHERENT OSCILLATIONS. A filter which attenuates ripple effectively is normally oscillatory. Hence damping out the oscillations is not practicable, nor would it remedy the transient dip in voltage, which may increase with nonoscillatory circuits. The filter capacitor next to the load should be large enough to keep the voltage dip reasonably small. An approximation which neglects the damping effect of load and series resistance is

$$\Delta e_B = \frac{1}{R_L}\sqrt{\frac{L}{C}} \qquad \text{(Eq 9)}$$

where Δe_B is the transient dip expressed as a fraction of the steady-state voltage across R_L. Although the tendency for key clicks in the signal may be reduced by attention to the dc supply filter elements, the clicks may not be entirely eliminated. Use a key-click filter where key-click elimination is necessary.

DESIGN NOTE 3B5* ELECTRICAL IGNITION OF COMBUSTIBLE MIXTURES

1. INTRODUCTION

A serious problem in an electromagnetic compatibility program involves the design of the fuel subsystem to suppress arcs and other electrical discharges to prevent ignition of explosive mixtures (see *NFPA 407-1975* or *ANSI Z119.1-1976*). The elimination of ignition sources has become increasingly important due to the common use of low vapor pressure fuel such as JP-4. This type fuel develops an explosive vapor concentration within an enclosed compartment throughout the range of ambient temperatures encountered in the field. With gasoline fuel, the saturated vapors over the gasoline are normally too rich to be combustible.

2. IGNITION ENERGY REQUIREMENTS

Tests have shown that saturated hydrocarbon gases and vapors require about 0.25 millijoules (mJ) of electrical energy for spark ignition of optimum mixtures with air.

3. FLAMMABLE AND COMBUSTIBLE LIQUIDS

Flammable liquids may form flammable vapor-air mixtures while being handled or stored. Characteristics of flammable and combustible liquids are given below:

a. If the temperature of the liquid is below its flash point, the mixture above its surface will be below the lower flammable limit, or too lean to burn.

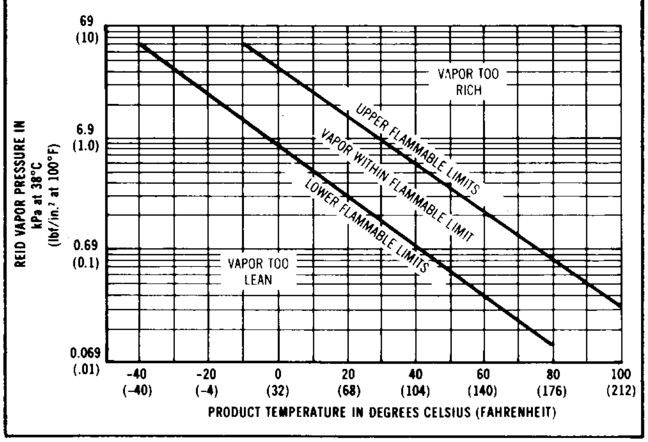
b. Liquid near its flash point is more likely to have a flammable vapor-air at any free surface.

c. If the liquid temperature is far above its flash point, the vapor mixture at the free surface will be above the upper flammable limit, or too rich to burn.

d. If the vapor mixture is below or above the flammable limits, it will not ignite, even though a spark should occur.

e. In general, when the vapor-air mixture at the liquid surface is midway between the upper and lower flammable limits, conditions are optimum for ignition. *Sub-Note 3(1)* shows the relation between (1) temperature, (2) Reid vapor pressure, and (3) flammable limits of petroleum products at sea level (see *NFPA 77-1972*).

SUB-NOTE 3(1) Relation Between Temperature, Vapor Pressure, and Flammable Limits of Petroleum Products



f. The principal characteristics of aviation fuels which are factors in susceptibility to inadvertent ignition are (1) flash point, (2) flammability limits, (3) vapor pressure, (4) autoignition temperature, (5) distillation range, and (6) electrostatic susceptibility. See *SN 3(2)* for principal characteristics.

4. ELECTROSTATIC SUSCEPTIBILITY

By their nature, Jet A and Jet B turbine fuels generally retain more impurities than AVGAS and are more prone to accumulating static charges. The degree to which a charge is acquired depends on fuel velocity, impurities, condition of charge separating surface, etc.

5. BONDING, GROUNDING, EARTHING, AND EXPLOSIONPROOFING

Proper application of bonding, grounding, and earthing techniques is essential in preventing sparks and potential differences in areas prone to ignition of flammable vapors (see *DN 5D6* and *DN 7B4*). Ensure that certified explosionproof electrical devices and components are used in such areas. See *MIL-STD-454, MIL-STD-810*, and the National Electrical Code in *ANSI/NFPA 70 -1975*.

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*This Design Note has been developed in part from *NFPA 77-1972*, and with the permission of the National Fire Protection Association.

SUB-NOTE 3(2) Principal Characteristics of Aviation Fuels

CHARACTER-ISTICS \ FUEL	AVGAS	JET A	JET B	JP-7	THERMALLY STABLE (*MIL–T–25524*)
Flash Points					
a TAG Closed-Cup Test (*FED–STD–791*)°C at Sea Level	−45 6°	+35° to +62 8°	−23 3° to −1 1°	—	—
b Pensky-Martens Closed-Cup Test °C (ASTM Std D93-66)	—	+60°	Below −23 3°	+60° Min	+43 3° Min
c Air Saturation Test °C (Utilizes Upward Flame Propagation)	−59 4° to −65°	—	Down to −51 1°	—	—
Flammability Limits					
a % by Volume*	1 4 to 7 6 in general	0.6 to 4 9 average	0 8 to 5 6 average	—	—
b Temperature Range at Sea Level in Storage Tank °C	−45 6° to −1 1°	+35° to +73 9°	−23 3° to +37 8° Approx	—	—
Vapor Pressures kPa (lbf/in²) Absolute (Measured by Reid Method at 37 8°C) (See ASTM D323-72)	38 to 48 (5 5 to 7 0)	About 0 7 (0 1)	14 to 21 (2 0 to 3 0)	—	—
Autoignition Temperatures** °C (Minimum)					
a Test Method A	448 9°	246 1°	248 9°	—	—
b Test Method B	440 6° to 575 6°	226 7° to 243 3°	243 3°	—	—
Distillation Range (Boiling Points Determined by ASTM Method D86-67) (1972)					
a Initial Boiling Point °C	43 3°	162 8°	57 2°	—	—
b. Approx Boiling Point °C	162 8°	232.2°	251 7°	—	—

NOTES. AVGAS—All gasoline grades of octane ratings suitable for reciprocating engines
Jet A (Known in the US as AVTUR)—Kerosene grades of fuel for turbine engines
Jet B (Known in the UK as AVTAG)—All blends of gasoline and kerosene fuel grades for turbine engines One grade of a Jet B fuel is JP-4 (*MIL–T–5624*)
JP-7—A low volatility turbine fuel (*MIL–T–38219*) that is used only by the SR71
Thermally Stable (*MIL–T–25524*)—Aviation Turbine Fuel

*Lower limit represents the minimum concentration while the upper limit represents the maximum amount of fuel vapor in air that will permit combustion

**These temperatures were derived by the reproducible laboratory test procedures as indicated, however, in actual field conditions these ignition temperatures may be higher

SECTION 3C SUSCEPTIBILITY

DESIGN NOTE 3C1* INTRODUCTION

1. GENERAL

Devices using electrical power are susceptible to electromagnetic interference in several critical areas. The detrimental effects extend from nuisance to malfunction of equipment. The dynamic range is compressed, gain is reduced at many frequencies, and threshold levels or false alarm rate deteriorate. Devices become conditionally stable and occasionally break into oscillations. Equipment can become increasingly vulnerable to jamming and accuracy may be completely lost. The system's compatibility may be adequate when it is delivered but without proper design the compatibility will not continue under normal usage and aging.

2. OVERLOADING

Overloading is caused by an increase in the amplitude of the desired signal. The increase may drive the channel into saturation so that no output response will result from an input command. There is a time lag between the period that the device goes into saturation and recovers from it. When the device becomes overloaded or saturated, the position of the shaft may drift or run to its zero position or to the extreme unbalance at one or the other ends of its excursion.

3. BLOCKING

Blocking occurs in systems when an undesired input renders a channel ineffective, e.g., the blocking of the radar receiver by the transmitted radar pulse. Because of space and complexity limitations, the same waveguide and antenna system is often used for both transmitter and receiver. Although the radar receiver is isolated from the antenna and waveguide assembly during the time the transmitter is on, the transmitted pulse still leaks into the receiver. The receiver sees this RF energy as a returned signal of high amplitude. It saturates the radar receiver and when the pulse is over, the receiver remains blocked. Unintentional blocking of one function by another can occur on a continuous basis or it may only produce a blind spot in a cycle of the operation. Continuous blocking can almost always be detected during the functional checkout and testing if the offending source or jammer is activated. The intermittent or part-cycle blocking usually occurs when different equipments are integrated together into one system.

4. OFFSETS

Offsets may occur as a result of conducted, coupled, or radiated energy which may be internal or external to the system. Equipment is susceptible when its output may be offset or biased from that which should occur for given command inputs. The electrical output of transducers is often proportional to displacement from zero position, which is established by alignment holes or other fixed mechanical arrangement. The holes and guide pins may become gouged or distorted and the mechanical configuration may get bent. Often the reference line or plane to which the transducer should be aligned is not available for measurement. In this case some intermediate reference must be selected.

4.1 OFFSET ERRORS

As a result of study, specify the mechanisms which are subject to offset errors. Tolerable errors can be defined in two ways. First, the mechanical tolerance can be specified. If a pitch gyro is to be installed, specify the reference plane in measurable terms. If the gyro must be located near the center of gravity, determine an allowable tolerance dimension. Second, specify the electrical tolerance. Resolvers, synchros, and pickoff elements that are sensitive to orientation must have measurable output tolerance to permit verification. Use levels and inclinometers to orient the case while the components are adjusted for zero output.

5. HIGH POWER RF SOURCES

High power RF sources both internal and external to the aircraft can cause overheating or malfunctioning of equipment on board. Metallic decals or labels in areas where high RF levels exist can get hot and cause damage to nonmetal parts. A high power RF source impinging on a metallic surface can generate sparks which could cause a fire or

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*This Design Note extensively revised 31 Jan 91.

explosion if fuel vapors are present. Restrict both high power RF sources and fuel vapors from entering areas in the aircraft where combustion can occur.

5.1 DIELECTRIC HEATING

At high frequency, dielectric materials exhibit a loss phenomenon which is analogous to hysteresis loss in magnetic materials. The material between the bridge wire and the case of a squib is susceptible to such effect. In the presence of high power jamming or radar equipment, squib action can occur due to dielectric heating. Restrict the choice of dielectric materials used or attenuate or shield dielectric devices from conducted RF or from strong RF fields.

5.2 POWER EQUATION

By the use of the basic power equation

$$P_r = \frac{P_t G_r G_t \lambda^2}{(4\pi r)^2} \qquad \text{(Eq 1)}$$

Where:

P_r = power received (watts)

P_t = transmitter power (watts)

G_r = gain of receiving antenna

G_t = gain of transmitting antenna

λ = wavelength (meters)

r = distance between antennas (meters).

Power versus frequency plots may be developed for each receiver from which isolation requirements may be derived. As design data becomes available, such plots may be changed to reflect the true system requirements more accurately.

5.2.1 DETERMINATION OF LIMITS. The requirement to determine limits stems from one of these situations:

a. No limits for interference or susceptibility control have been applied to the system by procurement compliance to *MIL-E-6051* or *MIL-STD-461*.

b. Limits have been applied to the system which do not necessarily pertain. For example, this may occur when an aircraft specification is applied to a ground support station.

5.2.2 ESTABLISHMENT OF LIMITS. In either of the situations described in *Para 5.2.1*, accurate limits for interference and susceptibility control must be established if assurance of a compatible system is to be derived. It may be necessary to develop different limits for different portions of a system depending on system parameters. Some of the parameters which should be considered are:

a. Equipment Location: In very large systems, separation is an important factor.

b. Time Sharing of Equipment: Interfering equipment, which is not operated during critical phases of system performance, need not meet the same requirements as the equipment which operates simultaneously.

c. Frequency Sharing of Equipment: Frequency density plots will present possible conflicts.

d. Mobility of Equipment: The equipment which may be moved from one portion of a system to another will require special consideration.

5.2.3 INTERFERENCE LIMITS. Interference must be limited to some value less than that which would cause erroneous responses in the susceptible equipment of a system. Therefore, the first step in establishing tolerable levels of interference is to determine the threshold levels of all intentional receiving equipment. When the gain of the respective antennas is taken into account, and by making certain basic assumptions of the gain over the frequency spectrum of interest, levels in terms of field intensity or power density versus frequency may be plotted. Unfortunately, receivers usually react to both broadband pulse continuous wave (CW) and CW interference. Therefore, additional assumptions or calculations must be made regarding those sensitivities which are not considered normal operating conditions. Thus, plots may be developed for each receiver in terms of both broadband and narrow band noise. When the plots from all receivers are combined, the allowable levels of interference are thereby established.

5.2.4 SUSCEPTIBILITY LIMITS. Susceptibility limits can be established in much the same manner as interference limits. However, the governing criterion is reciprocal, in that equipment must perform in the environment which will be generated by the system or other nearby systems. Thus, communication receivers should not be jammed by a collocated radar working on its assigned frequency, etc. Interference limits are established by determining the susceptible characteristics of receiving equipment.

5.2.5 POWER LEVELS FOR SAFETY. In reciprocal fashion, susceptible limits may be established by determining power levels from transmitting elements for off-frequency conditions as well as assigned frequencies. In like manner, the same assumptions must be made. Thus, power density levels at any specific location may be calculated by

$$P_d = \frac{P_t G_t}{4\pi r^2} \qquad \text{(Eq 2)}$$

Where:

P_d = power density (watts/m^2)

P_t = transmitter power (watts)

G_t = gain of transmitting antenna

r = distance from transmitting antenna to equipment location (meters).

5.2.6 SIDE AND BACK ANTENNA LOBES. In many subsystems, side and back lobes become more important than the main lobe. This is due to usual mounting mechanisms, where the antenna is located high above associated equipment and sweeps with a line-of-sight clear beam. However, considerable main beam power may be measured at great distances from the antenna for high power sets.

5.2.7 HAZARDOUS RF RADIATION. When dealing with high power transmitters, the area of hazardous radiation should be computed about the antenna. Thus

$$r = \sqrt{\frac{P_t G_t}{4\pi P_d}} \text{ meters} \qquad \text{(Eq 3)}$$

The near field effects should also be taken into consideration. For a parabolic dish or dipole:

$$r \approx \frac{D^2}{\lambda} \qquad \text{(Eq 4)}$$

Where:

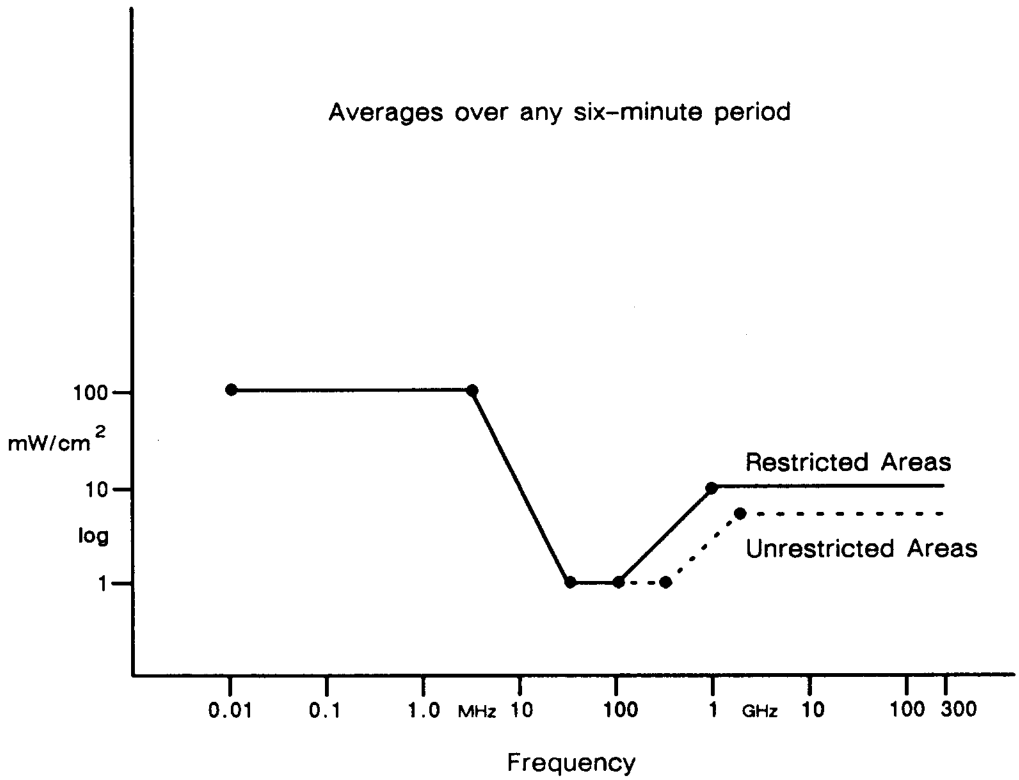
r = distance from the antenna to end of the near field

D = diameter of dish or length of dipole

λ = wavelength

The gain of antennas takes extreme excursions within the near field, depending on the exact point in space where the gain might be measured. However, far field equations will probably still provide reasonable estimates of worst-case power levels within this region. See *AFOSH 161-9* and *SN 5.2.7(1)* for more details on radiation limits as related to personnel safety.

SUB-NOTE 5.2.7(1) Maximum Permissible Exposure Limits



6. RESISTIVE HEATING

When ac or dc current flows through any resistive device, the energy dissipated in the form of heat is I^2R. Heat can act as an undesirable signal and can cause heating of devices which should not be heated without the application of a specified control current or which have operating characteristics dependent on temperature. The ac resistance cannot, in general, be assumed to be the same as the dc resistance. Squibs, for example, which have dc resistances under 1 ohm characteristically exhibit 30–40 ohms at UHF frequencies. I^2R loss is further dependent on the reactance portion of the ac impedance. The reactance of a squib varies from zero to several hundred ohms at UHF and changes from inductive to capacitive. No power can be dissipated in a reactance, but it does control the current flowing through the ac resistance in series with it.

6.1 TEMPERATURE COEFFICIENT

The resistive component of an electrical circuit has a temperature coefficient which is defined as the change in resistance per unit resistance per degree rise in temperature. The resistance varies according to the relation

$$R_t = R_0(1 + at) \qquad \text{(Eq 5)}$$

Where:

R_t = resistance at temperature t

R_0 = resistance at 0°C

a = temperature coefficient

t = degrees above 0°C.

6.2 DISSIPATION IN SPACE

Space applications make the I^2R heat dissipation problem serious if no artificial cooling environment is provided. Normally the I^2R heat can be carried away by convection, conduction, and radiation. If no atmosphere is available heat convection is not possible. Heat conduction and heat radiation exchanges can only be made between the electronic equipment and other parts of the system.

7. SPARK-THROUGH

Static voltages can build up on isolated or floating circuits. Winds blowing over ungrounded wires have resulted in static voltages which have caused inadvertent squib detonation. Squibs which employ ungrounded and shielded input cabling are subject to spark-through and placing a short across the squib input terminals will prevent inadvertent firing. Static buildup in other circuitry causes the ungrounded secondary of a transformer feeding an ungrounded amplifier grid to be subject to error. The cure is to provide a bleeder or static ground in susceptible circuits.

8. FALSE TRIGGERING

If a stray or false signal exhibits the characteristics of the true signal there is no way that a device (mechanical, electronic or human) can detect it. Use the following features to achieve discrimination against false triggering.

a. Pulse Shape. The desired pulse shape may be well defined and repeatable. If not, incorporate some simple waveform control techniques in the generating circuitry to make them unique compared to false triggers.

b. Rise-Time Control. Design the device being triggered or activated to respond to inputs having a certain rise time and to reject others having faster or slower rise times.

c. Pulse-Width Control. Make devices responsive to pulse width. By this technique, response will occur only to waveforms having the design pulse width.

9. FALSE SIGNALS

Bandwidth is the important consideration when evaluating susceptibility to false signals. Closed loops, servomechanisms, and regulators can often tolerate high levels of noise and false signals because of narrow bandwidth. Susceptibility to broadband noise is evaluated by determining the frequency spectra of the noise. Give consideration to the response of the system loop beyond its normal cutoff frequency. These characteristics are important because a high level interfering signal may exist a few octaves above the normal cutoff frequency and may be strong enough to penetrate the attenuation.

9.1 STRAY RESONANCES

High-gain amplifiers are particularly subject to stray resonances. Capacitors which should ideally exhibit low impedances tend toward self-resonance and a high effective reactance to ground. Lead length inductance may be high enough to resonate with bypass capacitances below the normal frequency of operation. For example, at 10 MHz, a 1000-pF bypass capacitor will series resonate with only $^1/_4$-µH inductance. Realize effective bypassing by forcing the capacitance to self-resonance with lead inductance at the operating frequency. Determine the self-resonant frequency of capacitors by cutting the lead lengths to equal those used in the actual circuit. Tie the leads together to form a series-resonant circuit. Loosely couple a grid-dip meter to the circuit to determine the frequency at which resonance occurs as evidenced by maximum circuit current.

9.2 ABOVE TEN MEGAHERTZ

There are many possible methods for coupling beyond 10 MHz. It is often necessary to shield the entire assembly to prevent entrance of spurious signals and to ensure high gain without instability. It is practically impossible to eliminate interstage inductive coupling effects in high gain amplifiers without an enclosing shield. With an enclosing shield, the box formed can be treated as a waveguide. For practical chassis and shield dimensions, the waveguide formed has a low-frequency cutoff many octaves above the amplifier frequency. In this instance, with the lowest mode of electromagnetic wave propagation, the box provides 27-dB attenuation for each unit of length equal to the largest width dimension. A small chassis of 25 × 51 mm (1 × 2 in.) cross section will provide 27-dB attenuation for each 51 mm (2 in.) of length. Make the physical spacing between stages large enough so that the gain per 51 mm (2 in.) of length is much smaller than 27 dB. Extra spacing provides more interstage isolation.

9.3 VIBRATION-INDUCED EMI

Some important aspects of subaudio interference susceptibility are that it is not often sustained for more than a few seconds, it is difficult to detect, and it is usually superimposed on desired signal flow and marked by higher frequency hash, which is ignored by the loop. Subaudio interferences are generated as airborne vehicles exhibit dynamic structural resonances. The approximate frequencies of different vehicle assemblies resonate as follows: (1) the total vehicle resonates at a few hertz, (2) structural resonances go up to 10 Hz, and (3) bulkhead and equipment racks resonate at hundreds of hertz. Equipment and cable bundles vibrate as the airborne vehicle experiences agitation and electrical disturbances result in two ways: either transducers and sensors "see" the resultant displacement, velocity, or acceleration and generate an undesired output signal; or wires, cables, and bundles are moved through electric and magnetic fields. Induced voltages and current result, and under these conditions, rate gyros have produced enough undesired output to cause gross guidance disturbances. To eliminate this severe effect, install a notch filter to block the narrow band of frequencies caused by structural vibration.

9.4 AUDIO SUSCEPTIBILITY

Because of extensive use of relays, motors, timers, switches, sequencers, steppers, amplifiers, power supplies, and servomechanism loops for basic guidance, navigation, and control, audio-conducted susceptibility forms a major part of the compatibility effort. Subject equipment to susceptibility tests for radiated interference and conducted audio and RF interference in accordance with *MIL-STD-462*. Problems result when applying these over-simplified guides to a specific system evaluation. Therefore, prepare a study of the susceptibility characteristics not only of individual black boxes but also of the loops they fit into. More sophisticated testing is required for units which are part of guidance, computing, and control loops. In this area, determine critical frequency ranges, circuits to be tested, amplitude, and source impedance. Formulate test setups to simulate actual operation and determine if open circuit voltage represents a valid closed-circuit condition. Discrepancies can arise from using the arbitrary 3-V ac open circuit type of spectral susceptibility approach.

9.4.1 TEST CONSIDERATIONS. Practical test considerations which apply to audio susceptibility principally are that audio filters are very large and the specification procedures are simplified for general application to many unsophisticated equipment. Establish special requirements for specific complex system equipment. Remember the testing precautions: (1) large dc currents will saturate the injecting transformer and (2) ripple voltage may already exist on the dc line to be tested.

10. CLIPPING

Clipping can generate unintentional effects in demodulator and detector circuits. To obtain linear detection, it is desired that the detector output follow the envelope of the input signal. The linear diode detector is widely used because it has the advantage of causing less harmonic distortion, particularly for large percentages of modulation. Although it requires appreciable input power, a diode detector delivers a large output voltage for a satisfactory input level compared to other detector types. The voltage to which the capacitor charges should be the peak value of the modulated carrier. The charge path is through the detector and source. If the time constant is too long the negative peaks of the output will be clipped and harmonics and distortion will result. If following stages are responsive to this distortion, undesirable responses will occur.

11. LIMITING

When a desired signal frequency is intentionally limited, the output waveform is distorted. It may be cut off flat as in an on-off limiter, or it may operate about a dynamic point so that the ratio of output-to-input falls off sharply. Semiconductor diodes are good voltage limiters because of their inverse or reverse conduction characteristics. They exhibit low resistance when applied reverse voltage exceeds the "avalanche breakdown" point. They also show substantially constant voltage limitation above this critical breakdown value. The term "breakdown region" describes the critical voltage range in which a junction changes rapidly from a high resistance barrier to a good conductor. This process is not destructive when confined to design limits. The networks to which the limited waveform is fed may be responsive to these frequencies and produce a false output. Tuned circuits may exhibit spurious resonances at those frequencies. As limiting action is made stronger, the waveform of the original signal will be made steeper and will have higher frequency components which couple across transformers, resistors, amplifiers, stray capacitances, etc. Perform an evaluation of sharp waveforms produced by limiting action and tabulate offenders.

12. RECEIVER SENSITIVITY

All receivers exhibit an on-frequency sensitivity variation which is frequency-dependent. The image response of all receivers also varies as the receiver is tuned across the band. At a specific high frequency the shielding, decoupling, and bypassing components become self-resonant. At this point the interference begins to flow through the receiver by electrostatic coupling. No requirement has been established to define the sensitivity of receivers to high-energy fields at frequencies many times above the receiver's normal frequency band. Establish this requirement in programs where antennas are subject to high-energy fields. Receiver rejection characteristics deteriorate at frequencies far above their normal operating point.

12.1 HIGH-POWER ENVIRONMENTS

Receivers are now designed without precautions against operation in high-power environments. In such an environment undesired responses can be categorized as destructive heating of front-end components, image responses, local oscillator harmonic heterodyne responses, stray resonant responses and high-end electrostatic coupling. It has been standard practice in the past to evaluate receiver interference on an average power basis. This is no longer valid because the kilowatt and megawatt peak-power levels are capable of destructive effects in receiver front-ends. In addition, modulation characteristics can be detected by the receivers. Therefore, evaluate receiver susceptibility for peak-power level effects. The stray responses vary widely due to nonuniform components, wiring inductance, stray capacity, and layout variations. Take the following steps to bring this potential problem under control:

a. Determine the high-power fields in which receiver antennas will be immersed. Placement, polarization, and antenna filters may eliminate otherwise difficult problems.

b. Determine the response characteristics of receivers to those fields. Do this regardless of the receiver's normal operating frequencies.

c. Determine the rejection required for compatible performance. Unit-to-unit variation must be anticipated.

d. Obtain the required rejection via optimum design and verify results.

DESIGN NOTE 3C2 PROPAGATION AND INTERACTION

1. INTRODUCTION

Interaction occurs when two functional systems exchange data in such a way that the characteristics of one system degrade the other. Interaction effects can usually be treated from a circuit standpoint. Propagation occurs when data is transferred from one system to another by means of radiation, usually over long distances. The radiation sets up an extremely complex electromagnetic field which is largely determined by the physical and electrical envelope inside with the propagated energy moves.

2. PROPAGATION

In the analysis of interference propagation it is often necessary to utilize the more sophisticated aspects of electromagnetic field theory. These deal with the space and time relations of the constituent electric and magnetic fields. The transmission line concepts presented in *DN 5B7* are a simplification of and an approximation to general field theory. Techniques for analysis of electromagnetic propagation may be found in standard text books.

2.1 INFORMATION THEORY

Information theory shows great promise as a technique capable of reducing system signal-to-interference levels. Understanding the coding and the reception theory aspects of the information theory will soon be a requirement for competence in compatibility engineering.

2.2 TRANSMISSION TECHNIQUES

Coding theory establishes data for optimum encoding of a modulation of signals for transmission through noise and interference. Reception theory provides data for optimum processing and extraction of signals combined with noise. Computers with large memory capacity are making it practical to utilize these advanced techniques. Work at the Massachusetts Institute of Technology has shown that it is necessary to store only the mathematical relationships for later encoding instead of storing a complete code structure.

2.2.1 RECEPTION TECHNIQUES. Outstanding successes are being achieved due to the use of reception theory techniques. Devices using coherent detection to extract signals submerged in noise have resulted from this work. Coherent receivers are designed for specified-signal waveforms and noise-interference statistical parameters.

2.3 APPLICATION OF INFORMATION THEORY

The full advantages of coherent detection and signal-to-interference optimization techniques can be realized only when the system interference environment is specified. Determine the basic definition of required statistical noise parameters by combining efforts of the compatibility engineer and the system engineer. These basic requirements become the goals for the entire interference measurement program.

2.3.1 CORRELATION TECHNIQUES. Correlation techniques, circuits, and devices are available which indicate the enhancement of signal-to-interference performance by several orders of magnitude. A simple optimum receiver has the task of determining the absence or presence of a single repetitive signal in additive white gaussian noise. Accomplish optimization of signal to interference by cross-correlating the incoming mixture with a locally supplied replica of the transmitted signal. Compare the result to a fixed threshold. Use correlator output, which is proportional to probability of signal presence, to determine that the probability of signal has exceeded the level required to assume its existence.

2.3.2 NEW DEVELOPMENTS. Some of the more useful developments resulting from information theory are:

a. Pulse Code Modulation. Pulse code modulation has the advantage of being able to function in high noise levels. It is the most ideal means of data

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transmission through noise. The transmitted signal is sampled periodically and each sample is quantified and transmitted as a digital binary code. The receiver-decoder need determine only the presence or absence of a pulse by using the correlation technique.

b. Bandwidth Reduction. Four-to-one bandwidth reduction systems have been developed. Transmitted data includes redundancies; therefore, codes can be found to remove the redundancies and compress the bandwidth requirements. It has been determined that great reductions are possible in nearly all systems with modulation. Redundancy elimination shows great promise in improving the spectral congestion problem. For example, normal speech required an information rate of 20 000 bits per second. This requirement is reduced to only 60 bits per second when a code is developed to boil the basic information down to nonredundant form.

3. INTERACTION

Interaction comprises signal, control, or power voltages and currents which have entered into circuits other than those intended. The ways by which interaction can be coupled are conductive coupling, capacitive coupling, inductive coupling, transmission line effects and radiation. Every circuit and loop must be evaluated to the frequency where the interaction effects are negligible compared to the system response threshold. Typical examples of interaction are frequency, voltage and current loading, inadvertent phase shift, deterioration of gain, bandwidth, dynamic response, and waveform distortion.

3.1 POWER LINES

Interaction and intermodulation propagating from the system power lines have been major problems, and they are so complex that they can be solved only by trial-and-error methods after the subsystem has been installed in the vehicle. A large number of wires in the inter-connecting cables are shielded; much of this shielding is specified in the original design before the equipment is installed. During test many hours are spent shielding other wires to reduce intermodulation. Some problems can be solved by merely twisting pars of wires. Noise problems are usually solved by going back into the black boxes and adding filters or making changes that will eliminate noise transmission. Noise, modulation, and interaction usually cause the radar presentations to jitter; in addition, range marks become distorted, PPI sweeps spike, and servo loops oscillate intermittently.

3.2 POWER SUBSYSTEM

Most installation intermodulation difficulties occur because the system requires two independent ac power subsystems. In vehicles having both a constant and variable frequency generation subsystem, the practice is to use the variable frequency power to energize as much of the electronic and heating loads as possible. This is done because it costs less to generate the variable frequency power than the constant frequency power. Intermodulation due to the presence of both power sources in the system is most prevalent when the variable frequency source is in the region of 800 Hz. The computers and the servomechanisms in the system are particularly sensitive to the presence of second harmonics in the constant frequency power lines. For this reason, the presence of 800-Hz and 400-Hz fields close to the inputs of high-gain servo amplifiers creates output signals which cause system instability. This problem can be solved by carefully shielding or grounding the interacting wires.

3.3 EXTERNAL ENVIRONMENT

Remote interference may be generated by hospitals, industrial plants, TV and radio broadcast stations, radar transmitters, and radiating devices. This interference can enter the subsystem via ground wave, sky wave, or line-of-sight radiation. It can also be picked up by power lines and telephone lines, carried into the area, and then coupled into the subsystem wither capacitively or inductively. Taxicabs, fire trucks, and other vehicles with mobile communications may get sufficiently close to the vehicle to ignite squibs. Site power may couple into the subsystem and transients on power subsystems can be conducted to the equipment. Telephone and power lines make good antennas, and can pick up RF radiations and reradiate them. The checkout areas contain fluorescent lamps which radiate noise and other devices such as pumps, motors, hoist, switches, and regulators which can put heavy noise on the base power lines.

3.4 RADAR INTERACTION

The most important interference factor is the broadband spectrum of the transmitted signal. Magnetrons are rich in harmonic and spurious interference. Consider high power waveguide filters as they are practical. Klystrons followed by limited-bandwidth amplifiers provide low-interference transmitters. Limit rise times and pulse widths to optimize functional requirements and the resultant broad-frequency spectrum. Pulse shaping techniques for klystron transmitters have been developed to produce narrow spectra.

3.4.1 GATING. Intensity-modulated displays are vulnerable to pulsed interference, which can make it very difficult to interpret the radar display. The receiver and tracking loops can be gated to the transmitted signal to exclude effects from other radars.

3.4.2 SYNCHRONIZATION. A group of radar transmitters operating in the same pulse repetition frequency (PRF) region may be synchronized and fired simultaneously. Another synchronization is PRF modulation. The PRF of one radar is moved, randomly or swept, with respect to the others. The rate of movement is made great enough so that the tracking and display circuits of the victim radars cannot respond. One radar can be made to appear to other radars as a target moving at 161 000 km/h (100 000 mi/h).

3.4.3 BLANKING. Minimize interference to intensity-modulated displays be blanking. A hole is temporarily put on the display sweep whenever an offending radar fires. Because the offending radar is not usually synchronized with the victim, this hole moves about on the display. The overall effect is a slight loss in sensitivity. Blanking becomes useless when the number of interfering sources causes a prohibitive scanning loss.

3.4.4 PULSE DISCRIMINATION. Use pulse discrimination to effectively block pulse interference from radars operating at different pulse widths. This technique is especially helpful for aircraft detection, where the target return length is 0.1μs/15-m (50-ft) length of target. A 20-percent tolerance on the sum of pulse width plus target width is adequate. Delay lines can be used to reject any signal that does not have this pulse width.

DESIGN NOTE 3C3 AUDIO SPECTRUM

1. INTRODUCTION

Experiments show that the audio spectrum may be divided into 20 bands of equal importance. These bands extend from 20 to 6100 Hz with the frequency scale compressed at higher frequencies. Frequency components outside this range have not been found to contribute to speech intelligibility. From a knowledge of the parameters of the system to be evaluated, the signal-to-noise ratio (S/N) in each of the bands of equal importance can be obtained. A percentile score of understandability of speech at the system output can be computed. Another approach was to consider "visible speech" as a time-frequency plot of speech signals as obtained from a sound spectrogram which can be read by a trained person. The speech intelligibility is considered as the running power spectrum of the speech. Tests were conducted by playing a standard speech sample tape together with various types of interference and sending them through the communication system under test. The following results were obtained:

a. A tilt or change in the slope of the audio spectrum does not affect intelligibility as long as the speech is still well above noise in the bands of equal importance.

b. Only the spectrum between 200 and 6100 Hz affects intelligibility.

c. The level of speech can be varied without affecting speech intelligibility.

d. Gradual changes in both frequency and time duration can be tolerated in the running power spectrum.

e. Single interfering tones impair intelligibility only slightly.

f. Word articulation percentage varies from 10 to 95% as a function of interruption rate.

g. Message coding and structure has much to do with intelligibility. Up to 14 dB more noise can be tolerated for words in a contextual framework as compared to the same words spoken individually. See *DH 1-3, Sect 3F*, for bioacoustic information. Also see *MIL-STD-1789* for sound pressure levels in aircraft.

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2. OPERATOR CHARACTERISTICS

Human responses are intermittent, even for continuous stimuli. The eye can see events in a little as 0.1 second. The ear can respond to signals as brief as 0.1 ms. For impulsive sounds the apparent loudness is the integrated effect over 1 ms. The intensity required for response is inversely proportional to duration. The sensitivity is maximum at 0.5 second and falls off rapidly below durations of 0.2 second. The ear and the brain appear to act as an integrator with a charging time of 10 ms and a discharging time of 500 ms. An increase of noise will cause the ear to raise the perception level and lower the signal detectability.

3. AUDITORY MASKING

Three arbitrary thresholds have been established for identification of speech sounds. These are detectability, perceptibility, and intelligibility. Detectability is the threshold for detection but not identification; it has an S/N ratio of -18 dB, with AM signal, and white noise. Perceptibility is understanding the overall context and requires an S/N ratio of 0 to 5 dB. Intelligibility is the range where nearly all words are understood, requiring an S/N ratio of 10 to 15 dB. Masking is the degree of incomprehensibility of the desired information. A word articulation or sentence intelligibility test determines the percentage of words or sentences correctly received. The fewer the syllables in a word, the fewer will be the number of words understood. Masking occurs either due to noise intensity level or due to distortion caused by intermodulation products. The most important characteristic of the ear is its selectivity to certain frequency components and the rejection of others. Masking is the extent to which the ear is not perfect in this respect.

4. SPEECH DISTORTION

Speech can be distorted by interruption, rate of speech, component clipping, and filtering. Intelligibility varies from 40 to 95% as cutoff rate goes from 1 to 2000 interruptions per second with best results from 10 to 100 interruptions per second. In addition, for 75% on and 25% off, the intelligibility is barely affected. As speech speed is varied 10%, its intelligibility is unaffected. If it is increased by 60% or slowed down to 30%, word intelligibility drops to 50%. In normal speech, the peak power is 12 dB greater than average speech power. If the peaks are clipped the chief effect is a quality change without loss of intelligibility. The voice produces high frequency bursts of 0.05-second average duration followed by low frequency bursts of 0.3- to 0.5-second duration at 100 to 200 Hz. The lows are vowels containing most of the power but contributing little to intelligibility. Peak clipping of 24 dB will barely affect the high frequency consonants. The speech is lacking expression, but readily intelligible. Rejection of frequencies above 7000 and below 700 Hz has negligible effect on intelligibility. It has been shown that use of 250 to 2500 Hz gives good intelligibility. To maintain intelligibility it is necessary to increase the intensity as the bandwidth is decreased.

5. THE HUMAN EAR

The ear is an integrating device. The apparent loudness of a sound impulse resulting from the integration of sound pressure over a 0.3-ms span is valid for an unexpected or unfamiliar sound impulse. For many years, the primary interference concern was the degradation of radio performance as discerned by the human ear. Most electronic device are not equivalent to the ear in terms of susceptibility to interference and interaction and the characteristics of the hearing process are required to make comparisons. These characteristics are summarized in the following subparagraphs:

a. The ear does not respond to individual transients and spikes having durations of microseconds.

b. The ear responds logarithmically to impulse magnitude.

c. Recurrent sounds seem to be louder.

d. Sound impulse effects are negligible after 1 second.

e. The full strength of sound is judged in about 0.2 second.

f. The ear can detect a 10% change in intensity at low levels and 25% change at high levels.

g. The ear will not hear noise 20 dB below signal level.

h. The ear notices 3-dB changes of noise in the presence of signals. Up to a 6-dB noise variation can go unnoticed.

i. The ear's maximum sensitivity is from 1000 to 3000 Hz.

DESIGN NOTE 3C4 TRANSIENTS

1. INTRODUCTION

Spikes or transients have often been overlooked either because equipment operators could easily distinguish and disregard them or because computers were the analog type and therefore not susceptible to transients. Transients are currently of extreme importance to compatible subsystem operation because these subsystems are now often digital types in which the human operator has been removed as a direct element in many functional loops. These loops respond to transients. Complex circuitry has been added to handle the many new interrelated functions and this circuitry is subject to activation and false judgment due to transients. Functional frequencies are increasing and as pulse widths become narrower, their constituent spectrum widens in frequency.

2. INTERMITTENT OPERATION

If the frequency of the carrier is high, an intermittent burst of continuous wave (CW) interference has the effect of a transient. Its waveform is detected by nonlinearities in the circuits into which it couples. Continuous wave interference will also appear as a transient when its path of propagation is intermittent or transient. This often occurs under flight conditions of shock and vibration. The interruption can be caused by mechanical contact of normally insulated conductors or inadvertent separation of normally conductive elements. This phenomenon is difficult to discern because the effect of the CW is often negligible while the effect of modulating it can be large.

3. FREQUENCY SPECTRA

High-frequency transients frequently have a spectrum that extends into the megahertz region. These pulse widths are so narrow that they exceed the response time (rise time) of today's circuitry. As transistor and tube capability is extended upwards into the 1000-MHz region these transients will prove troublesome. System programs have suffered catastrophic effects as a result of susceptibility to high-frequency transients. Missiles have been destroyed in flight; computer synchronization has been lost; guidance has been lost because transients damaged transistors; and many control functions have been inadvertently triggered.

4. SOURCES

Inductive kicks and the general effects of suddenly collapsed magnetic fields produce transients ranging from subaudio to megahertz region depending on the effective inductance and capacitance in the path of the current produced by the collapsing field. The resistance in the path controls the damping, which in turn controls the envelope of the oscillatory discharge.

5. SWITCHING TRANSIENTS

It is usually assumed that loop inductance is unchanged during the time under consideration. Hence, the current through an inductive loop cannot change instantaneously in the theoretical case or even nearly instantaneously in the practical case. In an electronic equipment complex inductances in one or more loops are switched. Each switching is accompanied by a rapid current surge with a high-voltage surge. Voltage surges of hundreds of volts actually occur and can be measured. It is often assumed that the voltage across a capacitor cannot change instantaneously or even nearly so. This is true only when the total capacitance connected to a node (junction of two or more circuit elements) remains unchanged. When capacitors are switched in or out of circuits, voltage changes occur across them and across other elements attached to the node. It is the total charge at a node which cannot be changed instantaneously.

5.1 RELAYS

High-speed oscillographic measurements of radio interference produced by relays lead to the following conclusions:

a. The coil of the relay can be replaced by an equivalent capacitor equal to the distributed capacitance of the coil without altering the shape of the transient during the first few micoseconds. This

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indicates that the distributed capacitance effectively "shorts out" the coil during this short interval and is responsible for the generation of interference transients.

b. Typical relay coils exhibit a high ratio of inductance to distributed capacitance, which results in high amplitude voltage surges with steep wave fronts caused by the collapse of the magnetic field about the relay coil when the current is interrupted. The voltage across the coil rises quickly to the 0.7 supply voltage when the circuit is closed, but on the break the potential rises to a value of approximately 100 times the supply voltage in about 3 μs and then decays to a zero value at a rate determined by the inductance, distributed capacitance, and resistance of the winding. It should be emphasized that this voltage surge possesses a steep wave front which is capable of producing violent shock excitations in receiver tunable over a wide range.

c. Switching units, with the exception of mercury switches, display mechanical bounce or chatter which causes repetitive closures and interruptions of the current when the switch is closed. The long duration sweep shows the effect of the bouncing switch contacts when the circuit is made. High amplitude voltage surges are evidence that the points remain in contact long enough to establish an appreciable current in the coil. These transients developed at the make of the circuits are of greater duration and severity than those developed at the break of the circuit.

d. In addition to the transients due to mechanical bouncing, rapid closures and interruptions of the circuit occur. These are at a faster rate than those due to the mechanical bouncing of the relay contacts at the make of the circuit. As the contacts move outward, the contact area for the flow of current decreases resulting in local heating, which causes the contacts to pit and sputter until the circuit is broken. The amplitude of the resultant induced voltage is high enough to imitate "cold" emission from the projecting area of the relay contacts. This is accompanied by local heating which causes the contact material to melt and neck out until the circuit is again closed. This process repeats at an exceedingly rapid rate until the relay contacts are separated far enough to prevent the voltage gradient from rising to the value necessary for cold emission. These closures and interruptions of the circuit are also responsible for the generation of steep wave forms, which cause radio interference in adjacent electronic circuits.

5.1.1 SHIELDING. A reduction of the interference is obtained by enclosing the offending relays and their associated circuits within a metallic shield. However, direct oscillographic measurements show that singly shielded conductors are incapable of completely eliminating radiations from the central conductor of a coaxial cable. A typical measurement shows that the radio of pickup voltage of an adjacent external pickup wire to the central conductor of a coaxial cable is approximately 1 to 1000. Therefore, it is frequently necessary to resort to multiple shielding of conductors where surges of extreme sharpness are propagated if effective interference reduction is to be obtained.

5.1.2 SUPPRESSION DEVICES. *Sub-Note 5.1.2(1)* shows the various suppression devices that can be used across coils to minimize transients. A properly matched resistance-capacitance (RC) circuit across an inductive load should make the load appear as a pure resistance. The resistance (R) in series with the capacitor should be 1/4 to 1/2 of the dc coil resistance (R_L). The value of the capacitance (C) can then be found with:

$$R \times C = \frac{L}{R_L} \quad \text{(Eq 1)}$$

Where:

L = inductance (henries)

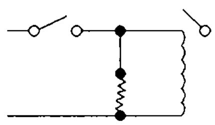
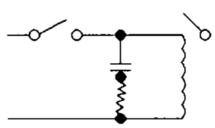
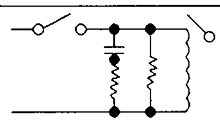
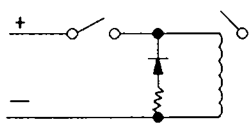
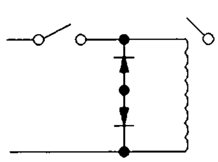
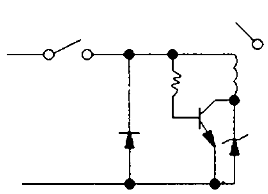
R_L = dc resistance (ohms)

If R is chosen a $R_L/4$, C can then be found with:

$$C = \frac{4L}{R_L^2} \quad \text{(Eq 2)}$$

If the computed capacitance is very large, use the closest practical smaller capacitor. Capacitance between 0.01 to 1 μF is usually sufficient to minimize most transients.

SUB-NOTE 5.1.2(1) Comparison of Various Suppression Devices Across an Inductor

TYPES OF INDUCTIVE SUPPRESSION	VOLTAGE INPUT	RELAY CONTACTS		REMARKS
		CLOSING	DROPOUT	
A  RESISTANCE DAMPING	ac or dc	No Effect	Function of Resistance	Increase in power consumption. Resistance should be as low as practicable. Observe power rating (E^2/R) and heat dissipation.
B  CAPACITANCE SUPPRESSION	dc	Slight Effect	Slight Effect	Need series resistance of a few ohms. Capacitance value around 0.01 to 1 μF. Capacitance rated 10 times input voltage.
C  RC SUPPRESSION	dc	Slight Effect	Function of Resistance	Combination of A and B above.
D  DIODE SUPPRESSION	dc only	No Effect	Slight Effect	Polarity critical, diode put in back-ward or nonconductive direction. PIV should be higher than any transient voltage plus safety factor. Series resistance of a few ohms might be needed to increase inductance life.
E  BACK-TO-BACK DIODE SUPPRESSION	ac	No Effect	No Effect	Avalanche voltage should be above input voltage. Power dissipation should be sufficient for transient current. Cost of device becomes significant factor.
F  DIODE-TRANSISTOR SUPPRESSION	dc only	No Effect	No Effect	Most effective in transient suppression and most expensive technique. The transistor is saturated, when the switch is closed, allowing the coil to become energized. The transistor is cut off, when the switch is opened, forcing the transient energy to dissipate through the Zener diode and the parallel diode.

6. INDUCED INTERFERENCE

Interference and interaction usually accompany changing currents. The basis for understanding electromagnetic induction is Lenz's law which states that a voltage will be induced in a conductor which links a varying magnetic field. The induced voltage or electromotive force (emf) is given by:

$$e = 10^{-8} N \frac{d\Phi}{dt} \qquad \text{(Eq 3)}$$

Where:

e = induced emf (volts)

N = conductors or turns

Φ = magnetic flux (webers)

t = time (seconds)

6.1 TRANSFORMER EFFECTS

The transformer provides a simple illustration of Lenz's law. Activation of the primary circuit builds up, producing magnetic flux flow. An emf is thus induced in the secondary by the varying flux flowing through the magnetic core. This emf tends to set up a secondary current which produces flux flowing through the magnetic core equal and opposite to that produced by the primary. Consider the possibility of transformer action in circuits where the elements of a transformer such as relays, solenoids, motor and generator windings, synchro and resolver windings, filter inductances, tuned circuits, magnetic amplifiers, inductive transducers, feedback elements, and inductive control windings are present. Undesired inductance, which is present in most electronic circuits, includes wiring and cabling inductance. Lead length inductance seriously impairs the high frequency effectiveness of capacitors and resistors. It is particularly troublesome when it resonates with stray capacity and causes damped exponential ringing. In many inductive circuits, the driving current causes a high flux level and a significant variation in permeability. This causes the induced voltage to be distorted and nonsinusoidal. Such distortion is equivalent to the generation of harmonics.

6.1.1 NONLINEARITIES. This standard induction coil provides a good example of nonlinear induced voltage. The heavy primary winding carries high current and strongly magnetizes the iron core. The core is built open (instead of a closed loop) to make the flux change faster. Fine iron wire is used to reduce core eddy current loss. The interruption of the large current level by the vibrator produces a steep rate of change of flux, which can generate potentials in the range of 10 000 to 100 000 volts. The spectra produced are wideband and rich in harmonics of the fundamental vibrator frequency.

6.1.2 SELF-INDUCTANCE AND MUTUAL INDUCTANCE. A change in current through a coil produces a changing magnetic field around the coil and hence a varying flux within the coil itself. This flux links the coil and produces an emf proportional to the rate of change of self-flux linkage. The flux linkages in an element or circuit due to current flowing through itself are self-inductances. The flux linkages produced in one element, due to current flow in a second element, are mutual inductances. In equation form:

$$L = N\Phi I \qquad \text{(Eq 4)}$$

where:

L = self-inductance in henries

N = turns, loops, or linkages

Φ = magnetic flux in webers

I = current in amperes

The reduction of self-inductance and mutual inductance is a major aspect of interference control. The control of induced voltages always involves limiting of the rate of change of flux linkages or current.

6.2 INDUCTIVE KICKS

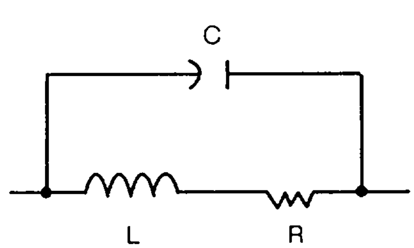
Circuits are often designed so that a steady current flowing through an inductive element is suddenly switched off. The element may be a coil, motor winding, relay, or other inductive element. When the current is switched off, the magnetic field collapses, and current decays in an inductance-resistance (LR) circuit. When current is switched on it will rise in an LR circuit.

6.2.1 DESIGN PRECAUTIONS. Design methods for prevention of inductive kick can be summarized as: (1) reduction of magnetic field build up, (2) reduction of self-inductance, (3) reduction of current rate of change, (4) reduction of mutual inductance, (5) use of alternate circuits or components, and (6) filtering. Reduction of the magnetic field energy may mean performing the control task at lower current. Reduction of self-inductance may be accomplished by selecting a lower inductance component or reducing inductance elsewhere in the circuit. Effective inductance may be reduced to near-zero by a self-bucking or cancelling circuit. The time constant of the circuit (L/R) may be selected so that the rise and/or decay rates are tolerable. Spacing, magnetic shielding, and reduction of circuit loop areas are effective in reducing mutual inductances. Often, desired functions can be performed by a noninductive circuit or device. Finally, if the inductive kick does not cause adverse effects in the generating circuit, a filter may be added to block the voltage pulse produced.

6.3 INDUCTORS' PARASITIC EFFECTS

In EMC analysis and design it is sometimes necessary to describe the non-ideal behavior of inductors. *Sub-Note 6.3(1)* is a model for an inductor including its parasitic effects.

SUB-NOTE 6.3(1) Inductors' Parasitic Effects



Where:

C = stray or distributed capacitance

$$C = \frac{1}{(2\pi f_R)^2 L}$$

f_R = resonance frequency

L = assigned value of inductor

R = losses in the winding and core

$$R = \frac{\omega L}{Q}$$

Q = quality factor

References 657, 658, and 660 give more information on accurate modeling techniques for EMC analysis.

7. SWITCHES

Any switching device causes transients during opening and closing. In designing all switches, the radio-interference problem must be considered from the outset. Arcing occurs during the normal operation of a switch, since the interruption of a current in a circuit consists of substituting a highly ionized and therefore conducting gaseous medium, i.e., an arc, for a part of the metallic circuit, and then subjecting this arc to strong de-ionizing influences. The arc is extinguished when the energy stored in the inductance of the circuit is dissipated and the voltage drops below the value required to maintain the arc. To prevent the arc, the current, instead of being interrupted, is channeled into another branch containing a series capacitance and resistor of a few ohms. Thus, the energy is partly stored in the capacitor and partly dissipated in the resistor, which also serves to damp any oscillations that may occur as a result of the added capacitance. Use RC arc-suppression networks whenever switches or relays are employed to interrupt currents large enough to cause radio interference. An alternative method is to completely shield and filter the unit. When the currents to be interrupted are large, this may be the only effective method.

8. ACTUATORS

Actuators are defined as devices for converting electric, hydraulic, or pneumatic quantities to mechanical force or torque. Electronic motors may serve as actuators. Most of the actuators are influenced by the amount of resistance they encounter in the load and this means that it is often not feasible to separate the mechanical subsystem from the actuator. In an electric motor, for instance, the emf due to the relative motion of the armature and field will be subject to wide variations caused by changes in the load. This is a result of the change in motor speed associated with the changing load. When the back emf varies, the current and applied voltage in the supply line will also be subject to these transient effects and the transients may be conducted along the power line to other pieces of equipment. Solenoids are employed as actuators where a translational motion or force is required. Being inductive elements, they may easily cause coupling problems with other circuits and components. Although solenoids themselves are not readily susceptible to stray electromagnetic energy, the fields which surround the solenoids may be relatively strong. Reduce this hazard to an acceptable level by proper shielding.

9. ROTARY STEPPING SWITCHES

In a typical rotary stepping switch, operation of the stepping magnet causes the armature to move toward the magnet, thus allowing the ratchet to be rotated by the pawl under the force of the driving spring. As the armature rotates about its pivot point, it contacts the interrupter spring which breaks the magnet energizing circuit. During this operation, arcing may occur at the interrupter contacts. Also, arcing at the wiper contacts of the circuit to be controlled may cause additional interference problems.

9.1 SUPPRESSION OF CONTACT ARCING

To secure proper contact and switch life and to eliminate interference due to arcing, provide adequate arc suppression. This can be done by suppressing the transient voltage across the inductive load. Another method of suppressing this arc is by shunting a resistor in series with a capacitor across the contacts or switch. Never connect a capacitor across the contacts without including a series resistance because the discharge of the condenser when the contacts are closed can cause a heavy surge if not controlled by the resistor.

10. CONTROLLING TRANSFORMER INRUSH CURRENTS

Transformer cores for aerospace systems are often tape-wound, cut cores made from grain oriented silicon steel, such as "Hipersil." The high permeability of this material results in low exciting voltamperes and low-core loss. Such cores yield better efficiencies, smaller size, and reduced weight. These characteristics make the cores applicable for use in high-power and high-power-frequency applications. However, because the cores operate at very high-flux densities, the high inrush currents are of particular concern. The maximum inrush current occurs when the circuit is closed at the instant the voltage is zero. See *Ref 58*.

10.1 GAP EFFECTS

The butt-joint air gap can be increased to control the inrush magnetizing current. In typical large cores, a spacer 0.13 mm (0.005 in.) thick, in addition to the normal gap of 0.05 mm (0.002 in.), will reduce inrush magnetizing currents by a factor of two or three; however, the exciting current is increased by about 2%.

10.2 TIMING TECHNIQUES

If a small increase in inrush current is not tolerable, one solution is to control the timing of the energizing relay so that the transformer is connected when the voltage is at a maximum. The relay used in this application must be able to close the circuit at or near voltage maximum when the flux is approximately zero.

DESIGN NOTE 3C5 ELECTROMAGNETIC PULSE (EMP)

1. INTRODUCTION

Electromagnetic pulse is the burst of radio frequencies that accompanies the detonation of a nuclear weapon. The radio spectrum covered is very broad and extends from extremely low frequencies into the UHF band. The magnitude of the EMP is very large. Electromagnetic pulse may present a potential threat to selected electronic and electrical systems. Good EMC/lightning design will go a long way toward providing EMP protection, but additional techniques may be necessary. These are covered in the reference sources listed below.

2. EMP REFERENCE SOURCES

The following reference sources should enable designers and engineers to harden the system/subsystem to EMP:

a. The current understanding of the effects produced by the EMP resulting from a nuclear detonation is presented in *Part I* of *DNA EM-1*, *Capabilities of Nuclear Weapons* (U), *Chap 7* and *8*. It discusses the methods required to eliminate or reduce the potential threat to military systems caused by EMP. The manual provides a common vocabulary, a common reference for the magnitude of EMP effects, and an insight into the theory of EMP.

b. *Reference 472* presents analytic and experimental techniques that should enable missile and aircraft designers to ensure EMP hardening during the design phase, to harden by retrofitting, or to establish vulnerability levels. The analytic techniques include (1) antenna and transmission line theories that can be applied to the appropriate models and (2) failure criteria for circuit components. The instrumentation section includes the formulation and running of a test program and the development of the associated vulnerability analysis.

c. *Reference 809* is a compilation of basic information presented in a manner to assist systems engineers in familiarizing themselves with EMP problems and, in certain areas, defining what initial steps can be taken to analyze and protect their systems against EMP effects.

d. *Reference 445* discusses the need for EMP protection and the hardening techniques which can be applied. This document includes an introduction to the EMP problem, basic EMP principles, environment, system degradation modes, interaction and coupling, design practices, testing, approaches to system hardening and vulnerability assessment, and examples at the system level.

e. *Reference 664* examines the utilization of fiber optics technology as an alternative to system EMP hardening and provides design guidelines for airborne system applications. Examines potential EMP vulnerabilities of the overall fiber optic data subsystems, defines and quantifies methods of protection against the EMP threat, and compares vulnerabilities with those of hard-wired data systems.

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SECTION 3D COMPONENTS AND PARTS

DESIGN NOTE 3D1* ELECTRON TUBES

1. INTRODUCTION

In high voltage-high wattage applications, electron tubes are still dominant as active devices. The electron tube has a capability to withstand considerable system abuse such as overvoltage spikes and radiation impulses. The EMC problems with electron tubes and their circuits are similar to those with transistors, differing primarily because of power levels, greater number of elements, and greater spacing between the elements.

2. EMC CHARACTERISTICS

Although ordinary vacuum tubes operating in the proportional-control or switching modes have EMC characteristics similar to those of transistors, gaseous conduction tubes (e.g., thyratron and ignitron) are quite different. The ignitor in an ignitron can be a source of noise because it acts like a spark-producing device. When a gaseous conduction tube is conducting, the space between anode and cathode contains a plasma that can oscillate by itself because of internal instabilities.

2.1 SHOT EFFECT NOISE

Shot effect (also called Schottky noise or Schot noise) is due to random fluctuations in the rate of electron emission from the cathode. When the cathode temperature is the current flow limiting factor, the shot noise component is

$$i_{sh}^2 = 2\ eI_bBW \qquad \text{(Eq 1)}$$

Where:

i_{sh} = rms noise current (amperes)

e = electron charge (1.6×10^{-19} coulomb)

I_b = average plate current (amperes)

BW = bandwidth (Hertz)

When the plate current is limited by the space charge, many of the fluctuations in the plate current are reduced due to the smoothing effect of the reservoir of electrons in the virtual cathode set up by the space charge. In this case, the following approximations can be used. For diodes

$$i_{sh}^2 = 4k(0.64)T_cgBW \qquad \text{(Eq 2)}$$

and for negative grid triodes

$$i_{sh}^2 = 4k\left(\frac{0.64}{\sigma}\right)T_cg_mBW \qquad \text{(Eq 3)}$$

Where:

k = Boltzmann constant (1.38×10^{-23}J/K)

T_c = cathode temperature (K)

g = diode plate conductance (siemens)

g_m = transconductance (siemens)

σ = tube parameter (between 0.5 and 1.0)

The shot effect noise of a triode can be expressed by considering a resistance which, if applied to the driving grid of a noiseless tube as a source of thermal noise, would produce the same anode current noise component as is actually present. For triode tubes, the equivalent grid noise resistance (R_{eq}) is equal to $2.5/g_m$. In amplifiers, the noise voltage generated by R_{eq} is considered to be applied in series with the grid

$$\epsilon^2 = 4kT_cR_{eq}BW \qquad \text{(Eq 4)}$$

Where:

ϵ = noise voltage (rms volts)

See *Ref 721* for more information on shot noise in electron tubes.

2.2 PARTITION NOISE

Partition noise occurs in multicollector tubes and is due to fluctuations in the division of current between the electrodes. The noise of a negative-grid pentode amplifier is represented by the equivalent grid resistance (R_{eq}), approximated by

$$R_{eq} = \frac{I_b}{I_b + I_{c_2}}\left(\frac{2.5}{g_m} + \frac{20\ I_{c_2}}{g_m^2}\right) \qquad \text{(Eq 5)}$$

Where:

I_{c_2} = dc screen current (amperes)

The values of R_{eq} of pentodes are usually three to ten times as great as those of comparable negative-grid triodes. Electron wave tubes, such as traveling-wave tubes, also exhibit partition noise.

2.3 NOISE CURRENTS

At very high frequencies (over 30 MHz), fluctuations in the number of electrons passing a negative grid will induce noise currents. Increasing with frequency, the noise currents will be introduced into the input circuitry

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*Extracted in part from *NAVAIR EMC Manual 5335.*

by electronic conductance. Gas noise is produced by erratic motion of gas molecules in gas or vacuum tubes. Ionization by collision produces noise when ionized gas atoms or molecules liberate bursts of electrons when they strike the cathode. Secondary emission noise is due to fluctuations in the rate of the production of secondary electrons. Flicker noise, more common in oxide-coated cathodes, varies as $1/f$ (f = frequency in Hertz) and is caused by a low-frequency variation in cathode activity. Some EMC problems involving electron tubes are given in *SN 2.3(1)*.

SUB-NOTE 2.3(1) EMC Problems, Causes, and Cures

INTERFERENCE	CAUSE	CURE
Shot effect	Random fluctuations in the rate of emission of electrons from the cathode	Proper design
Partition noise	Fluctuation in the division of current between electrodes	If important, use tubes with fewer elements
Induced noise	At very high frequencies, fluctuations in the number of electrons passing a negative control grid induces noise currents	Use tube with better grid geometry
Gas noise	Ionization by collision of ionized gas striking the cathode, liberating bursts of electrons	Proper design or use of other electronic components
Secondary emission noise	Fluctuations in the rate of secondary electron production	Proper design or use of other electronic components
Flicker noise	Inversely proportional to frequency: due to a low-frequency variation in cathode activity; more common in oxide-coated cathodes	Avoid oxide-coated cathodes
Microphonic effect (vibration of socket with or without sound emanation)	Shock or vibration changes element spacing and damped mechanical oscillation causes changes in plate current, usually setting up vibration through the tube socket or by means of sound waves	Reduced by use of ruggedized tubes
Hum	Use of ac for filament and heater-type tubes	Use dc, use hum-bucking circuits, use balanced filament supply, bias cathodes negative with respect to filaments.
Other tube noise	Leakage from the grid to another electrode, particularly a positive electrode; improper contacts (particularly with low level signals)	Tube replacement or ensure mechanically and electrically good contacts
Large number of unwanted frequencies at amplifier output	Possible feeding in of unwanted frequencies compounded with operation on the nonlinear portion of the characteristic curve	Proper design and shielding of the grid circuit
Interfering signals in an RF field	Pick up of RF signals through tube envelopes	Use tube shields
Nuclear radiation	Change in tube characteristics	Use of ceramic tubes
Noise current in catcher of klystron amplifier	Electron beam passing through the catcher causes noise current in the shunt impedance of the catcher	Proper design for minimum effect

DESIGN NOTE 3D2 SOLID-STATE DEVICES

1. EM RADIATION HAZARDS

Solid-state devices cover both transistors and microcircuits. These devices may be damaged by electromagnetic radiation encountered while in transit. It is recommended that these devices be individually wrapped, first with a suitable neutral wrap as required by *MIL-STD-794,* and further, individually sealed in a metal foil barrier conforming to *MIL-B-81705.* Devices not susceptible to EM radiation degradation will not require the use of barrier material. See also *MIL-HDBK-253, Guidance for the Design and Test of Systems Protected Against the Effects of Electromagnetic Energy.*

2. TRANSISTORS

The performance of transistors is limited by certain undesirable effects. The interference inherent in the transistor limits the minimum signal that can be effectively amplified and detected. Also, the natural temperature coefficient of semiconductors imposes a limit on the ambient temperature permissible for satisfactory operation.

2.1 INTERFERENCE

Much of the interference inherent in the transistor is similar to that in a composition resistor. Its characteristics differ from the interference in a resistor which consists principally of thermal noise and shot noise. The transistor junction and the recombination of holes and electrons in the semiconductor are more complex. Nevertheless, when treated linearly, its effect can be represented approximately by postulating the existence of noise voltages v_{ne} and v_{nc} in series with the emitter and collector terminals, respectively. These two voltages account for much of the interference developed in the transistor. In addition, when the transistor is connected to a source of signal voltage (v_s) having an internal source resistance (R_s), a noise voltage (v_{ns}) corresponding to the thermal noise in R_s is effective in series with that resistance, i.e., the noise inherent in the signal adds to the internal noise generated within the transistor.

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2.1.1 MEASUREMENT OF NOISE VOLTAGES. For measurement of the separate noise voltages in the emitter (v_{ne}) and in the collector (v_{nc}), the transistor is commonly connected to its two bias voltages with large inductance in series with the emitter and collector, and the voltages are adjusted so that operation takes place at the normal quiescent operating point. Thus R_s and R_L are replaced by inductive reactances that are large compared with the resistance they face at all frequencies of interest, and v_s is zero. The voltages across the inductances are v_{ne} and v_{nc}. The root-mean-square (rms) values of these voltages are usually measured as functions of frequency with a narrow-band tuned voltmeter having an effective bandwidth of a few hertz, such as a commercial wave analyzer. It is to be emphasized that v_{ne} and v_{nc} are not single-frequency voltages. Rather, they correspond to the integrated heating effect over a narrow band in a spectrum of frequencies, for the distribution of noise power is a continuous spectrum just as is the distribution of power in a light beam from an incandescent source. If the transistor noise were simply thermal-agitation noise associated with equivalent resistance of the transistor, the indication of the voltmeter would be independent of the center frequency of the band over which the measurement is made. Actually, the two rms noise voltages are found to vary approximately inversely as the square root of the center frequency. More accurately, the mean-square voltages vary as $1/f(\nu)^{1.1}$ or the noise power corresponding to the voltages decreases 11 dB per decade as the frequency increases. Specification of v_{ns} is commonly made in terms of the ratio of the rms voltage to the square root of the bandwidth at some selected center frequency. Typical values for the outdated point-contact transistor are 100 μV in a 1-Hz band at 1000 Hz center frequency for v_{nc} and about one or two percent of the value for v_{ne} in the same band. Values for junction-type transistors are much smaller.

2.1.2 NOISE FIGURE AND THERMAL NOISE. Interference is frequently described in terms of the noise figure. This noise figure may be defined as the ratio of (a) the noise power existing in the load in a specified frequency band as a result of all noise sources, divided by (b) the noise power existing in the load in the frequency band as a result only of the thermal noise in the internal resistance of the signal-voltage source. The noise figure is thus a measure of the interference that the transistor adds to the noise that would occur if all elements in the circuit were noise-free except the internal resistance of the signal-voltage source. Its significance is perhaps best understood from a consideration of methods by which it may be measured. One method involves, first, measuring the mean-square noise voltage ($\overline{v_n^2}$) across the load with a voltmeter such as the narrow-band wave analyzer mentioned in *Para 2.1.1*; second, measuring the voltage amplification (A); and, third, computing the mean-square thermal noise voltage corresponding to R_s, which is $4kTR_sBW$, from known values of the temperature, resistance, and bandwidth of the voltmeter. Since the noise power in the load is the mean-square voltage divided by the load resistance and if A is uniform throughout the bandwidth, the noise figure (F) is then given by:

$$F = \frac{\overline{v_n^2}\ (\text{Measured})}{4K\ TR_s\ BW\ A^2} \qquad \text{(Eq 1)}$$

Where:

k = Boltzmann constant (1.38×10^{-23} J/K)

$\overline{v_n^2}$ = mean-square noise voltage

T = temperature of the transistor (K)

R_s = source resistance (ohms)

BW = bandwidth (Hz)

A = voltage amplification

Alternately, the noise figure may be computed from measured values of v_{ne} and v_{nc}. If all the noise voltages were statistically independent, the total noise power in the load would be the sum of the values computed for each source acting independently. Since the collector noise voltage (v_{nc}) is effective in series with the load resistance (R_L) and the output resistance (R_{out}), the noise power output (N) due to v_{nc} alone is expressed as follows:

$$N = \frac{v_{nc}^2\ R_L}{(R_L + R_{out})^2} \qquad \text{(Eq 2)}$$

The noise power output due to v_{ns} alone may be computed as follows:

$$N = \frac{(A_{oc}v_{ns})^2\ R_L}{(R_L + R_{out})^2} \qquad \text{(Eq 3)}$$

The output caused by v_{ne} may be expressed similarly. The noise figure for the grounded-base connection when the noise voltages are statistically independent is then:

$$F = \frac{(A_{oc}v_{ns})^2 + (A_{oc}v_{ne})^2 + v_{nc}^2}{(A_{oc}v_{ns})^2} = 1 + \frac{v_{ne}^2 + (v_{nc}/A_{oc})^2}{v_{ns}^2} \qquad \text{(Eq 4)}$$

Where:

v_{ns} = noise voltage in transistor

v_{ne} = noise voltage in emitter

v_{nc} = noise voltage in collector

A_{oc} = open circuit voltage amplification

R_L = load resistance (ohms)

R_{out} = output resistance (ohms)

The terms involving R_L and R_{out} cancel and vanish in this result. The noise figure (F) is thus independent of the load resistance but is dependent on the noise voltages and A_{oc}. It also depends on R_s as follows where BW is the bandwidth in which v_{ne} and v_{nc} are effective.

$$F = 1 + \frac{v_{ne}^2 + v_{nc}^2 \left(\frac{R_s + r_e + r_b^2}{r_m + r_b} \right)}{4k\ TR_s\ BW} \quad \text{(Eq 5)}$$

Where:

r_e = emitter resistance (ohms)

r_b = base resistance (ohms)

r_m = equivalent emitter–collector transresistance (ohms)

When v_{ne} and v_{nc} are not statistically independent, the correlation between them must be taken into account in the addition in the numerator of *Eq 5* and the noise figure is larger or smaller than the equation indicates. Since R_s enters into both the numerator and the denominator of the expression for F, equating the derivative of the expression to zero with respect to R_s gives the value of R_s at a point where F is a minimum when the correlation between v_{ne} and v_{nc} is zero, namely,

$$R_s \text{ (for F min)} = (r_e + r_b)^2 + \left(\frac{v_{ne}}{v_{nc}}\right)^2 (r_m + r_b)^2 \quad \text{(Eq 6)}$$

With a small voltage ratio, the value for R_s is approximately $(r_e + r_b)^2$, which is the open-circuit input resistance of the circuit. For another approach to transistor noise, see *Ref 721*.

3. SEMICONDUCTOR INTEGRATED CIRCUITS

Semiconductor integrated circuits (IC), are considered the extension of the silicon transistor technology. Interference is the same as in transistors.

3.1 SUSCEPTIBILITY

Integrated circuits were found to be less susceptible to magnetic-field interference than to the electric-field interference because of their small size (see *Ref 1430*). The vulnerable points in the circuit are those which are connected to external leads, such as inputs, outputs, power supplies, and ground leads. It should be noted that these external leads can act as dipoles as well as susceptible loops. Consider proper circuit design, shielding, decoupling, good mechanical layout, and proper parts placement in all solid state applications. If not properly shielded or protected, serious problems may be encountered. Therefore, take into account the sensitivity of transistors and ICs to fields throughout the entire EM spectrum, including light and infrared.

3.2 UNUSED CIRCUITS AND CONNECTIONS

EMI can be generated in an integrated circuit by unused connections and floating circuits. Connect any unused leads to ground or to an appropriate voltage level.

DESIGN NOTE 3D3* DIODES

1. INTRODUCTION

Solid-state diodes are semiconductors, so they share many of the characteristics of transistors. Under conditions of forward bias, a solid-state semiconductor stores a certain amount of charge in the form of minority current carriers in the depletion region. If the diode is then reverse-biased, it conducts heavily in the reverse direction until all the stored charge has been removed. The resulting conditions are presented in *SN 1(1)*. The duration, amplitude, and configuration of the recovery time (also called switching time or period) pulse is a function of the diode characteristics and circuit parameters. These current spikes can generate a broad spectrum of conducted radio interference frequencies.

2. INTERFERENCE

Rectification involves switching from conduction to cutoff repetitively, causing di/dt rates dependent upon the input frequency, minority carrier storage in the diode, and the circuit characteristics. The interference effect can be minimized by one or more of the following measures:

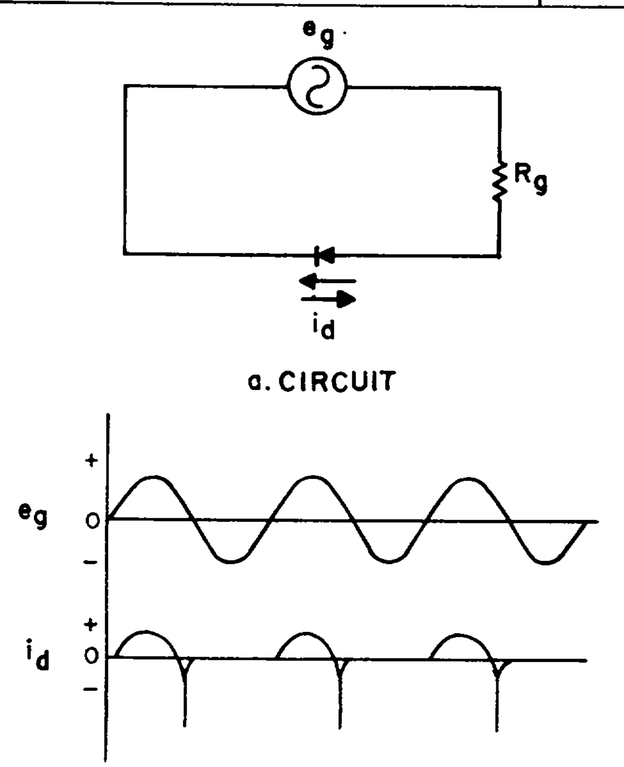
a. Placing a bypass capacitor in parallel with each rectifier diode

b. Placing a resistor in series with each rectifier diode

c. Placing an RF bypass capacitor to ground from one or both sides of each rectifier diode

d. Operating the rectifier diodes well below their rated current capability.

SUB-NOTE 1(1) Diode Recovery Periods and Spikes



a. CIRCUIT

b. WAVEFORMS

2.1 RFI

The ripple filter that normally follows a rectifier should not be relied upon to filter out the interference effect. The usual large-value capacitors used for ripple filters exhibit too much series inductance to function effectively as RF interference filters.

2.2 SWITCHING INTERFERENCE

Diodes are also used to switch at a particular voltage level. The switching action results in rapid di/dt changes. Diodes are used as limiters to cut off a certain input waveform at a certain level. The greater the amount of limiting, the greater will be the number of spurious frequencies that occur due to steepening waveform. These switching actions can result in interaction with other components, distributed or actual impedances, and discontinuities. Several design considerations to minimize switching interference are:

a. Operate at lowest possible voltages and currents

b. Anticipate diode-to-diode variation of characteristics

c. Use the lowest possible switching rate and amplitude

d. Select diodes with high working and peak inverse voltages

e. Use diodes with a slow recovery time (inherent with larger current ratings).

2.3 RF SUSCEPTIBILITY

The RF voltage can change the bias of a diode, resulting in improper switching, distortion, or improper output. All diodes are subject to reverse breakdown if they pick up RF voltages greater than their reverse breakdown voltages. Low-power devices (generally those rated 25 mW or less) and small junction devices such as point-contact diodes operating in the vicinity of a strong RF

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field can absorb sufficient radiated energy to be degraded or burned out. Large junction diodes have a large junction capacitance on the order of 10 to 15 pF, which will pass high frequencies. If this energy, added to the normal energy, exceeds the thermal limit of the device, damage can occur. Therefore, susceptible diodes subjected to these RF fields should be shielded.

2.4 OTHER EMC PROBLEMS

When used as an amplifier, a tunnel diode may couple with related circuitry inductance or capacitance to produce undesired oscillations, usually above 1 MHz. The oscillations should be suppressed by proper circuit design methods. All zeners generate shot and 1/f noise, but the noise level is higher in alloy zeners than in zeners made by a diffusion process. Generally, the noise increases with an increase in current but the noise may occur at some point on the zener curve and not at others. (This noise is called "spotty".) Most commercial zener diodes have above 1 to 1000 μV of noise over a decade of frequencies. Diodes with mechanical imperfections may generate noise when physically agitated. *SN 2.4(1)* lists the usual EMC problems.

SUB-NOTE 2.4(1) Usual EMC Problems Involving Diodes

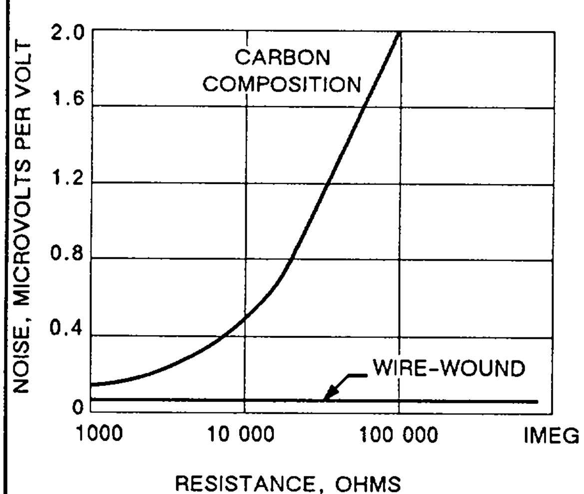
INTERFERENCE GENERATION	SUSCEPTIBILITY
Switching transients	Erroneous signals
Internal charge	Radiation
Harmonic distortion	Magnetic fields
Inherent noise	Temperature
Mechanical imperfections	Nonlinear characteristics

DESIGN NOTE 3D4 — RESISTORS

1. INTRODUCTION

Composition resistors, because of their granular nature, generate considerable noise when current flows through them, whereas wire-wound resistors, because of their homogeneous structures, are relatively noiseless under the same conditions. The noise voltages generated by several styles of resistors are shown in *SN 1(1)*. Measured against a wire-wound resistor as a standard, interference in a carbon composite resistor increases rapidly with resistance value. Both the metal-film and deposited-carbon types give a large improvement over the carbon composition of values of 10 000 ohms and larger.

SUB-NOTE 1(1) Resistance versus Noise Voltage



2. TYPES OF INTERFERENCE

Interference is generally divided into two components: Johnson or thermal noise and "fluctuation" noise. Johnson noise is independent of the material of which the resistor is made; it depends only on the resistance and temperature of the resistive element. Fluctuation noise is a characteristic peculiar to carbon-composition resistors because of their granular structure. In the generally accepted theory for this type of interference, it is assumed the resistance element is composed of a combination of series-parallel pressure contacts between discrete particles, and that the contact resistance between particles is subject to random charges.

2.1 JOHNSON NOISE

Most electronic system components generate some random voltage or current fluctuations. A metallic resistor, for example, contains electrons which drift randomly from molecule to molecule. When this resistor is connected into a circuit, the electron drift will produce a random current through the resistor and hence a voltage across its terminals. Such noise is called Johnson or thermal noise. The voltage generated across the terminals of an element is dependent upon the load into which it is operating. It is, however, convenient to be able to have a quantitative measure of noise power produced by a resistor which is independent of the circuit of which it forms a part, for this reason, the noise power produced by a resistor will be identified here with the amount of interference it generates in a matched load; i.e., a load whose resistance is identical to that of the resistor itself. Therefore, let the random (matched) noise voltage be $\nu(t)$, where t is time and T is period.Then the voltage autocorrelation function is

$$\phi\nu(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} \nu(t)\nu(t-\tau)dt \quad \text{(Eq 1)}$$

and the power spectral density is

$$\Phi\nu(\omega) = \int_{-\infty}^{\infty} \phi\nu(\tau)e^{-j\omega\tau}d\tau \quad \text{(Eq 2)}$$

It has been determined both experimentally and theoretically that for thermal noise

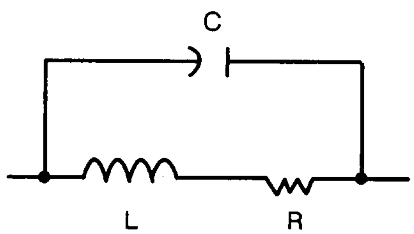
$$\Phi\nu(\omega) = \frac{kT}{2} \quad \text{(Eq 3)}$$

where k is the Boltzmann constant (1.38×10^{-23} J/K) and T is the absolute temperature of the resistor in kelvin. While $\Phi\nu(\omega)$ is not constant for all values of ω (this would indicate infinite power), the spectral density is flat out to extremely high frequencies, on the order of 10 GHz, where quantum effects occur.

2.2 RESISTORS' PARASITIC EFFECTS

In EMC analysis and design it is sometimes necessary to model the non-ideal behavior of resistors. The approximate model for a resistor including its parasitic effects is shown in *SN 2.2(1)*.

SUB-NOTE 2.2(1) Resistors' Parasitic Effects



Where:

C = stray capacitance
= 1.6 pF (default)

L = lead and intrinsic inductance = 20 nH (default)

R = assigned value of transistor

Without additional data, wirewound resistors cannot be completely modelled in this way because the value of the inductance is not known. The configuration of the models and the values of the R and C for wirewound resistors are the same as above; however, the value of the inductor in the model cannot be determined for these resistors unless additional data is obtained. For more detailed information on EMC analysis and design of resistors, see *References 657, 658, and 660.*

DESIGN NOTE 3D5 CAPACITORS

1. INTRODUCTION

Noise in capacitors can be due to the material construction or to its geometry. The following paragraphs give the noise mechanism in various types of capacitors.

2. CERAMIC CAPACITORS

Ceramic capacitors can be piezoelectric; therefore, spurious voltage may be generated by variations in pressure. In circuits having low signal-to-noise ratios, care must be taken to ensure that ceramic capacitors are not subject to extreme or rapid pressure variations, vibration, and thermal shock.

3. AIR, GAS, OR VACUUM TYPE CAPACITORS

Vibration may cause plates to flex in these types of capacitors and cause the capacitance to change. In tuned circuits, capacitor change may result in frequency shift or a type of frequency modulation.

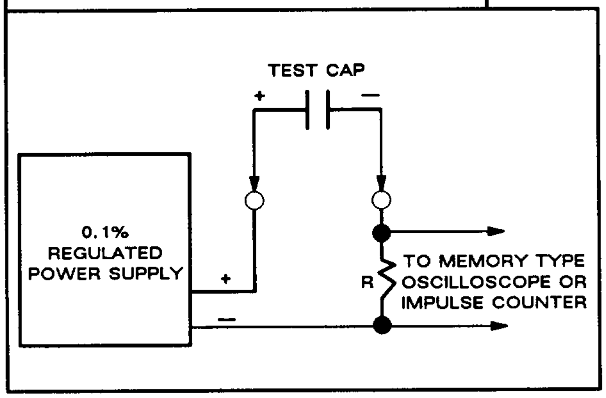
4. ELECTROLYTIC-TYPE CAPACITORS

Aluminum and tantalum are the most common types of electrolytic capacitors. Temporary dielectric breakdowns can occur on the order of a few microseconds due to the reforming process. Temporary dielectric breakdown is more prevalent in electrolytic-type capacitors but may occur in paper-and film-type capacitors also. Electrolytic capacitors should not be used in circuits where high ripple or transient voltages are present without proper derating. Wet-type electrolytics are not recommended for use in airborne equipments.

4.1 MONITORING TEMPORARY DIELECTRIC BREAKDOWN

Sub-Note 4.1(1) shows the test setup to measure the temporary dielectric breakdown. The resistance R is much lower than the leakage resistance of the capacitor so that the regulated power supply voltage appears across the test capacitor. The desired voltage is placed across the capacitor and temporary breakdown is monitored across the resistor (R). The magnitude and period can be monitored on an oscilloscope with a storage display cathode ray tube. The number of breakdowns can be monitored by an impulse counter.

SUB-NOTE 4.1(1) Measuring Dielectric Breakdown



5. CAPACITORS' PARASITIC EFFECTS

In EMC analysis and design it is sometimes necessary to model the non-ideal behavior of capacitors. The approximate model for a capacitor including its parasitic effects is given in *SN 5(1)*.

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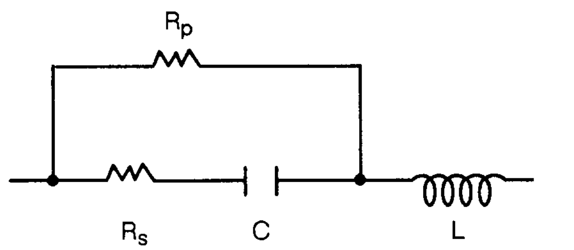
SUB-NOTE 5(1) Capacitors' Parasitic Effects



Where:

C = assigned value of capacitor

R_p = parallel resistor (R_p), a dc leakage path through the capacitor

R_s = series resistor (R_s) represents dielectric losses and determines the dissipation factor (DF)

$$DF = 2\pi f R_s C$$

L = series inductance represents lead inductance and other intrinsic inductances

If parasitic inductance is a problem, especially in the MHz region, make the capacitor lead as short as possible. For more detailed information on EMC analysis and design of capacitors see *References 657, 658, and 660.*

DESIGN NOTE 3D6 ELECTROEXPLOSIVE INITIATORS (EEI)

1. INTRODUCTION

Electroexplosives are employed as one-time sources of mechanical energy. They serve as actuators for valves, disconnects and ejection equipment; and are igniters for rocket engines, motors, destructors and prime movers of accessory power packages. These devices produce high energy output considering their size and weight and are very reliable owing to their simplicity. However, since they are electrically activated, the hazard of ignition by increasingly powerful sources of electromagnetic energy associated with weapon and space vehicle systems cannot be ignored. To minimize the possibility of inadvertent ignition, employ good firing circuit shielding, grounding, bonding, and filtering methods (*Chap 5*).

2. INITIATORS

Electroexplosives are ignited by an electrical initiator. An electrical initiator consists of a bridgewire surrounded by an explosive compound and enclosed in a case. The bridgewire is electrically insulated from the case. Ignition of the initiator is achieved by a temperature rise to the decomposition point of the explosive material, which is caused by current flowing through the bridgewire.

2.1 INADVERTENT IGNITION

The current flow can be induced by stray electromagnetic fields generated by RF transmitters or lightning and passed through the bridgewire in the prescribed manner. The energy required depends not only upon the electrical characteristics of the heat-converting element or bridgewire, but also upon the thermal properties of the adjacent explosive and some physical factors such as grain size and density of the explosive material.

3. SELECTING EEIs

Guidance for selecting EEIs for use on aerospace systems is contained in *SN 3(1)*.

4. EEI REFERENCE SOURCES

For extensive coverage of EEIs, see *TO 31Z-10-4, AFR 127-100, DN 4A3* in *AFSC DH 2-5, Ref 668, MIL-E-6051, MIL-STD-1385,* and *MIL-STD-1512.* Test procedures for RF impedance and RF sensitivity are contained in *MIL-STD-1512*. Statistical test methods are discussed in *DN 6A4.*

5. TERMINOLOGY

Refer to *MIL-STD-1512* for Air Force definitions of electroexplosive initiators and electroexplosive devices (EED). It may be some time before all Air Force handbooks and publications are revised to conform with these new definitions.

6. INVENTORY CONTROL

It is the intent of the Air Force to reduce the number of new EEIs entering the inventory to an absolute minimum. This can be accomplished by using a small, but thoroughly tested, standard family of EEIs for all EEDs. This will also result in lower cost in qualifying EEIs and EEDs.

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SUB-NOTE 3(1) Guidance for Selecting EEIs

1. Has *MIL–STD–1512* been fully reviewed and invoked on the program?

2. Has the USAF EEI inventory list been researched to see if an existing EEI already in the USAF inventory would meet the requirements? (Contact OO–ALC, Service Engineering Division, and AFATL/DLJCE, Eglin AFB FL 32542.)

3. Do the EEIs meet the 1A/1W for 5 min requirements of *MIL–STD–1512*? If not, has a waiver to this requirement been approved by the procuring activity and AFISC/SEV, Norton AFB CA 92409?

4. Is a hot wire EEI the right choice for this application? Are the required function time and available firing current and power consistent with the application?

5. Has the cost of the EEI been considered? Are the reliability requirements (and testing to verify the reliability) realistic in view of the intended use of the item?

6. Are the environmental and operational service-life requirements compatible with those of the weapons system?

7. Does the intended operational usage of the system call for any special anticipated requirements (lightning strike, vehicle electrification, high electromagnetic field environment, high temperature operation, etc.)?

8. Has a dual bridgewire device been considered or specified? If so, a single bridgewire is strongly recommended because bridgewire-to-bridgewire sensitivities seriously limit dual bridgewire devices.

SECT 3E INTERFERENCE SOURCES

SECTION 3E INTERFERENCE SOURCES

DESIGN NOTE 3E1 INTRODUCTION

1. GENERAL

Formerly, sources of interference were not troublesome since they fell inside the noise level ranges of the receiver. With the number, frequency, and power of sources of interference ever increasing, more attention is required to monitor acceptable performance and reliability. Accordingly the correct approach to the design of an electromagnetically compatible system requires the identification and tabulation of the possible sources of interference and interaction. These sources can be classified into one of two groups, functional or natural. Classification may assist the designer in determining or predicting system response and in taking the steps necessary toward eliminating, minimizing or neutralizing unacceptable effects.

2. NATURAL INTERFERENCE

Natural interference is inherent in our environment and includes atmospheric discharge, solar, cosmic and galaxy noise, interference due to equivalent temperature, differences between earth's atmosphere and outer space, and lightning and precipitation static. The minimum requirement is that all natural interference over the operating frequency range be considered as affecting the equipment. If the system is not affected when the most critical conditions are applied simultaneously, a detailed analysis on a probability basis is not necessary. If susceptibility is evident, even if only under the most rigorous conditions, take a probability approach. This could be accomplished by assigning distribution characteristics as a function of each of the independent variables. System response to interference variations is then calculated on a probability basis and an acceptable risk of susceptibility to natural interference is established.

3. MAN-MADE INTERFERENCE

Man-made interference may be divided into the following three types:

a. Continuous-wave interference, which usually emanates from transmitters and receiver local oscillators.

b. Pulsed continuous-wave interference generated by equipments or circuits that operate in a pulsed mode, such as radars, beacon sets and pulse-type jamming equipments.

c. Broadband interference, which generally originates either in equipment where arcing takes place, such as dc motors and generators, or in equipment containing relays, vibrators or gas-filled tubes. The interfering signals are random, narrow-pulse voltages that contain a broadband of frequencies.

The effect of man-made interference may range from sporadic noise, that is only annoying, to complete equipment inoperability.

3.1 FUNCTIONAL INTERFERENCE

Functional interference occurs when the normal functioning of one part of a system interferes with the normal functioning of another part. This is the greatest problem area to be overcome in achieving electromagnetic compatibility. Noise meters and screen rooms are helpful in overcoming this type of interference but sole reliance on these measures is not sufficient because system response may be affected by the nature of the environment during actual operation. Design compatibility between normal functions into the system. Also consider elements that are turned on and/or off during a mission as potential trouble makers until proven otherwise during design and production. Prepare a list of functions which could respond or be affected by the spectra as a guide for compatibility design.

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DESIGN NOTE 3E2 — CONTINUOUS WAVE

1. INTRODUCTION

Continuous wave (CW) interference is evaluated and handled on a different basis from broadband noise. A continuous sine wave exists at one frequency and occupies a single line in the spectrum. When a CW carrier is modulated it is represented by the carrier frequency and multiple sideband pairs which exist above and below the carrier frequency. With CW interference, the energy is concentrated at these discrete frequencies and other equipment is set to operate so as to block these frequencies. This is accomplished by frequency allocation and by rejection networks which block the energy over this narrow band-pass. The parameters which affect transmitter CW interference characteristics include peak and average power, frequency and its spectrum, antenna pattern and gain, type of modulation, distance of physical separation and reflection paths (multipath atmospheric and ground effects, and reflections from metallic surfaces by ray effect).

2. SOURCES

Continuous wave interference from a transmitter may emanate in several ways: from the main, side, back, and spurious lobes of the antenna; from the case surrounding the transmitting element, its driver and amplifier stages; and from the transmission lines. Radiation will leak through small imperfections in joints and seams, through ventilating ducts and screens, and through input and output connectors and cabling. Because the cabling is a poor transmission line at RF, the energy on the cabling will radiate into space or couple into nearby cabling by both inductive and capacitive coupling. As waveforms depart from a sine wave the different discrete CW frequencies which are present become more numerous until, in the extreme, the multiple frequencies appear to become a continuous broadband spectrum. Make an allocation study of frequencies to be used within the weapon system at the preliminary design stage. This eliminates undesirable problems such as several transmitters operating at the same frequency. Because of the nonlinear characteristics of practically every transmitter and oscillator, harmonics are generated and these may be evaluated as CW interference. Pulse generators, computer clocks, sawtooth deflection generators, trapezoid tracking waveforms, synchronizing multivibrators, and other periodic generators may be approximately evaluated as CW interference. The fundamental frequency will be the repetition rate. Depending on the waveform, two or three harmonics will suffice to describe the waveform accurately enough for interference control purposes. Often only the fundamental need be evaluated. The effects of radar pulse repetition frequency (PRF) are almost always troublesome. If the fundamental is made negligible, the effect of its harmonics is usually negligible. Continuous wave interference may be caused by many devices other than transmitters, oscillators, and pulse generators. Any fixed frequency device is a potential CW interference source. Relays which operate in a fixed rapid sequence can be most troublesome. Choppers, multivibrators, synchronous relays, steppers and stepper motors, ac reference generators, exciters for magnetic amplifiers, gyros, and transducers are all sources of fixed frequency interference. These devices operate at low power and audiofrequencies (af). Their effects are evidenced primarily by magnetic field inductive coupling and by resistive conductive coupling. Radiation is usually negligible below radio frequencies.

3. HUM

Hum is CW interference and is caused by a periodic low frequency signal entering the system. This usually occurs at a low level and is amplified by the successive stages. Hum frequency may be that of input power, power supply ripple, power source harmonics, repetition rate of pulse generation or timing, synchronization, frequency of sweep and scan circuits, clock rates, and sequencing rates. In a complex system hum effects may possibly be ignored during design, built in during production, or developed due to aging, shock, and vibration, or other environmental factors. The danger with hum interference in a system is that functional testing usually indicates go. However, hum effects in flight combine with other effects to exceed acceptable levels. In systems, a periodic variation of aim point, bias errors, and missing or false bits of digital data occurring at a hum rate are typical hum effects. Hum is superimposed on top of normal signals and is often caused by insufficient, improper, or deteriorated grounding. It frequently accompanies corrosion and film formation on contacts, bonding surfaces, shield grounding, and other connections.

3.1 FLUORESCENT AND NEON LIGHTS

Hum caused by interference from fluorescent and neon lights has a sinusoidal waveshape with sharp, irregular spikes. This type of hum is sometimes caused by high voltage transformers. If the input alternating current is half-wave rectified, or if voltage doublers are employed, hum at the power frequency is likely. Closely monitor

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power supply filter design, fabrication, and installation to ensure that input-output coupling does not occur and that the filter is well bonded and grounded. Leakage from filament transformers to nearby inductive elements often produces hum.

3.2 DEFECTIVE GROUNDING

Poor or deteriorated grounding has a ragged and erratic hum waveform. This hum is often caused by a poorly bonded outer conductor or shield. Corrosion around grounding screws and along bonding seams can also be a cause of erratic hum waveform. Pickup by tubes and transistors due to dc grounded shields may be anticipated. Similar hum occurs when the grid circuit becomes open due to breakage of leads and opening of large value grid resistors. See *Sect 5E* for more detail on grounding.

4. LOCAL OSCILLATOR (LO)

Because of local oscillator energy, two radio receivers located near each other will often interfere seriously. The local oscillator energy level is usually greater than the incoming signal energy. The LO output is coupled to the mixer via waveguide or transmission line, and unless shielded, this line will radiate energy. Inductive and capacitive elements are used to form the tuning circuits of the oscillator. Frequently, these are physical coils, capacitors, transmission line sections, stubs, cavities or waveguides which all exhibit reactive effects. Nearby reactive components form effective mutual inductance and capacitance with the oscillator. Evaluate parameters such as:

a. Oscillator voltage and currents

b. Ground currents and conductive coupling

c. Mutual inductance and capacitance coupling to nearby susceptible devices and cabling

d. Direct radiation from the oscillator and from the transmission line to the mixer

e. Coupling of LO frequencies into filament and bias supplies, power supply, and from then on feeding into cascading stages.

4.1 EVALUATION

Evaluate local oscillator interference to determine if the oscillator requires shielding to prevent direct radiation. If so, establish the degree of shielding attenuation necessary and the frequency band over which this attenuation is required. Ensure that magnetic field coupling via mutual inductance has been adequately reduced. Also, determine if the electric field coupling due to interstage and interequipment capacitance is sufficiently subdued. Interference generated by transmitters is classified as spurious or harmonic. Harmonic, or continuous wave (CW) interference, is radiated from the case, input-output wiring, the transmission lines to antennas, and directly from the antenna. The amplitudes of interference at different frequencies can only be approximated because of their nonlinear character. Since the variation of nonlinearities from one equipment to the next is large, a statistical approach is commonly used. Devise a test program to establish the level of compatibility desired.

5. INTERMODULATION PRODUCTS

Intermodulation is the product of undesired frequencies resulting from the unintentional mixing of two or more carrier frequencies. Frequency separation between transmitters is required to reduce intermodulation. Audio intermodulation in a transmitter results from nonlinearities of modulation and also from distortion of the modulating signal. It is customarily termed "sideband splatter." Common nonlinearities include overdriven modulators, modulation limiters, amplifier characteristics, poor power supply regulation, and a nonlinear modulation process. Audio intermodulation is increased by overmodulation, resulting in distortion on the positive modulation swing and clipping of negative peaks. Audio intermodulation produces sidebands which are not greatly different from the carrier. The sidebands enter into the passband of the receiver tuned to or close to the transmitter frequency. Conduct testing to evaluate sideband splatter characteristics. This can be done by either the noise load test, or the two-tone test.

5.1 NOISE LOAD TEST

The basic approach is to inject band-limited noise and photograph the output spectrum on a spectrum analyzer. An overlay representing the noise generator filter characteristic then yields the splatter spectrum as well as components beyond the filter cutoff.

5.2 TWO-TONE TEST

The two-tone test method consists of adjusting two equal amplitude tones to produce a given percentage modulation. The ratio of distortion to tone is then measured. Typical ratios for single sideband (SSB) transmitters are from –40 to -50 dB.

5.3 AUDIO INTERMODULATION SUPPRESSION

Accomplish the suppression of audio intermodulation by development of improved linearity characteristics and adequate dynamic range, avoidance of limiters and overdriven modulators, well-regulated power supplies, and use of filters to block all frequencies except the desired modulation.

5.4 RADIO FREQUENCY (RF) INTERMODULATION

Radio frequency (RF) intermodulation is caused by two or more signals interacting in a nonlinear device. See *DN 4A1* for a more complete discussion of this theory. Third-order products are the most common problem although second-order products sometimes can present a problem too. The frequency relations for the two-signal case are:

$$\text{Intermodulation frequencies} = mf_1 \pm nf_2 \quad \text{(Eq 1)}$$

Where:

f_1 and f_2 are the two signal frequencies and m and n are integers (0, 1, 2, 3, 4, . . . etc.). The second-order products are the cases where $m + n = 2$. They are: $m = 2$, $n = 0$; $m = 1$, $n = 1$; and $m = 0$, $n = 2$. The third-order products are the cases where $m + n = 3$. All possible combinations should be taken to determine intermodulation products. Examples of integers for third order are: $m = 3$, $n = 0$; $m = 2$, $n = 1$; $m = 1$, $n = 2$; and $m = 0$, $n = 3$.

DESIGN NOTE 3E3 BROADBAND

1. INTRODUCTION

Sub-Note 1(1) is representative of noise intensity of radio interference sources from 10 MHz to 10 GHz. See *DN 1B2, Para 8,* for more information on broadband interference versus frequency.

2. ATMOSPHERIC INTERFERENCE

Atmospheric interference, which is continuously generated, is impulsive and the spectrum is concentrated below 50 MHz. Higher frequencies are probably generated but do not experience ionospheric reflection and escape into outer space. The peak amplitude of the received noise varies as the square root of receiver bandwidth. Common preventive methods include reduction of receiver bandwidth so the highest modulation sidebands are at the edge of the bandpass. Another method is to utilize a directive antenna so that the direction of the disturbance may be avoided. The brute force method is to mask the interference by stepping up the transmitter output. Another method is to employ amplitude limiting and accept the audio limitation.

3. COSMIC NOISE

The level of cosmic noise is lower than that of atmospheric and man-made interference. It becomes critical only beyond the 50 MHz region where atmospheric noise falls off or at locations remote from the man-made noise environments. Space systems of high sensitivity must cope with cosmic noise interference in the frequency range from 10 to 300 MHz. Three types of cosmic noise exist: galaxy noise, thermal noise, and anomalous solar noise. Galaxy noise, which resembles celestial thermal electric noise, has a definite spatial distribution. It appears to emanate most strongly from Sagittarius with the strongest band from 150 to 200 MHz. Thermal noise is radiated from celestial bodies in a frequency range from 3 to 30 GHz. Anomalous solar noise is due to unexplained phenomena such as sunspots. Frequencies vary with different anomalies; however the upper high frequency (HF) band is subject to such interference.

4. PRECIPITATION STATIC

Precipitation static is a form of broadband interference. See *Sect 7B* for details.

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5. COMMUTATORS

Direct current machines with commutators produce interference in three distinct modes. First, the current in the armature coil reverses direction. Second, the voltage induced in each coil varies with its position in the magnetic field; hence the voltage will vary as the commutator moves from coil to coil. Third, as some armature coils are short circuited via the brushes, the total armature impedance between brushes varies. In addition to these distinct modes of interference generation, brush arcing usually occurs. Broadband interference produced by a telemetry commutator is conducted into its power supply lines. A Fourier analysis reveals a dc component and harmonics of the data sampling rate. These harmonics extend from the audio region upward into the hundreds of megahertz. Low-pass filters will block audio interference but are ineffective against the radio frequencies because of input-output and self-resonance of capacitors due to lead inductance.

6. ARCING

Arcing occurs when the electric field intensity between two conductors exceeds the breakdown strength of the dielectric between the conductors. In solids arcing will usually cause, or pave the way for, breakdown and malfunction. Arcing in gaseous media usually produces severe interference without equipment malfunction. The arc may be considered as a varying impedance. The rate of change of impedance depends on source and line impedance and voltage, and on the ionization and/or deionization characteristics of the gas.

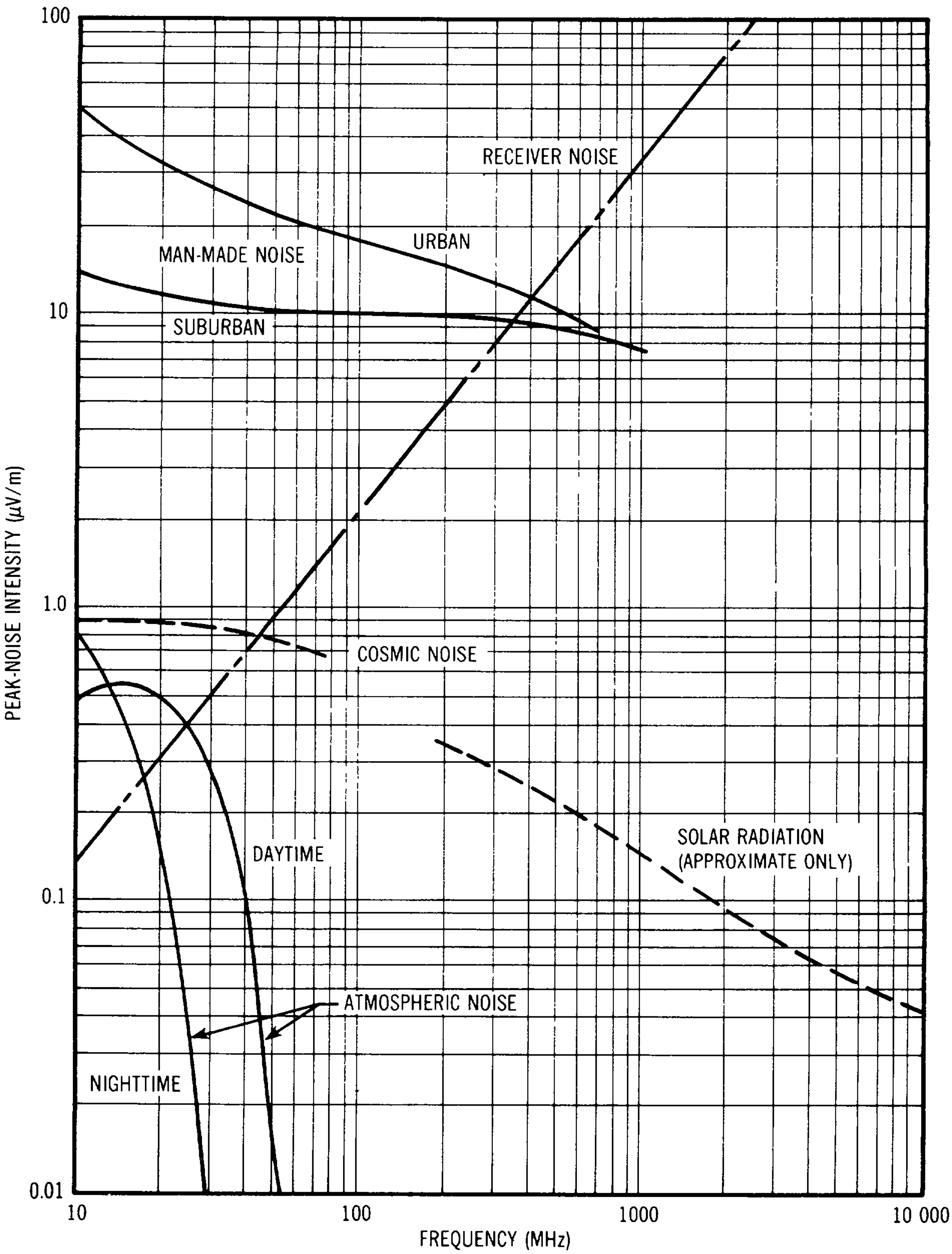
6.1 ARCING AND CORONA SUPPRESSION

Arcing and corona should be minimized or eliminated where practicable. Where they cannot be entirely eliminated, their effects should be controlled by shielding the equipment generating them. Filter all leads associated with the unit, and locate where they will have the least effect on other equipments and circuits.

6.2 ARC-OVER PREVENTION

The actual potential at which arc-over takes place at various altitudes depends greatly on the distance between the parts and the configuration of the parts. The effective surface creepage distance and actual air spacing between terminals or parts should not be less than that specified in *SN 6.2(1)* for the intended voltages. Surface creepage distance is actual distance between electrodes along

SUB-NOTE 1(1) Sources of Radio Interference



SUB-NOTE 6.2(1) Contact Spacing vs Working Voltages (*Ref 14*)

MINIMUM AIR SPACE		MINIMUM CREEPAGE DISTANCE		WORKING VOLTAGE AT 15 km (50 000 ft)		WORKING VOLTAGE AT 21 km (70 000 ft)	
mm	in.	mm	in.	dc	ac rms	dc	ac rms
		1.4	3/64	100	75	70	50
0.8	1/32	1.6	1/6	190	125	125	90
1.2	3/64	2.0	5/64	210	175	175	125
1.6	1/16	2.8	7/64	315	225	210	150
2.0	5/64	3.2	1/8	360	260	230	165
2.4	3/32	4.0	5/32	420	300	260	185
3.2	1/8	4.8	3/16	490	350	310	225
4.8	3/16	6.4	1/4	630	450	375	275
6.4	1/4	8.0	5/16	700	500	455	325
8.0	5/16	9.5	3/8	810	575	500	355

Parts or terminals should be continuously insulated There should be no open space existing between any part of the conductors having this mechanical spacing

surface of insulation between them including irregularities. The configuration of the parts is important to prevent corona, which would ionize the air and cause arc-over even at the specified safe air spacings. Sharp corners are most apt to cause corona, while rounded corners are least likely to do so. The degree of roundness, however, is also an important factor at the higher voltages. At sea level pressure, equipment that has exposed potentials of less than 1000 V needs no special considerations; even square corners are permissible. From 1000 to 6000 V, reasonably well-rounded corners are required. However, from 6000 to 20 000 V no set rules have been developed and special tests should be conducted on the equipment to determine the proper configurations. When it is not practical to modify exposed electrodes to rounded configurations and pressurization is not possible, a metal corona shield should be used. The shield should surround, though not necessarily completely, the poorly shaped electrodes in such a manner as to prevent any breakdown voltage gradient in the surrounding air. The corona shield must also be rounded. Maximum arc-over and corona discharge occurs at pressures between 0.1 to 6.5 Pa. Below a pressure of approximately 10^{-1} Pa, the air density is too low to support a corona discharge.

7. HEATER CIRCUITS

In temperature-sensitive equipment, heater elements are incorporated to compensate for thermal variations and provide constant-temperature operation. The thermostat heater contacts initiate on-off flow of power to the heating element. Power for heaters is usually 28 V dc with consequent heavy broadband interference on the 28 V dc power lines. Significant broadband interference may be caused by the heaters of an inductive pickup transducer extending well beyond 100 MHz. Devices having heater elements should be closely monitored for both conducted and radiated interference phenomena.

8. FLUORESCENT LAMPS

Fluorescent lamps develop an electrical voltage breakdown transient that produces modulated RF energy. Any facility housing a system during test or launch operations must be evaluated insofar as lighting interference is concerned for interference produced by the on-off transient and interference produced during normal lighting. Radio frequency interference produced by fluorescent lamps may be radiated from the lamps and fixtures, conducted through the power circuitry, or radiated from the wiring that supplies power to the fluorescent lights. The most important aspect is RF radiation from the power lines that supply the lamps. Suppress radiated interference from lamps and fixtures by proper grounding of the case and fixture. This provides an RF shunt to ground. It is usually better to eliminate the radiated noise along with the conducted noise by the use of capacitors across each lamp. Attenuation of radiation by 25 dB is practical this way. A ground loop nearly always exists between the ballast and the power source. The radio noise voltages arise from capacitive coupling between ballast coils and case. Grounding the fixture case can increase the conducted interference. This may occur due to decreased loop impedance when the capacity to ground is shorted. Lower RF impedance is then accompanied by higher RF loop current within the ballast and higher interference. The best solution is the addition of filter capacitors across the lamp (0.01 μF is typical).

9. MICROWAVE

Microwave transmitters pose a serious threat to satisfactory operation of sensitive receivers. Parallel the integration of high-powered radar into a system by a program to control the spurious energy radiated into space. Antenna gains of 30–40 dB are common for airborne antennas. A 250-kW radar transmitter having spurious signal levels rising to within 30 dB of the transmitted frequency produces a 250-W pulse interference level. Thirty dB of antenna gain raises this level to 250 kW. The effective radiated power of contemporary radar is 4–70 dBmW. This interference can be suppressed by magnetron design, shaping of modulating pulse and high power filters in the waveguide.

9.1 FILTERS

Waveguide filters may be classified in the following four classes: (1) coupled waveguide filters; (2) directional filters; (3) direct coupled filters; and (4) leaky waveguide filters. The first three types are reflection type filters. The last type is an absorption type.

9.2 FILTER DEVELOPMENT

The development of new waveguide filters is one of the most rapidly advancing areas in microwave electronics. The newer waveguide filters utilize techniques which involve the use of Tchebyscheff polynomials. The difference between the theoretical or ideal case and the actual case increases as frequency advances. At high frequencies the equal-ripple function (Tchebyscheff) becomes extremely useful.

9.3 FILTER TYPES

Included in a current listing of waveguide filters are found corrugated waveguide filters with longitudinal slots, dissipative filters with rectangular-side waveguides, offset dissipated-wall filters, serpentine leaky-wall circular dissipative-wall filters, dissipative filters with circular-side waveguides, complete transfer coupler filters, and leaky-wall wire-grid filters.

10. DATA PROCESSING MACHINES

Many systems now incorporate digital computers into the vehicle or use ground-stationed data processing support systems. These equipment generate large amounts of broadband noise. Interference sources include motors, commutators, cam contacts, clutch magnets, solenoids, relays, switches, tubes, semiconductors, diodes, amplifiers, flip-flops, gates, steppers, fluorescent lamps, mercury arc lamps, functional corona, high-voltage supplies, circuit breakers, printing devices, feeders, magnets, energizing circuits, actuating armatures, and other on-off switching circuits. Serious RF interference usually is conducted into supply power lines and data information flow lines. Integrate insertion of line filters on all input power into the original design concept.

10.1 DESIGN PRECAUTIONS

The most practical design precautions include integration of L-type filters in input power lines, use of conductive gaskets or serrated metallic spring-type fingers on access covers, use of transient limiting resistors in print and readout magnet and other energizing circuits, and use of copper mesh screens or other effective shields over all openings and apertures. Various covers, in order of decreasing shielding effectiveness, are listed below:

a. Reinforced plastic with 0.025 mm (10 mil) copper spray on inner surface

b. Reinforced plastic with imbedded copper screening

c. Standard steel covers

d. Reinforced plastic with glass fibers nickel-plated

e. Reinforced plastic with imbedded perforated aluminum foil

f. Untreated reinforced plastic.

10.2 INTERFERENCE LEVELS

Some typical interference levels in computers, and their sources are listed in *SN 10.2(1)*.

11. RADAR SITE

A radar site may have 400 items requiring RFI suppression. Interference generating equipment at a typical site consists of transportation equipment, auxiliary engine driven equipment, and accessory equipment.

11.1 DESIGN CONSIDERATIONS

Exercise the following design considerations at the site to obtain a permissible ambient interference level:

a. Shielding of high-tension leads from magnetos to spark plugs

b. Shielding of ignition coils

c. Shielding of distributors

d. Shielding of spark plugs

e Shielding of regulators

f. Shielding of generator leads

g. Shielding of magnetos

h. Using sheet metal shields around major equipment when needed

i. Watertight design on high-tension conduits to reduce moisture condensation

j. Use of bonding straps and conductive gaskets to bond electrical components to structure or engine assemblies.

12. STATIC POWER DEVICES

Rotary electrical power devices are being replaced by lighter and smaller static power devices, which generally produce many times more RF interference than the previous rotary equipment. The levels of interference commonly reach hundreds of millivolts and sometimes exceed 1 volt. The interference is practically all caused by diode reverse current spikes.

SUB-NOTE 10.2(1) Typical Interference Sources

SOURCE	FREQUENCY	MAGNITUDE
Magnet armatures	Transient spike 1.8 to 3.6 MHz	20 000 μV/kHz conducted
Circuit breaker cam contacts	Broadband 10 to 20 MHz	28 μV/kHz conducted
Vacuum cleaner	0.1 to 1.0 MHz	3 000 μV/kHz conducted
Mercury arc lamp	0.1 to 1.0 MHz	8 000 μV/kHz conducted
Corona	0.1 to 10 MHz	100 μV/kHz conducted
Fluorescent lamps	0.1 to 3 MHz peak at 1.0 MHz	20 to 300 μV/kHz conducted
Untreated access covers	0.01 to 10 MHz	1 000 μV/m·kHz radiated
Print magnets	1 to 3 MHz	200 μV/m·kHz radiated
Cams	10 to 20 MHz	200 μV/m·kHz radiated

DESIGN NOTE 3E4 NONLINEARITIES AND DISTORTION

1. INTRODUCTION

Nonlinearities which exist in many parts of the system/subsystem produce distortion that is unwanted in the output. In the initial program, set forth a concrete plan to investigate the nature and effects of major nonlinearities.

2. DISTORTION

Frequency, amplitude, and phase distortions can affect output.

2.1 FREQUENCY

Frequency distortion is produced by unequal amplification of different frequency components of a given signal. A signal consisting of the fundamental and second harmonic combine to form a complex waveform. The wave is then amplified by a device having twice the gain at the frequency of the second harmonic at the fundamental. The presence of frequency distortion can be evaluated from an input-output plot. Neglected resonances and peaking, which occur beyond the bandwidth of normal operation, can be troublesome. Although the channel produces the desired waveform it also passes on spurious interference signals. Frequency distortion is often caused by neglected or unsuspected reactive impedances external to tubes and transistors. Lead length inductances and stray capacitance also contribute.

2.2 AMPLITUDE

Amplitude distortion occurs when input signals of different levels are not equally amplified. This occurs when the dynamic transfer characteristic is not linear over the entire operating range. Additional stages may be required to obtain linearity and high gain over the required dynamic range From the standpoint of linearity or freedom from distortion, amplifier operation should be centered around a quiescent or bias condition so that the input-output relation is linear for the entire dynamic range of input signal swing. Lower power output amplification is used in about 90 percent of all electron tube applications. The maximum theoretical power conversion efficiency is 50 percent, but in practice values range from 2 to 20 percent. Hence, linearity is usually forsaken in power amplifiers. Electron tube power amplifiers operating Class B achieve efficiencies of 50 to 60 percent. Class C electron tube amplifiers can be operated at efficiencies to 70 to 85 percent. Because conduction occurs for as little as 50 to 100° of the full 360° cycle, distortion is extreme. For this reason Class C operation should be used only at frequencies where offending distortion products can be filtered out.

2.3 PHASE

Phase distortion occurs when phase shifts experienced by frequency components of the input wave differ. Phase distortion is caused by the presence of reactive elements. It may be prevented either by elimination of the reactive elements or by compensation with an equal and opposite reactive element or effect. Because the human ear is insensitive to phase distortion, it is usually neglected in audio systems. With signals used for control or computing purposes, phase shift distortion cannot be neglected.

3. PULSE SHAPE AND SPECTRUM

See *DN 4A2* for information on pulse shape and spectrum.

4. RECEIVER CHARACTERISTICS

The bandwidth is the width of the resonance curve (in hertz or kilohertz) of a receiver at a specified ratio. This characteristic of a receiver produces an output dependent on the total energy in that bandwidth. Signal energy may exist at one discrete frequency, or at several discrete frequencies across the bandwidths.

4.1 DC POWER

Ripple, which can be as much as 6 to 8 V at 600 to 1500 Hz, is exhibited in dc power subsystems. The rectification process involves a pulsating waveform with basic harmonics at some multiple of the input alternating current. The Fourier spectrum of the

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rectified alternating current is used to determine the interference ripple and harmonic voltage. The filter, which acts on the pulsating direct current, in itself consists of reactive elements. These elements are resonant at some frequency due to stray capacitances and unintentional series inductances. A damped oscillation superimposed on the dc output results and is distributed to all loads on the power supply unless blocked or bypassed.

4.2 AC POWER

Evaluate ac power subsystems as potential noise and interference generators. Because of the presence of nonlinear circuits, departure from sinusoidal characteristics is usually present in the voltage developed by ac generators. Voltage regulators for ac subsystems are subject to resonance which can be excited by load switching and damped oscillations will be superimposed on the basic ac supply as a result.

4.3 MOTORBOATING

In addition to basic ripple and high-frequency ringing, power supplies produce interference due to regulating characteristics. Many power supplies, when regulated, will produce a low-frequency variation termed "motorboating."

4.4 IGNITION

Ignition subsystems are one of the strongest sources of broadband interference. Deliberate generation of an arc with steep wavefronts is inherent to operation of the engine involved. The spectrum has a fundamental low-frequency wave and a multiplicity of harmonics and transients which extend across the complete radio frequency spectrum. It is strong at 10 MHz, hits peaks at 80-100 MHz, and has an effective power bandwidth of about 60-120 MHz. By close control of wiring dimensions and symmetry this bandwidth can be significantly reduced. The high frequencies radiate freely from the ignition wiring harness. Elimination of this interference at the source would negate the functional requirement, so the only approach is complete, quality shielding of the wiring harness.

5. FCC CLASSIFICATION OF INTERFERENCE

Rules and regulations have been established and published by the Federal Communications Commission (FCC) to control nonmilitary interference generation. This is presented in *Parts 15* and *18* of *Ref 633*. The FCC has classified interference generators on restricted radiation devices (RRD), incidental radiation devices (IRD), and industrial, scientific, and medical equipment (ISM).

5.1 RESTRICTED RADIATION DEVICES (RRD)

Restricted radiation devices (RRD) depend on the generation and application of RF energy. Therefore, RF energy radiated or conducted via power lines must be controlled by FCC regulations. Typical RRD equipment includes AM and FM broadcast radios; low power communication and control devices such as wireless microphones, garage door openers, and phonograph oscillators; and carrier current systems such as community TV, campus radio, telephone, and industrial systems.

5.2 INCIDENTAL RADIATION DEVICES (IRD)

Incidental radiation devices (IRD) are defined as those in which RF interference is unintentionally generated. There is no functional necessity for RF oscillators, etc., in IRD. Typical IRD equipment includes fluorescent lights, electrical appliances, electric pumps and motors, electric shavers, ignition systems, defective insulators, etc.

5.3 INDUSTRIAL, SCIENTIFIC, AND MEDICAL (ISM) EQUIPMENT

These include industrial heaters, induction and dielectric; medical diathermy and surgical tools; and miscellaneous items such as epilators, ultrasonic generators, radar cookers, electronic ovens, and neon signs.

5.4 FREQUENCIES ALLOCATED FOR ISM EQUIPMENT

The following frequencies are designated by the National Telecommunication and Information Administration for use by ISM equipment. The emissions of the ISM equipment must be confined within the frequency limits associated with each frequency:

13 560 ± 6.78 kHz
27 120 ± 160.0 kHz
40 680 ± 20.0 kHz
915 ± 13.0 kHz
2 450 ± 50.0 kHz
5 800 ± 75.0 kHz
24 125 ± 125.0 kHz

5.5 DESIGN CONSIDERATIONS

In the event harmful interference is caused by ISM equipment operation to any authorized radio service outside the frequency limits specified, the operator of the ISM equipment must promptly take necessary steps to eliminate such interference. The operator does not have to take action if the interference is due to direct intermediate frequency pickup by a receiver of the fundamental frequency emissions of ISM equipment operating on an ISM frequency.

6. INTERFERENCE MEASURING DEVICES

Inability to define the specific noise parameters which should be measured has made exact radio interference measurements difficult. Interference is all signals that are different from the desired signal and may be periodic or random. Each interference has its own characteristics. Only three quantities are needed to define a sine wave, while an infinite number of quantities are required to completely specify a general random process. Measuring the noise spectrum of a source requires the determining of enough of these parameters so that the effect of the noise on a given device can be determined and deductions made as to which parameters are significant. In interference measurement or in compatibility testing, what should be measured and how will the data be interpreted are two basic questions.

6.1 INTERFERENCE-FIELD INTENSITY METERS

Interference-field intensity meters and other test methods may be divided into four functional types:

a. Use of the actual device or its equivalent from a susceptibility standpoint.

b. Use of a sensitive, superheterodyne-type radio with its output indicated relative to a standard interference generator. This standard may be an impulse, a sine wave or random gaussian noise. This is commonly called the substitution method.

c. Use of a radiometer with an output circuit which is set up to simulate the characteristics of the human ear. This method is extremely effective for audio devices.

d. Use of laboratory-type equipment to measure statistical parameters of noise, such as probability distributions of waveform amplitude or number of peaks, or the average power spectral density.

6.2 EMI METERS

Electromagnetic interference (EMI) meters have traditionally been equipped with three modes of measurements: quasi-peak, average, and peak. Proper use of these modes required relatively detailed knowledge of the characteristics of the interference signal that often was not available. Measurements were often taken in all three modes for the same interference signal to ensure adequate data was taken. This resulted in excessive test time and cost. In numerous instances, interference testing resulted in "wearing out" one or more test articles due to the long test procedures. Semiautomatic procedures and techniques that can measure all types of interference except for low repetition rate transients have been introduced. The new techniques can record about 150 interference signals per minute. The data is recorded on X-Y records and is suitable for use in reports with no additional data processing or handling required.

The old measurement modes of quasi-peak, average, and peak are not expected to be retained on new instrument designs and, in general, should not be used after a measurement facility converts to semiautomatic measurements.

6.3 SPECTRUM ANALYZER

The spectrum analyzer, in general, consists of a superheterodyne receiver with a narrow bandwidth. The output signal is displayed on an oscilloscope which is incorporated into the spectrum analyzer. The receiver is scanned over a portion of the spectrum by the application of a sawtooth voltage to a voltage controlled local oscillator. The sawtooth voltage is also applied to the horizontal deflection plates of the oscilloscope. Thus the observer can select a finite portion of the spectrum to determine the variation of input signal amplitude with frequency. The resolution obtainable is a function of both the rate of sweep (scan) and the inherent bandwidth of the receiver. Other significant characteristics of the instrument are:

a. Spurious response

b. Dynamic range

c. Frequency coverage

d. Sensitivity

e. Linearity or other characteristics of the amplitude response

f. Calibration.

CHAP 4 INTERFERENCE PREDICTION

CHAPTER 4 INTERFERENCE PREDICTION

SECT 4A EMC ANALYSIS, MANUAL

SECTION 4A EMC ANALYSIS, MANUAL

DN 4A1 - NONLINEAR DEVICES

DN 4A2 - PULSE SHAPE AND SPECTRUM

DESIGN NOTE 4A1 NONLINEAR DEVICES

1. INTRODUCTION

Nonlinear devices such as electron tubes, semiconductors, and ferromagnetic inductors can produce a distorted waveform which can cause spurious emission in receivers. In nonlinear devices the voltage is not proportional to the current nor to its derivative or integral. The impedance of the device is not constant but is a function of its output current.

2. NONLINEAR CONVERSION

Consider an electron tube or transistor operating in its nonlinear region as shown in *SN 2(1)*. The output waveform is "clipped" or distorted. This transfer function can be represented by a power series of the form

$$I = C_0 + C_1e + C_2e^2 + C_3e^3 + \ldots C_ne^n \quad \text{(Eq 1)}$$

$$I = I_0 + i_1 + i_2 + i_3 + \ldots i_n \quad \text{(Eq 2)}$$

Where:

I = total output current (amps)

C_r = coefficient of "n" terms

e = total instantaneous output voltage

$$e = E_1 \sin \omega_1 t + E_2 \sin \omega_2 t + E_3 \sin \omega_3 t + \ldots E_n \sin \omega_n t \quad \text{(Eq 3)}$$

$$I_0 = C_0,\ i_1 = C_1e,\ i_2 = C_2e^2 \quad \text{(Eq 4)}$$

Since I_0 is the dc component of output current, then total instantaneous current

$$i = i_1 + i_2 + i_3 + \ldots\ i_n \quad \text{(Eq 5)}$$

Consider that e is in the sum of three different signals (not necessarily harmonics)

$$e = E_1 \sin \omega_1 t + E_2 \sin \omega_2 t + E_3 \sin \omega_3 t \quad \text{(Eq 6)}$$

Where:

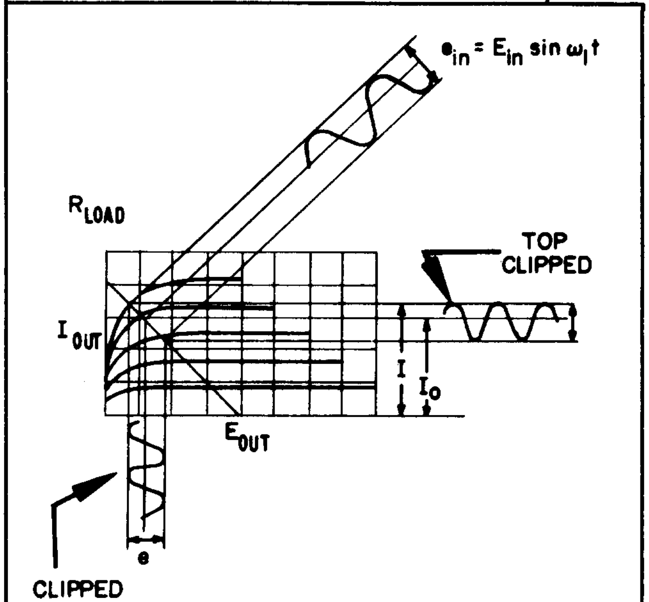
E = maximum signal voltage

t = function of time

$\omega = 2\pi f$ = angular frequency of carrier

ω_1 is the fundamental angular frequency, if $n\omega_1 = \omega_n$ then ω_n is the "nth" harmonic.

SUB-NOTE 2(1) Nonlinear Characteristic



Substituting and expanding yields

$$i_1 = C_1 (E_1 \sin \omega_1 t + E_2 \sin \omega_2 t + E_3 \sin \omega_3 t) \quad \text{(Eq 7)}$$

$$i_2 = C_2 (E_1 \sin \omega_1 t + E_2 \sin \omega_2 t + E_3 \sin \omega_3 t)^2$$

$$= C_2 \Big\{ \frac{1}{2} E_1^2 (1 - \cos 2\omega_1 t) + \frac{1}{2} E_2^2 (1 - \cos 2\omega_2 t) + \frac{1}{2} E_3^2 (1 - \cos 2\omega_3 t)$$
$$+ E_1E_2 [\cos (\omega_1 - \omega_2) t - \cos (\omega_1 + \omega_2) t]$$
$$+ E_1E_3 [\cos (\omega_1 - \omega_3) t - \cos (\omega_1 + \omega_3) t]$$
$$+ E_2E_3 [\cos (\omega_2 - \omega_3) t - \cos (\omega_2 + \omega_3) t] \Big\} \quad \text{(Eq 8)}$$

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$$i_3 = C_3 (E_1 \sin \omega_1 t + E_2 \sin \omega_2 t + E_3 \sin \omega_3 t)^3$$

$$= C_3 \Bigg\{ \frac{E_1^3}{4} (3 \sin \omega_1 t - \sin 3\omega_1 t) + \frac{E_2^3}{4} (3 \sin \omega_2 t - \sin 3\omega_2 t)$$

$$+ \frac{E_3^3}{4} (3 \sin \omega_3 t - \sin 3\omega_3 t)$$

$$+ \frac{3E_1^2 E_2}{2} [\sin \omega_2 t + \frac{1}{2} \sin (2\omega_1 - \omega_2)t - \frac{1}{2} \sin (2\omega_1 + \omega_2)t]$$

$$+ \frac{3E_2^2 E_3}{2} [\sin \omega_3 t + \frac{1}{2} \sin (2\omega_2 - \omega_3)t - \frac{1}{2} \sin (2\omega_2 + \omega_3)t]$$

$$+ \frac{3E_1^2 E_3}{2} [\sin \omega_3 t + \frac{1}{2} \sin (2\omega_1 - \omega_3)t - \frac{1}{2} \sin (2\omega_1 + \omega_3)t]$$

$$+ \frac{3E_2 E_3^2}{2} [\sin \omega_2 t + \frac{1}{2} \sin (2\omega_3 - \omega_2)t - \frac{1}{2} \sin (2\omega_3 + \omega_2)t]$$

$$+ \frac{3E_1 E_2^2}{2} [\sin \omega_1 t + \frac{1}{2} \sin (2\omega_2 - \omega_1)t - \frac{1}{2} \sin (2\omega_2 + \omega_1)t]$$

$$+ \frac{3E_1 E_3^2}{2} [\sin \omega_1 t + \frac{1}{2} \sin (2\omega_3 - \omega_1)t - \frac{1}{2} \sin (2\omega_3 + \omega_1)t]$$

$$+ \frac{3E_1 E_2 E_3}{2} [\sin (\omega_1 + \omega_2 - \omega_3)t + \sin (\omega_1 - \omega_2 + \omega_3)t$$

$$- \sin (\omega_1 - \omega_2 - \omega_3)t - \sin (\omega_1 + \omega_2 + \omega_3)t] \Bigg\} \qquad \text{(Eq 9)}$$

The first-order component of the output current i_1 is of fundamental importance when an active device is used as an amplifier; all other components represent distortion. The second-order term i_2 is sometimes of importance when the device is used as a mixer because of the image response.

3. MIXER CROSS-PRODUCT CALCULATIONS

In a typical mixer subsystem, two frequencies f_H and f_L mix to produce an output f_0, which is generally either the sum or difference of the two input frequencies. Either or both of the input frequencies may vary over a total bandwidth Δf. Then, the mixer output usually passes through a bandpass filter of bandwidth Δf to eliminate the undesired products. However, some undesired higher-order modulation products may appear within the passband and cannot be removed by filtering. (These paragraphs extracted from *Ref 59*©.)

3.1 MIXER FREQUENCY CHART

Sub-Note 3.1(1) displays the mixer cross products so that a designer can see what products occur, and where the spurious responses are, with respect to the desired output frequency. These charts show modulation products up to the seventh order, although higher-order products can be added. Chart A is used when the output frequency is the sum and Chart B is appropriate when the output frequency is a difference.

3.2 CHART PARAMETERS

Both charts in *SN 3.1(1)* show modulation products to the seventh order and bandwidths of −50% to +50% of the desired output frequency. The ordinate of the graphs represents the ratio of the two mixed signals, and is always made less than one. Each graph's abscissa is the frequency separation of cross-modulation products with respect to the desired output frequency f_0.

3.3 MATHEMATICAL BASIS

The basis for charts in *SN 3.1(1)* is the expansion of Eq 10, which describes the nonlinear behavior of a diode mixer.

$$i = i_0 (\epsilon^{eV/kT} - 1) \qquad \text{(Eq 10)}$$

Expanding Eq 10 in a power series, and substituting the summation of mixer input signals, represented in the form of

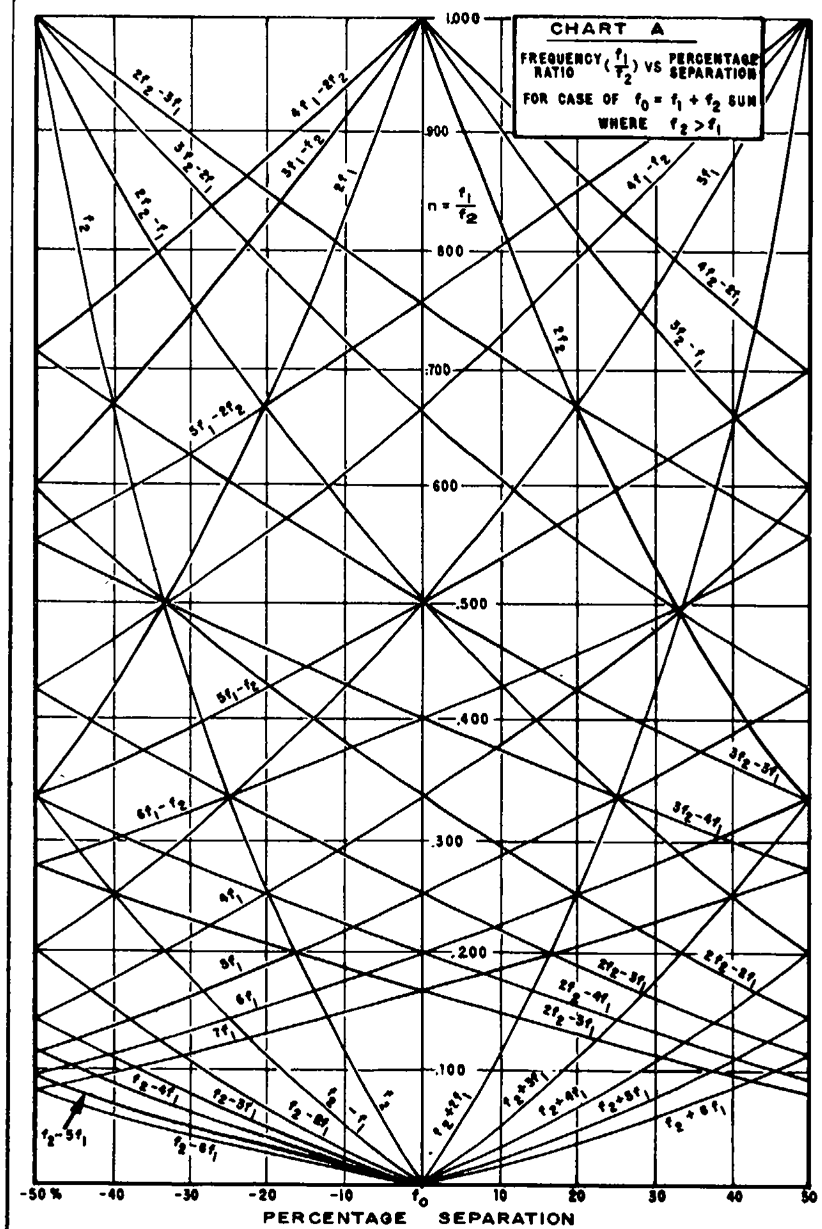
$$V = E_1 \operatorname{Cos} (2\pi f_1 t) + E_2 \operatorname{Cos} (2\pi f_2 t) \qquad \text{(Eq 11)}$$

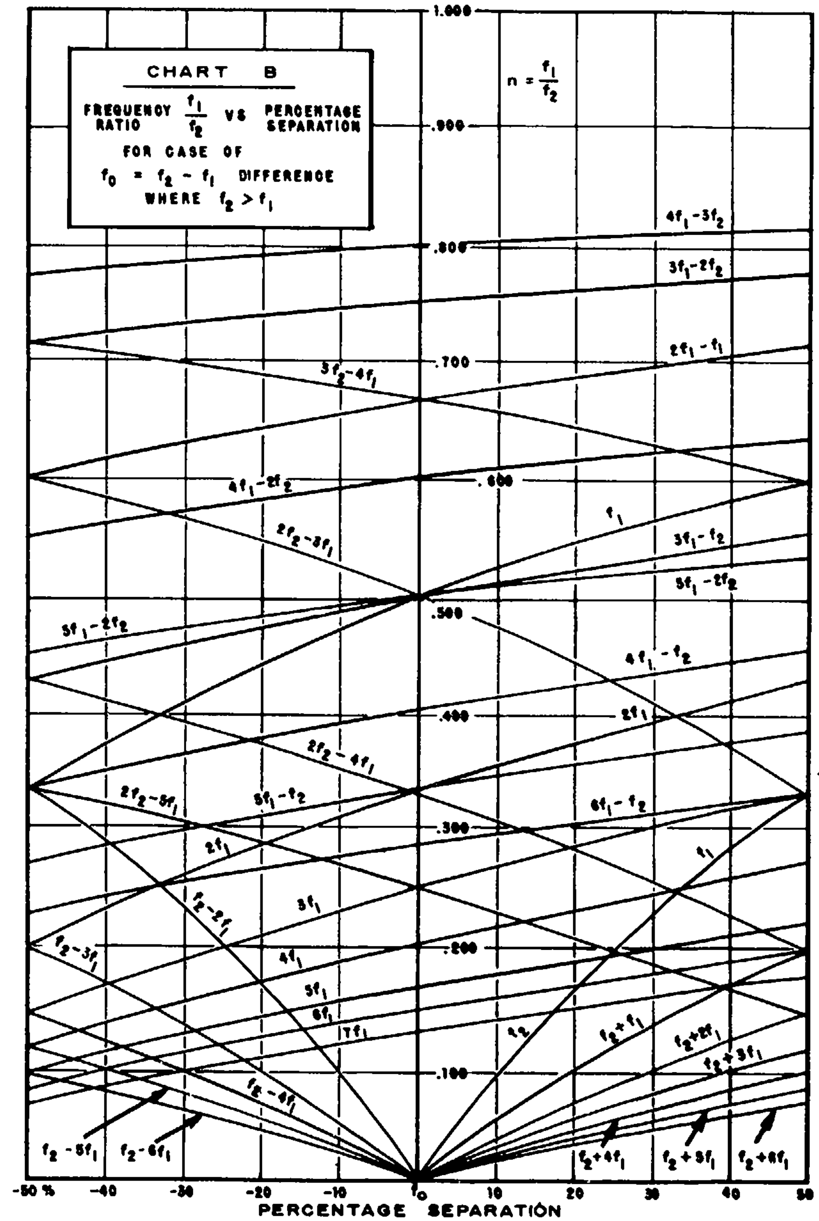
the resulting cross-modulation products have this general form:

$$M = Nf_1 + Pf_2 \qquad \text{(Eq 12)}$$

where N and P are positive and negative integers. The absolute sum of N and P represents the order of the product. If the ratio of the lowest and highest mixed frequency is n, a ratio always less than one, and f_0 is the desired output frequency of the mixer, then for $f_1 + f_2 = f_0$, $f_2/f_1 = n$, and $1 > f_2/f_1 > 0$. Similarly, if $f_2 - f_1 = f_0$, $f_1/f_2 = n$, and $1 > f_1/f_2 > 0$.

SUB-NOTE 3.1(1) Mixer Frequency Charts (Cross Products to the Seventh Order)





3.4 CROSS-MODULATION PRODUCTS

Cross-modulation products higher than the desired output frequency f_0 may also be expressed in "positive percentage separation." Likewise, cross-modulation products below the desired output frequency represent "negative percentage separation." Let M be the disturbing cross-modulation products described in the general form of Eq 12. Then, the general equation for percent positive or negative separation (S) is:

$$S = \frac{-(f_0 - M)}{f_0} \times 100 \qquad \text{(Eq 13)}$$

Substituting Eq 12 and 13, and recalling that $f_1 - f_2 = f_0$

$$n = \frac{S + 100(1 - N)}{S + 100(1 + P)} \qquad \text{(Eq 14)}$$

Equation 14 shows that the ratio of input frequencies as a function of percent separation S may be plotted for any cross-modulation products merely by substituting the coefficients N and P of the cross product under investigation. Charts A and B of *SN 3.1(1)* were plotted, using this equation and the coefficients resulting from the expansion of the nonlinear Eq 10.

3.5 CHART CALCULATIONS

To locate cross-modulation products in the charts in *SN 3.1(1)*, the two input frequencies and the desired output frequency must be known to determine which chart is applicable. Calculate the ratio of the two input frequencies and locate it on the ordinate. Then, draw a horizontal line through this point. Its intersection with the different curves tells the order of each encountered harmonic and the separation in percent with respect to the output signal.

3.5.1 FREQUENCY EXAMPLE. The charts in *SN 3.1(1)* give indications of relative difficulties in various alternate design approaches to the generation of a certain output frequency. As an example, take the design of a frequency synthesizer where there are several choices of frequencies to produce a required output. Assume that a 10 MHz signal and the available frequencies are 2, 8, and 18 MHz. Output may be derived from the difference of 18 and 8 MHz or the sum of 2 and 8 MHz.

3.5.2 CHART CHOICE. In the first approach, where the ratio of signals is 0.445, Chart B of *SN 3.1*(1) shows that there are two interferences which are −18% and +19% away from the desired 10 MHz output. The signal ratio is 0.250 in the second case, where Chart A shows that there are two interferences exactly on the output frequency. Thus, the first approach is preferable.

DESIGN NOTE 4A2 PULSE SHAPE AND SPECTRUM

1. INTRODUCTION

Pulse shape and spectrum evaluation are two complementary methods for analyzing waveform effects. The characteristics of desired signals in a subsystem are usually accumulated on a pulse shape basis. When evaluating the propagation of these waveforms along transmission lines, the waveform is converted into its equivalent spectrum. The velocity of propagation, phase shift, attenuation, reflection, and wave characteristics depend on frequency. The waveform must be analyzed in terms of its constituent frequency components. Waveforms with a fast rise time contain high frequency components.

2. FOURIER PREDICTION OF EMI ENVELOPE

Sub-Note 2(1) is the electromagnetic interference (EMI) prediction graph for Fourier analysis of wave shapes for prediction interference levels. Use this graph as follows: (For EMI current predictions in this analysis, substitute "ampere" for "volt" and "microampere" for "microvolt." Right-hand scale becomes "decibels above 1 μA/MHz.")

a. Given rise time, duration, and amplitude of basic pulse, determine the envelope of EMI voltages measured at EMI meter input as follows:

b. Work from right to left. Find the sloping line which represents rise time and follow it up to intersect with the basic reference line. Follow the reference line up to intersect with the horizontal line representing the duration of the pulse. Follow the horizontal line to the left to the lowest frequency of interest.

c. For transient or "worst case" when pulse information is not available, use the basic reference line to define the EMI envelope.

d. For EMI voltage levels, read the right edge for decibels above 1 μV/MHz bandwidth.

e. For voltages other than 1 V, find the number of decibels equivalent to 20 times the log of the new voltage. Add this number of decibels to the right-hand scale.

f. For radiated levels at 305-mm (1-ft) distance in the absence of any shield, subtract 30 dB from all points on the envelope found in Step e. Subtract 42 dB for 1-m (3-ft) antenna distance.

3. BASIC ANALYSIS CONSIDERATION (Extracted in part from Ref 1445©.)

The basic consideration for the successful prediction of interference levels is the proper application of the results obtained when a Fourier analysis of particular signal characteristics has been mede. To illustrate, when making a Fourier analysis of a square wave pulse, the level of radio interference can be represented by a straight line drawn tangent to each lobe. The following sample calculation shows the mathematical steps employed to arrive at interference levels in units of decibels above 1 μV/MHz (dBμV/MHz) as outlined in *MIL-STD-461*. The following equation is used to solve the harmonic content of the pulse:

$$e_n = \frac{2Ad}{T} \frac{\sin \pi Fd}{\pi Fd} \qquad \text{(Eq 1)}$$

Where:

A = magnitude of pulse voltage

d = pulse width, seconds

T = pulse period, seconds

PRR = pulse repetition rate, hertz

F = frequency of harmonic, hertz

e_n = noise voltage

Receiver summation of the harmonic amplitudes falling in its bandwidth results in:

$$S(f) = \left| \left[\int_{n_a - 0.5}^{n_b + 0.5} \frac{2Ad}{T} \frac{\sin \pi Fd}{\pi Fd} \, dn \right] \right| \frac{1\text{ MHz}}{I_{BW}}$$

in units of V/MHz peak (Eq 2)

Where all parameters are as defined above except:

I_{BW} = receiver impulse bandwidth

$F = \frac{n}{T}$

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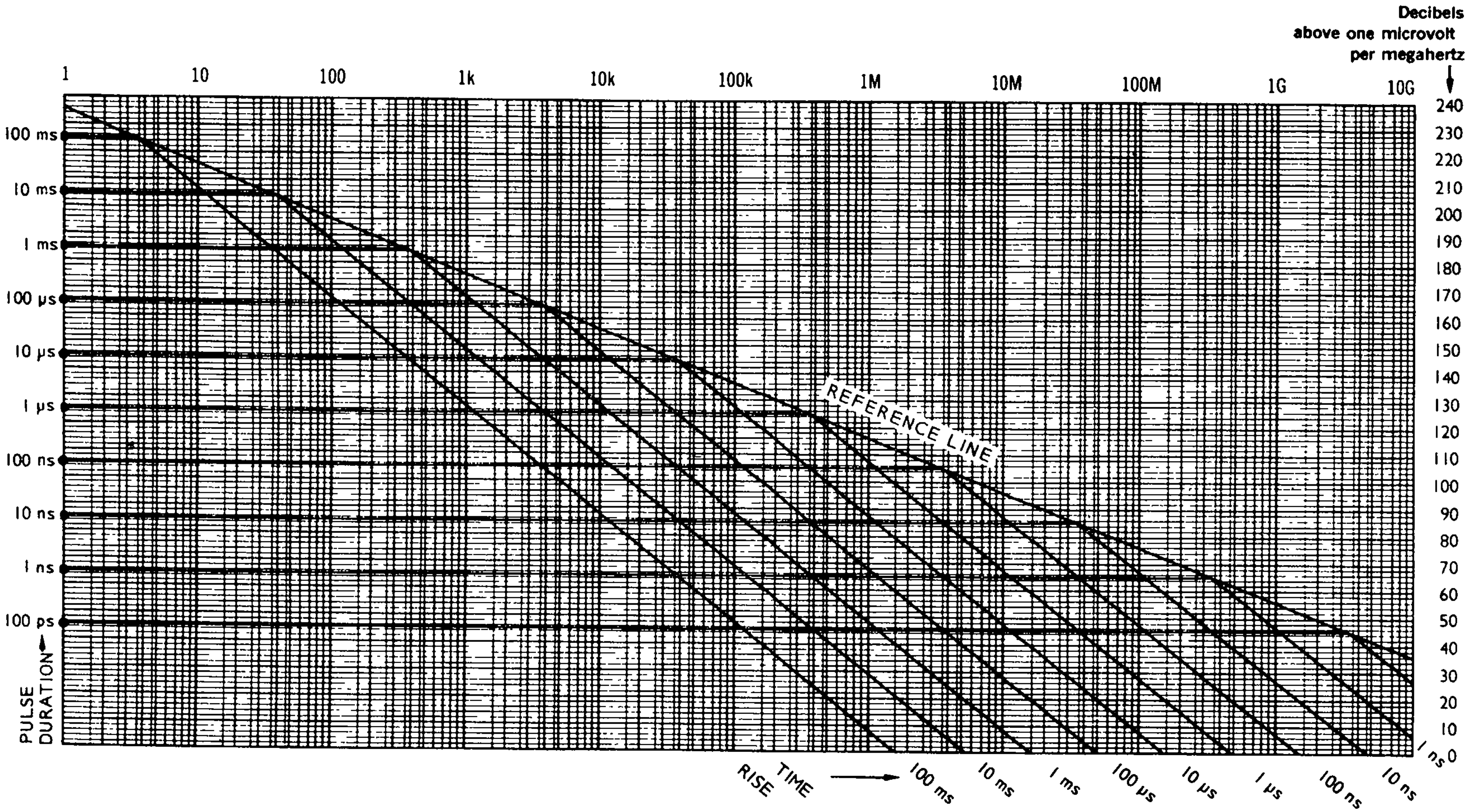
SUB-NOTE 2(1) EMI Prediction Graph for Rectangular and Trapezoidal Pulse Interference



Courtesy of
Solar Electronics

n = harmonic number

n_a = harmonic number of lower limit of receiver impulse bandwidth

n_b = harmonic number of upper limit of receiver impulse bandwidth

S(f) = amplitude of broadband interference.

Although harmonic number n is normally considered discrete and not subject to integration it can be shown that for this case it can be treated as continuous and, therefore, subject to integration. The solution to *Eq 2* is

$$S(f) = \left| \frac{2A}{\pi} \left[\frac{n\pi d}{T} - \frac{\left(\frac{n\pi d}{T}\right)^3}{3.3!} + \frac{\left(\frac{n\pi d}{T}\right)^5}{5.5!} - \frac{\left(\frac{n\pi d}{T}\right)^7}{7.7!} + \ldots \right] \right|_{n_a - 0.5}^{n_b + 0.5} \frac{\Delta f}{PRR} \text{ in V/MHz} \quad \text{(Eq 3)}$$

4. SQUARE PULSE ANALYSIS

In order to simplify the Fourier analysis of a square pulse, the following expressions can be derived from *Eq 2*:

Nulls occur when $\sin \pi Fd = 0$, i.e., $S(f) = 0$.

$\sin \pi Fd = 0$ when $\pi Fd = \pi, 2\pi, 3\pi, \ldots$ etc.

Therefore, the frequencies at which the nulls occur are:

$$F = \frac{1}{d}, \frac{2}{d}, \frac{3}{d}, \text{etc.} \quad \text{(Eq 4)}$$

The frequencies at which the tangent points occur are when $\sin \pi Fd = 1$.

$$\sin \pi Fd = 1 \text{ when } \pi Fd = \frac{\pi}{2}, \frac{3\pi}{2}, \frac{5\pi}{2}, \text{etc.}$$

Therefore:

$$F = \frac{1}{2d}, \frac{3}{2d}, \frac{5}{2d}, \text{etc.} \quad \text{(Eq 4a)}$$

When:

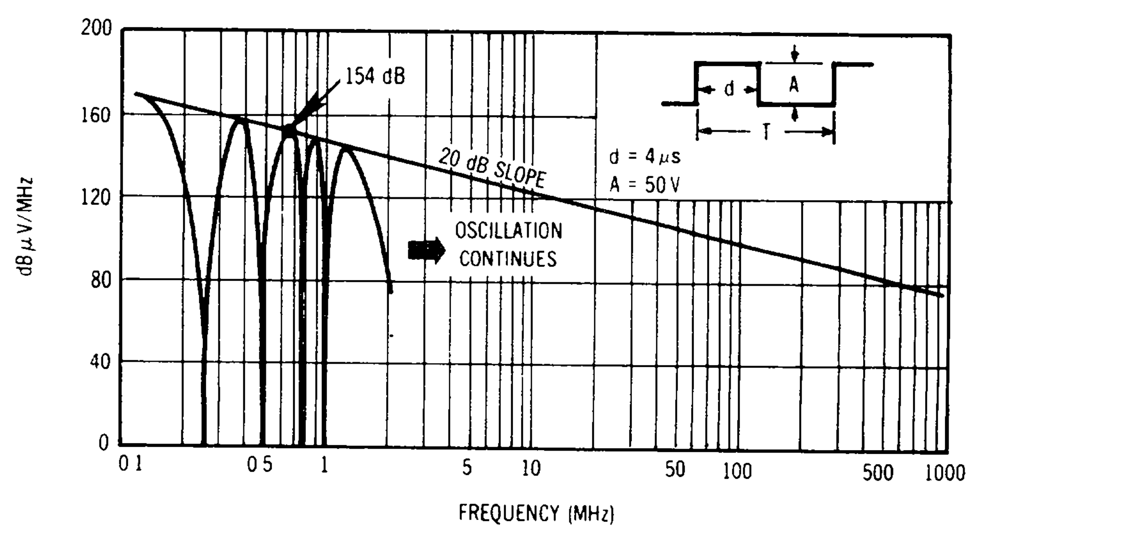
$$\pi Fd = \frac{\pi}{2}, \frac{3\pi}{2}, \frac{5\pi}{2}, \text{etc.}$$

Then:

$$\frac{\sin \pi Fd}{\pi Fd} = 0.637, 0.212, \text{and } 0.127$$

For increasing frequencies, the harmonic content of a square pulse (in decibels) decreases at a rate equal to 20 × log of the ratio of the frequencies.

SUB-NOTE 4(1) Fourier Analysis Sample



For frequency No. 1:

$$S_1(f) = \frac{2Ad(\sin \pi F_1 d)}{\pi F_1 d} \quad \text{(Eq 5)}$$

For frequency No. 2:

$$S_2(f) = \frac{2Ad(\sin \pi F_2 d)}{\pi F_2 d} \quad \text{(Eq 5a)}$$

As shown previously, $\sin \pi Fd = 1$ at the tangent points. Therefore:

$$S_1(f) = \frac{2Ad}{\pi F_1 d} \quad \text{(Eq 5b)}$$

$$S_2(f) = \frac{2Ad}{\pi F_2 d} \quad \text{(Eq 5c)}$$

Applying Eq 5:

$$\beta \text{ in dB} = 20 \log \frac{S_1(f)}{S_2(f)}$$

$$= 20 \log \frac{2Ad/\pi F_1 d}{2Ad/\pi F_2 d} \quad \text{(Eq 6)}$$

Reducing:

$$\beta \text{ in dB} = 20 \log \frac{F_2}{F_1} \text{ when } F_2 > F_1 \quad \text{(Eq 6a)}$$

Where:

β = spectrum magnitude

From the above equation, it is apparent that the level of interference decreases at a rate of 20 dB per decade. Knowing the frequencies at which the tangent points occur, and the rate at which the interference level decreases, the noise level for a square pulse can be quickly calculated and plotted. See *SN 4(1)*.

SECTION 4B — EMC ANALYSIS, COMPUTER

DN 4B4 - Contd

DN 4B5 - PRECIPITATION STATIC ANALYSIS PROGRAM (PSTAT)

DESIGN NOTE 4B1 — INTERFERENCE PREDICTION PROCESS (IPP-1)

1. INTRODUCTION

The Interference Prediction Process (IPP-1) should prove useful to system or equipment planners, designers, and operational personnel. The process which may be used to analyze compatibility for both communication and radar systems provides a basis for defining EMC problem areas, identifying potential solutions, and making engineering decisions. The IPP-1 consists of a set of computer routines that may be used to analyze and predict potentially interfering situations among a proposed or existing deployment of transmitters and receivers. Although the program is written in FORTRAN IV for use on the computer at Rome Air Development Center (RADC), the program can be modified so that the process can be adapted to other computer systems. This Design Note discusses the various applications for the IPP-1, describes the IPP-1 computer program and the various computer subroutines that are available through the IPP-1, identifies the various options that are available to the user, defines the inputs that are required to utilize the process, and discusses the outputs that are obtained.

2. APPLICATIONS FOR IPP-1

The IPP-1 computer program provides an engineering tool that is a valuable asset in various phases of communication-electronic equipment development, such as (1) the preliminary system or equipment planning and design, (2) the preparation of system or equipment requirements and specifications, (3) the preparation of specification compliances test plans, (4) the evaluation of test results, (5) the revision of either specifications or equipment for conditions of noncompliance, and (6) the evaluation of systems in a specific operational environment. Typical problems that may be handled by IPP-1 include the following:

a. Examine the EMC situation for a given complex of equipment and identify problem areas.

b. Examine the impact of changing the operating frequency of equipment in the complex.

c. Examine the impact of adding a transmitter to an existing complex of equipment.

d. Examine the interference produced in a receiver when added to an existing complex.

e. Determine which of several possible locations for a transmitter or receiver provides the least probable interference.

f. Determine the source and cause of a known interference problem.

g. Determine the amount of suppression required to correct a specified interference situation.

h. Obtain site survey or EMC environment information for a given location.

i. Obtain susceptibility information for a given receiver or group of receivers.

j. Determine propagation loss over a specified path.

k. Obtain specific interference characteristic data on transmitters, receivers, or antennnas contained in the equipment characteristic tape file.

l. Provide information as to the adequacy of given specifications for a new item of equipment.

m. Provide information as to the best frequency band to use for a system being defined.

3. DESCRIPTION OF IPP-1

To determine if an EMC problem exists between a potentially interfering transmitter and a receiver, it is necessary to consider the susceptibility of the receiver to the design and spurious outputs (both individually and collectively) of the potentially interfering transmitters. The factors that must be included in the analysis for each transmitter output (or group of transmitter outputs) include: the transmitter power (P_t), the transmitting antenna gain in the direction of the receiver (G_t), the propagation loss between the transmitter and receiver (L), the receiver antenna gain in the direction of the transmitter (G_r), and the amount of power required to produce interference in the receiver (P_r).

3.1 ANALYSIS CONSIDERATIONS

The factors to be considered in interference analysis include not only the design and operational performance characteristics of equipment, but also the nondesign and nonoperational characteristics. The necessity for considering parameters, such as transmitter spurious outputs, receiver spurious responses, antenna side lobe and back lobe radiation, and unintentional propagation paths, introduces complications because it is necessary to obtain information on equipment nondesign characteristics. Unlike equipment design characteristics (which are usually well defined and may be readily obtained from equipment specifications), equipment spurious characteristics cannot be defined in a precise

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manner and are not usually available in equipment specifications.

3.2 SPURIOUS CHARACTERISTICS VARIATIONS

Measurements demonstrate that there are large inherent variations in spurious characteristics of equipment. As a result of these inherent variations, two equipment complexes that are identical in all visible physical respects may exhibit widely different spurious characteristics. For this reason, it is desirable to specify equipment spurious characteristics statistically (i.e., in terms of the likelihood that a particular spurious level will be equaled or exceeded). If the spurious characteristics are described statistically, the analysis results will also be defined in terms of the probability that a particular interference situation exists.

3.3 AVAILABLE POWER

The procedure that is used for each transmitter output can be demonstrated by considering the interference situation that exists between a particular output of a potentially interfering transmitter and the receiver. For the case of the interfering transmitter fundamental output, the power available at the receiver is given by

$$P_t(f_o) + G_t(f_o) + L(f_o) + G_r(f_o)$$

Where:

$P_t(f_o)$ = transmitter power (in dBmW) at the fundamental frequency (f_o)

$G_t(f_o)$ = transmitter antenna gain (in dB) in the direction of the receiver

$L(f_o)$ = propagation loss (in dB) experienced by the signal

$G_r(f_o)$ = receiving antenna gain (in dB) in the direction of the transmitter at the transmitter fundamental frequency

3.4 INTERFERENCE IN RECEIVERS

By comparing the power available at the receiver, as a result of this particular interfering transmitter fundamental output, to the power required to produce interference in the receiver at the frequency in question, $P_r(f_o)$, it is possible to determine the interference situation for the particular transmitter output being considered. The requirement for EMC is that the power available at the receiver be less than the power required to produce interference in the receiver. That is, the condition for compatibility is

$$P_t(f_o) + G_t(f_o) + L(f_o) + G_r(f_o) < P_r(f_o)$$

On the other hand, if the power available at the receiver is equal to or greater than the power required to produce interference in the receiver, a compatibility problem exits.

3.5 COMPUTER-AIDED EMC DESIGN

In an actual problem it is necessary to repeat the procedure for each transmitter output with each receiver being considered in the problem. Because of the large number of calculations required in practical interference analysis problems, the analysis process has been programmed in FORTRAN IV. The IPP-1 consists of a number of separate computer routines, each of which is subject to the control of the executive control program. In any given problem, the analysts may choose to use one, a few, or all the routines depending on the type of information that is available for the problem and the type of answers required.

4. BASIC STRUCTURE

Sub-Note 4(1) shows the basic structure of IPP-1. The process consists of a short executive program which controls the major subroutines. Each of the major subroutines in turn uses other minor subroutines and functions. The major subroutines of IPP-1 may be considered to be divided into preparatory and analysis subroutines. The preparatory subroutines include the problem input, data acquisition, equipment catalog, and data synthesis subroutines. The major purpose of these subroutines is to provide the data required to perform an analysis. The remaining subroutines are used to perform the various types of analysis that may be required.

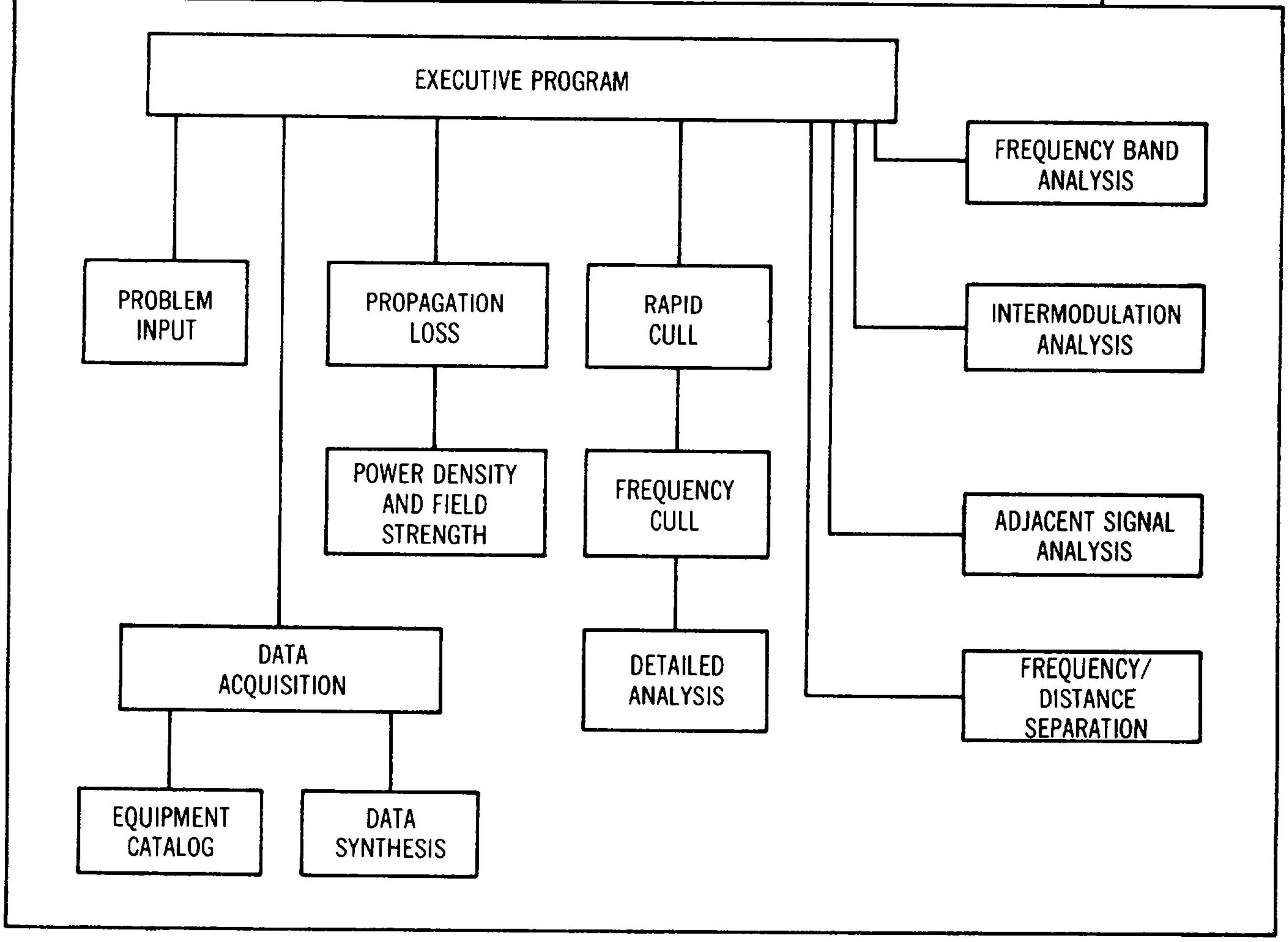
4.1 PROBLEM INPUT

The function of the problem input routine (*SN 4.1(1)*) is to provide specific input information necessary to initiate a given EMC analysis. Input information is read into the computer and stored in arrays that are accessible to the analysis routines of the program. In order to utilize IPP-1 to perform an analysis of equipment listed in the catalog, it is necessary to provide the nomenclatures, the specific operating frequencies, and the locations for equipment to be included in the analysis. If unlisted equipment is to be included in the analysis, it is necessary to provide as input the standard catalog data for the unlisted equipment.

4.2 DATA ACQUISITION, EQUIPMENT CATALOG, AND DATA SYNTHESIS

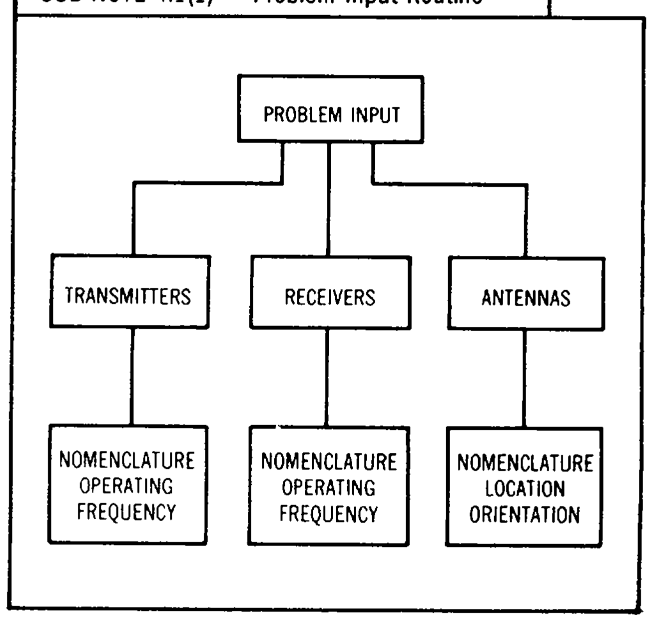
Equipment characteristic data required for the analysis routines are supplied by the data acquisition routine (*SN 4.2(1)*) for each transmitter, receiver, and antenna nomenclature within the complex as prescribed by the problem input routine. The data acquisition routine makes use of equipment catalogs which are stored on

SUB-NOTE 4(1) Basic Structure of IPP-1

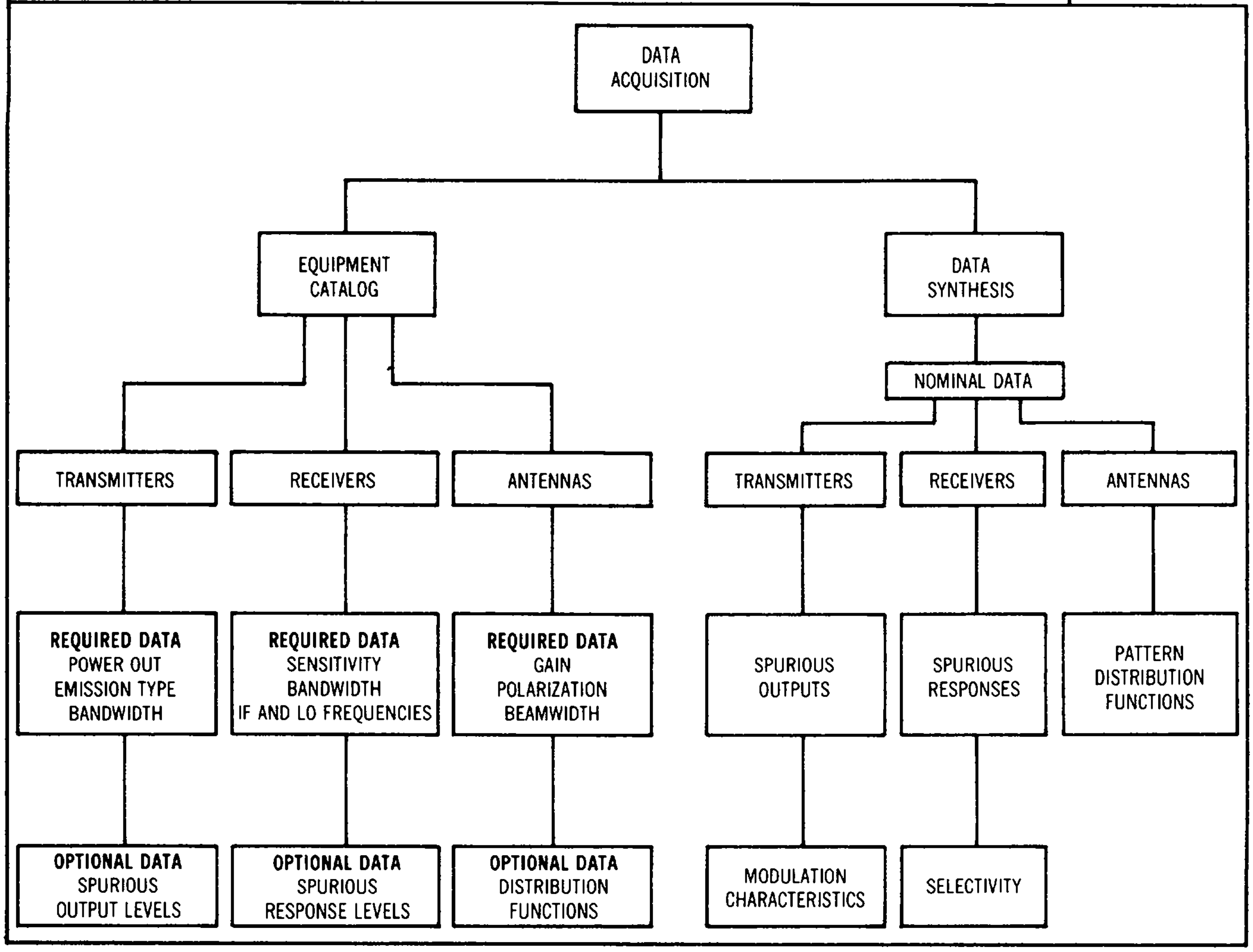


magnetic tape and data synthesis routines which generate the required data from nominal equipment characteristics. The data contained in the equipment catalog (*SN 4.2(1)*) includes nominal equipment data such as: (1) nomenclature, (2) operating frequency range, (3) fundamental power output, emission type and bandwidth for transmitters, (4) sensitivity, bandwidth, and IF and local oscillator frequencies for receivers, and (5) antenna type, gain, polarization, and beamwidths. Also included are specific interference characteristics data on transmitter spurious outputs; receiver selectivity, spurious response intermodulation, and adjacent signal interference characteristics, and antenna gain characteristics for the side lobe and back lobe regions. The data synthesis routine (*SN 4.2(1)*) makes use of nominal equipment characteristics to generate interference data for transmitters, receivers, and antennas that are not contained in the catalog The resulting synthesized data permit a user to perform an interference analysis of a complex containing equipment for which specific interference characteristics are not available.

SUB-NOTE 4.1(1) Problem Input Routine



SUB-NOTE 4.2(1) Data Acquisition, Equipment Catalog, and Data Synthesis Routines



4.3 PROPAGATION LOSS

The propagation loss routine provides a capability for calculating propagation loss for a particular situation or for providing propagation loss information for use in the detailed analysis portion of the interference analysis process. *Sub-Note 4.3(1)* shows a block diagram of the propagation loss routine. The propagation routine provides a capability for calculating line-of-sight, radio horizon beyond line-of-sight, and near field propagation loss.

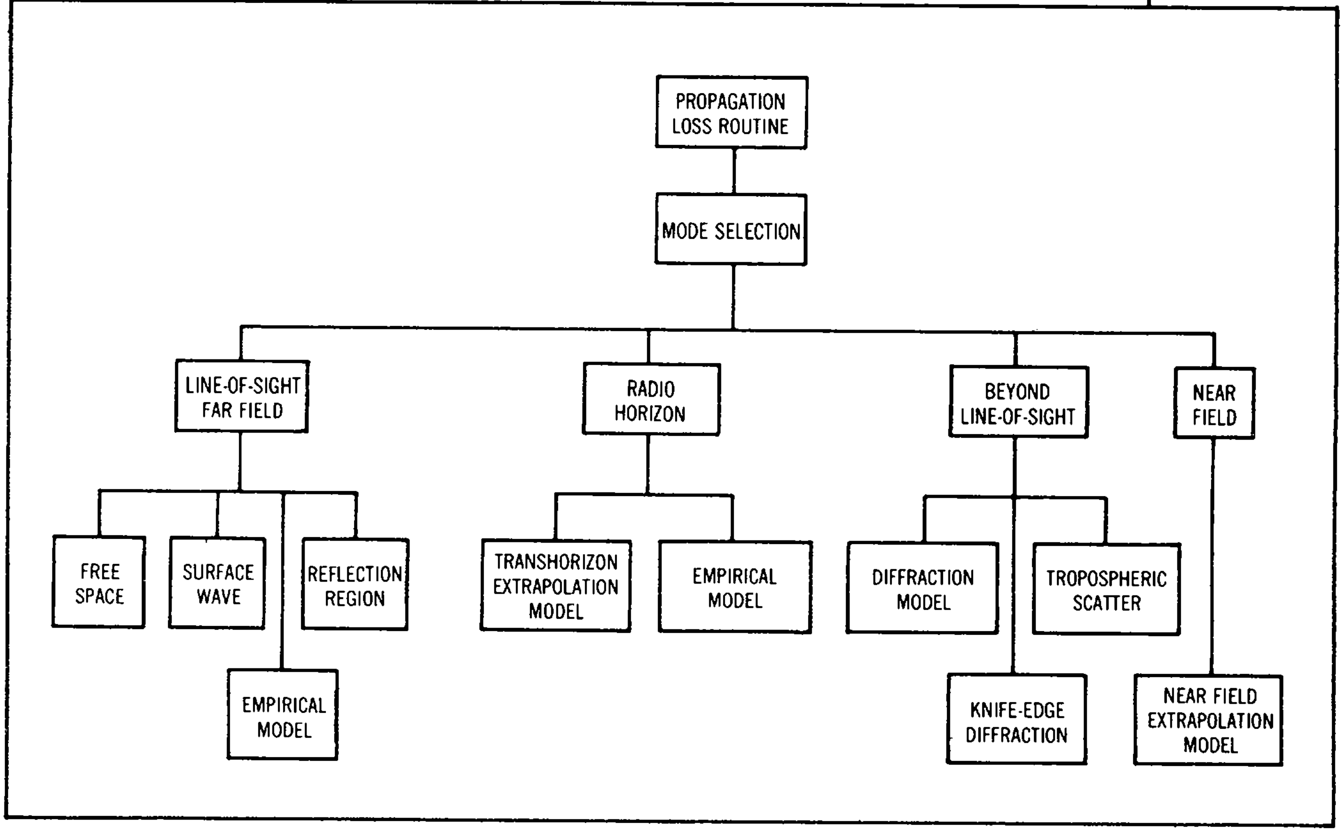
4.4 POWER DENSITY AND FIELD STRENGTH

The power density and field strength routine provides elevation cuts of field strength and power density at user specified distances from the source antenna, distance cuts at user specified elevations, or total contours of field strength or power density at incremental distances and elevations specified within the program. The user may specify the type of terrain (i.e., smooth earth or rough earth) or specific terrain data points. Relative antenna directive gains are used in all calculations.

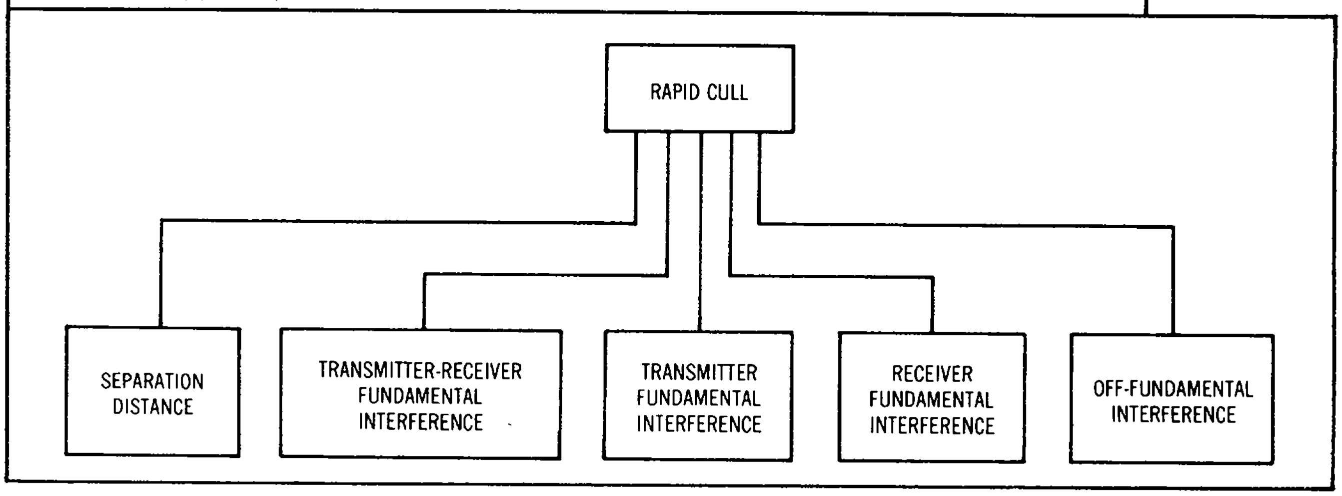
4.5 RAPID CULL

The rapid cull routine (*SN 4.5(1)*) takes a quick worst-case look at the total problem to eliminate as many cases as possible from more detailed analysis. The rapid cull assumes main beam gain for the antennas and some worst-case propagation mode, such as free space. Also, the rapid cull uses simplified representations of amplitude versus frequency for the transmitter, receiver, antenna, and propagation functions. In addition to eliminating from further consideration the cases obviously not causing interference, the rapid cull results define the frequency range which must be considered for cases that are not eliminated and provide an indication of the magnitude of potential problems.

SUB-NOTE 4.3(1) Propagation Loss Routine



SUB-NOTE 4.5(1) Rapid Cull Routine



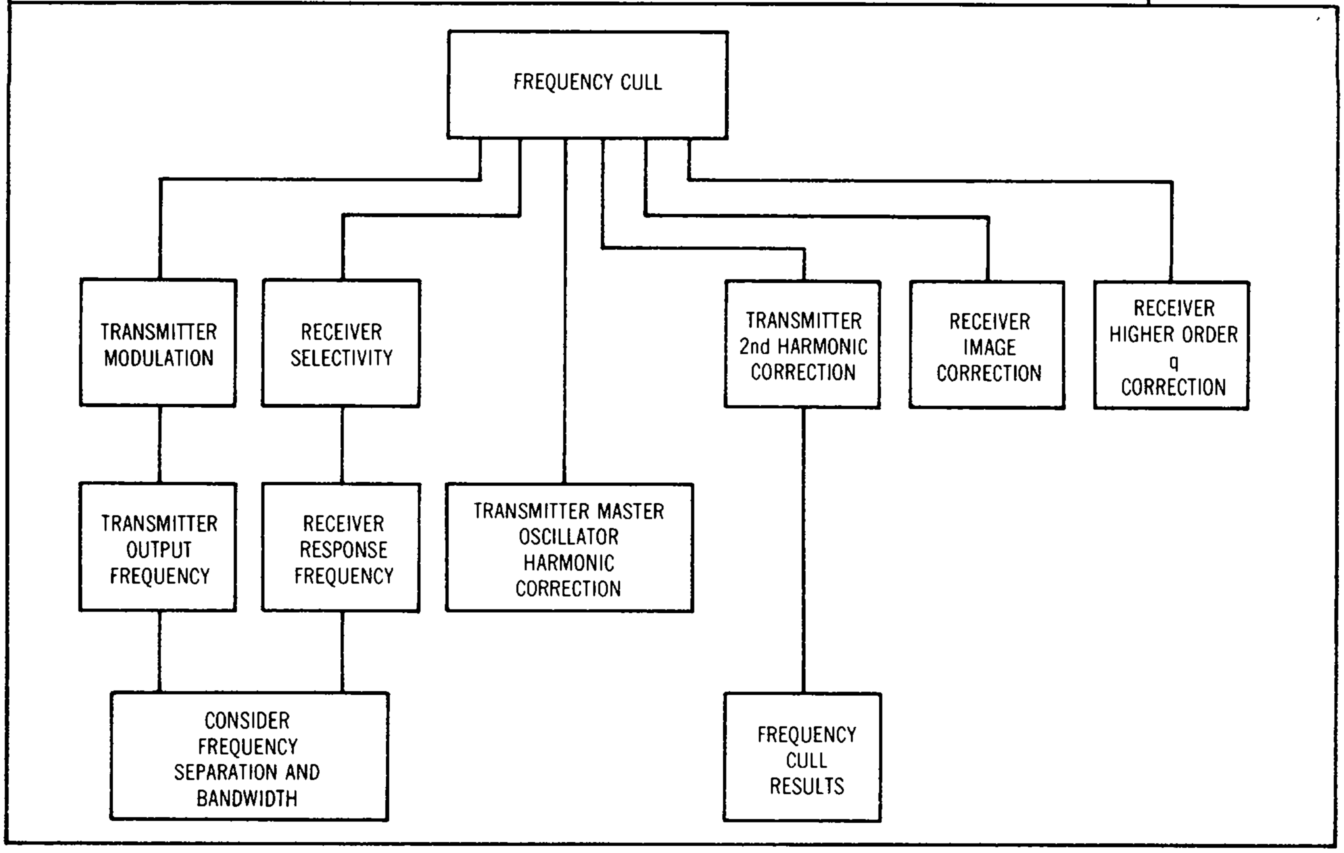
4.6 FREQUENCY CULL

The frequency cull (*SN 4.6(1)*) considers the (1) bandwidths and frequency separation between potentially interfering outputs and (2) responses remaining from the rapid cull. The routine eliminates from further consideration those outputs and responses that are sufficiently separated in frequency to provide the necessary interference protection.

4.7 DETAILED ANALYSIS

The detailed analysis phase (*SN 4.7(1)*) of the IPP-1 performs a more rigorous investigation of those potentially interfering equipment pairs remaining after the rapid cull and frequency cull. The detailed analysis takes into account such factors as the actual mode or modes of propagation that are likely to exist; statistical representations of the transmitter, antenna, receiver, and

SUB-NOTE 4.6(1) Frequency Cull Routine



propagation functions; and time dependent conditions resulting from rotating antennas. Results of the detailed analysis are given in terms of the probability of interference in a particular case.

4.8 INTERMODULATION ANALYSIS

The intermodulation analysis routine provides a capability for performing an intermodulation analysis either on the basis of frequency considerations alone or on the basis of both frequency and power considerations. The intermodulation analysis routines may be used to generate lists of all possible second-, third-, fifth-, and seventh-order intermodulation interactions between equipment within a complex, or to generate lists of intermodulation interactions between specific equipment and an equipment complex.

4.9 FREQUENCY BAND ANALYSIS

The frequency band analysis routine is designed to be utilized for problems involving equipment for which specific frequency assignments are not available, and minimal equipment data can be obtained. This routine is most applicable to equipment in the definition or design states. Although the routine makes use of the rapid cull and detailed analysis routines, simpler models are used to represent the equipment characteristics.

4.10 ADJACENT SIGNAL ANALYSIS

The adjacent signal analysis routine provides a capability for analyzing the effects of potential interfering signals within or near the receiver RF passband. The specific interference effects that are evaluated in the adjacent signal routine include desensitization cross modulation, intermodulation, and sideband emission. Results are expressed in terms of signal-to-interference, and signal-to-noise ratios.

4.11 FREQUENCY-DISTANCE ROUTINE

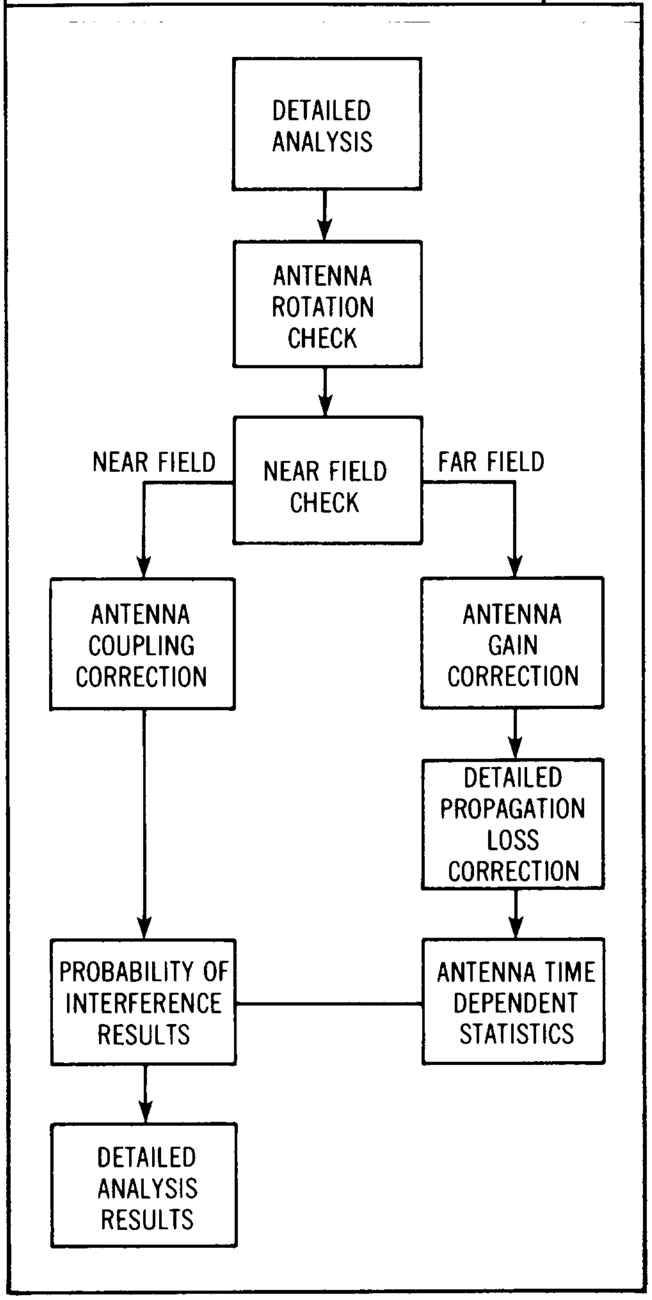
Two variables which may be varied over a wide range are operating frequency and location. The frequency-distance routine provides an evaluation of the trade-off relationships between adjacent signal effects, frequency, and distance.

5. OPTIONS

The IPP-1 is an extremely flexible program with many user options built into the executive program. Examples of some user options are:

a. The user has access to the equipment catalog subroutine for either updating existing equipment files or reading equipment characteristics from the files.

SUB-NOTE 4.7(1) Detailed Analysis Routine



b. The user may perform only the rapid cull.

c. The user may perform both the rapid cull and frequency cull.

d. The user may perform the rapid cull, frequency cull, and detailed analysis.

e. The propagation loss calculation routines may be used independently.

f. The power density and field strength routines may be used independently.

g. Lists of intermodulation frequencies may be generated for second-, third-, fifth-, and seventh-order intermodulation

h. An analysis of intermodulation interference between specified equipment and an equipment complex may be performed.

i. An interference analysis may be performed on the basis of frequency band considerations instead of specific frequencies.

6. INPUT INFORMATION

To utilize the process to perform an interference analysis, it is necessary to specify the nomenclature, location, and operating frequency for equipment contained in the equipment catalog. If the catalog does not list the equipment, it is necessary to provide additional nominal equipment data as: (1) transmitter power output, emission type, and bandwidth; (2) receiver sensitivity, bandwidth, and IF and local oscillator frequencies; and (3) antenna gain, type, polarization, height, orientation and beamwidth. In addition to the input information specified, it is desirable (but not necessary) to have terrain data, specific information on equipment interference characteristics, and data on special fixes which may be supplied on specific equipment.

7. OUTPUT INFORMATION

The specific answers that are obtained in a particular problem are determined by the extent to which the analysis is carried out.

7.1 RAPID CULL

If only the rapid cull is performed, the results (1) identify all potentially interfering equipment pairs by nomenclature, (2) define the frequency range over which interference problems may exist, and (3) specify the interference margin (defined as the amount by which the interfering signal exceeds the level required to produce a standard response at the output of the receiver) over each frequency range of interest. Other outputs from the rapid cull include the distance separation between potentially interfering equipment pairs and their respective tuned frequencies.

7.2 RAPID AND FREQUENCY CULL

If both the rapid cull and the frequency cull are performed, the answers obtained from the process will provide additional information as to the specific transmitter outputs and receiver responses which may result in interference problems.

7.3 DETAILED ANALYSIS PHASE

The detailed analysis phase of the process provides additional answers such as (1) the elimination of rapid cull and frequency cull potentially interfering equipment pairs by considering specific propagation modes and antenna directivity characteristics, (2) a statistical description of the interference margin, (3) the details of time dependent statistical, and (4) a summary of the combined effects of time dependent and time independent statistics. The IPP-1 is designed to print the significant results at the end of each analysis in several standard formats. Complete results are available in the computer at the end of each of the above analyses. Either the standard format can be used or (with simple modifications to the process) all or any subset of the results can be obtained in a format meeting the user's requirements.

DESIGN NOTE 4B2 INTRASYSTEM EMC SYSTEM MODELING ANALYSIS

1. INTRODUCTION

Modern aerospace vehicles contain increasing numbers of complex and sophisticated avionics subsystems that must operate harmoniously to achieve mission objectives. Ensuring electromagnetic compatibility for such avionics is a complex and time consuming problem. To assist the engineer in establishing and maintaining intravehicle electromagnetic compatibility, a complete program was developed to predict and analyze electromagnetic interference (EMI) between avionics subsystems on aerospace vehicles. The program is used to derive information which is otherwise impractical or difficult to obtain. The program is described in *Ref 444*.

2. DESCRIPTION OF ANALYSIS PROGRAM

The four interrelated computer programs which comprise an electromagnetic compatibility analysis follow:

a. Antenna-to-Antenna Compatibility Analysis Program (ATACAP). Analyzes EMI from transmitters to receivers when the coupling path is between their antennas.

b. Wire-to-Wire Compatibility Analysis Program (WTWCAP). Analyzes EMI resulting from cross coupling within a wire bundle.

c. Field-to-Wire Compatibility Analysis Program (FTWCAP). Analyzes EMI induced in the loads of an aircraft wire bundle from exposure to on-board antenna radiation through dielectric apertures in the vehicle skin.

d. Box-to-Box Compatibility Analysis Program (BTB-CAP). Analyzes EMI resulting from low frequency magnetic fields coupling into sensitive transformers and electron beam devices within equipment boxes.

Each program exists as a separate deck of punched cards, and input data formats are compatible between them. All four programs can be run for a given vehicle to obtain a complete EMI analysis or they can be run independently, as desired. The programs are in FORTRAN IV language and were written for the CDC 6600 computer.

2.1 CONCEPTUAL AND DESIGN PHASE

Since the EMI predictions are most valuable early in the conceptual and design phases of vehicle development, the programs should be used before many of the basic equipment parameters are known. Therefore, the programs have many built-in default parameters which can be used for the unknown parameters. The values are based on the applicable military specification or on mathematical expressions. An analysis can be performed initially using the default values so that the major EMI problem areas can be determined and corrective measures taken. Later, when the actual data and specifications become available, new analyses can be made to update the previous ones. Each program prints a summary of all data including any default values that were inserted. Thus, a record of the data on which the analysis was based is provided. All default values are identified in the printout.

2.2 EMI MARGINS

The analysis results are provided as EMI margins in decibels (dB). The EMI margin is defined as the ratio of the received signal at a given receptor from a given interference source to the susceptibility level of that receptor. Thus, interference is clearly indicated as a positive number. Information on the cause of the interference and the analysis method utilized are also given in the output for each interference situation. In the antenna-to-antenna program, for example, the maximum EMI frequency and the maximum and minimum frequencies of coincidence between the transmitter and receiver are given in addition to the EMI margin.

2.3 DATA ERROR

The programs also provide extensive data error diagnostic outputs. For example, if an input code is not recognized by the computer, it prints out the type of code as well as the bad data. This aids the user in locating a mispunched or out of sequence data card.

2.4 CLASSIFIED DATA

Provisions are also included for the use of classified data. The security classification is specified for each subsystem, and the highest classification is printed on the top and bottom of each output page.

3. EXAMPLE OF THE ANTENNA-TO-ANTENNA COMPATIBILITY ANALYSIS PROGRAM

This program surveys a vehicle for interference between transmitters and receivers where the coupling path is via their antennas. It examines transmitter frequency ranges, including harmonics, for coincidence with the receiver ranges. Where coincidence is found, the worst-case signal level from the transmitter at the receiver input is calculated for all antenna combinations. Each received signal level is compared to the receiver threshold by calculating the EMI margin. If the margin is positive, the

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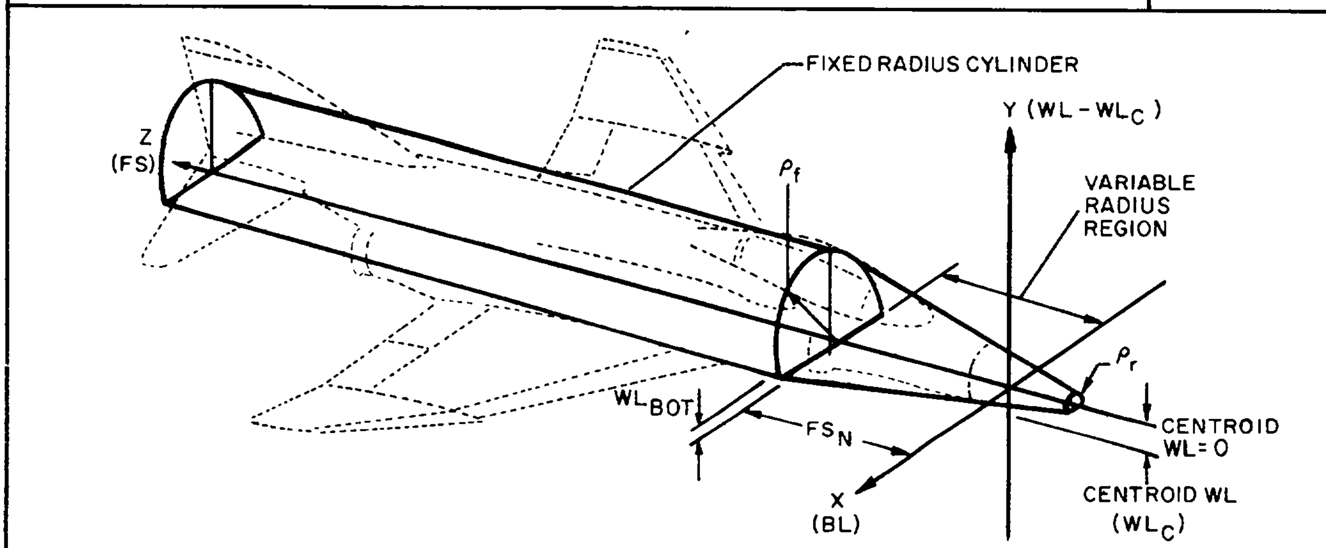
received signal exceeds the threshold; and if negative, it is below the threshold. Therefore, a positive margin number indicates interference; and a negative one, no interference. However, receiver discrimination circuitry and unknown parameter variations may prevent interference even with a positive margin. Hence, the margin is only an indicator of potential interference, and the predicted interference situations should be examined with this in mind.

3.1 AIRCRAFT DATA

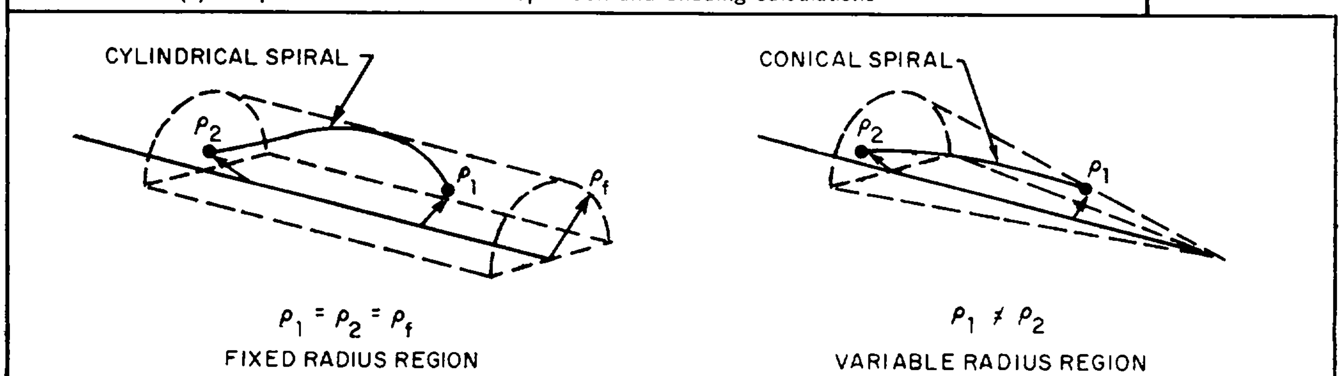
For antenna propagation calculations, a flat- or round-bottomed cylindrical model is used to approximate the vehicle shape. A visualization of the flat-bottomed model fitted to an F-4 aircraft is shown in *SN 3.1(1)*. The model is divided into fixed and variable radius regions with the dividing point at FS_N, as shown. If one or both antennas are in the fixed cylinder region, cylindrical spirals are used to compute antenna separation and fuselage shading. If both antennas are in the variable radius region, separation is calculated by a conical spiral fitted between the locations of the two antennas. The cone will vary depending on the radii of the two antennas. These two spirals are illustrated in *SN 3.1(2)*. If the shortest path is not around the fuselage, a straight line is used. When the flat-bottom option is specified and both antennas are below WL_{BOT}, a straight line is used for the separation calculation; and there is no fuselage shading.

3.1.1 WING AREA. When the path between the antennas is around the wing, it is calculated in two segments, transmitter antenna-to-wing and wing-to-receiver antenna. *Sub-Notes 3.1(1)* and *3.1(2)* are used to calculate distances and fuselage shading for each segment. Using this, the path giving minimum propagation loss, including diffraction around the wing, is determined.

SUB-NOTE 3.1(1) Basic Aircraft Parameters (Flat-Bottomed Cylinder)



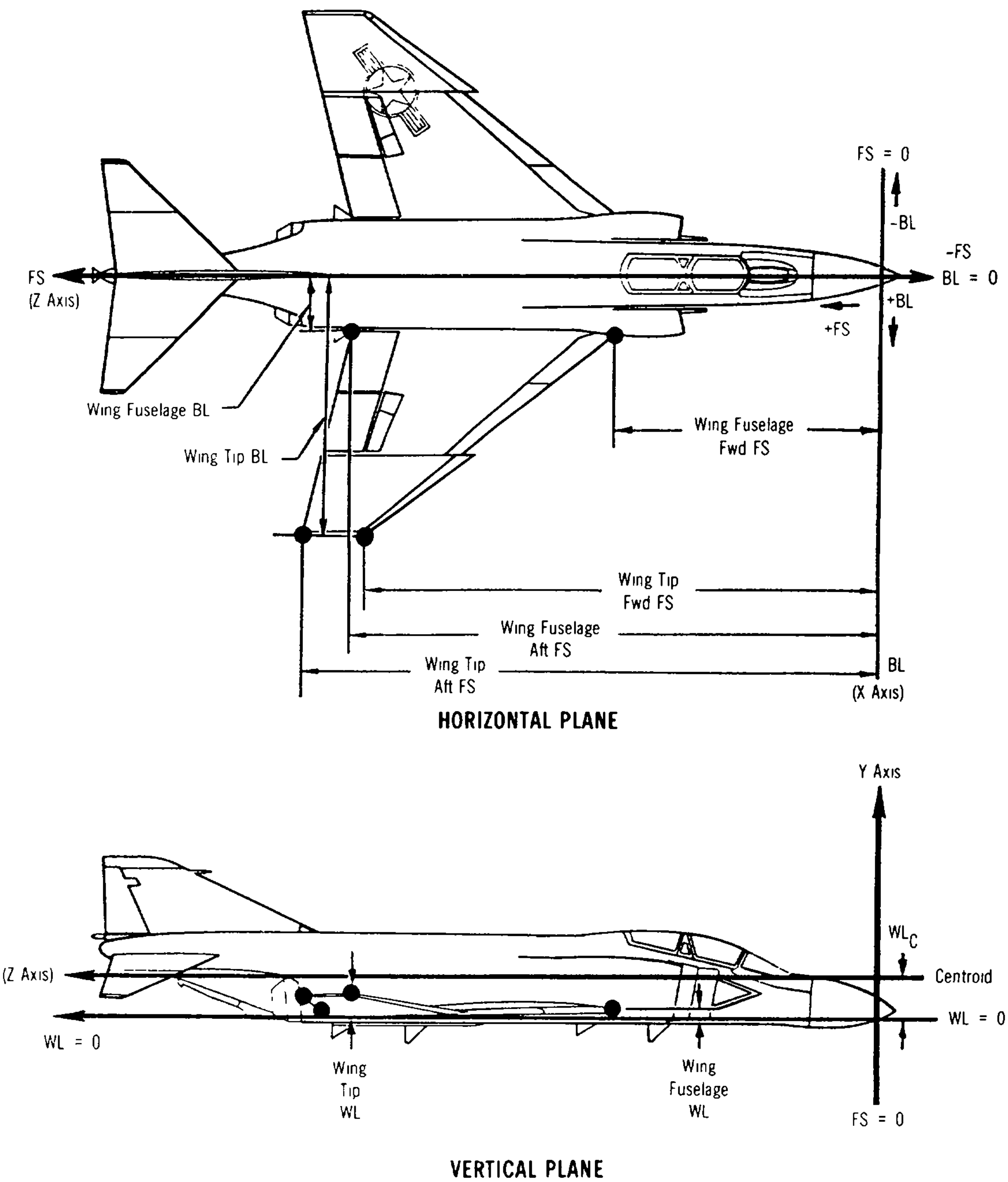
SUB-NOTE 3.1(2) Spirals Used in Antenna Separation and Shading Calculations



3.1.2 DESCRIPTIVE PARAMETERS. Parameters describing the model are referenced to the standard butt-line (BL), water line (WL), and fuselage station (FS) system used for aerospace vehicles, as shown in *SN 3.1(1)*. The butt-line is the horizontal distance to the right (positive) or left (negative) from centerline, water line is the vertical distance from the vehicle bottom, and fuselage station is lengthwise distance from the nose. The origin of this coordinate system may vary from vehicle to vehicle.

3.1.3 WING PLANE. The wings are specified by locating the four corners of the wing plane. The eight parameters describing this, as illustrated in *SN 3.1.3(1)* apply to the right wing (positive BL). The second aircraft card applies to the points nearest the fuselage, and the third applies to those at the wing tip.

SUB-NOTE 3.1.3(1) Wing Point Location (Horizontal and Vertical Plane)



DESIGN NOTE 4B3 HIGH FREQUENCY PROPAGATION PROGRAM

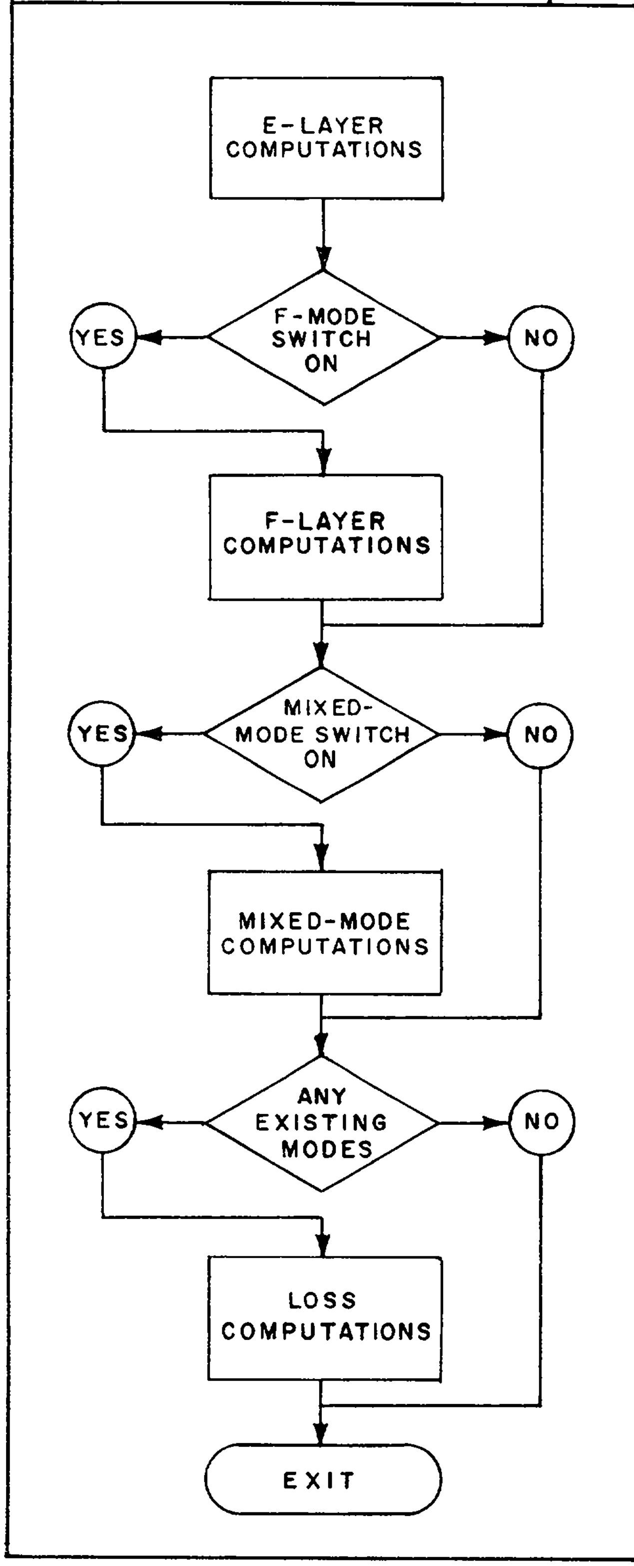
1. INTRODUCTION

The high frequency (HF) propagation program is designed to predict propagation skywave transmission losses that occur in the 3 to 30 MHz frequency band. The program was written to provide propagation loss models for the IPP-1. (See *DN 4B1.*) The HF propagation program can perform the propagation loss calculations for the interference analysis. The program can also be used for design and detailed analysis of HF circuits and for predicting skywave losses for HF signals. The determination of which of the various skywave modes of propagation may exist is one of the first operations of the HF computer program. Transmission of a signal via the E-layer, both the E- and F-layers, and the F-layer alone may occur simultaneously. This program determines whether various modes as described can exist for the conditions specified by the input data, and if they did exist, the loss for each mode is evaluated. Propagation occurs via both ionospheric and ground reflections. Therefore, both the ground wave losses and losses incurred by signals reflected from the ionosphere are calculated by the program and combined at the receiving location to provide the final propagation path loss. Statistics for all losses are carried throughout the computations. This program is limited to the evaluation of losses occurring in the 3 to 30 MHz frequency range and is written to be operated on the computer system at the Rome Air Development Center. The HF model that has been programmed represents an efficient technique for predicting propagation losses that occur in skywave transmission. The anomalous behavior of the ionosphere may contribute significantly to interference. Therefore, prediction accuracy is limited by this effect.

2. MODELS AND TECHNIQUES

A basic flow diagram of the HF computer program is shown in *SN 2(1).* The first computations use E- layer characteristics to determine possible E-layer modes. Takeoff angles are computed for each of the various modes. If F-modes are possible, the next set of computations determines F-modes and respective takeoff angles. The E- and F-mode calculations used with proper logic determine the possibility of mixed modes. Additional calculations provide the necessary radiation angles. Losses are computed after mode and takeoff angles are determined. These losses, referred to as quasi-minimum losses, require correction. Lookup statistics for excess losses for various geographic regions are available in the program. Parabolic layer theory is used throughout the program.

SUB-NOTE 2(1) Basic Flow Diagram



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3. BASIC THEORETICAL CONSIDERATIONS

Basic calculations of hop distances are made in the program on the assumption of a parabolic variation in refractive index. The basic equation of the refractive index for a parabolic layer is given by

$$\mu^2 = 1 - az + bz^2 \qquad \text{(Eq 1)}$$

where μ is the refractive index and z is the height in relation to the bottom of the parabolic layer. The constants a and b are found by

$$a = 2f_c^2/f^2 z_m \qquad \text{(Eq 2)}$$

and

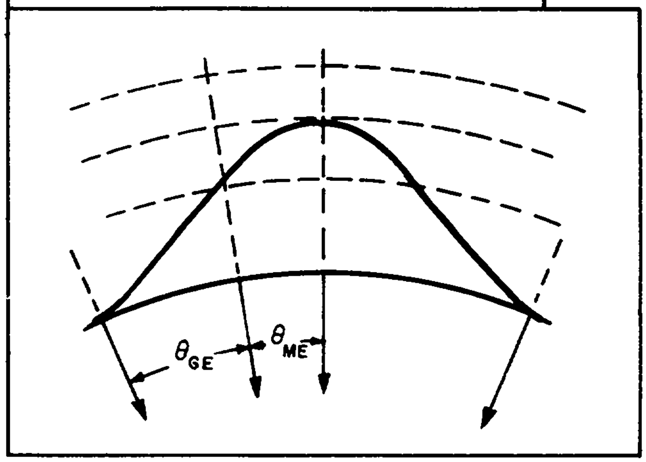
$$b = f_c^2/f^2 z_m^2 \qquad \text{(Eq 3)}$$

where f_c is the critical frequency, f is the operating frequency, and z_m is the height at which peak ionization occurs. Hop distances can be determined by using this model.

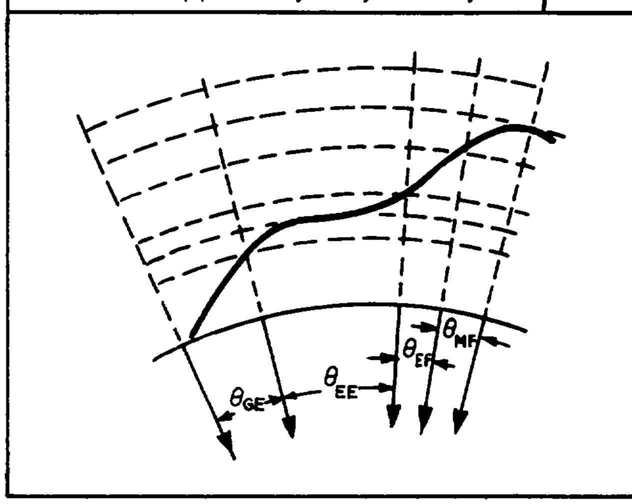
3.1 HOP DISTANCE

Sub-Note 3.1(1) shows the type of calculations that must be employed in determining the hop distance in E-layer transmission. The takeoff angle is Δ. The angular distance the ray travels from the ground to the bottom of the E-layer is represented by θ_{GE}. This distance is calculated by spherical trigonometry techniques. The distance θ_{ME} is calculated by equations derived from a parabolic layer and spherical geometry. If the two angular distances are known, it is a simple matter to determine the actual hop distance for a ray having a takeoff angle Δ. The F-layer hop distances are more complicated. *Sub-Note 3.1(2)* shows the basic calculation required to determine this distance. With a takeoff angle Δ, θ_{GE} may be determined as previously discussed. The E-layer bending occurs in F-layer transmission. Ray-tracing equations provide a mathematical expression for angular distance θ_{EE}. The distances θ_{EF} and θ_{MF} are determined in exactly the same manner as θ_{GE} and θ_{ME}, respectively. By knowing layer heights, thickness, and critical frequencies, hop distances can be determined.

SUB-NOTE 3.1(1) E-Layer Ray Geometry



SUB-NOTE 3.1(2) F-Layer Ray Geometry



3.2 BOUGUER'S RULE

One of the important relationships employed throughout the computer program is Bouguer's rule. Bouguer's rule is essentially Snell's law for spherical geometry. Briefly, it states

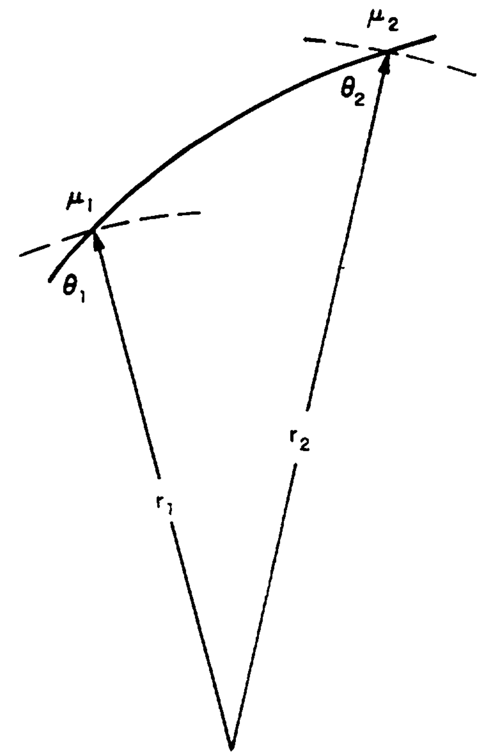
$$\mu r \sin\theta = \text{constant} \qquad \text{(Eq 4)}$$

where μ is the refractive index, r is the radius of curvature, and θ is the angle included between the ray path and radius vector. Bouguer's rule is further explained with the aid of *SN 3.2(1)*. The equation (*SN 3.2(1)*) shows the basic relationship that exists between the values of refractive index, radius of curvature, and angle of incidence at one position and the values for the same parameters at a second position. Bouguer's rule may be used to determine the reflection height and to indicate the minimum angle of incidence which will support reflection. The minimum angle may be determined by letting $\theta_2 = \pi/2$ and $z = z_m$.

3.3 RELATIONSHIP BETWEEN ANGLES

In the program, the basic use of parabolic layer theory and Bouguer's rule lies in the establishment of critical angles and in the construction of curves which relate the takeoff angle Δ to the hop distance. A simple functional relationship exists between Δ and the angle θ. *Sub-Note 3.3(1)* shows the relationship between the angle of incidence θ at the reflecting layer and the hop distance h. This curve may be reconstructed by using the relationship

SUB-NOTE 3.2(1) Bouguer's Rule



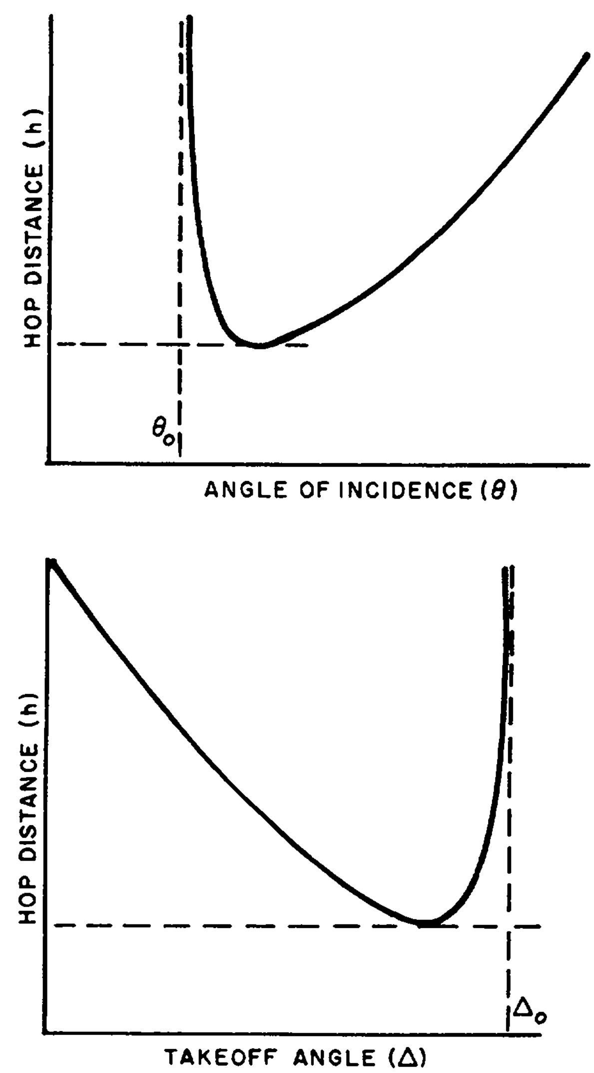
$$\mu_1 r_1 \sin\theta_1 = \mu_2 r_2 \sin\theta_2$$

between Δ and θ to show the relationship of hop distance to takeoff angle (*SN 3.3(1)*). For single-layer transmission, the parameters required for the construction of curves are parabolic layer height, layer semithickness, critical frequency, and operating frequency. If, as in the case of F-layer transmission, an intervening layer is present, the height, semithickness, and critical frequency of that layer are also required. A single curve represents a condition of fixed layer heights, fixed semithicknesses, and fixed ratios of critical frequencies to operating frequency.

3.4 SKIP DISTANCE

In *SN 3.3(1)* the angle θ_o, is determined directly from Bouguer's rule. At angles less than θ_o, ionospheric reflections do not occur. The angle θ_o is directly related to a critical takeoff angle, shown as Δ_o. In *SN 3.3(1)*, a minimum value is shown to exist for the hop distance. This value is commonly referred to as the skip distance. It should also be noted that two angles may be found for a given hop distance that is greater than the skip distance. One of these represents the high-angle ray and the other the low-angle ray. The skip distance exists for a certain set of ionospheric conditions and a given operating frequency. As the operating frequency is increased, the skip distance becomes greater; therefore, the operating frequency becomes the maximum usable frequency when the hop distance equals the skip distance.

SUB-NOTE 3.3(1) Hop Distance Curves



4. PROGRAM DESCRIPTION

The major portions of the HF propagation program consist of an executive control program, an input data program, an output printing program, and the main HF propagation loss control program. The four primary routines employed by the program are the E-layer, F-layer, and mixed mode routines, and the loss calculation routine. Twenty-five auxiliary subroutines are used within the HF program. These subroutines perform the necessary operations of distance and takeoff angle evaluation, mode selection, loss calculations, and the routines for performing the functions required by the primary calculation routines.

DESIGN NOTE 4B4 INTRASYSTEM ELECTROMAGNETIC COMPATIBILITY ANALYSIS PROGRAM (IEMCAP)

1. INTRODUCTION

Performance of modern weapons systems is increasingly dependent upon the compatible functioning of electrical and electronic subsystems. The typical system of today includes numerous such subsystems with their associated interconnecting wires and, often, with large numbers of antennas for transmission and reception of required signals. Thus, electromagnetic compatibility (EMC) assurance is increasingly an integral and crucial part of subsystem and system design engineering. The Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP) can assist the engineer through detailed modeling of a system, whether it be a ground based, airborne, or a space/missile system. This DN discusses the capabilities of IEMCAP as well as its basic structure and components. Further information concerning IEMCAP is contained in *Ref 192.*

2. CAPABILITIES OF IEMCAP

IEMCAP is a link between equipment and subsystem EMC performance and total system EMC characteristics. The IEMCAP performs the following tasks:

a. Provides a data base which can be continually maintained and updated to follow system design changes.

b. Generates EMC specification limits tailored to the specific system.

c. Evaluates the impact of granting waivers to the tailored specifications.

d. Surveys a system for incompatibilities.

e. Assesses the effect of design changes on system EMC.

f. Provides comparative analysis results on which to base EMC trade-off decisions.

3. DESCRIPTION OF IEMCAP

This system incorporates state-of-the-art communications and EMC mathematical models into a computer program which efficiently evaluates the spectra and the transfer modes of electromagnetic energy between generators and receptors within a system. These capabilities are combined by IEMCAP into a modular framework which facilitates IEMCAP modification as the state-of-the-art in modeling progresses. This provides a flexibility in updating IEMCAP as new or improved mathematical models are developed. It also means IEMCAP may be easily applied to a wide variety of EMC analysis and design problems by utilization of only the necessary modules for a specific problem.

3.1 EXERCISE OF IEMCAP

The program is designed for use by an EMC systems engineer with a minimum of computer experience. The input data requirements, program control, and output formats are engineering oriented. To allow it to be run on a wide range of computers, the program is written in USA standard FORTRAN language. It runs with approximately 86K (decimal) words of computer core memory.

3.2 IEMCAP DATA ORGANIZATION

Air Force systems typically contain vast numbers of emitters and receptors of electromagnetic energy. A hierarchy structure is defined in IEMCAP, as shown in *SN 3.2(1)*, to organize this data into a form convenient for collection and utilization by the user and IEMCAP. The system (aircraft, spacecraft, or ground) is divided into subsystems. Subsystems are groups of equipment performing related tasks. For example, an aircraft system might have a navigation subsystem which is composed of several groups of equipment such as a transmitter-receiver unit, and a navigation computer. Electromagnetic energy may enter or leave these equipment via ports. Examples of equipment ports include antennas, wires, and equipment cases.

3.3 BASIC ANALYSIS APPROACH

All intentional ports must generate and/or receive certain types of signals to perform their intended function. The signals or responses which are intentionally generated and coupled from port to port are called operationally required and cannot be altered without affecting system operation. In addition to the required signals, there may be additional undesired signals and/or responses. These are called operationally nonrequired. For example, an emitter can have nonrequired outputs in the form of harmonics, and a receptor can have a nonrequired response in the form of an image response. Nonrequired responses may be produced both by nonrequired signals and/or by required signals which are unintentionally coupled to the wrong ports. An incompatibility is said to exist when sufficient signal from an emitter port, or ports, is unintentionally coupled to a receptor port to exceed its susceptibility threshold. Required signals and responses, by definition, cannot be restricted by EMC specification. The nonrequired signals and responses are spurious and

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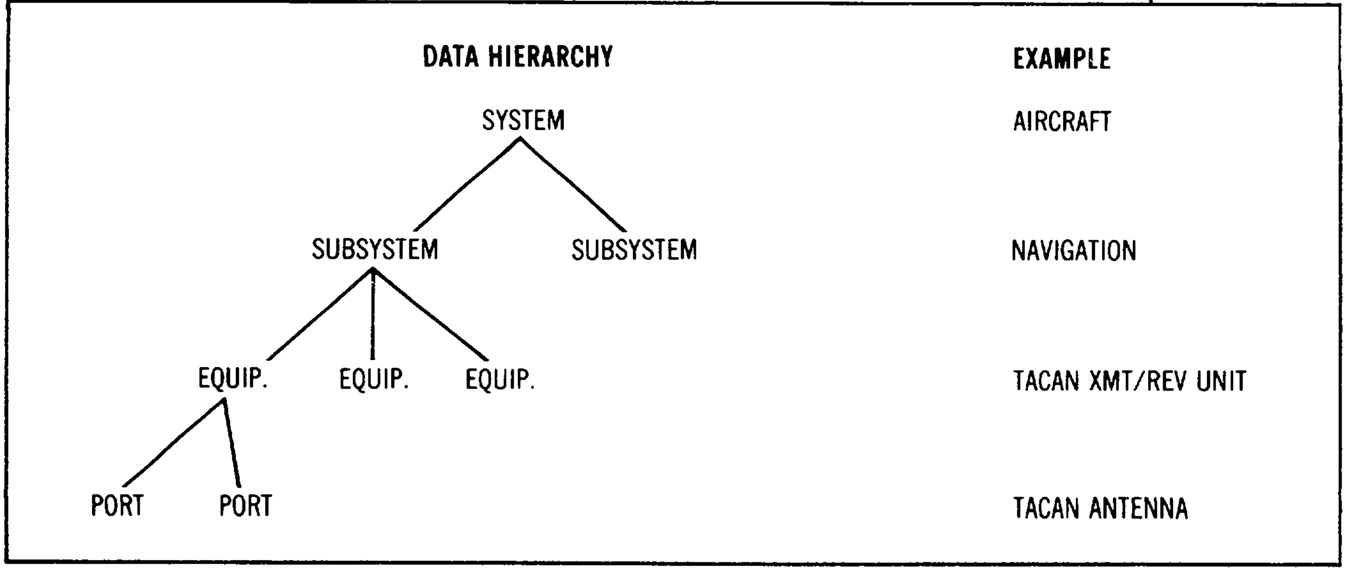
SUB-NOTE 3.2(1) IEMCAP Data Hierarchy



can be controlled; that is, limits can be set for them to make the system compatible. These limits are called EMC specifications. Ideally, if no ports have nonrequired emissions or susceptibilities exceeding these limits, the system is compatible. An important task of IEMCAP is the generation of a set of specification limits tailored to the specific system under analysis.

4. PROGRAM OPERATION

The IEMCAP is divided into two sections, and the basic flow through them is shown in *SN 4(1)*. These sections are executed independently with intermediate data storage on a number of disk or tape files known as working files. Depending on the analysis and the size of the system being analyzed, the program sections can be executed in succession or run separately.

4.1 INPUT DECODE AND INITIAL PROCESSING ROUTINE

The first section of IEMCAP, called the Input Decode and Initial Processing Routine (IDIPR), is divided into three basic routines: Input Decode Routine, Initial Processing Routine, and Wire Map Routine. The Input Decode Routine reads and decodes the free-field input data from punched cards and checks the data for errors. If an error is found, a message is printed along with the card containing the error, and the program continues. If after all cards have been processed, there are errors, the program normally stops. (The user can override this error stop if desired.) If there are no input errors, the program proceeds into the Initial Processing Routine (IPR). This routine performs data management, interfaces with the spectrum models, and generates the working files. Data defining the system and all its components is stored on a magnetic disk or tape called the Intrasystem File (ISF). For a given run, the system to be analyzed can be defined from punched cards only, from a previously created ISF, or from an old ISF updated by cards. The IPR assembles and merges the data to be analyzed and writes this data on a new ISF for future runs and on the working files for analysis. During this process, IPR interfaces with the spectrum math model routines. From IPR, the program enters the Wire Map Routine which generates cross-reference map arrays for use by the wire coupling math models during analysis. At this point, execution of IDIPR terminates. The computer can either stop or continue into the second section, depending on the job setup.

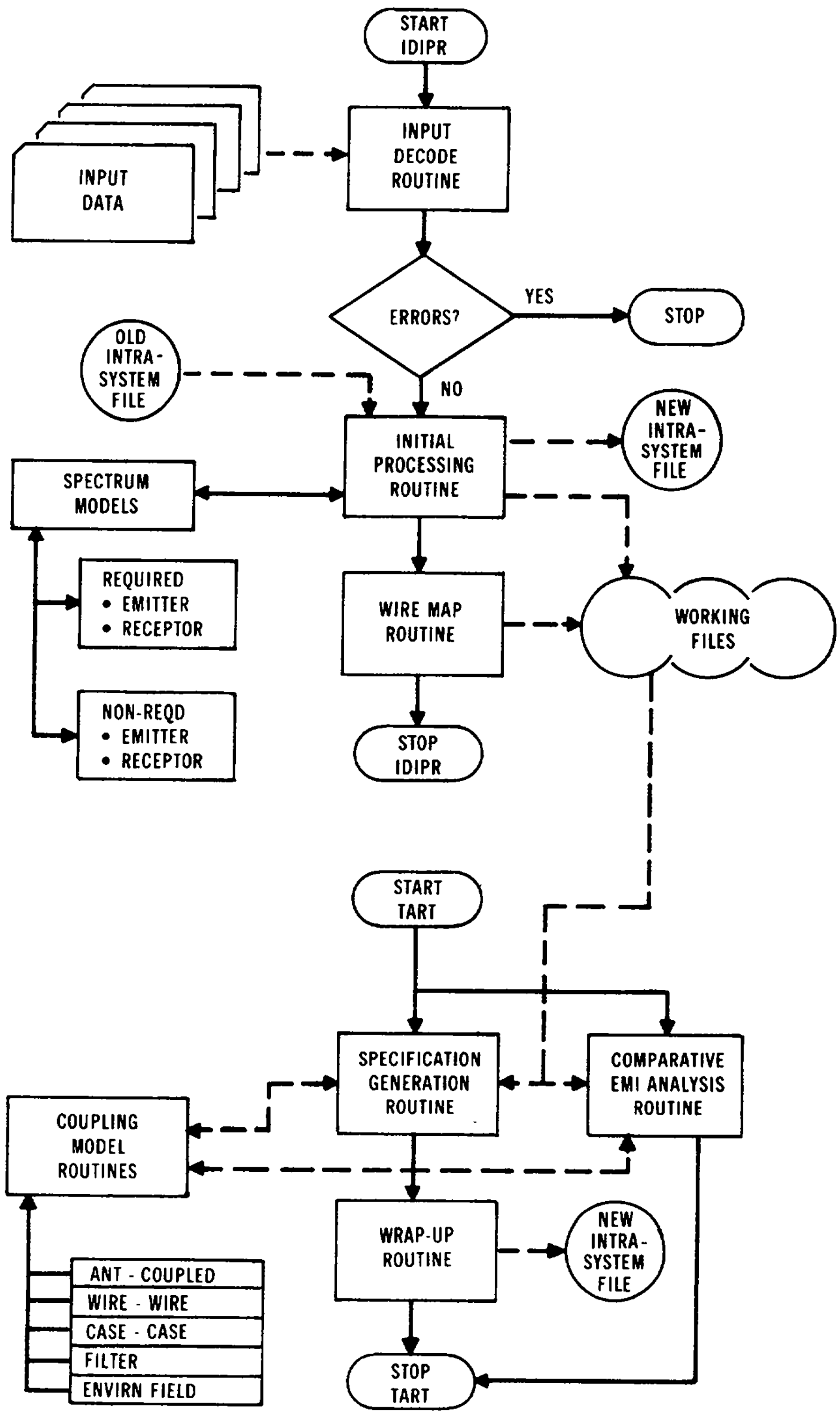
4.2 TASK ANALYSIS ROUTINE

The second section of IEMCAP, called the Task Analysis Routine (TART), uses the data compiled by IDIPR to perform the desired analysis task. This is any one of the following four tasks:

a. Specification Generation. Adjusts the initial nonrequired emission and susceptibility spectra so that the system is compatible, where possible. The user-specified adjustment limit prevents too stringent adjustments. A summary of interference situations not controlled by EMC specifications is printed. The adjusted spectra are the maximum emission and minimum susceptibility specifications for use in EMC tests.

b. Baseline System EMC Survey. Surveys the system for interference. No adjustments to port spectra are made. From this, the EMC of a system due to existing equipment can be determined. A summary of the predicted interference is printed.

SUB-NOTE 4(1) IEMCAP Functional Flow*



*Extracted from *Ref 192*

c. Trade-off Analysis. Compares the interference for a modified system to that from a previous specification generation or survey run. The effect on interference of antenna changes, filter changes, spectrum parameter changes, wire changes, etc., can be assessed from this.

d. Specification Waiver Analysis. Shifts portions of specific port spectra as specified and compares the resulting interference to that of a previous specification generation or survey run. From this, the effect of granting waivers to specific parts of the specification can be assessed.

TART is composed of two basic routines. The Specification Generation Routine performs this first task, and the Comparative EMI Analysis Routine performs the remaining three. These routines interface with the coupling math model routines to compute the transfer ratios between emitter and receptor ports.

5. MODELS

The mathematical models used by IEMCAP can be divided into the general classifications of emitter models, receptor models, transfer models, and the system model.

5.1 EMITTER MODELS

The emitter models relate the parameters of the equipment and emitter data to the power spectral density output by the emitter port. The following emitter models are incorporated in IEMCAP for the common emitter types (provision is made for user input of spectral densities for those types not modeled):

a. Binary Frequency—Shift Keying

b. Amplitude Modulation (AM) with Stochastic Process

c. Angle Modulation with Stochastic Process

d. Single Sideband Amplitude, Phase and Frequency Modulation (FM) with a Stochastic Process

e. Bounds on the Emission Spectra of Chirp Radars

f. Pulse Code Modulation/AM—Nonreturn to Zero

g. Pulse Position Modulation

h. Pulse Code Modulation/AM—Biphase

i. Pulse Amplitude Modulation—FM

j. Pulse Duration Modulation

k. Various Pulse Trains—Rectangular, Trapezoidal, Triangular, Sawtooth, Exponential, Damped Sinusoid

5.2 RECEPTOR MODELS

Receptor models relate the energy spectrum at the receptor port to the response produced by that spectrum. The basic approach for receptors employed in IEMCAP is to accept input data on in-band sensitivity, along with a bandwidth parameter, and to then form a rectangular shaped susceptibility function in the required spectral region. This required spectra connects to nonrequired spectra defined by user-adjusted military specification interference limits. An RF receiver representation in IEMCAP will, in general, actually have a trapezoidal shaped susceptibility function (in-band) due to the skirt slopes of the normal selectivity curve. If more is known about the details of its responsive curve than simply the flat response, the user can specify the known response curve.

5.3 TRANSFER MODELS

The transfer models are used to compute the ratio between the energy output at an emitter port and that present at the input to a receptor port. The following transfer models are included in IEMCAP:

a. Filter Models. Single Tuned, Transformer Coupled, Butterworth Tuned, Low Pass, High Pass, Band Pass, Band Reject

b. Simplified Theoretical Ground Wave Model

c. Antenna Models. Monopole, Dipole, Slot, Loop, Horn, Parabolic Dish

d. Antenna-to-Antenna Coupling

e. Field-to-Wire Coupling

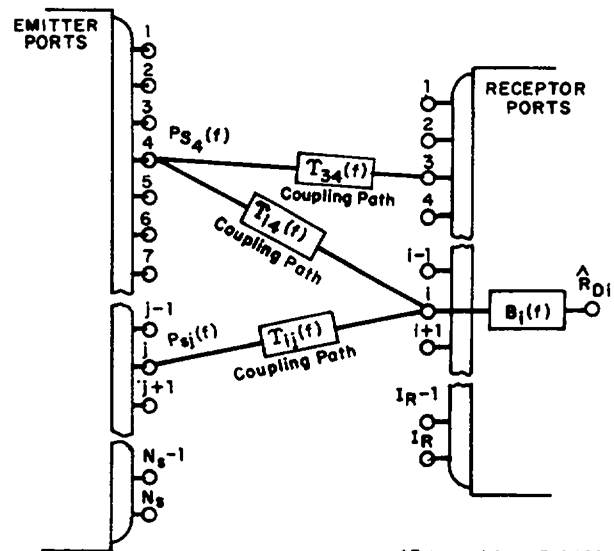
f. Wire-to-Wire Coupling

g. Case-to-Case Coupling

5.4 SYSTEM MODEL

The system model is used to structure the emitter, transfer, and receptor models to account for simultaneous operation of all equipment. This enables calculations for compatibility and specification generation to be performed not only between pairs of equipment, but also among all equipment when all are operating simultaneously. The system model for IEMCAP employs the standard EMC approach of identifying all ports in the system having potential for undesired signal coupling. These ports are divided into arrays of emitter ports and of receptor ports having identifiable coupling paths. A simplified diagram of this approach is given in *SN 5.4(1)*. Each element of an array of N_s emitters is considered to have a coupling path to one or more elements of an array of I_R receptors. In this simplified diagram only three coupling paths are shown, illustrating the general idea that more than one emitter can couple to a given receptor and further illustrating that a given emitter can couple to more than one receptor. All ports and coupling media are assumed to have linear characteristics. Emissions from the various emitter ports are assumed to be statistically independent so that signals from one or more emitters entering a receptor port combine on an rms or power basis. The function of IEMCAP is to determine, by analysis, whether signals from one or more emitters entering a receptor port cause interference with the required operation of that receptor. This electromagnetic interference is addressed in IEMCAP by computation of an EMI Margin for each receptor port. This EMI Margin is simply the ratio of power received at a receptor port to that receptor's susceptibility. IEMCAP computes this margin in decibels; the more positive the number in decibels the greater is the interference while the more negative the number in decibels the greater is the compatibility.

SUB-NOTE 5.4(1) Diagram of IEMCAP System Approach*



*Extracted from *Ref 192.*

DESIGN NOTE 4B5*

PRECIPITATION STATIC ANALYSIS PROGRAM (PSTAT)

1. INTRODUCTION

The flight of airborne vehicles through precipitation often causes the accumulation of static electricity on the vehicle surfaces. This precipitation static causes electromagnetic interference (EMI) which can directly affect overall vehicle effectiveness and safety. The Precipitation Static Analysis Program can aid the system design engineer by predicting the electromagnetic noise at an aircraft antenna due to precipitation static. The Precipitation Static Analysis Program is a computer program which models the electromagnetic noise created by either the corona discharge or the streamer discharge modes of precipitation static. This DN presents the theoretical and empirical foundations of PSTAT.

2. PRECIPITATION STATIC PHENOMENA

The operation of an airborne vehicle in precipitation causes a frictional electrification effect. The impinging precipitation particles acquire a net charge and also deposit an equal and opposite charge on the vehicle itself. The particle impact rate in a typical cloud is sufficient to cause aircraft surfaces to reach a potential of hundreds of kilovolts in less than a second.

2.1 CORONA DISCHARGE

When the vehicle potential reaches roughly 100 kV, the electric field intensity at the aircraft extremities is sufficiently high to cause electrical breakdown of the air. This breakdown is called corona discharge. At the normal operating altitudes of aircraft, the corona discharge occurs not as a continuous flow of charge but as a series of pulses. These pulses have roughly a 10-ns rise time and 200-ns duration; consequently electromagnetic noise is generated over a broad spectrum.

2.2 STREAMER DISCHARGE

A similar situation exists on the dielectric surfaces of an airborne vehicle. As charge accumulates on the dielectric surfaces, the potential with reference to the airframe rises. When the electrical field intensity becomes sufficiently high, electrical breakdown occurs across the dielectric surface. This breakdown is called streamer discharge. A surface streamer involves the rapid transfer of charge over a substantial distance and generates serious electromagnetic noise.

3. CORONA DISCHARGE MODEL

The corona discharge model of PSTAT predicts the noise field present at an aircraft antenna due to corona discharges. The noise field at an antenna is calculated from the noise spectrum generated at each aircraft extremity. The noise spectrum of corona discharges is dependent upon the total aircraft charging current. Users of PSTAT can quiet selected discharge locations to observe the effect of installing quieting devices such as static dischargers.

3.1 TOTAL CHARGING CURRENT

The total charging current on an aircraft is dependent on aircraft speed, aircraft intercept area, and cloud type. The value for the total charging current calculated by PSTAT is based on extensive flight test and laboratory studies involving a KC-135 aircraft. The charging current for different sized aircraft is extrapolated by using the ratio of the effective intercept area of the aircraft to the KC-135. The total charging current is apportioned among the various aircraft extremities as follows: each empennage tip, one-seventh; each wing tip, two-sevenths.

3.2 SOURCE NOISE SPECTRUM

The corona noise spectrum is obtained from the corona discharge current at each aircraft extremity by applying empirically derived formulas. These formulas are plotted in *SN 3.2(1)* with the experimental data.

3.3 COUPLING FACTOR

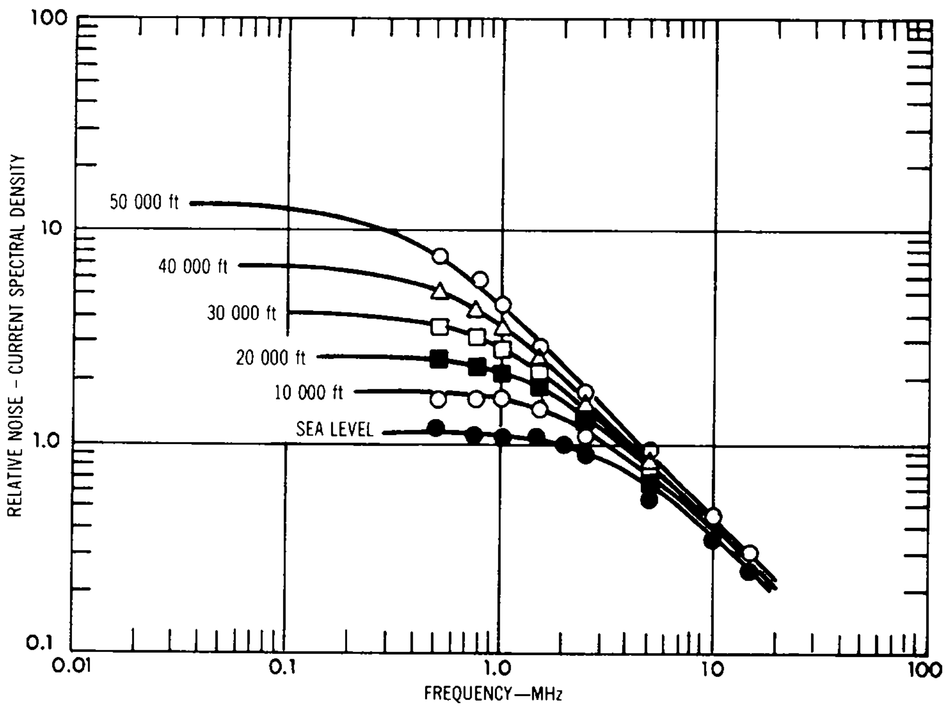
The noise spectrum at an aircraft antenna is calculated from the source noise spectrum by applying the appropriate coupling factor. The PSTAT uses coupling factors derived from measurements as shown in the graphs of *SN 3.3(1)*. The program scales the resonant frequencies of these coupling factors to make them valid for different sized aircraft. The total received noise spectrum at an antenna is calculated by summing the noise contributions from each extremity on an rms basis.

3.4 EQUIVALENT NOISE FIELD

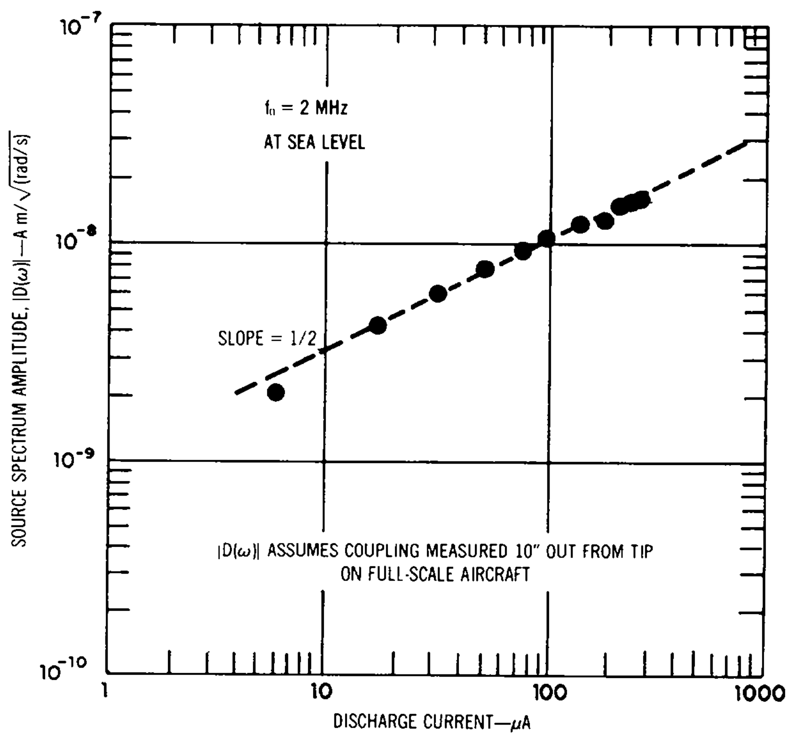
A more useful expression of the corona noise spectrum at an antenna is in terms of the field intensity required to generate the noise spectrum in the antenna. The PSTAT uses a quasi-static model to estimate the equivalent noise field at a particular antenna location.

REO ASD/ENACE
*Material in this DN extracted in part from *Ref 1432*

SUB-NOTE 3.2(1) Corona-Noise-Source Spectrum Characteristics

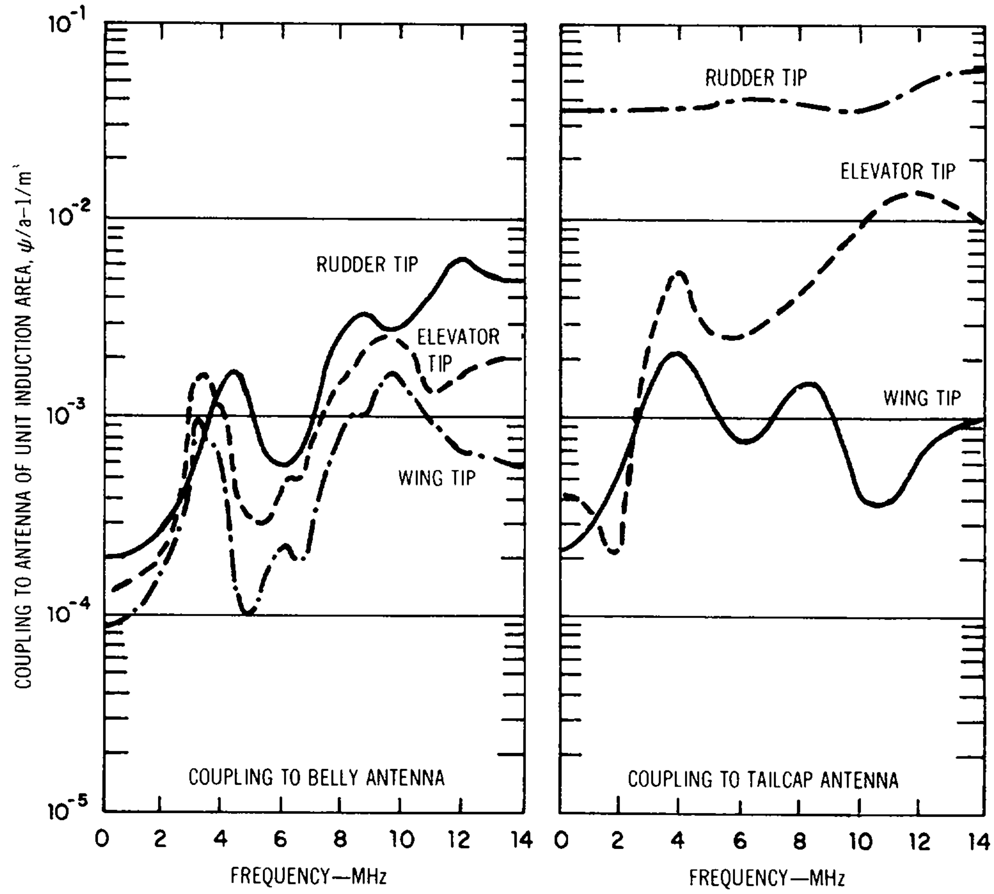


(a) NORMALIZED SPECTRUM SHOWING ALTITUDE EFFECTS



(b) RELATIONSHIP OF ABSOLUTE NOISE LEVEL TO DISCHARGE CURRENT

SUB-NOTE 3.3(1) Measured Coupling Factors for Antennas on Boeing 367-80 Aircraft



4. STREAMER DISCHARGE MODEL

The streamer discharge model of PSTAT predicts the noise spectrum or equivalent noise field at an aircraft antenna due to streamer discharges. The noise at an antenna is calculated from the noise spectrum generated at an aircraft dielectric surface, such as nose radome or canopy. This noise spectrum is dependent upon the streamer discharge current.

4.1 STREAMER DISCHARGE CURRENT

The charging current responsible for streamers is dependent upon the total aircraft charging current and the relative intercept area of the dielectric material. This program relates these quantities in an empirically derived formula based on flight test measurements made on an F-4 aircraft.

4.2 NOISE SPECTRUM

Flight testing and laboratory studies indicate that streamer discharges induce pulses of the form shown in *SN 4.2(1)*. Because the time waveform (and hence the noise spectrum) of each streamer pulse depends on the length of the streamer, PSTAT uses a statistical model to represent noise spectrum. This statistical model is based on a series of discharge pulses occurring at random times with randomly varying time waveforms.

4.3 COUPLING

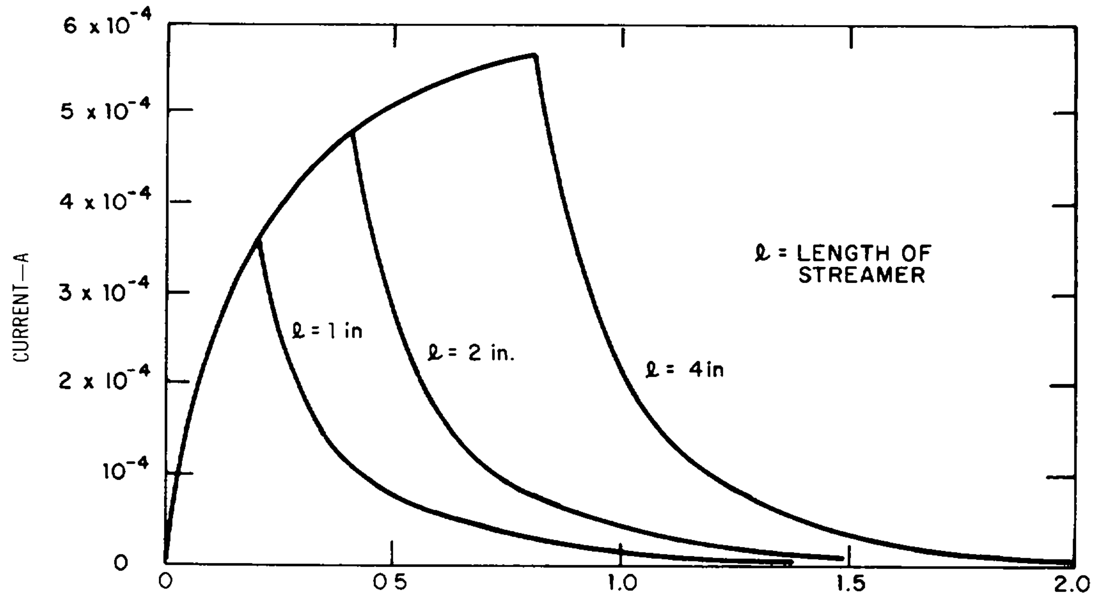
This program models the coupling from a streamer noise source to an aircraft antenna by categorizing the streamer source in one of three physical locations relative to the antenna. Each of the following categories uses empirically derived coupling data:

a. Antenna is located on the fuselage aft of the region (such as radome) on which streamers are occurring.

b. Antenna is located beneath a windshield or canopy on which streamers are occurring.

c. Wire antenna is located on the underside of the dielectric on which streamers are occurring.

SUB-NOTE 4.2(1) Typical Current Pulses Induced by Streamer Discharges



4.4 EQUIVALENT NOISE FIELD

The PSTAT uses a quasi-static model to calculate the equivalent noise field for configurations in *Para 4.3a* and *Para 4.3b*. For the configuration in *Para 4.3c*, the streamer source is so close to the wire antenna that the streamer coupling is independent of wire length and, hence, also antenna induction area. Thus, PSTAT calculates the noise current spectrum in the wire rather than the equivalent noise field.

CHAPTER 5 BASIC EMC DESIGN

SECT 5A INTRODUCTION

SECTION 5A INTRODUCTION

DN 5A1 - INTERFACES

DESIGN NOTE 5A1 INTERFACES

1. GENERAL

To ensure an interference free system, follow the interface guide for the areas shown in *SN 1(1).*

2. SYSTEM INTERFACE PROBLEMS

Most interface problems are generated by lack of proper direction or lack of coordination by the overall system cognizant personnel. It should be the responsibility of system personnel to dictate to, and provide resolution of, interface problems which are usually the result of the philosophy that "if my equipment works, why should I worry about his?" From a compatibility approach this thinking can be disastrous.

2.1 DISCIPLINES

Ensure that a good interface exists between cables, connectors, electrical bonds, grounds, shields, and filters to obtain an EMC tight system.

2.2 SHIELDING INTERFACES

Care should be taken to ensure that connectors maintain the shielding integrity of both the cable and the chassis or panel to which the connector is attached. Cabinets and cable shields with a high degree of shielding may be compromised by leakage through and around certain connectors.

3. SNEAK CIRCUITS

Some types of interface problems have been called "sneak circuits" because they are an insidious aspect of design caused by the size and complexity of modern systems. One definition is: "a sneak circuit is a latent path which causes an unwanted function to occur or inhibits a desired function without regard to component failure." Sneak circuits include sneak paths, sneak timing, sneak indication, and sneak labels.

a. A sneak path is an unexpected/undesired route for current or energy.

b. A sneak indication is an ambiguous or false display of system operating conditions.

c. Sneak timing occurs when current or energy flows unexpectedly or when a function is inhibited at an unexpected time.

d. A sneak label is initiation of an incorrect stimulus.

Conduct systematic analysis for sneak circuits during the design of new equipment and modifications.

3.1 CAUSES OF SNEAK CIRCUITS

The following are typical causes of sneak circuits:

a. Design changes which are not properly integrated into the system or do not fully consider all operating and test modes.

b. Incomplete design review caused by overlapping or changes in design authority from designer, integrators, configuration boards, and test groups.

c. Size and complexity of system.

d. Human factors that contribute to confusing or out-of-sequence procedures.

3.2 EXAMPLES OF SOFTWARE PROBLEMS

Some causes and effects of problems are:

a. Causes—incorrect implementation, conflicting commands, incorrect initiation, missing logic, incomplete testing, incorrect sequences.

b. Effects—logic loops, open ended logic, unused logic, logic bypass, unnecessary logic, invalid test or output.

SUB-NOTE 1(1) Interface Guide

	CABLING	CONNECTORS	BONDING & GROUNDING	EARTHING	SHIELDING	FILTERING
CABLING	SECT 5B	5C3	5D5	5E2	5F1	5G5
CONNECTORS	5B5	SECT 5C	5D4	5E2	—	5G5
BONDING & GROUNDING	5B7	5C2	SECT 5D	SECT 5E	5F5	5G5
SHIELDING	5B6	5C4	5D5	—	SECT 5F	5G5
FILTERING	5B7	—	5D5	—	5F1	SECT 5G

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3.3 DATA REQUIRED FOR SNEAK CIRCUIT ANALYSIS

In order to make an analysis, the following data are necessary:

a. Minimum data required—assembly/compiler listings, reference manuals for computer language, operating system, interfacing peripherals, symbol definitions, and design specifications.

b. Additional desirable data—source listing, system description/requirements, module descriptions, flow diagrams, interface specifications, and data structures definitions.

3.4 SOFTWARE ANALYSIS

An analysis can be beneficial in identifying problems since it provides a systematic review of possible paths, identifies abnormal as well as normal operating conditions, does not require execution of the software, provides a means of verifying software/hardware interactions, is relatively independent of language, and can identify cause of problem without waiting for effect to occur. The characteristics of sneak circuits can be detected through early application of proper analytical techniques and thus, possibly prevent catastrophic events and identify problems which otherwise might go undetected in the design phase.

SECT 5B CABLING

SECTION 5B CABLING

DN 5B4 - Contd

DN 5B5 - AEROSPACE VEHICLE WIRING

DN 5B6 - CABLE MEASUREMENTS

DESIGN NOTE 5B1* INTRODUCTION

1. GENERAL

The transfer or coupling of extraneous signals into wiring cables has been a problem ever since devices such as sensitive radio receivers and sensitive microphones have been employed. The many uses of electronic subsystems have developed complex and often-occurring problems of interference on wiring. A generalized discussion of interaction and propagation is given in *DN 3C2, Para 3.* For additional information, see *MIL-STD-454, Requirements 65, 66,* and *69.*

2. CONCEPTS OF CABLE COUPLING PHENOMENA

To analyze the coupling between two or more cables, assume that they run parallel. The coupling may be expressed in terms of the transfer impedance. The transfer impedance can be defined as the ratio of the voltage appearing between the conductors of the second cable to the current applied at the first. At low frequencies, i.e., those frequencies for which the total length of one is short compared to the wavelength (these are defined as those cables shorter than one-sixteenth wavelength), the current and voltage along the cable may be considered to be constant; therefore, it does not matter at which end of the cable the current or voltage is measured. At higher frequencies, standing waves on the cables must be taken into account if the cables are not terminated in their characteristic impedances.

2.1 TRANSFER IMPEDANCE

The transfer impedance is clearly dependent upon the impedances terminating between the source and the susceptible cable. It will depend upon both magnetic and capacitive coupling effects. At low frequencies capacitive coupling is easily prevented by placing one or both of the cables in metallic shields. If the concern is with individual sensors in a cable, this shielding will not be possible, and both magnetic and capacitive coupling will be significant.

3. FLAT MULTICONDUCTOR CABLES

See *MIL-HDBK-176* for guidance in reducing EMC problems in flat conductor cables.

4. CONSIDERATIONS

The decision as to types and length of cables connecting equipment of separate subsystems should be made by the cognizant system engineers in coordination with each of the respective subsystem engineers. Likewise, shield terminations, lead twisting, and cable routing should be coordinated. Thus, the integrity of the grounding philosophy and shielding may be maintained. Coupling problems, cross talk, and ground loops will be minimized while compatible integration will be greatly enhanced.

4.1 ROUTING OF WIRES AND CABLES

Routing of the wires and cables within a modern aircraft and missile is no longer the simple matter of getting a circuit from one point to another by the shortest, least complicated way. Wires and cables are actually part of the individual electronic subsystems. The term "routing" includes separation, segregation, and sorting into bundles and cable placement.

4.2 VIBRATION AND MECHANICAL COUPLING

Vibrating electrical and electronic wiring and cables can generate a small voltage that degrade susceptible circuits. Vibration can also cause chafing of insulation on sharp metal edges which can cause short circuits and electrical fires. Ensure that cables and wires do not come in contact with sharp metal edges by shielding these edges and using bushings when cables are fed through the frame.

4.3 CABLING GUIDE

The information contained in *SN 4.3(1)* is furnished for guidance.

REO: ASD/ENACE
*Extracted in part from *Ref 631.*

SUB-NOTE 4.3(1) Guidance for Cabling

1. Analyze for both inductive and capacitive coupling.
2. Separate power wires from signal wires and input lines from output lines (do not install in same wire bundle or connector).
3. Route susceptible wires away from power supplies, transformers, and other high power devices.
4. Use twisted pairs instead of shielding power cables.
5. Use *DN 5B5* for determining wiring methods and classifications.
6. Terminate wires and cables as suggested in *DN 5B5* and *DN 5C4*.
7. Select and mate coaxial cables with RF connectors according to *MIL-HDBK-216*.
8. Ensure cables (wires) interface with the other EMC disciplines (shielding, filtering, and bonding).
9. If EMI/EMP is a factor and cannot be resolved by shielding, filtering, bonding, or grounding, consider using fiber optical link(s).

DESIGN NOTE 5B2* COUPLING AT LOW FREQUENCIES

1. INTRODUCTION

Low frequency coupling is considered to be one-sixteenth of a wavelength or lower.

1.1 MAGNETIC COUPLING

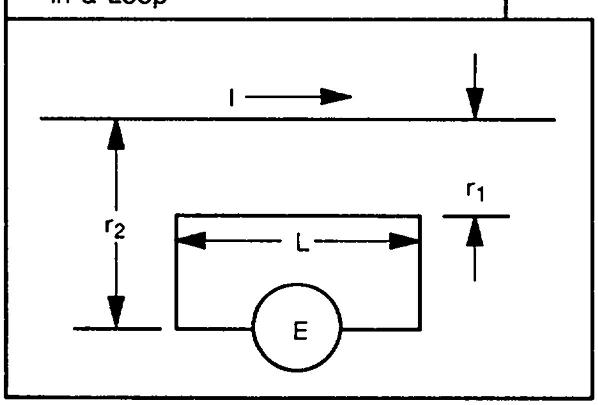
Magnetic coupling will be most noticeable as a contributor to interference when the circuitry attached to the cable operates into low impedances at each end. Interference voltages are induced into a wire by flux linkage to the source of interference. The source of interference will be a generator of magnetic flux which may be a transformer, a solenoid, or another current-carrying wire. The voltage induced in a loop by an adjacent wire of infinite length carrying current as represented in *SN 1.1(1)* will be

$$E = C_1 \, f \, L \, I \ln \frac{r_2}{r_1} \qquad \text{(Eq 1)}$$

Where:

f	=	frequency, hertz
L	=	length
I	=	current, amperes
constant C_1	=	1.26×10^{-9} when L and r are in mm
constant C_1	=	3.19×10^{-8} when L and r are in in.
E	=	induced voltage, volts
r_1 and r_2	=	loop distance

SUB-NOTE 1.1(1) Voltage Induced in a Loop



If the susceptible loop is at an angle to the interference source, *Eq 2* holds true. *Sub-Note 1.1(2)* illustrates a source loop coupled to a sensitive wire loop.

$$E = C_2 \, f \, L \, I \left[\ln \left(\frac{R_1^2 + W^2 + 2R_1W \cos\theta}{R_1^2 + W^2 - 2R_1W \cos\theta} \right) - \ln \left(\frac{R_2^2 + W^2 + 2R_2 \cos\phi}{R_2^2 + W^2 - 2R_2 \cos\phi} \right) \right] \qquad \text{(Eq 2)}$$

Where:

constant C_2	=	6.27×10^{-9} when L and R are in mm
constant C_2	=	1.593×10^{-8} when L and R are in in.

The induced voltage rises with frequency, source current, and length of closed loop. The induced voltage also increases with effective area enclosed by the pickup loop. The induced voltage will act in circuits by driving current through the impedances in the pickup loop and its loads. For low frequencies, the impedance of the pickup loop will consist primarily of wire resistance, and maximum power will be delivered to a load of low resistance. It is assumed that the source circuit is a low impedance circuit since the most significant interference will result from a high current source. The voltage delivered to the circuits attached to the pickup loops will rise to half the induced voltage as the load impedance in the pickup loop rises to match the driving impedance due to the coupling. As the load impedance rises from this point, the voltage at the circuit loads will rise to the full induced voltage as a maximum.

2. REDUCING INDUCTIVE COUPLING

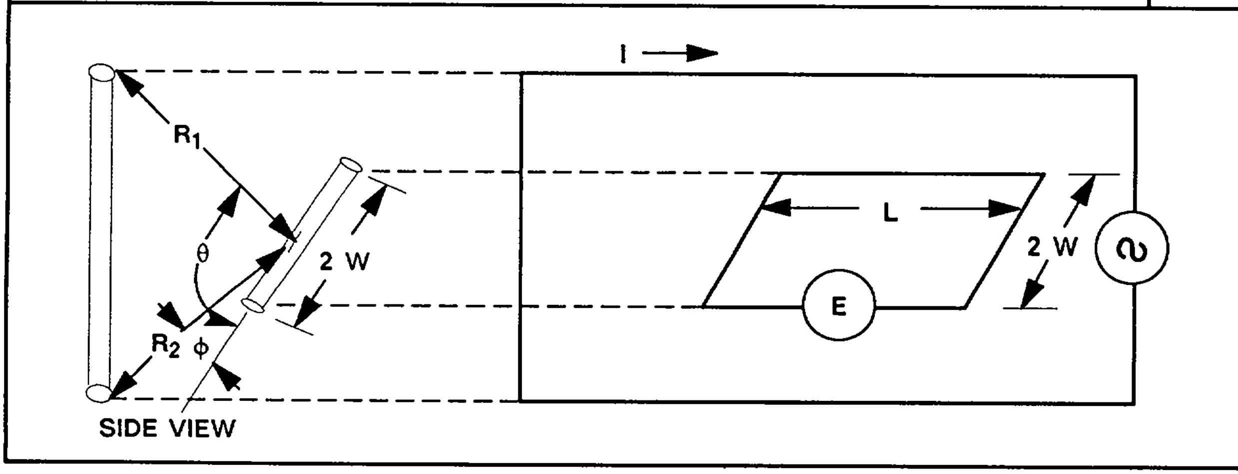
The following subparagraphs discuss methods to reduce inductive coupling.

2.1 FILTERING

The higher frequency components of interfering source current and the resulting voltage in pickup loop may be reduced by filtering. It is usually preferable to filter the source of the interfering signal since it may couple into several susceptible circuit.

REO: ASD/ENACE
*Extracted in part from *Ref 631*.

SUB-NOTE 1.1(2) Susceptible Loop at an Angle



2.2 REDUCING SOURCE AND PICKUP LOOP AREAS

Reducing the physical area enclosed by the pickup loop and the source loop will reduce coupling. The loop area can be made effectively smaller by running the signal or current-carrying wire adjacent or parallel to it return wire. Twisting pairs of wires whose total loop area reduces to a minimum is also effective in reducing coupling. Using a structure for return wire can result in a large pickup or exciting loop area. A susceptible loop in a large installation is made by running cables at the ceiling of a building while the return circuits are grounded to the metal flooring. Providing a cable trough in flooring can avoid many interference problems.

2.2.1 MOUNTING OF BYPASS CAPACITORS. Bypass capacitors should be mounted directly against the chassis or shield which is used as the ground return. By-pass capacitors carry relatively large currents by virtue of their filtering function. Exercise care in restricting the loop area in the capacitor's grounding return. A bypass capacitor used across distributor points is particularly effective in suppressing ignition interference.

2.3 DISTANCE BETWEEN LOOPS

The most obvious means to reduce coupling in the pickup and source loop is to increase the distance between them. This will reduce the induced voltage exponentially.

2.4 LOOPS ORIENTED PERPENDICULARLY

Coupling between the source and pickup loop is reduced to a minimum when the conductors are oriented in perpendicular planes. Crossing cables at right angles, however, is not always feasible and other means must be utilized to reduce coupling.

2.5 TRANSPOSITION OF LOOPS

The transposition of a wire and its return conductor is an old technique originating in telephone line construction. The use of twisted pairs often will minimize a difficult interference problem. Recent developments include twisted pairs of special configuration which yield an extremely tight and uniform twist. Shielding of various types is often used to minimize RF coupling.

2.6 SHIELDING OF CABLES

Other mean of reducing interference coupling which are not directly apparent from *Sub-Notes 1.1(1)* and *1.1(2)* are associated with shielding. Two basic principles may be used to provide shielding: (1) magnetic flux from the source may be isolated from the pickup loop by high permeability materials or (2) the magnetic flux may be reflected away from a pickup loop by high conductivity materials. Recent developments in cable shielding have made available braided shields of high permeability materials. This development offers 20-dB attenuation at 400 Hz with minimum penalties on weight and flexibility.

2.6.1 HIGH PERMEABILITY MATERIALS. High permeability materials restrict the leakage flux path from magnetic components such as transformers and may be used to enclose susceptible cables. High permeability tape has been used successfully to contain the magnetic interference fields from long lengths of power transmission lines. To be most effective, a high permeability shield must present a closed path for magnetic flux with a minimum of reluctance in the magnetic circuit. To prevent coupling, care should be exercised to avoid passing cables near an air gap in a magnetic circuit.

2.6.2 MAGNETIC COUPLING. Any of the usual shields on shielded wiring provide no significant protection against magnetic coupling at low frequencies.

3. CAPACITIVE COUPLING

In long cable runs, an appreciable capacitance is likely to exist between adjacent wires and from each wire to ground or shield. Additional capacitance will exist at connectors and associated wiring. The voltage induced into one wire from an adjacent one is a function of these capacities. *Sub-Note 3(1)* illustrates one model for the capacitive coupling in a cable. The interfering voltage (E_o) couples through stray capacity (C_c) to produce voltage (E_x) on an adjacent cable. The interfering cable and the adjacent cable have stray capacities to ground C_a and C_b. Each cable has its system loads Z_1 and Z_2, and Z_3 and Z_4 across which the stray capacities appear. An equivalent circuit is shown in *SN 3(2)*. If cable load impedances are high, the frequency spectra of voltages E_o and E_x may be affected by C_a and C_b. The voltage division ratio E_x/E_o will be

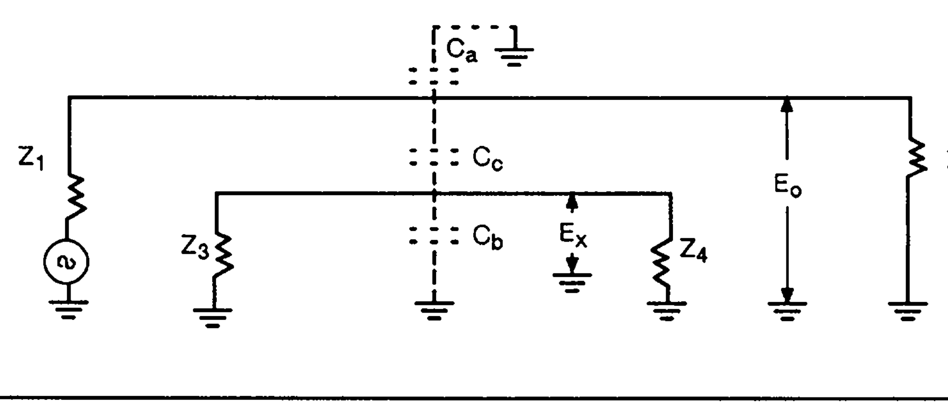
$$\frac{E_x}{E_o} = \frac{Z_x Z_b/(Z_x + Z_b)}{Z_c + Z_x Z_b/(Z_x + Z_b)} \qquad \text{(Eq 3)}$$

If Z_x is a high resistance load (R_x), then

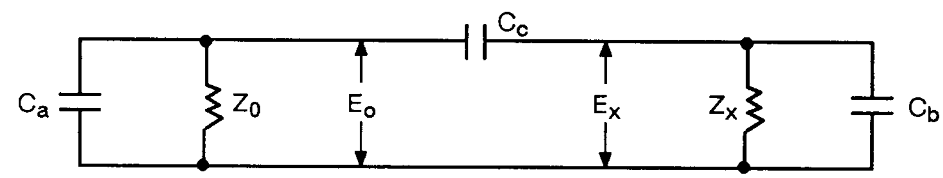
$$\frac{E_x}{E_o} = \frac{C_c}{C_c + C_b}\sqrt{\frac{R_x^2}{R_x^2 + [1/2\pi f(C_c + C_b)]^2}} \qquad \text{(Eq 4)}$$

A plot of this ratio against R_x is linear until the reactance of $C_c + C_b$ is approached by R_x, from which region the ratio approaches $C_c/(C_c + C_b)$, asymptotically. The plot of E_x/E_o against frequency will have the characteristic shape shown in *SN 3(3)* for $Z_x = R_x$. When Z_x contains inductive reactance, resonances may cause variations in coupling with frequency. Such effects are likely to be noticeable at the higher frequencies and are likely to exhibit broad resonances due to loading in dielectrics and connected circuits. When Z_x contains capacitive reactance, it is equivalent to an increase in C_b.

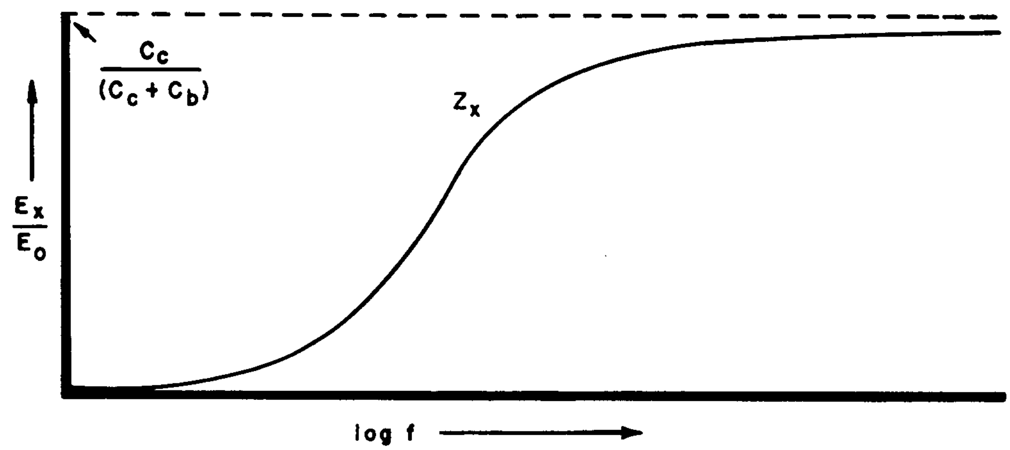
SUB-NOTE 3(1) Capacitance Coupling in a Cable



SUB-NOTE 3(2) Capacitance Coupling Equivalent Circuit



SUB-NOTE 3(3) Characteristic Shape of E_x/E_o Against Frequency



4. REDUCING CAPACITIVE COUPLING

Coupling capacitor (C_c) can be reduced by increasing the wire separation or by shielding either wire in the cable. The shield needs to be grounded at only one end to prevent any low frequency interference.

4.1 FILTERS TO ATTENUATE HF INTERFERENCE

Using filters at either or both the interference source or the susceptible receiver will attentuate any high frequency interference signal. It is preferable to filter at the source since there may be several susceptible wires in a cable.

4.2 INCREASING BY-PASS CAPACITOR (C_b)

An increase in the bypass capacitor (C_b) on the sensitive wire, to the degree consistent with circuit performance, can be accomplished through proper wiring techniques as well as by circuit design. By routing wiring next to the ground plane, C_b is increased. When shielding is used on the sensitive wire, a large increase in C_b occurs as well as a reduction in coupling capacitor (C_c).

4.2.1 ALTERNATE METHOD. An alternate but less satisfactory method of increasing C_b and decreasing C_c can be achieved by arranging the cable so that the sensitive wires are surrounded by wires which do not carry the interference signals. These associated wires must have low impedance and be operated at near ground potential.

4.2.2 PRECAUTIONS. Care should be exercised to ensure that interference is not introduced by magnetic coupling. The technique of surrounding sensitive wires by wire near ground potential can be carried into the plug and connector region where it will assist in reducing stray capacity coupling. Grounded shields can also be built into plugs and connectors.

4.3 LOWERING INPUT IMPEDANCE

Lowering the input impedance (Z_X) in the susceptible receiver is a very effective way to reduce capacitive coupling if it can be accomplished by circuit design. The opposite is true for inductive coupling (see *Para 2.5*). A compromise value of Z_X may be between 150-600 ohms.

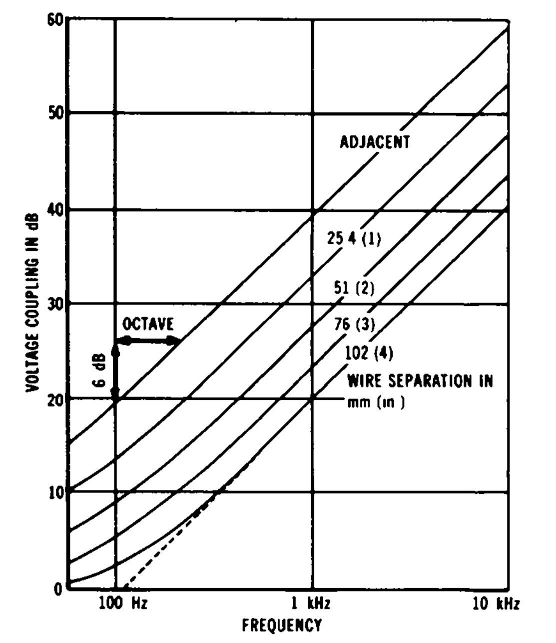
4.4 BALANCED LINES AND CIRCUITS

Another method by which interference voltage and current may be canceled out of the susceptible wiring is through the use of balanced lines fed by balanced circuits. The signal wire and its return are maintained at the signal potential with respect to each other and are equally balanced between the ground potential. The coupled interference voltage appears equally on both wires, 180° out of phase, thus canceling the interfering voltage. This interference cancellation is effective if a perfect balance condition is maintained and interference source does not drive the circuit into the nonlinear response region. Two-wire shielded cable can be used to reduce the magnitude of this type of interference coupling.

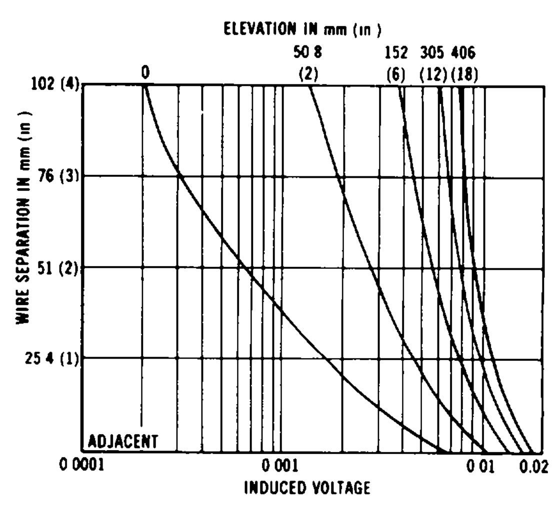
5. WIRE SEPARATIONS

At low frequencies, up to approximately one-sixteenth of a wavelength, cable coupling data closely follows *Eq 1* and *2* (see *Ref 631*). When plotting this data (*SN 5(1)*) the slope of the curve follows the basic 6 dB/octave coupling inductance. *Sub-Note 5(2)* shows typical cable coupling parameters at different elevations above the ground plane at 400 Hz for two parallel wires. Spacing, length of run, and elevation will also produce the same 6 dB/octave coupling relationship. The nomograph in *SN 5(3)* was then constructed from this data so that wire separation can be calculated from different elevations above the ground plane. The frequency of 400 Hz and a cable run of 3.05 m (10 ft) were each selected as a zero dB reference.

SUB-NOTE 5(1) Frequency Versus Voltage Coupling in Cables

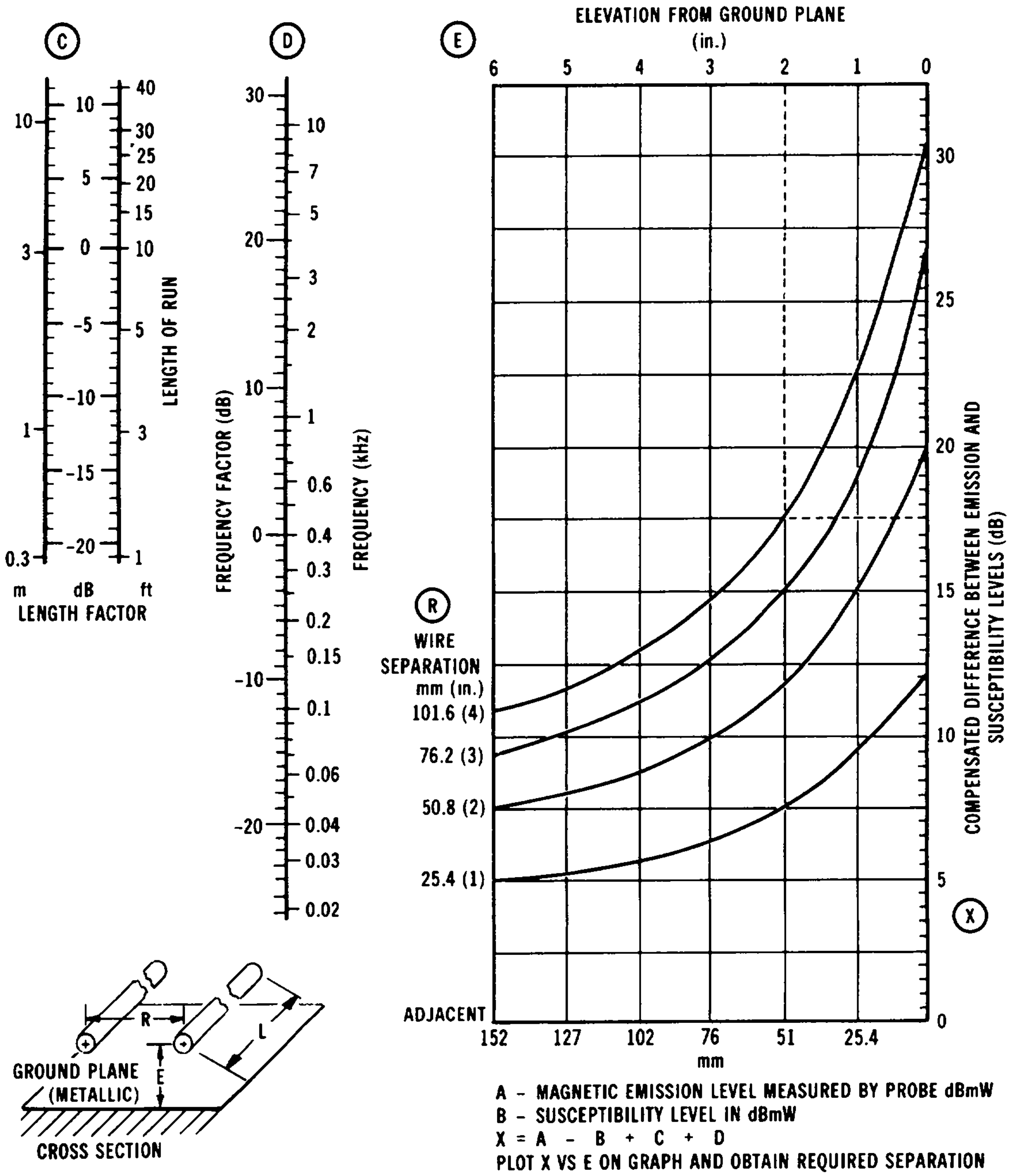


SUB-NOTE 5(2) Effect of Elevation Above Ground Plane on Secondary Induced Voltage



Primary and Secondary Wires
Wires 10 ft long, Primary Current = 2 A, 400 Hz

SUB-NOTE 5(3) Wire Separation Nomograph



5.1 EXAMPLE

Given the following parameters and using the nomograph in *SN 5(3)*:

A = Emission Level B25 dBmW

B = Susceptibility Level B30 dBmW

C = Length 20 ft, from scale C = 4.5 dB

D = Frequency 1000 Hz, from scale D = 8 dB

Where:

$X = A - B + C + D$

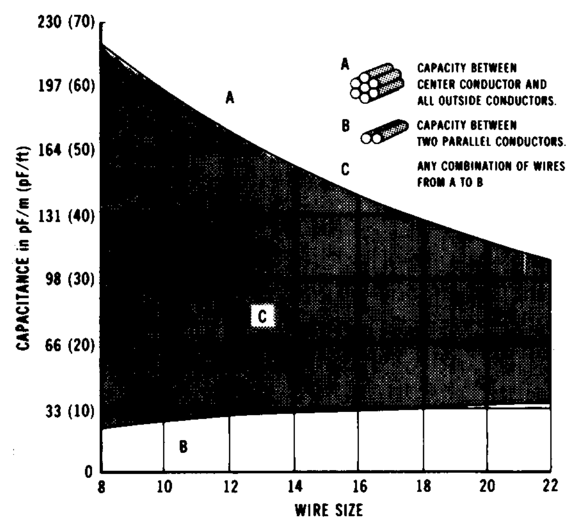
Solving for $X = -25 - (-30) + 4.5 + 8 = 17.5$ dB

Plotting 17.5(X) vs 2 in. elevation (E) yields 4 in. separation (R).

6. CAPACITANCE BETWEEN WIRES

The capacitance between unshielded aircraft interconnecting wiring is given in *SN 6(1)*. The capacitance of standard aircraft shielded wiring is excessive when long cable runs are involved, as calculated from *SN 6(2)*. The capacitance between unshielded aircraft interconnecting wiring can also exceed the limitations for many circuits. In either case use standard coaxial cables to control this capacitance.

SUB-NOTE 6(1) Capacitance vs Wire Size for Various Grouping of Wires



SUB-NOTE 6(2) Capacitance of Various Shielded AN Wires

CAPACITANCE IN PICOFARAD PER FOOT AND METRES

TYPE	ONE WIRE SHIELDED				TWO WIRE SHIELDED				THREE WIRE SHIELDED		ONE WIRE DOUBLE SHIELDED	
CONFIGURATION												
Wire Size	16	18	20	22	16	18	20	22	20	22	22	22
Conductor To Shield					(Either Conductor To Shield)				(Any Conductor To Shield)		(Conductor To Inner Shield)	(Inner Shield To Outer Shield)
pF/ft pF/m	89 292	91 300	74 243	98 322	68 223	65 213	64 209	62.5 205	60 197	52 171	98 322	340 1116
Conductor To Conductor												
pF/ft pF/m					42 138	39.5 130	38 125	36.5 120	36 118	30 98		

NOTE: DATA FOR USE IN CALCULATING THE EFFECTS OF CAPACITANCE IN SUBSYSTEMS WIRING.

7. SINGLE LOOP RESONANCE

A single circuit or cable can be self-resonant and magnify signal. This effect can occur when the circuit is excited at its resonant frequency. The energy exiting the resonant circuit can be induced from spurious frequencies present in the power or other circuits and from a Fourier component of a transient (spike) which falls in the resonant frequency. The following approaches can be used to minimize the problem.

a. Change the resonant frequency of the circuit.

b. Reduce the Q of the circuit to lower the magnification factor.

c. Eliminate or reduce the spurious signal causing the resonance by use of shielding or filtering.

8. ESTIMATING MAGNETIC SHIELDING AND INDUCED VOLTAGE*

Sub-Note 8(1) provides a simple method of estimating induced voltage in cables and determining the magnetic shielding required. The nomograph is useful for many applications; however, the safety margins and example shown are for submarine application. They should be used with care for aerospace applications to avoid weight penalties.

8.1 INSTRUCTIONS FOR USE OF NOMOGRAPH

The nomograph (*SN 8(1)*) is based on the following: (1) the low frequency flux density vs frequency limit line set forth in *MIL-STD-461*, (2) Faraday's law $V = \partial\psi/\partial t$, and (3) the readily obtained equivalent areas of twisted and coaxial cables. Note that the cables along the equivalent area axis are correctly placed along that axis only if the signal and its return are in the same cable. The expected induced voltage on any coaxial or twisted signal cable is easily calculated by connecting the desired frequency and cable (or equivalent loop area if the cable in question is not listed) with a straight line and noting the intersect on the induced voltage axis. This intersect yields the induced voltage in (1) microvolts or (2) decibels per volt.

Since *MIL-STD-461* is an upper decile presentation of observed shipboard fields, the following quantities are required to ensure safety when computing shielding requirements:

	400 Hz and below	400 - 4000 Hz	4 - 100 kHz
Add to induced voltage level	40 dB	30 dB	20 dB

8.2 EXAMPLE

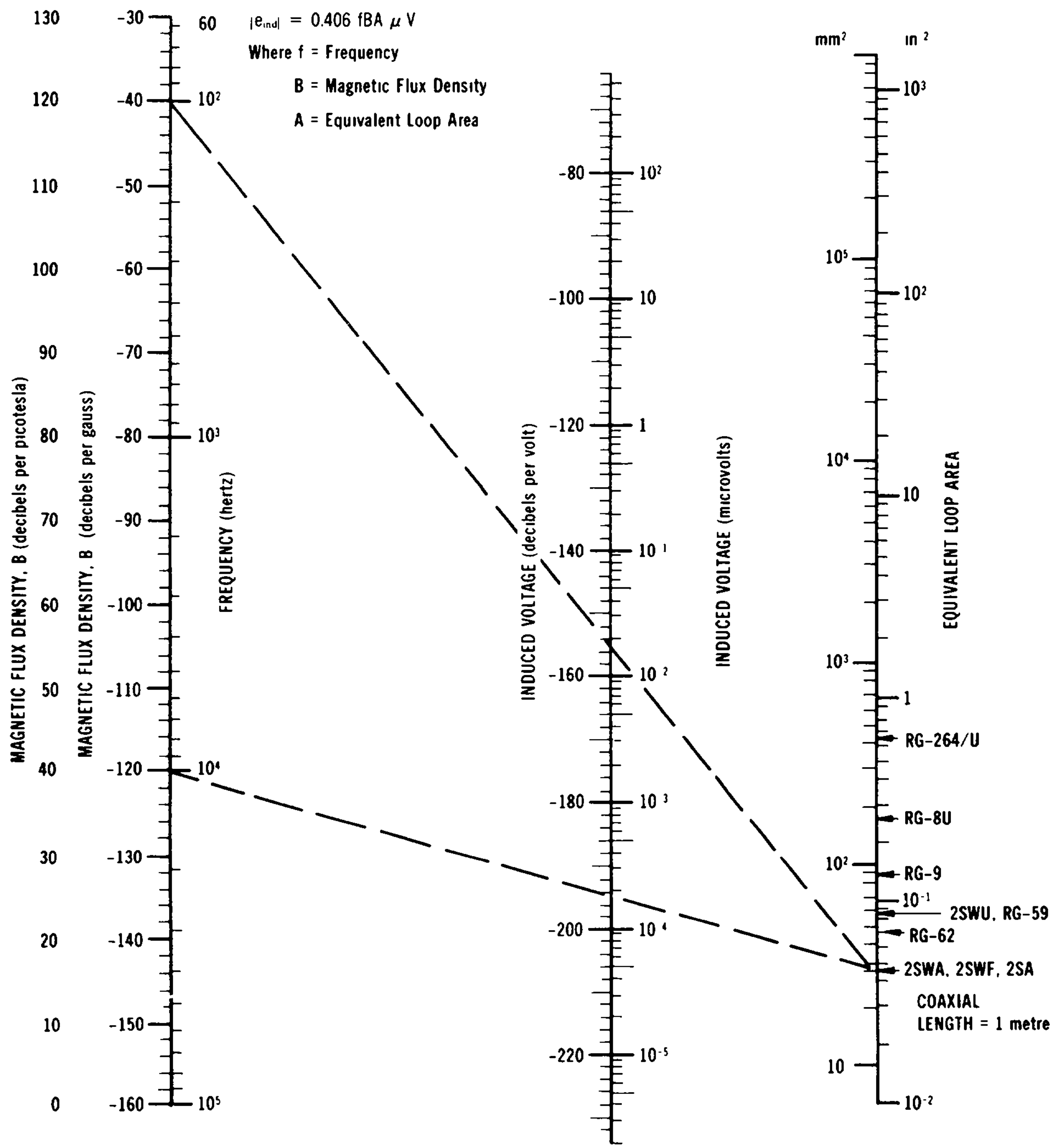
Given a cable whose signal and return are in the same magnetically unshielded 2SWA cable, the passband is 0.1 to 10 kHz. If the noise voltage must be kept below -140 dB V/Hz within the passband to effect electromagnetic compatibility, resolve the minimum amount of shielding. Straight lines are drawn from 2SWA point (4.5×10^{-2} in.^{2}) on the equivalent area axis to the frequency extremes of interest. One sees that the expected induced voltage at 100 Hz is -155 dB/V and at 10 kHz the expected voltage level is -195 dB/V. Adding the recommended correction quantities, we obtain a worst-case voltage of -115 dB/V at 100 Hz and -175 dB/V at 10 kHz. Clearly, 25 dB of magnetic field shielding is required to ensure electromagnetic compatibility at 100 Hz. Conversely, there is a 35-dB safety margin at 10 kHz, and no shielding would be required at this frequency. Because of the linear nature of the Faraday relationship, $|e_{ind}| = 0.406\ fBA$, shielding requirements between the two frequency extremes would be intermediate to these calculated. Therefore, the minimum amount of shielding effectiveness required is 25 dB.

a. Careful routing of signal cables a minimum of 152 mm (6 in.) away from interference sources would eliminate the need for the safety margins. In the above example, no shielding of the 2SWA cable would be required anywhere throughout the band of interest if isolation of signal and power cables were strictly maintained at 152 mm (6 in.).

b. The limit line from *MIL-STD-461* is based on measurements of ambient magnetic fields. A spectrum plot of these field levels vs frequency invariably yields "spikes" at the power line frequencies (60 and 400 Hz) and their harmonics. The limit line represents the locus of the tonal levels (upper decile) measured.

*Paragraphs 8 through 8.2 are added by courtesy of the Navy Underwater Sound Laboratory.

SUB-NOTE 8(1) Nomograph for Estimating Cable Magnetic Shielding



DESIGN NOTE 5B3 — COUPLING AT HIGH FREQUENCIES

1. INTRODUCTION

High frequency cables are those in which lines are longer than about a quarter wavelength. For such lines the distributed reactances in the wiring cannot be treated as lumped reactances, and standing waves of current and voltage may exist along wires. With standing waves, the coupling of a given circuit to another may be substantially reinforced either because of increased radiation effectiveness or because of increased sensitivity. At high frequency it is not useful to distinguish between magnetic and capacitive coupling. These coupling concepts break down because of the standing waves and the associated impedance variation. Along its length, wire could then be alternately sensitive to magnetic and electric fields.

2. COUPLING EFFECTS

At very high frequencies, the dimensions of wiring required to provide significant effective radiation or pickup become quite small. At 100 MHz, a 25-mm (1-in.) length of wire, formed into a loop, can be an effective inductance and have significant induced voltages from stray electromagnetic fields. This emphasizes the importance of minimizing return circuit dimensions on wire shield ground connections, bypass condenser ground leads, and similar wiring associated with low impedance circuits. Although important at low frequencies, it is imperative at high frequencies that the wiring of filters be carefully controlled to prevent inductive coupling between input and output of the filter, which will make the filter ineffective.

2.1 GROUNDING CONCEPTS AT HIGH FREQUENCIES

At high frequencies, grounding concepts must be directed toward massive multiple grounding practices, since with single point grounding, standing waves may occur on ground leads. All connectors must be electromagnetically tight to reduce RF currents external to the shield. A massive ground plane should exist between equipment connected to the cable, and the cable should be carried close to the ground plane. A second alternative is the maintenance of no other ground path than the external cable shield between equipment; this is extremely difficult at very high frequencies because of paths to ground through stray capacity and power leads. The objective is to avoid RF currents to the external surface of the cable shield. Such currents can couple signals into or out of the inner cable wiring. To reduce such coupling, double shielding is used frequently in radio frequency cabling.

3. CAPACITIVE COUPLING

At high frequencies, any open-ended wire should be given careful attention to determine if it is a pickup point for high frequency excitation. Since small stray capacities will provide effective coupling to a high impedance point at high frequencies, wires can frequently be excited when they are attached to vacant connector pins or open switch contacts. At a quarter wavelength distance, such open wires will be carrying maximum current and can readily couple into other wiring or circuits by the fields generated. An open wire may represent an effective antenna in the presence of stray electromagnetic fields. High radio frequencies are readily coupled into power wiring either magnetically or electrically, depending upon the standing wave which may be excited in the power wiring at the coupling point.

4. CONDUCTIVE COUPLING

Conductive coupling is particularly difficult to avoid at high frequencies since multiple points grounding may be required. A very short length of wire can represent an appreciable common inductive reactance to connected circuits. It is particularly important at high frequencies to insulate shielded cable sheaths so that they cannot make contact and form common return connections with other shielded cables. The wiring to a bypass capacitor may represent more inductive reactance than the capacitive reactance of the capacitor, making it an ineffective bypass and altering associated filter design constants.

4.1 NOISE GENERATOR

Noise may be generated in equipment by accidental contact between wire shields or between shield to ground due to the variable coupled-in voltages resulting between circuits. A massive ground plane will provide a minimum of conductive coupling between equipments or circuits. In any wiring or grounding connections at high frequencies, give particular attention to resonances which may exist due to stray capacities and lead inductances.

REO ASD/ENACE

DESIGN NOTE 5B4 — HIGH-LOW FREQUENCY COUPLING

1. INTRODUCTION

At relatively low frequencies the cable coupling effect presented in *DN 5B2, SN 1.1(2)* and *SN 3(1)*, can be combined and represented by an equivalent circuit such as that shown in *SN 1(1)*. The corresponding formulas, Eq 1 and Eq 2, give the cable coupling in terms of the voltage ratio. At high frequencies when standing waves become more significant the equivalent circuit will become more complex.

GENERATOR END

(Electric Component)

$$\frac{E_{2G}}{E_0} = \left[\frac{R_1}{R_1 + R_0} \times \frac{R_2}{X_c}\right]$$

(Magnetic Component)

$$+\left[\frac{X_M}{R_1 + R_0} \times \frac{R_{2G}}{R_{2G} + R_{21}}\right] = K_G f \quad \text{(Eq 1)}$$

LOAD END

(Electric Component)

$$\frac{E_{2L}}{E_0} = \left[\frac{R_1}{R_1 + R_0} \times \frac{R_2}{X_c}\right]$$

(Magnetic Component)

$$-\left[\frac{X_M}{R_1 + R_0} \times \frac{R_{2L}}{R_{2G} + R_{2L}}\right] = K_L f \quad \text{(Eq 2)}$$

Where:

$$R_2 = \frac{R_{21}\ R_{2G}}{R_{21} + R_{2G}}$$

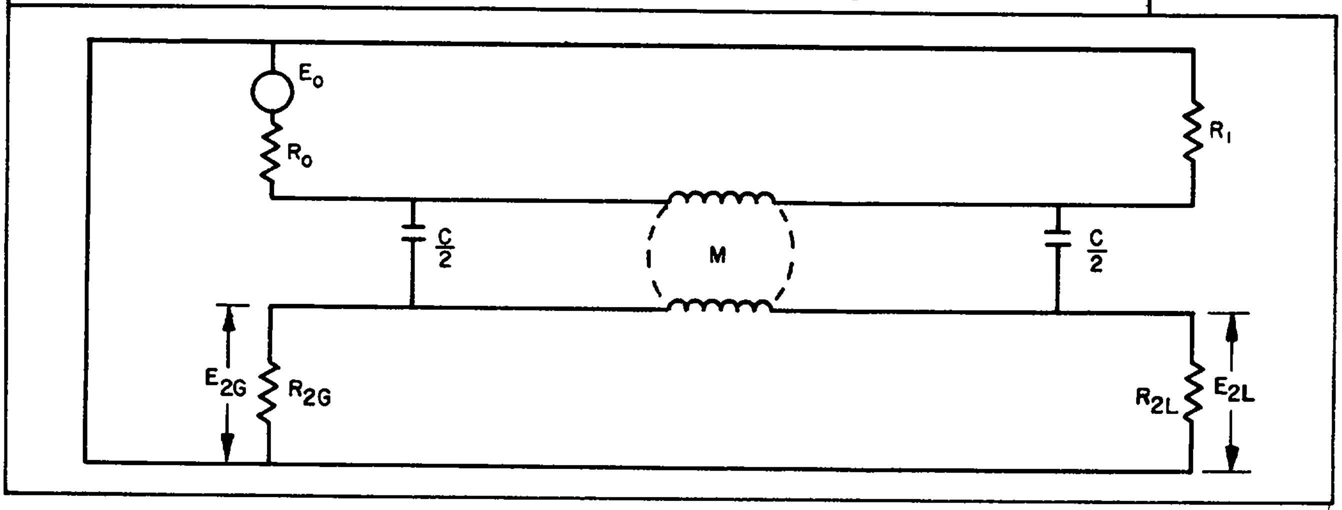
2. COUPLING CONSIDERATIONS

When considering only linear circuit elements for small magnitude of coupling, the voltage coupled electrically and that coupled magnetically may be calculated separately, and the results added for the total coupled voltage. The calculation and addition must be in terms of complex numbers.

3. INTERFERENCE

From the formula, Eq 1, note that at the generating end of the susceptible circuit the coupled voltage E_{2G} is the sum of the electric and magnetic components. At the load end (Eq 2) of the susceptible circuit, the coupled voltage E_{2L} is shown as the difference of the electric and magnetic components. For the approximation made here, the two components of E_{2L} will be in phase opposition. Rather than depend upon a difference voltage, the larger of the two components is assumed to be the coupled interference. As frequency increases, it is common to assume that voltage transfers are proportional to frequency until unity transfer is reached and then the transfer is approximated at unity for all higher frequencies. For a considerable variation in loading above or below 300 ohms, $K_G = 2K_L$ is very good approximation.

SUB-NOTE 1(1) Circuit Representing Electric Coupling and Magnetic Coupling Between Parallel Wires



REO. ASD/ENACE

4. COUPLING EFFECT VERSUS FREQUENCY

Sub-Note 4(1) shows a plot of the approximate voltage transfer ratio which consists of a 6 dB/octave rise up to unity. Typical experimental data are plotted with the approximation. Note that the approximation results in slightly more coupled-in interference than is shown by the experimental data. In situations of light circuit loading, resonances in the wiring may produce an inversion, so experimental data may rise above the approximation in a narrow frequency band.

5. PARAMETERS

The electric and magnetic coupling components may be determined with the aid of the following formulas for capacity between wires and mutual inductance between wires.

a. Capacitance (in farads) between two wires above a ground plane:

$$C = \frac{a_1 \ell \left[\log\left(\frac{S_{12}}{D}\right)\right] \left[K_{eff}\right]}{\left[\log\left(\frac{4h}{d}\frac{1}{\sqrt{2-\sqrt{d/D}}}\right)\right]^2 - \left[\log\frac{S_{12}}{D}\right]^2} \qquad \text{(Eq 3)}$$

Where:

constant $a_1 = 24 \times 10^{-12}$ when ℓ is in m

constant $a_1 = 7.35 \times 10^{-12}$ when ℓ is in ft

$$K_{eff} = K_0 + \frac{\left(\frac{d_1}{d}\right)^2 - 1}{\frac{1}{2}\left(\frac{d_1}{d} + \frac{D}{d}\right)^2 - 1}(K_1 - K_0)$$

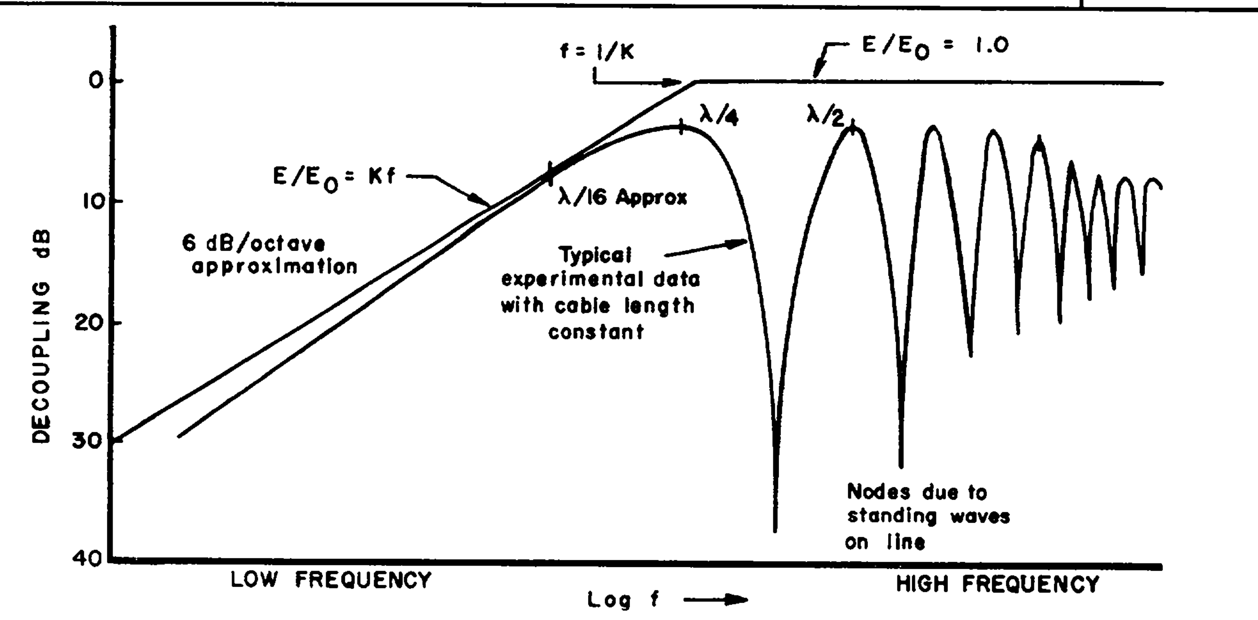
$$S_{12} = \sqrt{D^2 + 4h^2}$$

The factor $\frac{1}{\sqrt{2-\sqrt{d/D}}}$ was determined experimentally.

b. Mutual inductance (in henries) between two wires above a ground plane:

$$M = a_2 \ell \left(\log\frac{S_{12}}{D}\right) \qquad \text{(Eq 4)}$$

SUB-NOTE 4(1) Cable Decoupling Calculated vs Measured Data



Where:

constant a_2 = 4.61×10^{-7} when using SI units

constant a_2 = 1.405×10^{-7} when using customary US units

ℓ = length of wires, metres (feet)

D = separation of wires, millimetres (inches)

h = height above ground plane, millimetres (inches)

d = diameter of the wire conductor, millimetres (inches)

d_1 = diameter of the wire including the insulation, millimetres (inches)

K_0 = relative dielectric constant. For air $K_0 = 1$

K_1 = relative dielectric constant of the wire insulation.

1. INTRODUCTION

This design note discusses wiring methods according to aerospace vehicle circuit classification. It gives shielding termination and proper routing of these wires to obtain an EMC tight system. Use wire insulation that will remain flexible without breaking or cracking due to age or environment. See *MIL-W-5088*.

2. DESCRIPTION AND CLASSIFICATION

Assign each circuit a specific classification on the basis of closest similarity to one of the classes described below.

2.1 POWER AND CONTROL

2.1.1 DIRECT CURRENT (dc) CIRCUITS (CLASS I). A dc power circuit is one which uses more than 2 amperes. A dc control circuit is one which uses less than 2 amperes.

2.1.2 ALTERNATING CURRENT (ac) CIRCUITS (CLASS III AND IV). An ac circuit is supplied by the aircraft or ground power sources. To minimize problems with battle damage, aircraft are often designed with two totally independent electrical distribution systems or buses. One distribution system is called a left hand bus (Class III) and the other a right hand bus (Class IV). If one bus is damaged or destroyed the other will provide ac power and control circuits to complete the mission.

2.2 REFERENCE CIRCUITS

2.2.1 DIRECT CURRENT (dc) REFERENCE CIRCUIT (CLASS II). A dc reference circuit requires critical tolerances on the voltage or current. The voltage or current of these circuits will normally be less than 1 V rms or 200 mA rms. Direct current reference circuits and audio frequency (af)-susceptible circuits are conidered as Class II circuits.

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2.2.2 ALTERNATING CURRENT (ac) REFERENCE CIRCUIT (CLASS III AND IV). An ac reference circuit is one in which a single phase line is used to supply critical voltages or frequencies.

2.3 AUDIO FREQUENCY (af)-SUSCEPTIBLE CIRCUITS (CLASS II)

Audio frequency-susceptible circuits are those whose performance may be degraded in the presence of an undesired audio signal.

2.4 RADIO FREQUENCY (RF)-SUSCEPTIBLE CIRCUITS (CLASS V)

Radio frequency-susceptible circuits are those whose performance may be degraded in the presence of an undesired RF signal.

2.5 INTERFERENCE CIRCUITS

Interference circuits are those from which undesired signals may emanate.

2.5.1 AUDIO FREQUENCY-INTERFERENCE (afi) CIRCUITS (CLASS III OR IV). Audio frequency-interference circuits are those operating below 15 kHz and whose amplitudes will normally be greater than 1 V rms or 200 mA rms.

2.5.2 RADIO FREQUENCY-INTERFERENCE (RFI) CIRCUITS (CLASS VI). Radio frequency-interference (narrowband) circuits are those in which the signal levels exceed the following values with respect to 50 ohms:

a. -45 dBmW at 150 kHz reduced at 20 dB per decade of frequency to -75 dBmW at 5 MHz

b. -75 dBmW from 5 to 25 MHz

c. -75 dBmW at 25 MHz increased at 10 dB per decade of frequency to -45 dBmW at 1 GHz

d. -45 dBmW above 1 GHz

Radio frequency-interference (broadband) circuits are those which conduct pulse information or transient disturbances such as those caused by relay actuation, switch contacts, or clock pulses.

2.5.3 ANTENNA CIRCUITS (CLASS VII). Antenna circuits are those which connect subsystems or equipment to system antennas.

3. SHIELD TERMINATIONS

Terminate shields as described in the following paragraphs.

3.1 SHIELDED CONDUCTORS

Shielded conductors are used to prevent undesired radiation from conductors and to protect a conductor from stray fields. Insulate all shields to prevent undesired grounding. Do not use shields for signal returns except in the case of coaxial cables. Make terminations through a collectively crimped peripheral ring or equivalent as illustrated in *SN 3.1(1), 3.1(2),* and *3.1(3)* for all shields exclusive of coaxial cables and shielded leads classified as af-susceptible. The collective crimping ring or equivalent utilizes two ground wires; connect one wire from the ring to the connector shell where connector design permits; one wire can 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.)

3.1.1 CLASS VI CIRCUITS. Use a shield for all circuits to prevent undesired radiation. Connect the shield to ground at both ends, and at intermediate connectors, where feasible, as shown in *SN 3.1(2)*.

3.1.2 CLASS VII CIRCUITS. Coaxial cables are the only exception to the rule prohibiting the use of a shield as a signal return. Ensure shields are continuously grounded at both ends and at intermediate connectors, where feasible, as shown in *SN 3.1(3)*.

3.2 PROTECTING SUSCEPTIBLE CIRCUITS

Shield to protect susceptible circuits as follows:

a. Class II Circuits. Ground shields on af-susceptible circuits at one end only, as shown in *SN 3.2(1)*. Insulate shield to prevent undesired grounding, and never use shield for a signal return.

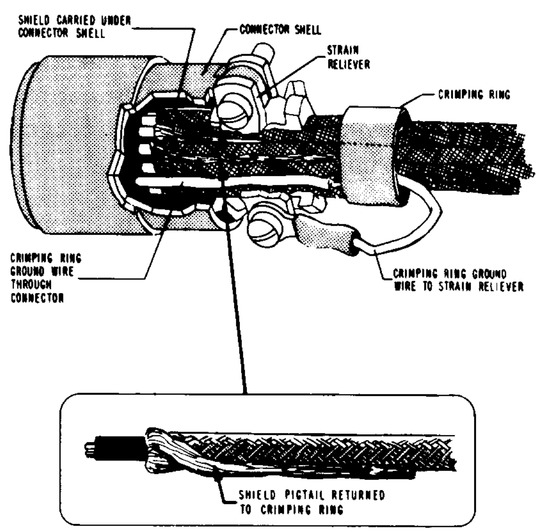
b. Class V Circuits. Ground shields on RF-susceptible circuits at both ends and at intermediate connectors, where feasible, as shown in *SN 3.1(2)*.

c. Class II and V. Ensure circuits which are both af- and RF-susceptible are tightly twisted shielded pairs. The shorter the twist (6 mm ($^1/_4$ in.) max) the greater the shielding effectiveness. Ground the shield at both ends as shown in *SN 3.1(2)*.

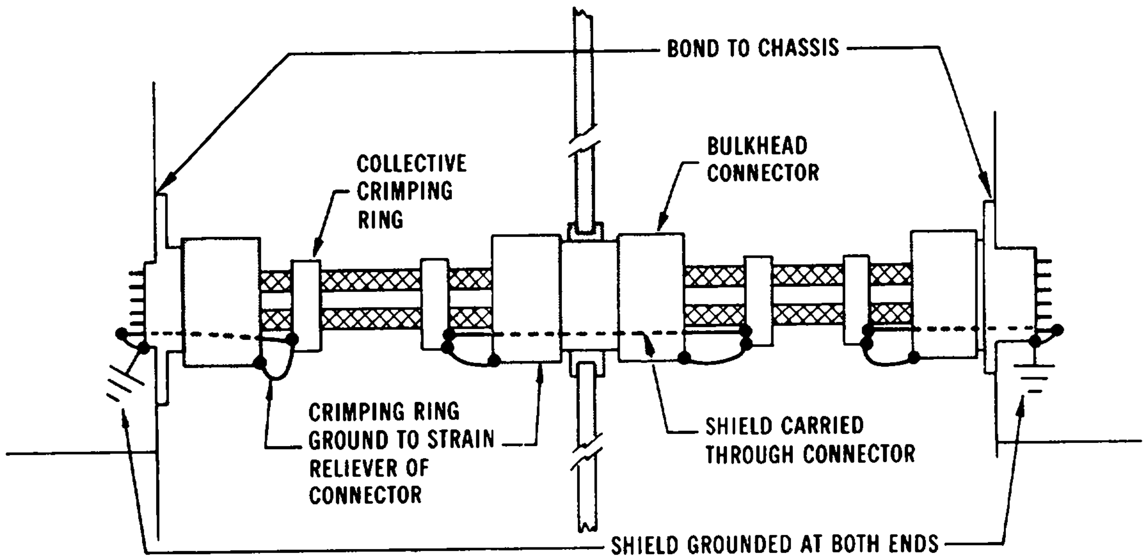
3.3 CIRCUIT RETURNS

Class I dc power and control circuit returns may be terminated at the "black box" or to aerospace vehicle structure. Route Class II dc reference circuits as twisted pairs. Specify the minimum number of twists per millimeter (inch).

SUB-NOTE 3.1(1) Collective Crimping Termination of Shields in Connector Shell

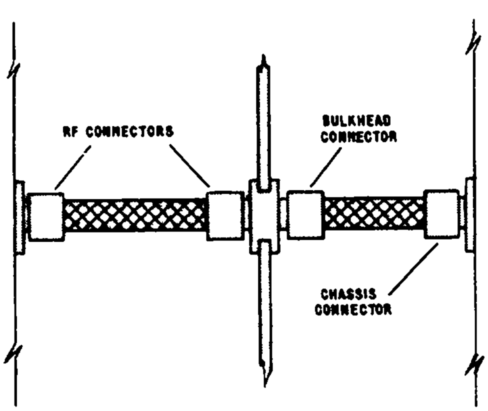


SUB-NOTE 3.1(2) Termination of Shielded Wires (Class V and VI Circuits)



NOTE IF CRITICAL, MAKE GROUNDING PINS AS LEADERLESS AS POSSIBLE TO PREVENT ANY RF ENTERING THROUGH GROUND LOOP SEE *SN 3.1(1)* FOR DETAILS OF COLLECTIVE CRIMPING

SUB-NOTE 3.1(3) Termination of Coaxial Cable Shields (Class VII Circuits)



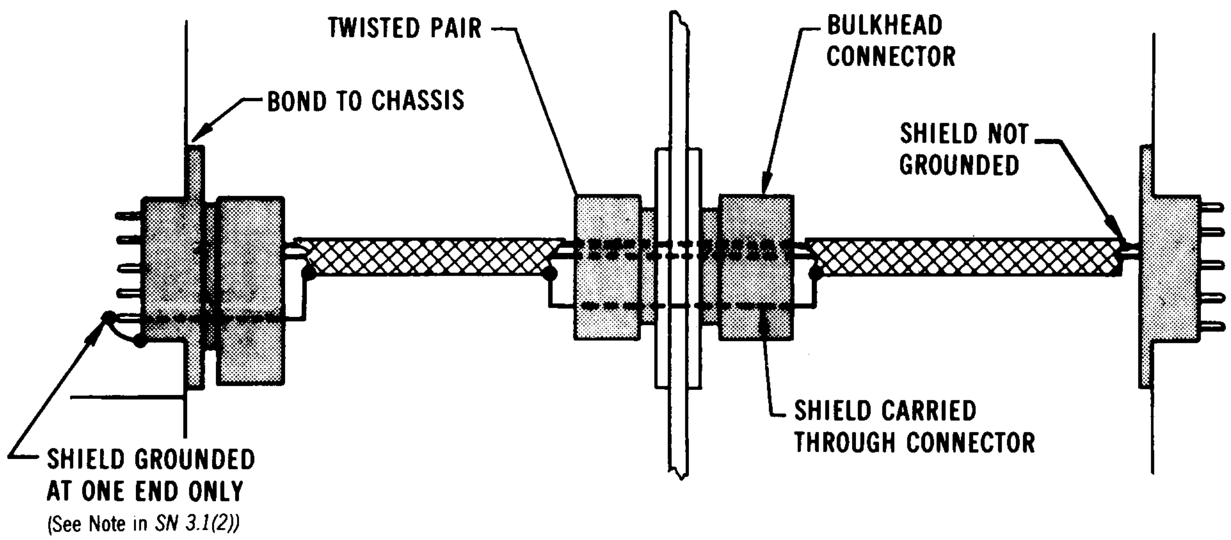
3.4 ALTERNATING CURRENT (ac) POWER, CONTROL, AND REFERENCE CIRCUITS

Route single-phase ac control circuits and reference circuits as twisted pairs. In power circuits depending on OD of the wire, insulation will determine the amount of twist. Connect the single-phase ac power circuit returns and the neutral of three-phase power circuits to the structure.

3.5 ALTERNATING CURRENT (ac) SIGNAL RETURNS

Route af circuit returns as twisted pairs; the shorter the twist (6 mm ($^1/_4$ in.) max) the greater the shielding effectiveness. In RF circuit returns, ensure coaxial cable shields are continuously grounded at each end and at all intermediate connectors (see *SN 3.1(3)*).

SUB-NOTE 3.2(1) Termination of Shielded Audio Circuits (Class II)



4. WIRE ROUTING

In layout wiring and routing, the maximum practical separation must be maintained in accordance with the general rules described below. A 51-mm (2-in.) separation between wires in different classes is a minimum design goal.

4.1 POWER AND CONTROL CIRCUITS

Route dc power and control circuits in a separate wire group. The ac power and control circuits are divided into groups when the system uses more than one source of electrical power. The following general rules apply:

a. The ac wiring supplied by different power sources must never be routed together.

b. The ac wiring from different ac power sources must never be connected to a subsystem or equipment, unless there is a specific design and installation.

4.2 REFERENCE AND SUSCEPTIBLE

Do not route reference and susceptible circuits with power and interference circuits. The dc reference and af-susceptible circuits may be routed together in the same wire provided proper isolation is maintained through shields, shield terminations, and connectors. The ac reference circuits may be routed with ac power circuits if the rules governing multiple power sources are not violated, and the circuits are not classified as susceptible. The RF-susceptible circuits may be routed with Class II circuits providing the RF-susceptible circuit is not a source of interference to the other circuits.

4.3 INTERFERENCE CIRCUITS

In routing interference circuits, the following rules apply.

a. Audio Frequency-Interference (afi) Circuits. Route afi circuits with ac power and control circuits.

b. Radio Frequency-Interference (RFI) Circuits. RFI circuits may be routed together.

4.4 ANTENNA CABLES

Comply with the requirements of *MIL-W-5088* for antenna coaxial cables.

4.5 WIRE DESIGNATION FOR CABLING

Label each wire at each end at a point no greater than 152 mm (6 in.) from its entry into a connector, bulkhead, or equipment and at 381-mm (15-in.) intervals throughout its entire length (see *MIL-W-5088*). Wire classification from *SN 4.5(1)* will be part of the label. Wires with the same designation may be routed in the same harness. In no case will wires with different designations be routed in the same bundle without prior consent of the EMI control group. For production installation, classify wire groups in accordance with the wires within that wire group. This method will promote a suitable means for easy identification of a wire grouping when installed in the aerospace vehicle.

5. CONNECTOR-WIRING INTERFACE

When designing connector-wiring interfaces, consider circuit types to be connected, pin requirements for shield terminations, and shielding capability.

SUB-NOTE 4.5(1) Circuit and Wire Classes

CIRCUIT TYPE	WIRE* CLASS	DESCRIPTIVE PARAGRAPH	SHIELD TERMINATION (REF PARA)	CIRCUIT RETURN (REF PARA)	WIRE ROUTING (REF PARA)
dc Power and Control	I	2.1.1	n/a	3.3	4.1
dc Reference	II	2.2.1	3.2 (As required)	3.3	4.2
ac Power and Control	III and IV	2.1.2	n/a	3.4	
ac Reference	III and IV	2.2.2	3.2 (As required)	3.4	4.2
af-Susceptible	II	2.3	3.2a or c	3.3 3.5	4.2
afi	III and IV	2.5.1	n/a	3.5	4.3a
RF-Susceptible	V	2.4	3.2a or c	3.2c 3.5	4.2
RFI	VI	2.5.2	3.1.1	3.1b 3.5	4.3b
Antenna	VII	2.5.3	3.1.2	3.5	4.4

*NOTE: Class III is left hand bus; Class IV is right hand bus.

5.1 CIRCUIT TYPE

Allow for a sufficient number of connectors so different types of circuits are not required to be routed within close proximity of a single connector. It is permissible to pass power and control circuits (*Para 2.1*) and afi circuits (*Para 2.5.1*) through a common connector provided they are separated after passing through the connector. Pass RFI circuits (*Para 2.5.2*) through individually isolated connectors. It is permissible to pass dc reference voltage circuits and af- and RF-susceptible circuits (Class II and V) through a common connector provided they are separated after passing through the connector. Route the audio signal wire and its associated return on adjacent pins. Do not route input and output signal wires in the same bundle or through the same connector. It is a design objective that a minimum separation of 51 mm (2 in.) be maintained between the cable routing of susceptible-type circuits and power, control, and interference-type circuits.

5.2 PIN REQUIREMENTS

Select connector types to provide a sufficient number of pins for shield terminations. Shielded, af-susceptible circuits will require a separate pin for each shield. Connect such shields as shown in *SN 3.2(1)*. Do not gang to a single pin. The shields for interference-type circuits may be connected to a common pin by collective crimping.

DESIGN NOTE 5B6 CABLE MEASUREMENTS

1. INTRODUCTION

The measurement of cable coupling requires the determination of the voltage induced in a susceptible cable by energy on the source interference cable. The ratio of the voltage induced to the applied voltage is the decoupling value. The cable coupling varies with frequency, circuit configuration, and impedance values, and whether the coupling is predominantly capacitive or inductive depends primarily upon the circuit impedances. Coupling between two circuits having high impedances is most likely to be capacitive because the effect of a voltage in transferring across the intercable capacitance is greater than the magnetically induced voltage caused by the relatively low current. Coupling in circuits having low impedance is likely to be inductive.

1.1 CAPACITIVE COUPLING

Capacitive coupling measurements are made with the load end of the source interference cable open-circuited. The capacitive reactance varies inversely with the frequency. The coupling impedance varies with frequency at 6 dB/octave.

1.2 INDUCTIVE COUPLING

Inductive coupling measurements are made with the load end of the source interference cable short-circuited. The mutual inductive reactance varies directly with frequency. The coupling also varies with frequency at 6 dB/octave.

2. CALCULATED VERSUS EXPERIMENTAL RESULTS

If values of mutual inductance and capacitance are calculated (see *DN 5B4*, Eq 3 and 4), the measured values can be plotted and checked against them. The measured value of the coupling of a circuit having an intermediate value of impedance is a function of the vector sum of the capacitive and inductive coupled-in voltages due to the intercable capacitance and the mutual inductance, respectively. This coupling also varies with frequency at 6 dB/octave.

3. VALIDITY OF COUPLING MEASUREMENTS

Generally, coupling measurements are valid up to frequencies where the length of the coupled line is less than one-sixteenth wavelength. At higher frequencies, standing waves start to appear and it becomes difficult to interpret the measured results and to draw generalized conclusions from them.

4. PRECAUTIONS

a. In making measurements, take care to account for the instrument impedance.

b. When measurements are made at frequencies higher than one-sixteenth wavelength, care should be taken that when a single instrument is connected to several points in the circuit, the impedance of the interconnecting instrument cabling is considered.

c. Care should be taken that the coupling is predominantly taking place across the desired coupling patch and not around the ends or directly from instrument to instrument.

d. When wires are placed near each other take care that they remain constant along the length of the line. Generally, it is easier to place the wires a finite distance apart, such as 6 mm (¼ in.), and to keep the separation constant within a certain percentage than it is to place the wires side by side (i.e., touching). When calculations are to be made of the capacitance between closely spaced wires, the dielectric constant of the insulation is an important factor.

e. When making coupling calculations, the capacitance to be used should be the actual capacitance between the wires and not the larger combined capacitance that includes the capacitances from the two wires to the ground plane.

f. When more than one instrument is used to make similar measurements, care should be taken that both instruments give the same indication. This is true only when relative measurements are made and especially if the instruments are operated beyond their designed frequency limits.

g. The smallest amount of coupling that can be measured depends upon the strength of the signal source, the sensitivity of the receiver, the ambient noise level, and the shielding of the sensitive pickup circuits from the signal source.

5. SHIELDING EFFECTIVENESS

Shielding effectiveness may be measured by comparing the coupling measurements made on two configurations, one having shielding and one having no shielding. The

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difference in coupling (in dB) is defined as shielding effectiveness. Since shielding effectiveness varies with frequency, a complete frequency plot is necessary.

5.1 CAPACITIVE AND INDUCTIVE COUPLING

Since the shielding effectiveness for capacitive coupling is different than for inductive coupling, two sets of measurements are necessary. Electric (capacitive or high impedance) fields for these measurements are produced by terminating the transmitting wire in an open circuit. Magnetic (low impedance) fields are obtained by terminating the transmitting wire in a shot circuit. For low-impedance circuits, the coupling is better reduced by twisting the wires.

5.2 LOW FREQUENCIES

Shielding and twisting effectiveness against interference coupling can be simply measured only when the electrical length of each wire under test is short, compared to the wavelength. Experimental results indicate that the wire length should be less than one-sixteenth wavelength. For longer lengths not terminated in its characteristic impedance, the presence of standing waves complicates the relation between line separation, type of shield, line impedance, etc., and the shielding effectiveness.

5.3 SHIELDING WIRES

Measurements show that the shield is most effective when placed over the susceptible wire. When both the interference-carrying wire and susceptible wires are shielded, the shielding effect is almost doubled.

5.4 TWISTING WIRE PAIRS

Twisting wire pairs is equally effective on either the transmitter or receiver circuit. When both circuit wires are twisted, the reduction of coupling depends on the longitudinal position of the two twisted-wire pairs. In general, twisting wire pairs in both circuits cannot be depended upon to give appreciably more reduction of coupling than twisting in just one alone. See *DN 5B5, Para 3,*and subparagraphs for details on twisting of wire pairs.

5.5 LIMITATIONS

Usually, the types of circuits and range of frequency over which shielding can be measured are limited by the instrumentation available. The power of the source and the sensitivity of the receiver usually restrict measurements on well shielded and twisted circuits to high frequencies. At low frequencies, the coupled voltage is below the instrument noise level.

6. MACHINE COMPUTATION

Any wiring and equipment installation becomes an extremely complex circuit network when all interference sources and susceptible equipment terminals are considered along with all coupling paths which may interconnect sources and susceptible equipment. Any one situation, for which parameters are known or measurable, can be computed by slide-rule technique. Large-scale digital computers can be used to extend such computations throughout very complex interconnections and coupling networks between many units of equipment. The main problem in attempting interference analysis by computer is the acquisition of adequate input data. As attempts are made to conduct such computer analyses, the problems of securing input data may become less formidable. See *Ref 632* for more detailed information on machine computation.

DESIGN NOTE 5B7 RF TRANSMISSION LINES AND CONNECTORS

1. INTRODUCTION

The common types of transmission lines and the formulas required to calculate the characteristic impedance are shown in *SN 1(1)*. Characteristic impedances for the following lines are given on pages 588–594 of the *Reference Data for Radio Engineers Handbook (Ref 453)*:

a. Dielectric beads

b. Wire in square enclosure

c. Balanced 4-wire line

d. Parallel strip line

e. 5-wire line

f. Parallel lines in sheath

g. Balanced 2-wire with unequal diameters

h. Balanced 2-wire near ground

i. Single wire between grounded parallel plates ground return

j. Balanced line between grounded parallel plates

k. Single wire in trough

l. Balanced 2-wire line in rectangular enclosure

m. Eccentric line

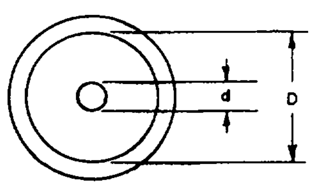
n. Balanced 2-wire line in semi-infinite enclosure

o. Outer wires grounded, inner wires balanced to ground

p. Slotted air line.

Comply with *MIL-HDBK-216* when selecting coaxial cables, RF connectors, and wave guides.

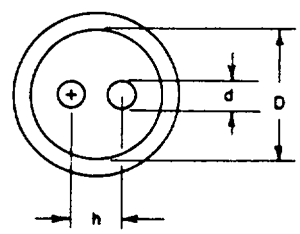
SUB-NOTE 1(1) Transmission Lines and Formulas to Calculate Impedance



$$Z_0 = \frac{138}{\sqrt{e}} \log_{10} \frac{D}{d}$$

e = dielectric constant (In air, e = 1)

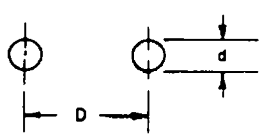
a. Single Coaxial Line



$$Z_0 \approx \frac{120}{\sqrt{e}} \ln \frac{2h}{d}\left(\frac{1-\sigma^2}{1+\sigma^2}\right)$$

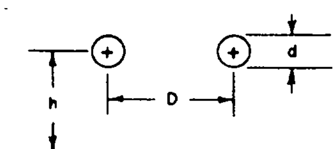
where $\sigma = \frac{h}{D}$

b Balanced Shielded Line



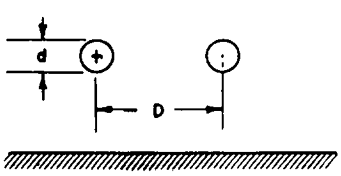
$$Z_0 \approx 120 \ln \frac{2D}{d}$$

c Open Two-Wire Line in Air



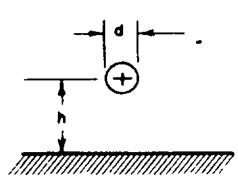
$$Z_0 = \frac{69}{\sqrt{e}} \log_{10}\left[\frac{4h}{d}\sqrt{1+\left(\frac{2h}{D}\right)^2}\right]$$

d Parallel Wires Near Ground



$$Z_0 = \frac{276}{\sqrt{e}} \log_{10}\left[\frac{2D}{d}\sqrt{\frac{1}{1+\left(\frac{D}{2h}\right)^2}}\right]$$

e Balanced Pair Near Ground



$$Z_0 = \frac{138}{\sqrt{e}} \log_{10} \frac{4h}{d}$$

f. Single Wire Near Ground

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2. DESIGN CONSIDERATIONS

The parallel-wire subsystem may be a two-wire subsystem or a multiwire subsystem depending primarily on the power handling capacity required. Corona effect is the most important power limiting factor in the parallel-wire subsystem, while arcing is the most important power limiting factor in coaxial line subsystems, particularly in pulsed subsystems. These factors are important, due to the possibility of direct coupling to nearby subsystems. In parallel open-wire subsystems operating over reasonable distances, the possibility of objectionable direct coupling decreases as the number of wires employed increases. In general, parallel-wire subsystems exhibit less loss than equivalent coaxial lines. However, the coaxial lines do radiate less energy.

3. COAXIAL CABLES

Corona effects and attenuation per unit length at a given frequency are of particular interest in interference considerations. Higher order harmonics and other spurious signals are not attenuated at the same rate. The greater attenuation rate observed at the higher frequencies is not necessarily a desirable factor in braided-shield coaxial lines which radiate more readily through the shield as frequency increases, thus giving the appearance of greater attenuation. If, however, it is shown that such leakage is low, the inherent low-pass characteristic of the line can be used to good advantage. Use of a double shielded cable, instead of a single shield of the same construction, can yield an improvement on the order of 25 dB. Systems that do not require the use of flexible coaxial cable can use coaxial cables with a solid copper shield. These cables have negligible radiation. One intriguing factor in the leakage by braided shield cable is that the electromagnetic leakage fields are not always concentric about the coaxial line. The attenuation of the RF energy at the shield is due to two distinct effects; reflection of the energy at the shield boundary and the absorption of the wave as it passes through the shield. The combined effect of reflection and absorption losses is termed the "attenuation" of the cable.

4. RF FILTERS

In some applications, filters are placed in the subsystem just before the antenna. If this is the case, the filter will, of course, have no effect on the leakage of the transmission line and will only enhance the overall system as far as the antenna's radiation is concerned. The level of radiation from the coaxial line is greater than the indicated theoretical levels.

5. RF CONNECTORS

Another source of leakage originates from the connectors of the subsystem. Quick-disconnect connectors introduce impedance discontinuities. These discontinuities enhance leakage. When an impedance match is made at one point there is no reason to presume that the function is matched over broad frequency ranges. Reduce leakage from connectors by proper installation procedures such as making a good bond between the cable shield and the shell of the connector, eliminating all air gaps in the connector, using connectors built to close mechanical tolerances, and capping all panel-mounted connectors not in use. See *SN 5(3)* in *DN 5B2* for more details.

5.1 TYPE N RF CONNECTOR COMPATIBILITY

Some varieties of type N RF connectors have had problems with mechanical tolerances, which can degrade electrical characteristics, including RF leakage. To avoid these problems, specify the applicable *MIL-C-39012* type N connector.

5.2 CONNECTOR REQUIREMENTS

For new and existing equipment:

a. Select connectors from *MIL-STD-1353.*

b. Comply with *MIL-C-22520* for standard crimping tools.

c. To interface RF connectors, use requirements of *MIL-C-39012.*

6. IMPEDANCE MATCHING

Reduce transmission line interference by correct matching of the line characteristic impedance to the load impedance. The characteristics for matching networks are given on page 583 of *Ref 453*. The matching networks include.

a. Single quarter-wave section

b. Multiple quarter-wave section

c. Shorted stubs

d. Open stub

e. Coupled sections

f Resonant detuning.

7. APPLICATION OF THEORY

Determine three basic factors about transmission lines in a system complex:

a. What devices are susceptible to either steady-state or transient transmission line effects? This evaluation covers the frequency spectra of normal signals, transients, and also those frequencies over which interference and interaction spectra extend. After the susceptible devices have been isolated it is necessary to tabulate tolerable threshold levels. The specific parameters are (1) voltage standing wave ratio (VSWR), (2) impedance mismatch (as a function of frequency), (3) phase shift, (4) propagation delay and (5) reflections.

b. What interference and noise signals are induced into transmission lines?

c. Does this line modify these interference signals so that further degradation occurs?

8. SPECIAL TECHNIQUES

8.1 FERRITE BEADS

The reactance and RF resistance of short straight leads may be increased by placing ferrite beads over the wire. The attenuation or insertion loss characteristics of RFI suppression filters may be improved by adding ferrite beads to internal leads with almost no increase in size and weight. Other applications of ferrites and beads in RFI related work include:

a. Improved isolation between stages of electronic devices by placing ferrite beads on filament leads, B+, and bias lines.

b. Improved isolation between modules by putting ferrite beads on interconnecting leads.

8.2 TAPES AND COATINGS

The amount of noise guided and conducted by power transmission lines may be greatly reduced by wrapping the conductor with a thin high-permeability metallic tape. The skin effect losses, present with any conductor carrying RF energy, are greatly magnified by coating the conductor with a thin layer of high permeability material. The effect due to the coating is large in the range of 25 kHz to 50 MHz.

8.3 COAX

Special coax is available for use in severe radiation and leakage problems such as those encountered in high power pulse applications. Use triple-shielded coax where pulse generators are separate from the transmitter or other load. To obtain maximum performance from triple-shielded coax, design the terminal ends to take advantage of the three shields.

DESIGN NOTE 5B8 FIBER OPTICAL CABLE

1. INTRODUCTION

Fiber optical cable is an alternative to the use of electrical cable for data transfer within an aerospace system. It is immune to both electromagnetic interference (EMI) and electromagnetic pulse (EMP), provides electrical isolation, secure data transfer, and will not short out. With signal conditioning and multiplexing it can transfer a large amount of data on a single cable.

2. CABLE ADVANTAGES

Twisted shielded pairs have a 5 dB/km loss at about 10 kHz while coax has a 5 dB/km loss at about 10 MHz. Both twisted pairs and coax have frequency dependent losses which require equalization. Fiber optical cable has a low transmission loss of about 2 dB/km and is independent of frequency. Fiber optical cable does not suffer from problems associated with mismatch as in conventional wired systems, and it is relatively free of grounding potential difference, standing waves, signal ringing, echoes, and crosstalk. Fiber optic can transmit analog signals to the gigahertz range and digital signals of high data rate transfer of over 100 M bit/s. *Sub-Note 2(1)* gives the size-weight advantage of fiber optical cables.

SUB-NOTE 2(1) Comparing Fiber Optics to Coax and Twisted Pairs

CABLES	DIAMETER mm	(mils)	WEIGHT kg/km	(lb/kft)
Fiber Optic	1.14 2.29	(45) to (90)	5.1	(3.7)
Twisted Shielded Pairs	≈3.2	(125)	22	(16)
Coax-RG-584	5.1	(200)	48	(35)

3. TOTAL OPTICAL LINK

Fiber optical cables need a device such as a light emitting diode (LED) or solid state laser to transduce the electrical/electronic signal into a light signal. At the receiving end, the light signal is then detected by a photodiode and transduced back to an electronic signal; see *SN 3(1)*. However, the transmit-receive device (modem) is not immune to EMI/EMP and may have to be interfaced with other EMC disciplines, such as shielding, filtering, and bonding.

4. RECOMMENDATIONS

The following are recommendations in the use of fiber optics.

a. Consider fiber optical links in the design of any system whose cable runs are greater than 10 meters and which must adhere to military system EMP requirements.

b. Consider the use of fiber optics in secure data systems.

c. Consider fiber optics in the design of any system whose operation is dependent upon the survivability of its personnel, where personnel nuclear survivability requirements are the limiting factor in the system's operation.

d. Enclose the transmit-receive electronics in an electromagnetic shield to EMP-harden fiber optic links.

e. Reduce EMP-induced transients on the power, control, and nonoptical links by shielding the lines, or suppress by protective devices at the electronics interface.

f. Consider fiber optical links in areas where there are high electric or magnetic fields in explosive vapor areas, and in areas where vibration can cause instrumentation errors.

g. Protect the transmit-receive electronics by shielding, filtering, and bonding; and by vibration- and explosion-proofing.

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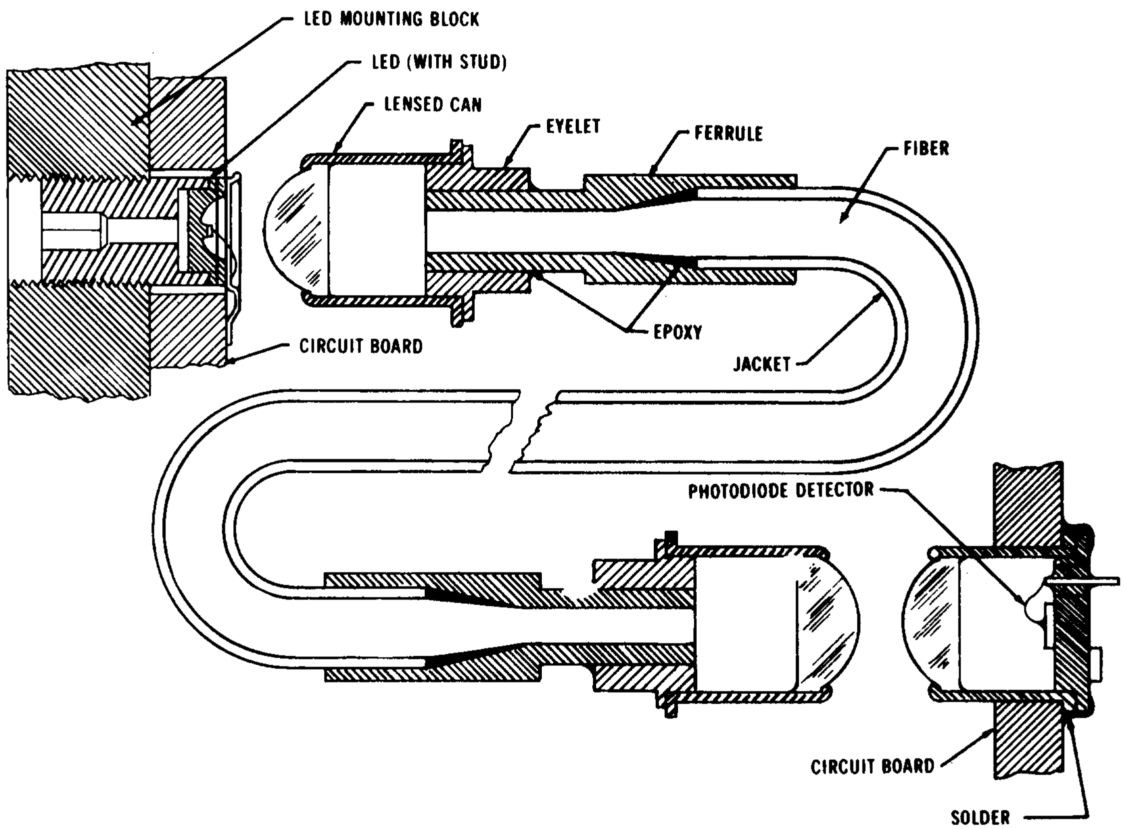
5. INFORMATION SOURCES

Contact WRDC/AAAD at Wright-Patterson AFB OH 45433 for more detailed information on fiber optics as applied to aerospace systems. The following references are good sources of information on fiber optics:

a. *Ref 664*, R. A. Greenwell, *EMP Hardening of Airborne Systems Through Electro-Optical Techniques: Design Guidelines*. NOSC-TR-469. Naval Ocean Systems Center, San Diego CA. Dec 79. (DTIC No. AD A080650)

b. *Ref 717*, J. E. Shaunfield, *EMI/EMP Resistant Data Bus*. AFAL-TR-76-99. Spectronics, Inc, Richardson TX. Sep 76. (DTIC No. AD B014579)

SUB-NOTE 3(1) Total Optical Link



SECT 5C CONNECTORS

SECTION 5C CONNECTORS

DESIGN NOTE 5C1 INTRODUCTION

1. GENERAL

A connector is an assembly of mating contacts to link or separate quickly. The contacts are usually embedded in insulating material to isolate them from one another and to prevent them from coming in contact with bare hands. In link position the connector will provide a low impedance bond. In EMC design, shielding and filtering should also be considered in proper termination of connectors. Comply with *MIL-HDBK-216* and *MIL-STD-454* (*Requirement 10*) when selecting electrical and electronic connectors for electronic subsystems and equipment.

2. DESIGN FEATURES

Design connectors to have the following features:

a. Conductivity high enough so that the resulting resistance will be negligible.

b. Surfaces which will not corrode, tarnish, oxidize, or be attacked by organic or inorganic contamination.

c. Surfaces which will not gouge or be gouged during mating.

d. Foolproof alignment under field conditions without pin bending.

e. Adequate force transmitted to the contact surfaces to be maintained for the life of the connector. Define and measure this force. The connector life for installed cabling is usually the life of the system.

f. Surfaces having coefficients of friction low enough so that withdrawal-insertion abrasion does not cause resistance to exceed acceptable values.

g. Physical configuration to minimize entry and collection of dirt, moisture, fumes, and contamination.

h. Physical configuration which minimizes damage and deterioration due to use.

i. Ensure the connectors are reliable and durable enough for mating and disconnecting for life of the equipment.

j. Locate connector receptacles where they are easily accessible, with adequate clearance to assure positive connection. Failure to do so will result in EMI, increased maintenance time, broken coaxial cables, and unverified connections.

3. CONNECTOR GUIDE

Sub Note 3(1) contains connector guidance.

SUB-NOTE 3(1) Guidance for Connectors

1. Does connector shell have conductive finish?
2. Are signal and power circuits routed in separate connectors?
3. Are input and output signal circuits in separate connectors?
4. Have provisions been made for termination of shields?
5. Have provisions been made for peripheral shielding?
6. Have shielding terminations been designed so that maintenance is not degraded?
7. Have filter pins been incorporated where necessary?
8. Have provisions been made for use of shielded (coaxial) pins for circuits which must have isolated continuous circuits?
9. Has electrical continuity through the shell been verified during vibration tests?
10. Have chassis or bulkhead mounted connectors been mounted by methods that ensure good electrical connections?
11. Use nonmagnetic-type connectors to prevent intermodulation. (See *DN 5C3*.)

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DESIGN NOTE 5C2 CONNECTOR CONTACTS

1. INTRODUCTION

Contacts should maintain a low-impedance bond in the link position. This Design Note will discuss the aspect of connector contacts.

2. DETECTING AND ISOLATING HIGH-IMPEDANCE CONTACTS

The requirements for testing connectors to detect and isolate high-impedance contacts are as follows:

a. Ensure that the applied voltage is 1/10 to 1/5 the normal working voltage. This is so the normal film and tarnish accumulation is not broken down by the test voltage.

b. Use the highest frequency to which the loads are susceptible. It is sufficient to conduct dc resistance measurements on audio and low frequency circuits. A safety factor of 10 should be used to measure ac impedance.

c. Submit the connector to low-level, low-impedance testing, then submit it to an environmental test of mechanical forces, wear, and corrosion.

d. Contact resistance of a few thousand ohms is not critical in intercabling of high-impedance circuit inputs of amplifiers, vacuum tube voltmeter (VTVM), transducers, and analog-type computers.

3. FAULTY CONTACTS

A common cause of faulty contacts is damage during mating. Ensure adequate contact floating to permit insertion without binding, and prevent wedging by correct pin layout. Properly placed guide pins will reduce bending, gouging, and abrasion due to misalignment. Provide guides so that alignment occurs without trial-and-error scraping of pins across the female contact to find the alignment position. Ensure that protective coverings extend over the male pins to reduce pin damage. Pin overdesign for an extra low length-to-diameter ratio provides ruggedness. Provide inexpensive protective plastic caps for use during handling and storage. Potting the back ends of connectors decreases entry of moisture, fumes, contaminants, and foreign objects. Clamps prevent wires being pulled and twisted from their contacts. Ensure good contact pressure over a long time by use of low fatigue high-resilience spring materials. Ensure that the connector cannot be installed wrong.

4. HIGH CONDUCTANCE CONTACTS

High conductance of low-impedance contact can occur in either of two ways: (1) simple contact under pressure - the pins are pressed together to break or wipe away film and tarnish, or (2) breakdown contact - the pins have a film which is not ruptured by connector mating. Light arcing forms channels of molten metal which provides a low resistance contact due to reduced cross section. A capacitive effect can exist if the voltage level between the pins is not enough for the dielectric oxide film breakdown. High resistance contact can be produced on some metal oxides on the surface of the connectors.

5. GOLD CONTACTS

Contact plating, which can be a major factor in high conductance circuit connectors, yields the advantages of increased tarnish and corrosion resistance. Gold satisfies both of these parameters. Certain hard gold alloy platings are preferred for their electrical conductivity corrosion resistance as well as their wearability. For an underplate for the gold alloy, 2.54 μm (0.1 mil) of ductile nickel (elongation of not less than 5%) provides the best overall combination from a performance aspect for a sustained period of time.

5.1 HERMETICALLY SEALED CONNECTORS

Nonhermetically sealed connectors contain a copper-based alloy while the hermetically sealed connectors usually consist of an iron nickel alloy. The gold underplating in the case of hermetic seals should be copper over the iron nickel. If gold is plated directly to the copper plating the gold will be diffused into the copper thereby establishing a seal leakage as well as a corrosion mechanism. See *Ref 114* for more details on the plating of electrical connectors contacts.

5.2 MICROFINISH OF THE CONTACT BASE METAL

The finer the microfinish of the contacts mating surfaces the better the corrosion resistance characteristics and the less the insertion and withdrawal forces. Microfinishes as low as 0.0254 μm (10 μin.) can be achieved.

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DESIGN NOTE 5C3 CABLES AND CONNECTORS

1. INTRODUCTION

Cables and their connectors can contribute to the overall degradation of the electrical and electronic subsystem. Discrepancies can cause complete malfunction, introduce random or intermittent errors, or can cause steady-state errors. These problems can exist in cables and connectors between subsystems, equipment, transducers, modules, and other interconnecting black boxes.

2. REPLACEMENT OF CABLE ASSEMBLIES

Care and skill is required to properly remove and replace cable assemblies. Use factory inspected or tested cable assembly replacements whenever possible. Avoid field replacement if possible. Allow for impedance buildup during system life in the initial design and production phases. Make an initial design study to list (1) critical connectors in low-signal and low-impedance circuits, (2) connectors which can cause an undetected error due to increased impedance, and (3) connectors which are usually not tested because of their aerospace ground equipment hookup configuration.

3. CHECKOUT EQUIPMENT CABLES

A big operational test problem with interequipment cabling is that it is often not a part of the functional testing. Checkout equipment supplies its own commands and measures the systems response. In so doing, checkout equipment cabling is often substituted for system cabling. While black boxes and modules can be easily removed and replaced, the cabling between compartments and equipment is difficult to replace. Build in tolerable design safety factors to allow for intercabling deterioration during the operational life of the system.

3.1 TEST UMBILICALS

The intercabling between the system and the aerospace ground equipment is a troublesome area because aerospace ground equipment must insert into the system command signals which would normally come from sensors, transducers, and feedback elements. Stray signals which are superimposed on these desired commands are seen by the system under test as part of the true signal. If no devices to test automatic checkout equipment are available consider the following factors during the design phase:

a. Determine which circuits are sensitive to connector impedance.

b. Maintain impedance levels so that resulting errors and system effects will be negligible.

c. Determine what deviations are expected in the manufacturing process.

d. Allow a safety factor for degradation during system life.

e. Set up limits that will help operational personnel know whether the intercabling between the checkout equipment and the system will not cause significant voltage drops.

4. SUBSYSTEM COMPATIBILITY

Cable connectors usually present a problem because the designer of one subsystem does not realize that another designer's subsystem will be connected to his via shielded leads where each shield may require a separate connector pin. Thus, first subsystem designer may provide a connector with one pin allocated for shield terminations while the second subsystem designer wants all his shields isolated. The second subsystem designer may send shielded leads to control interference radiation only to find that the first subsystem designer is using a connector with a nonconductive finish which will not maintain the shielding integrity. These problems must be resolved by the systems/subsystems engineering personnel before the fact.

5. INTERMODULATION PRODUCTS

Intermodulation (IM) products can degrade system performance through interference, especially in situations where high power sources coexist with sensitive receivers. Coaxial cables and connectors can exhibit sufficiently nonlinear behavior to generate intermodulation interference. See Appendix A2 for definitions.

5.1 INTERMODULATION LEVELS

With input power levels of 44 dBmW (i.e., two equal, applied signals of 12.5 W each), the IM levels produced in coaxial connectors range between -98 and -69 dBmW depending on the type of connector and the frequency of the applied signal. For example, the IM level of silver-plated, Type N connectors with an input power of 44 dBmW and an IM frequency of 350 MHz is of the order of -96 dBmW. Similarly, with input levels of 44 dBmW, the IM levels generated in typical cable-connector combinations range from -100 to -62 dBmW. The IM levels

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generated in coaxial cables alone are not significant when compared to the levels generated in typical connectors and typically constructed cable-connector combinations.

5.2 IM LEVEL RELATION TO VARIOUS PARAMETERS

The levels of the IM products generated in coaxial connectors and cable-connector combinations are functions of various physical, material, and electromagnetic parameters. The functional relationships for the most important parameters are as follows.

5.2.1 POWER. The IM level is a linear (in dB) function of the total input power (i.e., linear sum of the two equal input signal power levels). For connectors, the IM level increases 2.6 dB for each dB increase in the total input power. For cable-connector combinations, the IM level increases 1.9 dB for each dB increase in the total input power.

5.2.2 CONNECTOR TYPES. The use of different types of connectors can change the level of the IM products. If Type N connectors are used as the reference, the differences in the IM levels for connectors alone as a function of connector type are as follows:

a. 0 dB for Type N
b. -2 dB for Type HN
c. -3 dB for Type LC
d. 6 dB for Type TNC

Using the same reference, the differences in IM levels for cable-connector combinations as a function of connector type are as follows:

a. 0 dB for Type N
b. -2 dB for Type HN
c. 0 dB for Type TNC

5.2.3 CONNECTOR PLATINGS. Different platings on connectors can significantly change the IM levels produced. With silver-plated connectors as the reference, the differences in IM levels for connectors alone as a function of platings are as follows.

a. 0 dB for silver
b. 0 dB for beryllium-copper silver
c 0 dB for gold
d. 5 dB for stainless steel
e. 7 dB for nickel

With the same reference, the differences in IM levels for cable-connector combinations as a function of connector plating are as follows:

a. 0 dB for silver
b. 0 dB for beryllium-copper silver
c. 2 dB for gold
d. 11 dB for nickel

5.2.4 CABLE TYPES. Connectors and/or the junctions between cables and connectors are the predominant sources of IM products. The relative effects due to cables in typical installations are minimal.

5.2.5 CABLE LENGTH. The level of IM products generated in typically constructed cable-connector combinations are inversely proportional to cable length (attenuation). The IM level decreases between 1 and 3 dB for each dB increase in the total attenuation of the cable.

5.2.6 FREQUENCY. At low frequencies (approximately 20 MHz), the IM levels are 15 to 20 dB higher than the IM levels at frequencies near 300 MHz. At higher frequencies, the IM level increases with increasing frequencies.

5.3 RECOMMENDED PRACTICES

The levels of IM products generated in coaxial cables and connectors employed in all installations can be minimized by observing the following practices:

a. Silver- or gold-plated connectors, preferably silver, should be used. Nickel-plated and stainless steel connectors should be avoided; they can produce IM levels as much as 11 dB higher than silver-plated connectors.

b. Physically large connectors should be used where possible. For example, Type LC connectors produce IM levels that are 9 dB lower than TNC and Type N connectors are as much as 6 dB lower than TNC.

c. Care must be exercised in mounting connectors to cables; established procedures (e.g., those of MIL-HDBK-419) must be followed exactly. The construction practices employed can affect the resulting IM levels to a higher degree than the physical and material properties of the cables and connectors.

d. Threaded connector surfaces should be cleaned thoroughly and regularly; oxidized or dirty surfaces between connections can cause significant increases in IM levels.

e. Connectors must be carefully threaded together and should be tightened with hand tools. When connectors are incorrectly screwed together, the IM levels can increase 40 dB or more.

f Cable-connector interconnections between equipment as well as the equipment itself must be rigidly mounted. Mechanical vibrations of the connections and equipment can also increase the resulting IM levels by as much as 40 dB.

DESIGN NOTE 5C4 SHIELDING EFFECTIVENESS OF CONNECTORS

1. INTRODUCTION

Not all connectors are designed to preclude the entry of Radio Frequency (RF) energy. Each connector surface represents 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. Radio frequency energy could enter at this point and cause a hazardous situation. 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. If the effectiveness of cable shields is to be maintained, the cable shield must be properly terminated. In an otherwise adequately shielded enclosure, RF currents that are conducted along the shields will be coupled to the system wiring from the point of improper cable termination.

2. PROPER TERMINATION

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. The use of epoxy or other synthetic conducting material has been found to be unacceptable for bonding in this situation.

3. METHODS OF TERMINATION

Sub-Note 3(1) illustrates cable-shield-to-connector termination. *Sub-Note 3(2)* 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 then bonded to the connector; no portion of the shield should be broken before it is bonded to the connector shell. Individual shields for connectors that are routed through multipin coaxial connectors should be terminated individually in the manner described above.

4. CONSIDERATIONS

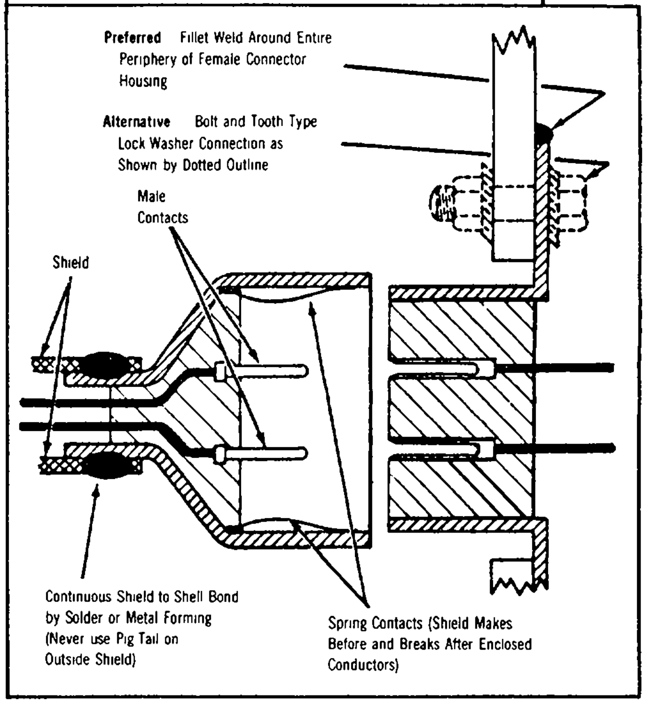
To prevent RF energy from entering a sensitive circuit at connector interfaces, consider the following features:

a. There should be no break in the shield through the connector and cable which would allow RF energy to "leak" into the power circuit.

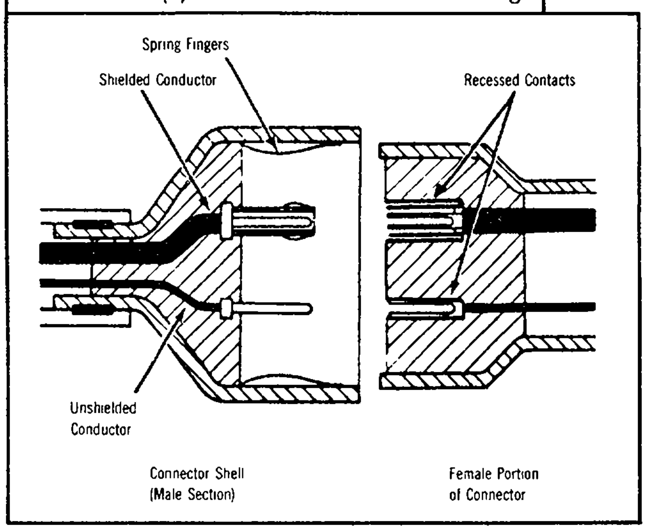
b. The connector should be able to withstand environmental conditions (vibration, high and low temperatures, corrosion, etc.) without degradation of the shielding characteristics of the connector.

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

SUB-NOTE 3(1) Shield Termination for Electrical Connectors



SUB-NOTE 3(2) Multicoaxial Connector Design



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d. 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.

e. Do not route power and signal circuits through the same connector.

f. Do not route input and output signal circuits through the same connector.

g. See *DN 5B3, Para 3*, for additional information on connectors shield termination according to wire classification.

SECT 5D ELECTRICAL BONDING AND GROUNDING

SECTION 5D ELECTRICAL BONDING AND GROUNDING

DN 5D6 - Contd

DESIGN NOTE 5D1 — INTRODUCTION

1. BONDING

Electrical bonding is the process of mechanically connecting certain metal parts so that they will make a good low-resistance electrical contact. Bonding is required to ensure that a system is electrically stable and relatively free from the hazards of lightning, static discharge, and electrical shock and to assist in the suppression of RF interference. Usually, the resistance of electrical bonds should be in the order of 0.0025 ohm.

2. 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. Good grounding techniques depend on good bonds. A uniform grounding philosophy is mandatory to avoid conductive coupling, low impedance ground loops, and hazardous operation conditions.

3. BONDING AND GROUNDING FOR LIGHTNING PROTECTION

See *Sect 7A* on bonding and grounding for lightning protection.

4. BONDING AND GROUNDING GUIDE

Guidance for electrical bonding and grounding is contained in *SN 4(1)*.

SUB-NOTE 4(1) Guidance for Electrical Bonding and Grounding

1. Clean all bare metal mating surfaces.
2. Weld all mating surfaces when possible.
3. Where protective films are absolutely required, ensure that the film material is a good conductor. Some suitable protective films are: silver or gold plating or other plated metals of good conductivity (oakite #36, alodine #1000, iridite #14, and iridite #18P).
4. Ensure that the fastening method exerts sufficient pressure to hold the surfaces in contact with the equipment and its environment.
5. If the surfaces are not inert in their storage and operating environments, provide surface protection according to rule "3" or take other suitable measures to ensure the maintenance of the bond for the service life of the equipment.
6. Do not use paint to establish an electrical or RF bond.
7. Do not use threads of screws or bolts to establish RF bonds.
8. Do not use ohmmeters to evaluate RF bonds or RF gaskets.
9. Consider bonding of dissimilar metals (see *DN 5D3)*.
10. Compress all RF gaskets.
11. Ensure a uniform grounding philosophy.
12. Check for ground loops, impedance coupling, floating grounds, and personnel and system safety.
13. Ensure good electrical bonding practices for ground terminations.
14. Use *SN 7(1)* in *DN 5D6* for determining minimum resistance to ground for maximum subsystem current.

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DESIGN NOTE 5D2* ELECTRICAL BONDING CONSIDERATIONS

1. INTRODUCTION

Bonding is defined herein as the establishment of the lowest obtainable resistance between two conducting surfaces. The following conditions are necessary to achieve the lowest resistance between surfaces:

a. Use no films or layers of material between the surfaces unless the film material is a better conductor than the materials being bonded, and

b. The mating surfaces must be smooth and contoured so that maximum surface area is in actual contact.

2. TYPES AND CLASS OF BONDS

See *MIL-B-5087* for extensive coverage of the type and classes of bonds. This specification also covers bonding jumpers and clamps.

3. CHOICE OF BASE METALS

When bonding one metal surface to another it is essential that a good dc connection be made. *Sub-Note 1.1(1)* of *DN 5F2* gives the conductivity of various metals used in bonding. The dc parameter can be easily checked in the milliohm range with a Kelvin Bridge. When the application requires good shielding effectiveness to radio frequency, the bonding impedance at 1 MHz as well as the dc should be determined.

4. SURFACE OXIDE

The choice of base metal is not the only criterion for good bonds. If two unprotected metals (in contact) are exposed to a corrosive atmosphere, the resulting impedance can become high enough to destroy the bond effectiveness.

5. CLEANING OF SURFACES

5.1 ALUMINUM

Aluminum and aluminum alloy surfaces can be prepared according to *MIL-S-5002* and *MIL-C-5541*.

5.2 MAGNESIUM

Magnesium alloy surfaces can be prepared according to *MIL-M-3171*. The use of magnesium is discouraged. (See *DH 1-7*, *DN 3A1-6*.)

5.3 COPPER, NICKEL, SILVER

Copper, brass, bronze, nickel, or silver can be cleaned by degreasing and then slightly etching the surface.

5.4 DEGREASING

Excessive amounts of grease or oil can be removed by vapor degreasing, ultrasonic cleaning, organic solvent, or emulsion cleaning which employs a mineral oil distillate and an emulsifying agent.

5.5 ETCHING OF THE SURFACE

The metal can be dipped and agitated in a bath of chromic dry acid (CrO_3), 240 kg/m^3 (2 lb/gal), and sulfuric acid (H_2SO_4), 30 kg/m^3 (4 oz/gal). Average dip time is between 2 and 30 seconds. Prolonged exposure of parts in this bath may cause severe etching and loss of dimension. The bath must be followed by a thorough rinse in cold running water and then in a hot water rinse to facilitate drying.

6. PROTECTIVE FINISHES

Since most military specifications require a salt-spray environmental test for electronic equipment, all surfaces used for bonding should have a protected finish. It is also necessary that all exposed metal surfaces be treated so as to be wear resistant. The wear-resistant finishes such as anodized film are usually nonconductive. Some suitable conductive protective films for bonding

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*Extracted in part from *Ref 667*.

surfaces are silver or gold plating or other plated metals which have good conductivity such as oakite #36, alodine #1000, iridite #14, and iridite #18P. See *SN 6(1)* for shielding effectiveness degradation caused by finishes on aluminum. *MIL-C-5541* gives the treatment and film material for aluminum and aluminum alloys. *MIL-HDBK-132* provides guidance for other base metal finishes.

7. INDIRECT BONDING

When items are subject to shock and vibration or sections are removable, indirect bonding methods are used. Clamps and jumpers are discussed in *MIL-B-5087*. Finger stock and contact strip used in access doors are discussed in *DN 5F7, Para 5*.

7.1 CONDUCTIVE PASTES

There are several types of pastes, caulkings, and sealing compounds available for applications such as pipe and conduit threads, shielded room or enclosure seams, removable cover plate seams, expansion joints, and fastener hardware caulking. Resistivity varies with:

a. Type of metal loading used in the paste,

b. Configuration of the metallic content,

c. Condition of the metal surfaces upon which the paste is applied, and

d. The pressure applied to the joint after application of the paste.

The design engineer planning to use conductive paste should provide a means of achieving flanging pressures up to 69 kPa (10 lbf/in.^{2}) to fully realize the low resistivity of the paste. Unless silicones, or a special epoxy are used, the plastic binder used in the conductive paste is limited to continuous operation below 260°C.

7.2 GASKET MATERIALS

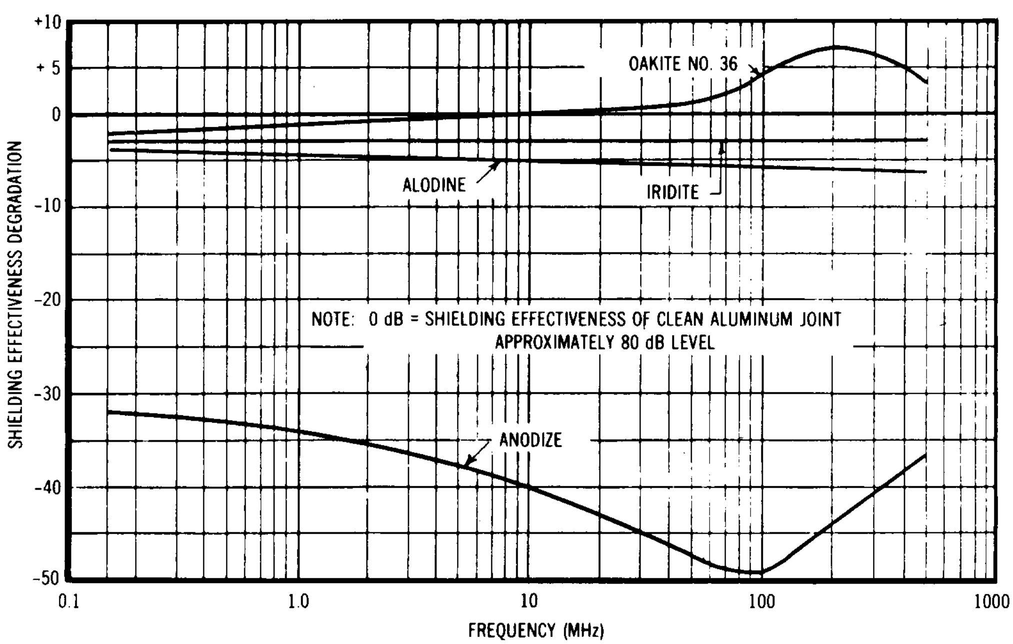
The problems involved in designing gaskets are:

a. To provide the minimum thickness which will allow for the expected surface discontinuities of the joint.

b. To provide correct height and pressure.

c. To contain adequate resiliency to allow for the frequency of opening and closing the joint and yet be hard enough to break through any nonconductive films on both mating surfaces to make a low resistance bond. See *DN 5F6* for more details on RF gaskets.

SUB-NOTE 6(1) Shielding Effectiveness Degradation Caused by Finishes on Aluminum



DESIGN NOTE 5D3 CORROSION AND DISSIMILAR METALS

1. INTRODUCTION

Dissimilar metals must often come into contact with each other. Direct contact of dissimilar metals in the presence of moisture may result in electrolytic reaction (corrosion). To avoid dissimilar metal corrosion adhere to the requirements of *MIL-STD-889; MIL-STD-1250* provides additional information, including general corrosion. *MIL-STD-1568* provides information on selection of materials to minimize corrosion.

2. GALVANIC SERIES

Sub-Note 2(1) lists some metals as they occur in the galvanic series. Metals at the top of the left column are more positive (anodic) in innate potential. *MIL-STD-889* provides a more detailed listing of metals. In general, any metal or alloy in this series will tend to become more active when coupled to a metal below it when the two metals are exposed to a corrosive environment. Contact between adjacent members from the same group will, in most cases, be considered as compatible. A third metal, intermediate in the electromotive series, may be inserted in the bond between the dissimilar metals to reduce galvanic reaction. This can be done by plating either or both of the parts, or by inserting a thin piece of the third metal. When the bond is adequately accessible for inspection and maintenance, a replaceable washer made from the most active of the two dissimilar metals may be inserted between the parts to be bonded. Cadmium-plated washers are most frequently used.

SUB-NOTE 2(1) Bonding for Minimum Corrosion

ANODIC METAL (Metals higher in table are more positive and more easily corroded than metals below them.)		CONNECTION FOR ALUMINUM, COPPER, or COPPER JUMPER	
		REQUIRED WASHER BETWEEN JUMPER AND STRUCTURE	OTHER PARTS
I	Magnesium	Aluminum Alloy (also under installation nut or screw head whichever is applicable)	Screw and nut cadmium- or zinc-plated
II	Aluminum Aluminum Base Alloy Zinc-Cadmium	None	
III	Carbon Steel (except Stainless Steel) Iron Lead Tin Tin-Lead Solders		
IV	Nickel Chromium Stainless Steel	Tinned or cadmium-plated washers for aluminum jumper. None for tinned copper or copper jumper.	Screw and nut stainless steel preferred (cadmium-or zinc-plated alternates)
V	Copper Silver Gold Platinum Cobalt Graphite Base Alloys of above Titanium		Bond only with copper jumper – remove all tinning thoroughly from contact surfaces

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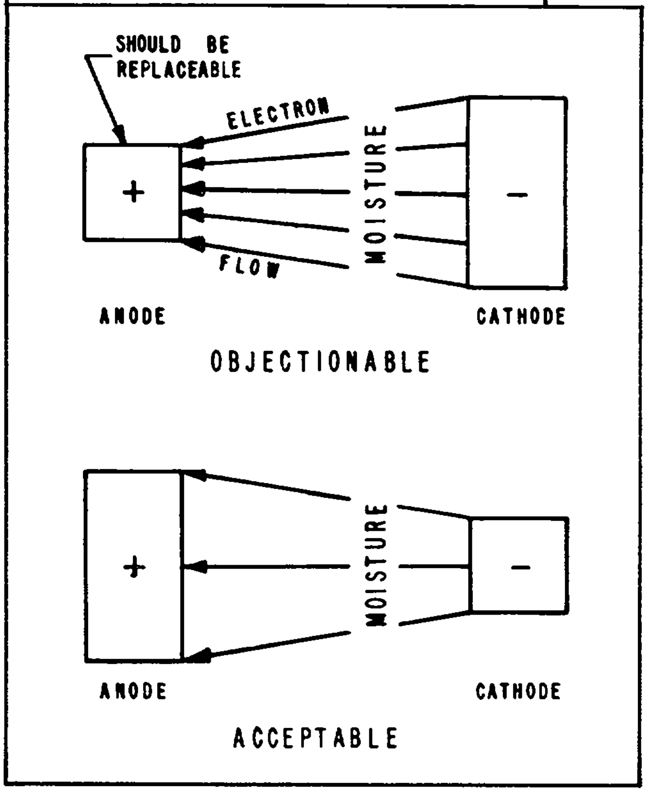
3. RELATIVE SIZE OF ADJACENT METAL

Consider the relative areas of the anode and cathode when dissimilar metals are bonded. A larger cathode implies greater electron flow (due to a greater source of supply) and, therefore more corrosive action at the anode (see *SN 3(1)*). A reduction in cathode size results in less electron flow and therefore less corrosion. Moisture must be present and this factor is significant in considering the area of metal under attack.

SUB-NOTE 3(1) Relative Anode Cathode Area



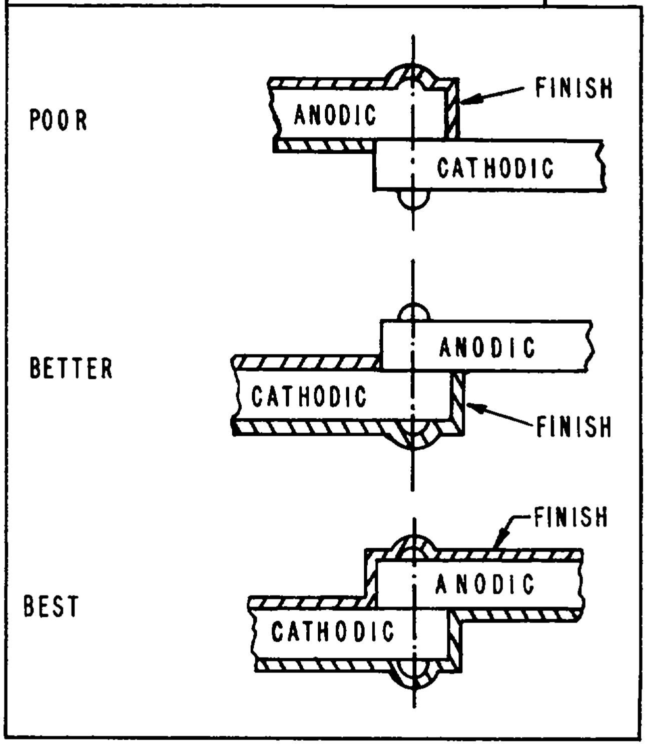
3.1 EXAMPLE

As an example, an iron enclosure or box of large surface area is bonded to a small washer, bolt head, or bonding strap made of nickel, copper, or lead. Since iron is more anodic than nickel, copper, or lead, it will corrode slightly from the cathodic small parts (see *SN 2(1)*). If, however, the bolt head, the washer, or the bonding strap are made of iron and the large box is made of copper, corrosion will be relatively more rapid due to the large cathodic copper surface.

4. JOINT SURFACE TREATMENT AND SEALING

Specify additional finishes, such as paint or plating, with caution. Finishing of the anodic material alone may produce severe corrosion at any finish imperfection. When dissimilar metals are in contact, do not cover the surface of only the anodic material; either cover the surface of both metals or only the cathode (see *SN 4(1)*). This is again due to the unfavorable anode to cathode area ratio.

SUB-NOTE 4(1) Finishing Around Dissimilar Metal Bonding Joints



5. MOISTURE IN BONDING JOINTS

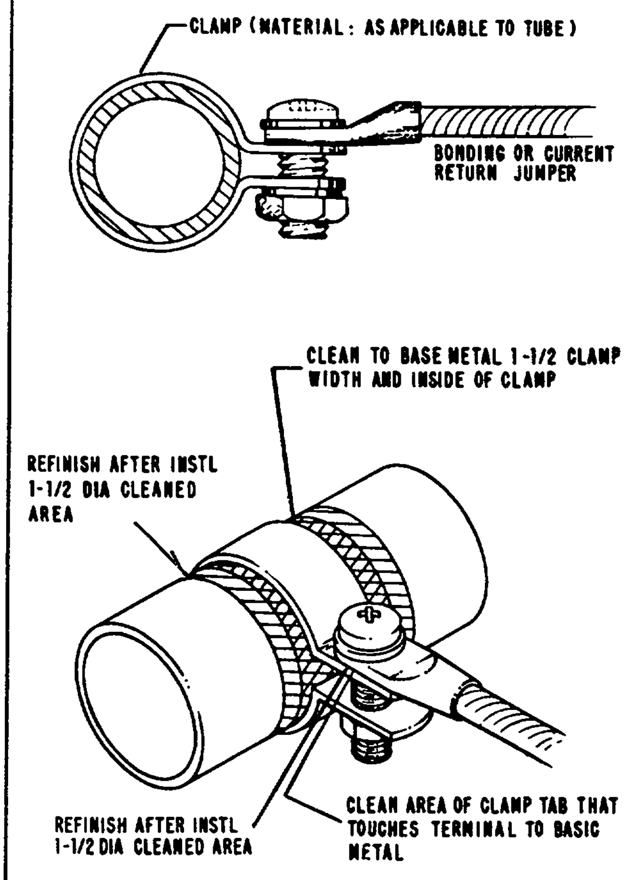
The most effective means of minimizing corrosion, other than avoiding the use of dissimilar metals, is to exclude moisture from the bonded areas. For small contact areas, edge-seals around the peripheries of contact areas are sometimes effective. For larger areas, conductive paste coatings of nonhardening, moisture, and corrosion resistant compounds are sometimes used. *MIL-STD-889* recommends suitable sealant materials such as those shown in *MIL-S-8802, MIL-S-23586,* and *MIL-S-81733.*

DESIGN NOTE 5D4 — METHODS OF ELECTRICAL BONDING

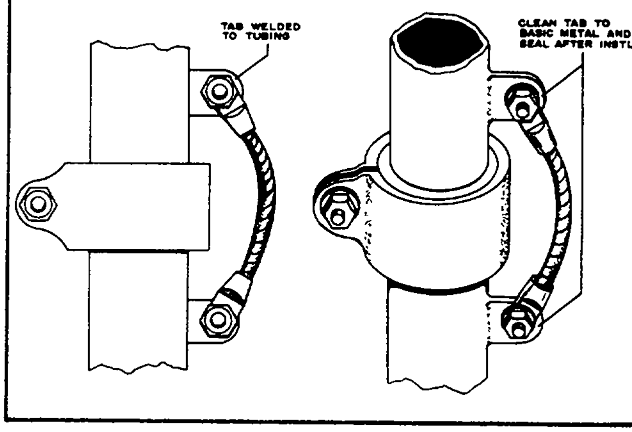
1. INTRODUCTION

Sub-Notes 1(1) through *1(14)* show typical methods of electrical bonding.

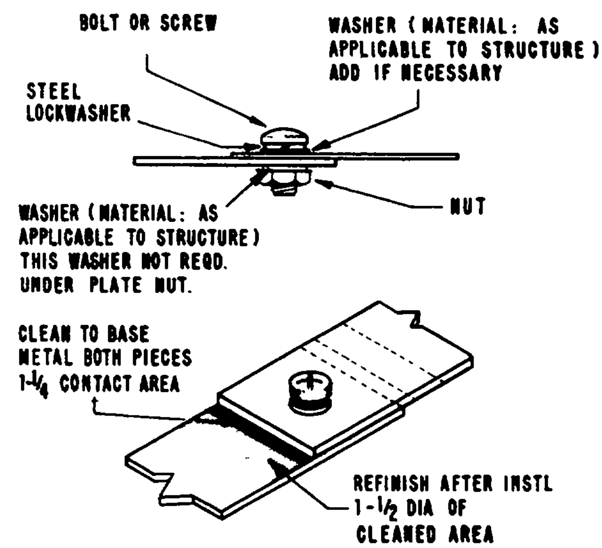
SUB-NOTE 1(1) Clamp Connection — Jumper to Tube



SUB-NOTE 1(2) Typical Method of Bonding Tubing Across Clamps



SUB-NOTE 1(3) Preparation of Bonding Connection in Bolted Structural Joints



NOTE. USE EITHER HEAVY OR LIGHT SERIES WASHER, DEPENDING UPON DESIGN DETAIL ON ENGINEERING DRAWING (SEE ALSO DN 5D3)

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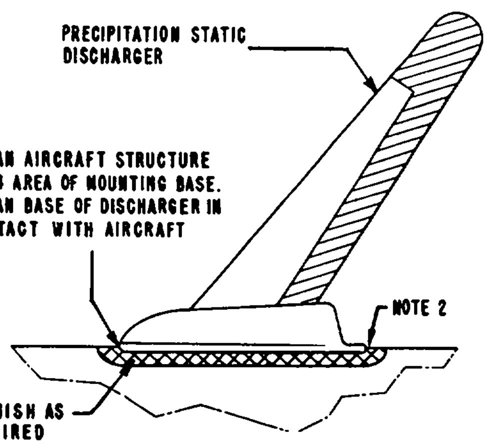
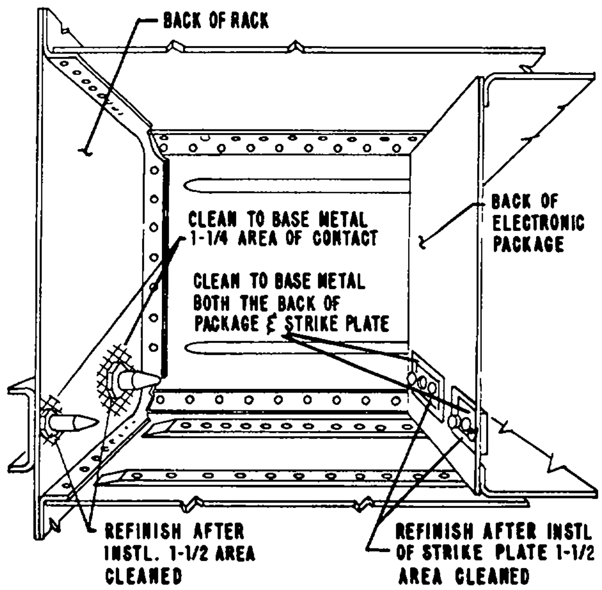
SUB-NOTE 1(4) Typical Method of Bonding Precipitation Static Discharger Assembly to Exterior of Aircraft



NOTES:

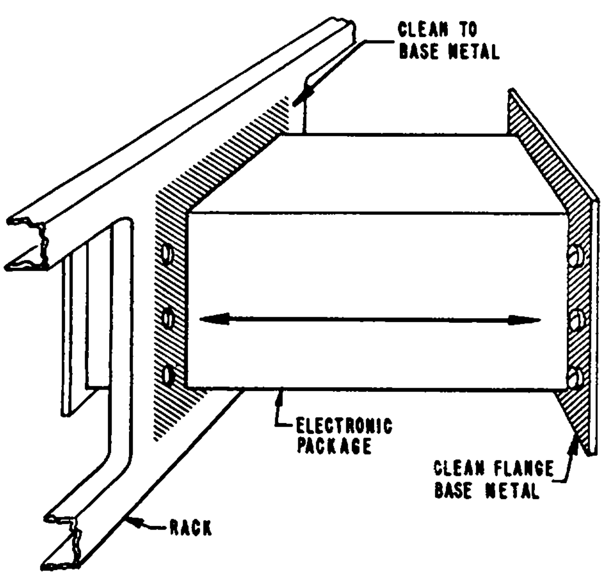
1. INSTALL IN ACCORDANCE WITH MANUFACTURERS' PROCEDURE.
2. MOUNTING PROVISIONS TO BE SPECIFIED ON INSTALLATION DRAWING (SEE DN 7B2)

SUB-NOTE 1(6) Typical Method of Bonding with Dagger Pins

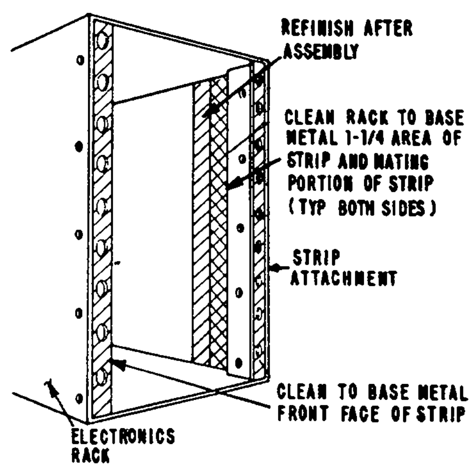


NOTE. CLEAN ALL DAGGER PINS AND STRIKE PLATE HOLES AFTER INSTALLATION.

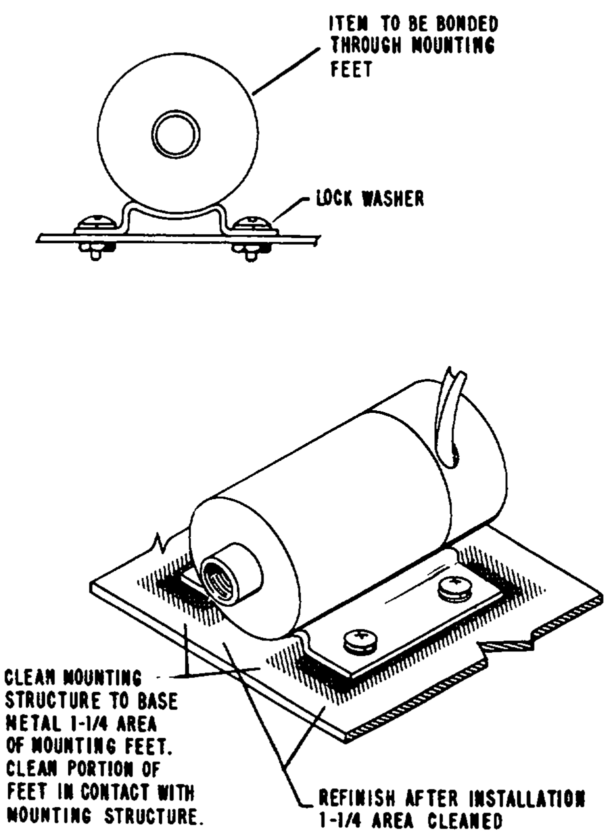
SUB-NOTE 1(5) Typical Method of Bonding Between Attaching Flange of Electronic Package and Rack



SUB-NOTE 1(7) Typical Method of Bonding Electronic Package to Rack Through Front Attachments

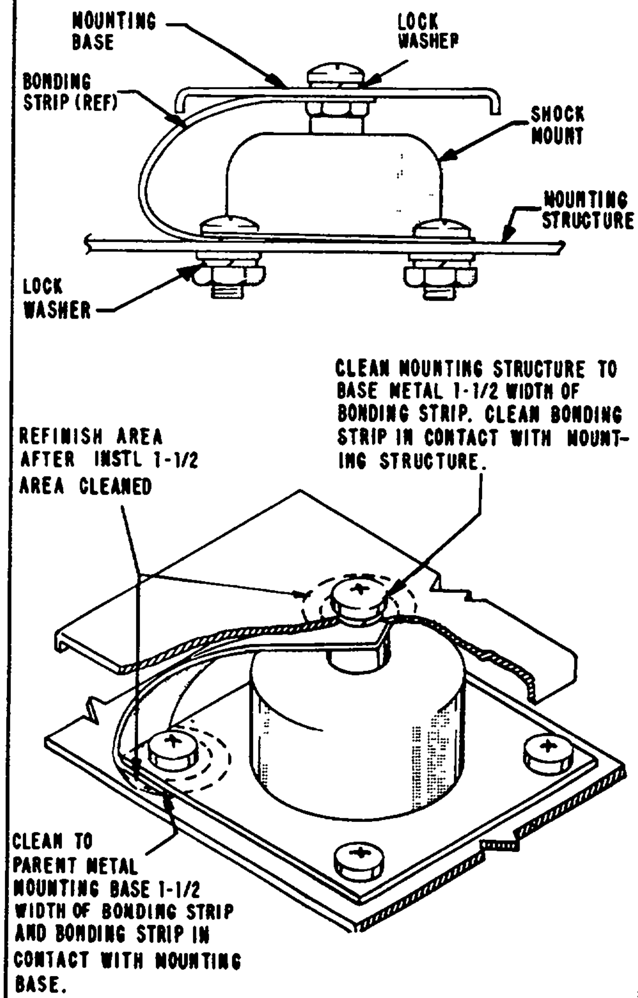


SUB-NOTE 1(8) Typical Bonding of Equipment Installed on Structure with Mounting Feet



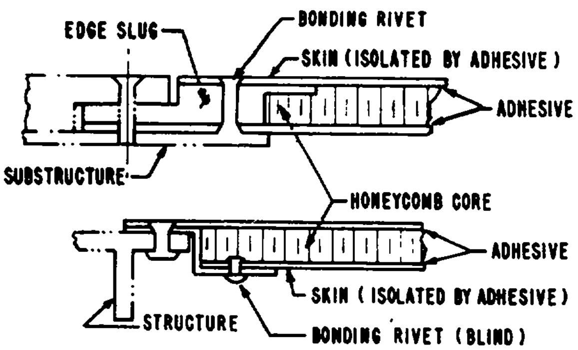
NOTE ON ITEMS THAT HAVE THE BOLTS SPACED MORE THAN 152 4 mm (6 in) APART, IT IS ONLY NECESSARY TO CLEAN THE AREA 50 8 mm (2 in) EACH SIDE OF THE BOLTS OR SCREWS

SUB-NOTE 1(9) Installation of Bonding Strips on Shock Mounts



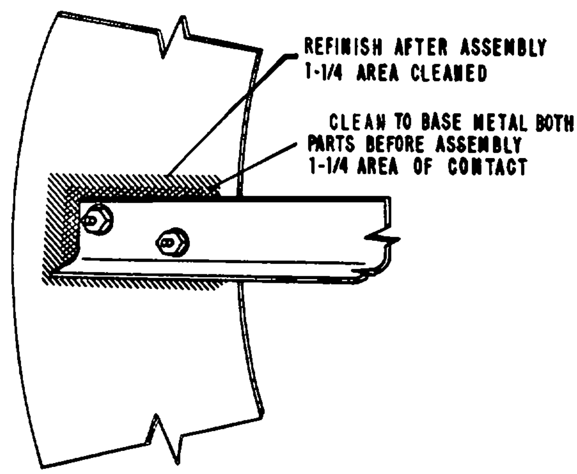
NOTE INSTALL BONDING STRIP UNDER SHOCK MOUNT PAD IN SUCH A MANNER THAT THE STRIP DOES NOT ALTER SHOCK MOUNT FUNCTION

SUB-NOTE 1(10) Typical Bonding of Details Which Are Isolated by Adhesives

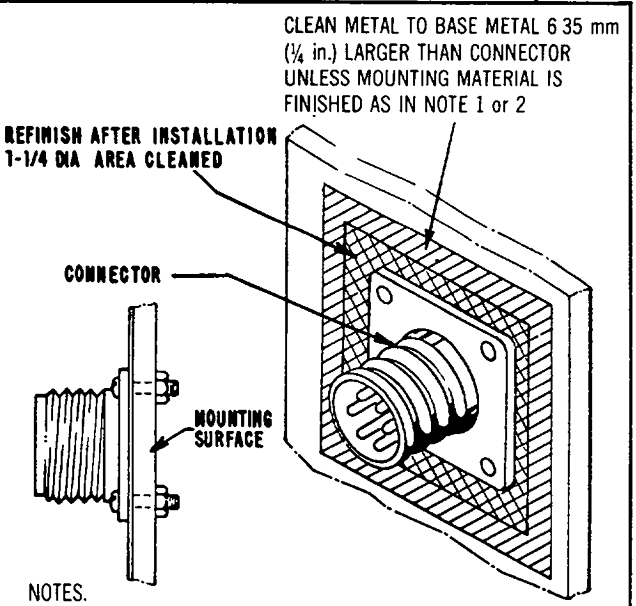


NOTES
1. USE A MINIMUM OF TWO RIVETS (TOTAL AREA ELECTRICALLY EQUIVALENT TO TWO 3 2-mm (⅛-in) DIAMETER RIVETS) FOR ANY ONE CONNECTION. INDICATE THE TOTAL NUMBER OF RIVETS AND RIVET SPACING ON THE INSTALLATION DRAWING.
2. DRILL HOLES FOR ALL RIVETS AND INSTALL RIVETS AFTER ADHESIVES ARE CURED.

SUB-NOTE 1(12) Typical Method of Bonding Through Bolted Connection

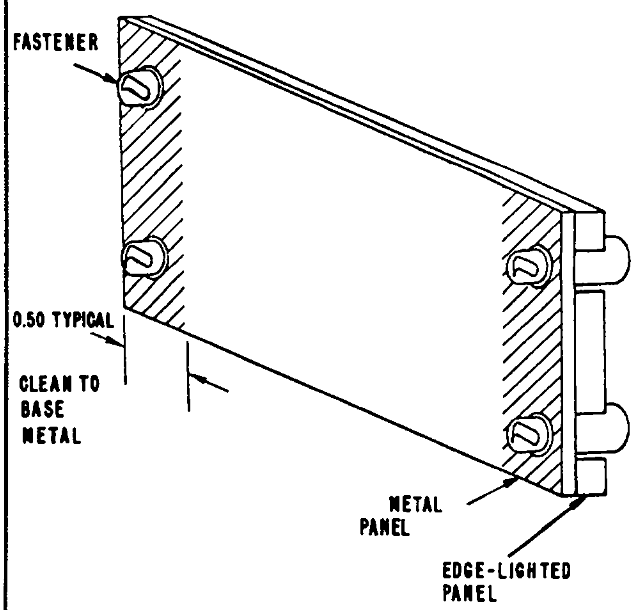


SUB-NOTE 1(11) Typical Method of Bonding Connectors to Attaching Parts



NOTES.
1. CLEAN AND REFINISH ALUMINUM SURFACE MATING WITH CONNECTOR
2. MAGNESIUM SURFACE MATING WITH CONNECTOR MAY BE FINISHED WITH CHROME PICKLE CONFORMING TO SPECIFICATION *MIL–M–3171*,TYPE 1

SUB-NOTE 1(13) Typical Method of Bonding Edge-Lighted Panels



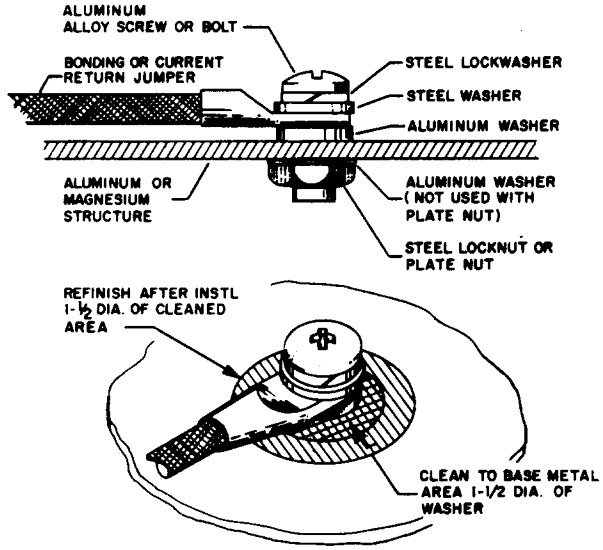
SUB-NOTE 1(14) Connection Jumpers

BOLT SIZE:

BONDING – NO. 6 & NO. 8 SCREW WHERE EDGE DISTANCE WILL NOT PERMIT NO. 10 SCREW
– 4.76-mm ($^3/_{16}$-in.) DIA. MIN. WHERE POSSIBLE

100-A RETURN – 6.35-mm ($^1/_4$-in.) DIA. MIN.
200-A RETURN – 9.5-mm ($^3/_8$-in.) DIA. MIN.

NOTE: Electrical bonding to magnesium structure for current return is prohibited

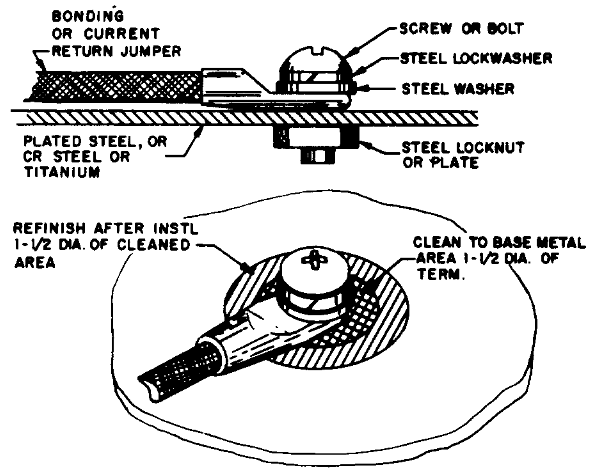


a. BOLTED TO ALUMINUM OR MAGNESIUM ALLOY STRUCTURE

BOLT SIZES:

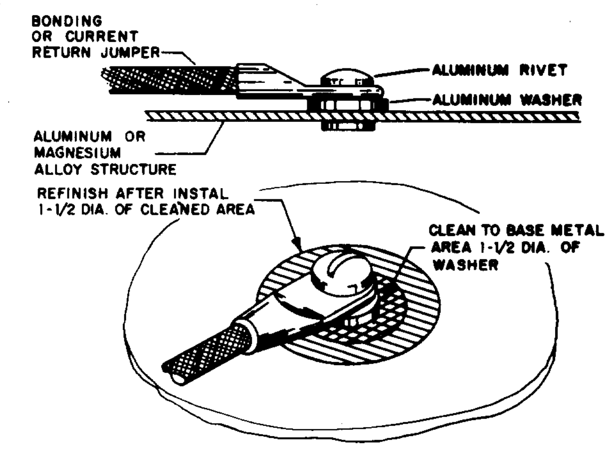
BONDING – NO. 6 & NO. 8 SCREW WHERE EDGE DISTANCE WILL NOT PERMIT NO. 10 SCREW
– 4.76-mm ($^3/_{16}$-in.) DIA. MIN. WHERE POSSIBLE

100-A CURRENT RETURN – 6.35-mm ($^1/_4$-in.) DIA. MIN.
200-A CURRENT RETURN – 9.5-mm ($^3/_8$-in.) DIA. MIN.



b. BOLTED TO ALLOY STEEL, PLATED STEEL OR TITANIUM

NOTES:
1. Not applicable to bonding jumpers used for current return
2. Use bolted connections where jumper is used for current return
3. Ensure that rivet size is equal to the equivalent bolt size



c. RIVETED TO ALUMINUM OR MAGNESIUM ALLOY

DESIGN NOTE 5D5 GROUNDING CONSIDERATIONS

1. POWER RETURNS

There are two primary concepts regarding power returns. These are ground or structure common return and wired return. In the ground or structure common concept one side of the power system is grounded at the power source and all loads use the vehicle frame or structure as the return conductor. In three-phase connected ac systems the neutral is grounded and all single phase loads use the structure for the return circuit. The principal advantage of this system is the reduced weight resulting from the elimination of a great many heavy power return wires. The disadvantage of the common return system is that it does not distribute the power efficiently. The flow of currents 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, therefore, creating potential interference problems in any electronic system using the structure as a power return. Even systems using structure as a ground plane for shield grounds are subject to induced voltages in susceptible circuits. In the wired return concept all systems are grounded at one point only 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 which exist with the common return system. This reduces ground loops and common impedances which are the basis of most incompatibilities.

2. CONDUIT GROUNDS

Conduit ground is used to prevent shock hazard and to carry lightning current. Conduits, however, may be a source of interference due to possible ground loops, conductive coupling, and poorly bonded connections.

2.1 CONDUIT AS AN RF SHIELD

Conduits made from solid or woven strands of metal may be used effectively to shield cables and wiring from the RF energy environment. The shielding effectiveness of a solid armor conduit is the same as that of a solid metal sheet of the same thickness and material (see *SN 1(1)* of *DN 5F5*). To make an RF tight conduit, ensure that connections are properly bonded. A conductive paste used in bonding may be applied to the joints. Keep currents off of conduits to prevent ground loops and conductive coupling.

3. GROUNDING FOR RF

Good grounds require short, high conductance leads. The inductive reactance of ground leads at radio frequencies requires extremely short or leadless ground to avoid high impedance connections. Make all ground for a particular stage at a single point. As the frequency increases even a relatively short ground lead no longer acts as a bond to ground but tends to become an effective radiator. However, radio frequency may be contained in a given area in the equipment through the effective use of filters and enclosures. Use short or leadless ground on components (such as electron tube, transistors, capacitors, resistors, and coils) inside the enclosures for containing RF circuits. The enclosure itself is a ground plane. See *SN 3(1)* for typical grounding terminations.

3.1 GROUNDING AND SHIELDING TERMINATION FOR RF ENCLOSURE

A completely shielded (RF) enclosure should be welded or soldered directly to the equipment chassis with one continuous seam around the base for the best grounding. Shielded and coaxial cables should be terminated by a continuous weld around the periphery or the opening in the enclosure. These cables can also be rigidly secured to the enclosure through RF-type connectors.

4. SENSITIVE EQUIPMENT

Sensitive equipment such as electronic microammeters and low level amplifiers may need a direct ground connection to the earth or to the aerospace vehicle structure itself. If equipment is found to need direct grounding the following is recommended:

a. If long wire grounds are necessary, use large diameter (6 mm (¼ in) or larger) copper bus or stranded wire between equipment and ground termination

b. To reduce RF coupling make ground leads direct and as short as possible and observe resonant frequency effects.

c. To reduce conductive coupling keep ground leads away from conduits, magnetic and RF fields, and other noise producing wires. Do not bundle ground wire with other wires.

d. When direct ground wire is used disconnect any other external ground (e.g., conduit) from the equipment

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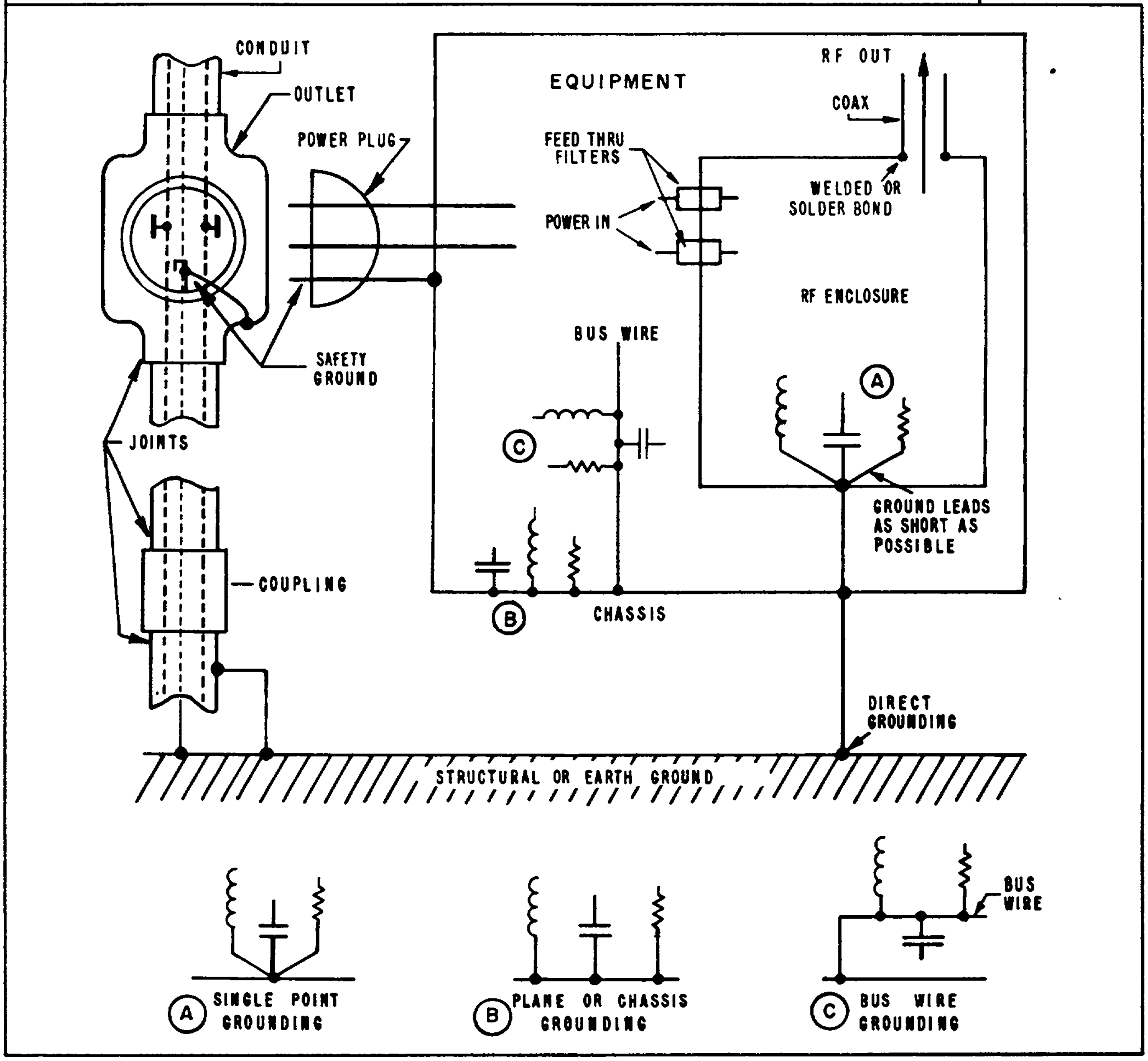
SUB-NOTE 3(1) Typical Grounding Terminations

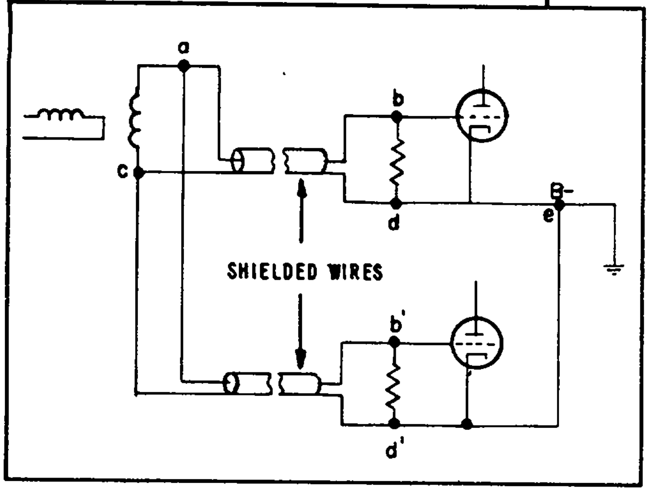


case if possible. Remove external grounds on allied equipment if the sensitive equipment is connected to it through interconnecting shielded cable, the cable being terminated at each end. Sensitive equipment may be isolated from a console when using structural or earth ground. Likewise the whole console may be grounded at this point provided all other external grounds are removed.

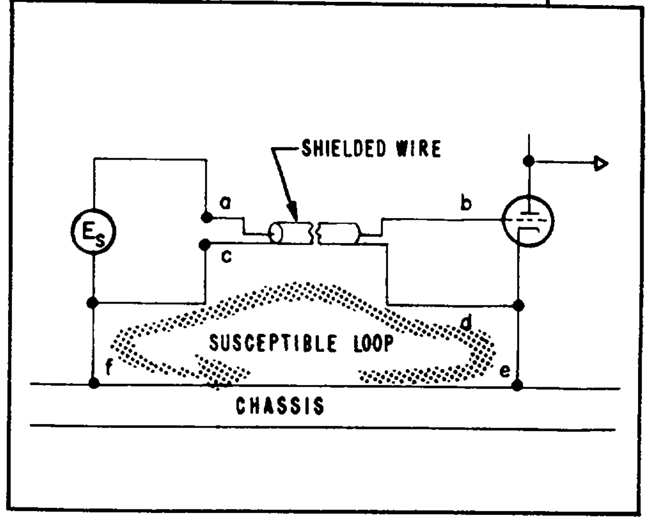
4.1 INDUCTIVE GROUND LOOPS

Inductive loops are often the result of interconnection of different circuits to the power supplies. *Sub-Note 4.1(1)* shows two amplifiers connected in parallel. B- is supplied to both amplifiers from point e of the power supply, which is also the low side of each signal line. A loop exists at the points c, d, e, d′. Interference pickup may occur at the grids of both amplifiers as a result of stray flux cutting this loop. This may be opened by removing one of the B-leads. Since the resultant inductive interference is proportional to the physical area of the loop, an inductive ground loop may occur in which the current flow is negligible and yet the induced interference is high level. This type of loop is illustrated in *SN 4.1(2)*. Ground loops can be removed by disconnecting the shield at point c or d and d′.

SUB-NOTE 4.1(1) Inductive Loop Caused by Circuit Interconnection



SUB-NOTE 4.1(2) Inductive Ground Loop



DESIGN NOTE 5D6*

BONDING AND GROUNDING TO PREVENT FAULT CURRENTS

1. INTRODUCTION

In equipment/subsystems which use a large amount of current, simultaneously consider bonding and grounding.

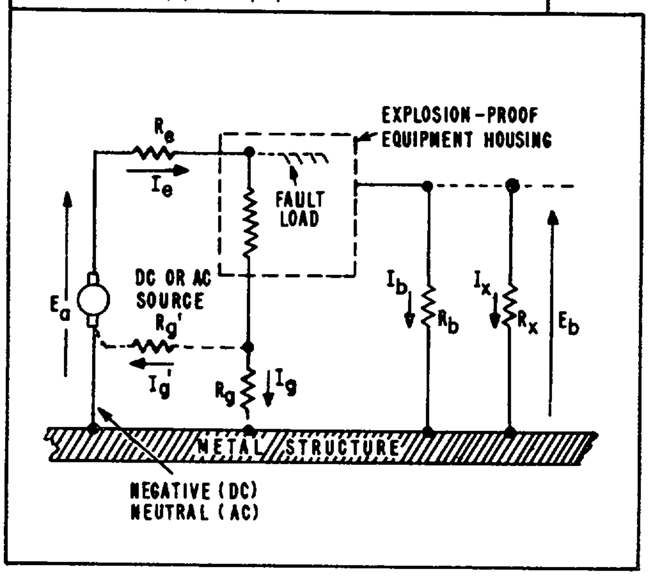
2. EXPLOSION HAZARD AREAS

Ignition of flammable mixtures can occur as the result of a ground fault or, as a special case, the starting inrush current of a dc or ac electric motor. Several accidents have resulted from ignition of explosive mixtures due to localized hot spots caused by passage of heavy current through points in ground circuits having excessive resistance. None of these accidents would have occurred if an adequate bond had existed between the equipment mounting flange and basic structure.

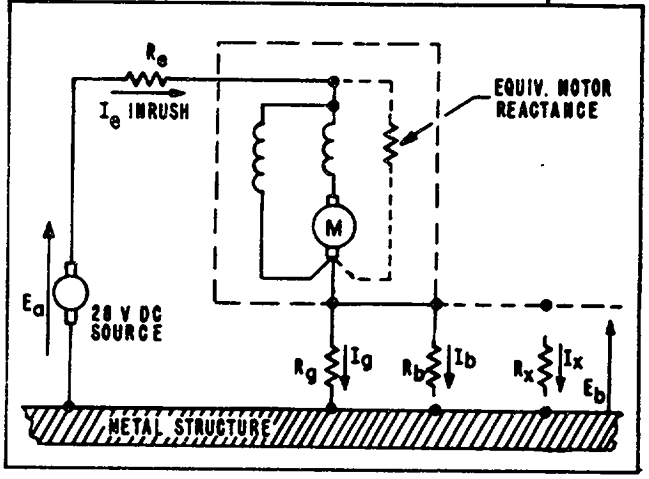
3. EQUIPMENT WITH GROUND FAULT

Sub-Note 3(1) shows a typical equipment with a ground fault. *Sub-Note 3(2)* shows the special case of an internally grounded dc motor. Typically, for *SN 3(1)*, inrush currents in the 500 to 1000 A range must pass through the case ground to the structure. For $R_b = R_g = 0.005$ ohm, inrush current = 700 A, the IR drop across the ground circuit is 1.75 V. In a similar way, a ground fault in *SN 3(1)* will generate a voltage across the ground circuit. *Sub-Note 3(3)* is the legend to *SN 3(1)* and *3(2)*.

SUB-NOTE 3(1) Equipment With Ground Fault



SUB-NOTE 3(2) Internally Grounded DC Motor



SUB-NOTE 3(3) Legend to SN 3(1) and 3(2)

E_a	=	Source voltage
E_b	=	IR drop voltage developed across the ground-path
I_e	=	Current available to a fault at the load (amperes)
I_b	=	Current through case ground to structure (amperes)
I_g	=	Current through circuit ground to structure (amperes)
I_g	=	Current through circuit to power source common (amperes)
I_x	=	Current through extraneous parallel ground-path (amperes)
R_e	=	Combined source and line impedance (ohms)
R_b	=	Resistance of housing ground to supporting structure (ohms)
R_g	=	Return-line impedance where structure provides current return-path (ohms)
R_g	=	Return-line impedance where single-point ground system is used (ohms)
R_x	=	Resistance of extraneous parallel ground-path (metallic debris or filament of wire) (ohms)

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*Extracted in part from *Ref 214*

4. HOT SPOTS

If these high currents in the ground circuit pass through a point contact of low-current capacity, a hot spot can occur. Such a point of contact often is heated to incandescence and expulsion of molten metal which can result in ignition of fuel vapors.

5. BRIDGING THE GROUND

Another ignition source results from metallic objects bridging the ground connection and forming a parallel path (R_x) across the joint. This can be caused by metal debris or by safety wires installed on nearby screws (see *SN 5(1)*). This ignition source can ignite combustible mixtures even though the equipment has been "explosion-proofed." Conventional explosion tests consider only internal ignition sources.

6. IGNITION AT RIVETED JOINTS

Tests on small cross-section riveted joints indicate ignition of vapors when the joint is subjected to 1000 A. Of 10 samples tested, all showed evidence of spark showers, spot welding, and overheated finish. Design riveted joints with care when they are to be used in areas of possible explosion hazards.

7. BONDING RESISTANCE FOR FAULT CURRENT PROTECTION

Sub-Note 7(1) gives the maximum bonding resistance for fault current protection for fuels according to *Section 500-2, Group D, of the National Electrical Code.*

8. DETERMINING THE MAXIMUM BOND RESISTANCE

Sub-Note 8(1) illustrates a typical problem where it is necessary to determine the maximum allowable bond resistance (R_b) for an electrical device to be installed in an explosion-hazard area. In the sample calculation below, the following assumptions are made:

a. The regulation will maintain the line-to-ground voltage (E_a) at 120 V ac rms during a ground-fault in the equipment.

b. The total line impedance is lumped at R_e, and the calculated dc resistance is used as this impedance (a small error occurs in ignoring ac impedance effects, but this is in a direction which increases the factor of safety).

c. For determination of the fault-current capability (I_e) the resistance of the fault (R_f) and bond resistance (R_b) is assumed to be zero.

d. The line leads between power panel and equipment are American wire gauge (AWG) size 14, and are 7.3 m (24 ft) long.

Solution:

(1) Determine line resistance:

AWG 14 copper at 20°C is listed in handbooks as 0.008 284 Ω/m, round off to 0.0083 Ω/m (0.002 525 Ω/ft, round off to 0.0025 Ω/ft).

then; 24 ft = 24(0.0025) = 0.06Ω

(2) Solving for maximum fault current capability;

$$I_e = \frac{E_a}{R_e} = \frac{120}{0.06} = 2000 \text{ A}$$

(3) Referring to *SN 7(1)*, at 2000 A the lower curve lists a maximum of 0.037 mΩ.

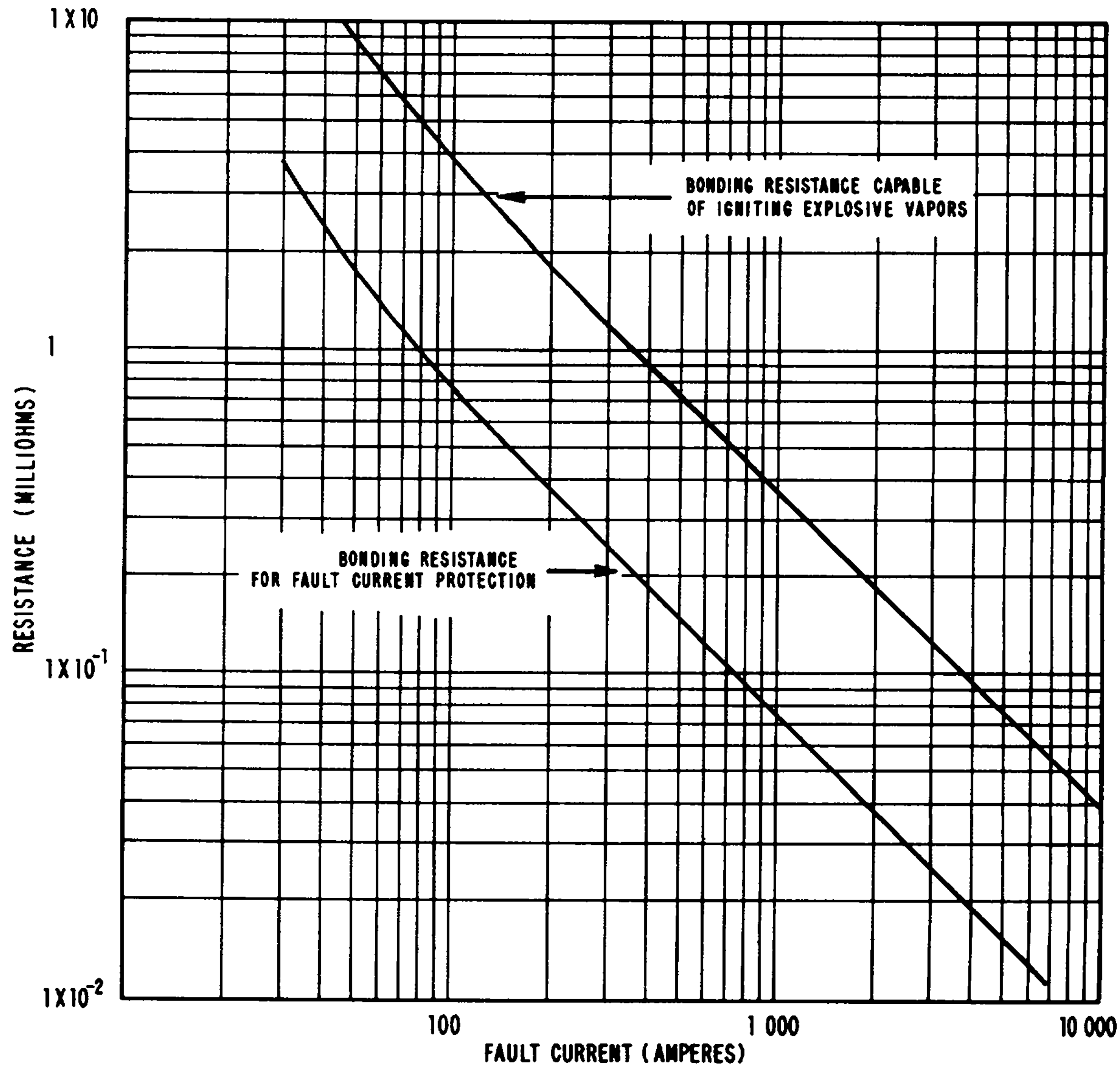
(4) The value from (3) is the theoretical maximum allowable bond resistance. In practice, it is recommended that this be rounded off by reducing the value to 0.035 ± 0.003 mΩ for the drawing callout.

SUB-NOTE 5(1) Examples of Conditions Causing Explosions or Ignition

BRIDGING MATERIALS	DIAMETER mm	(in.)	LENGTH mm	(in.)	AVG VOLTS	AVG A*
Copper Wire	0.635	(0.025)	5.08	(0.2)	0.41	220
Copper Wire	0.305	(0.012)	2.54	(0.1)	0.45	58
Aluminum Wire	0.508	(0.020)	17.8	(0.7)	0 55	30
Aluminum Washer	12.7	(1/2)		0.41	700	
Aluminum Washer	19.05	(3/4)		0.43	675	

*The value of the current is not minimum required for ignition

SUB-NOTE 7(1) Fault Current vs Maximum Allowed Resistance for Bonding Between Equipment and Structure



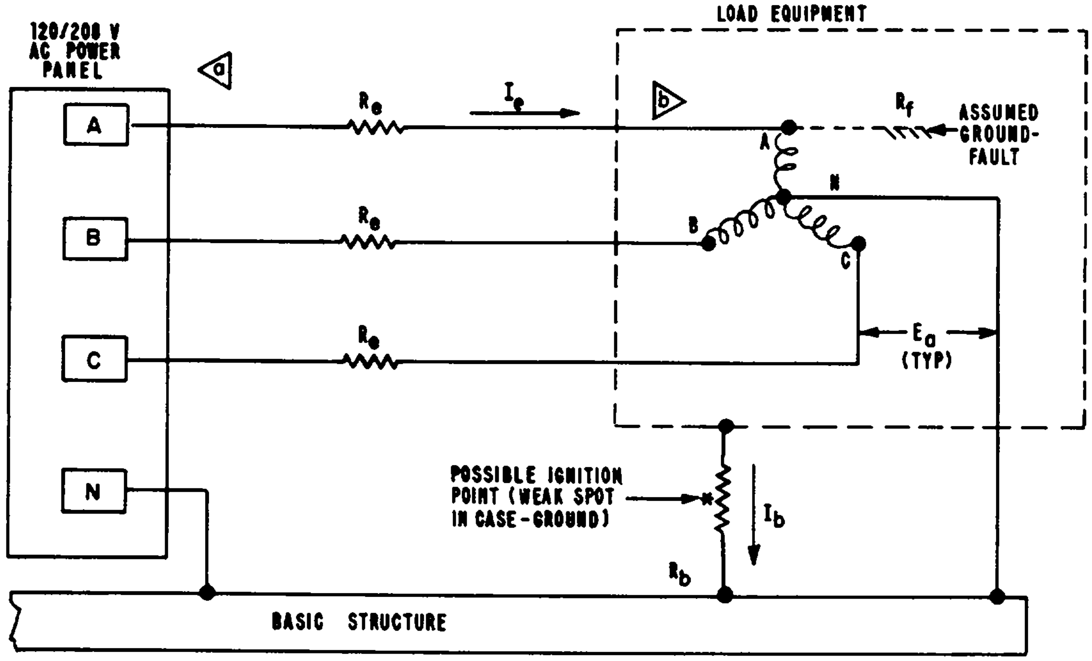
8.1 DIRECT CURRENT CALCULATIONS

An ac system was shown in the *SN 8(1)* example because of the present trend toward this type of power in aircraft. Exactly the same technique would be followed if the problem concerned dc power, rather than ac, and the accuracy of calculations would be slightly improved because the wire resistance would constitute the true impedance.

8.2 WORST-CASE CONFIGURATION

Sub-Note 8(1) and the sample calculation were based upon the worst-case configuration in which the possible ignition mechanism is a point having low-current carrying capacity located within the case-ground, or the equipment housing itself. In the sample calculation associated with this figure, a small error occurs through the assumption of zero resistance for R_f and R_b. When

SUB-NOTE 8(1) Three-Phase Equipment Ground Fault



NOTE

a - Regulating point of power system

b - Fault current capability $I_e = \frac{E_a}{R_e}$

calculating the theoretical available fault current (I_e), the value obtained is slightly higher than would occur had these resistances been added to the line impedance, R_e. This slight error, however, is of negligible magnitude, and works in the direction of increasing the margin of safety.

8.3 RECOMMENDATIONS

In further justification of the exclusion of these items from the calculation of I_e, it should be noted that at the time of solving this problem, resistances R_f and R_b are hypothetical, and each could approach zero ohms. As they approach zero, the error from omitting them becomes negligible. *Sub-Note 7(1)* would require changes for each line voltage utilized. Accordingly, the simplified approach as used in *SN 7(1)* is recommended.

9. MEASUREMENT OF ELECTRICAL BONDS IN EXPLOSION HAZARD AREA

A safe meter for measurement of bonds should always be used in areas of possible explosion hazards. An instrument suitable for measuring electrical bonds is discussed in *Ref 214*.

SECTION 5E EARTHING

DESIGN NOTE 5E1 CONSTRUCTING AN EARTHING SYSTEM

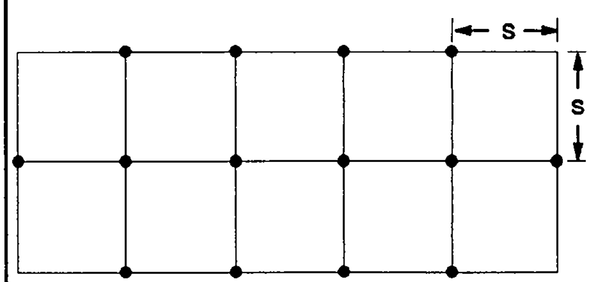
1. INTRODUCTION

An ideal earthing system would consist of a single large conducting plate covering the entire area of the installation and connected to the earth at an infinite number of points. This, of course, is not a practical solution. Effectively, this kind of system can be approached by installing a suitable ground grid surrounding the area of the installation consisting of a continuous copper cable (or other suitable conductor) buried beneath the earth's surface and connected to driven ground rods, plate electrodes, or a water system. The ideal size for the ground bus will depend on the magnitude of the available ground fault currents and operating time of protective equipment. But for practical purposes it should have an equivalent conductivity of not less than 4/0 AWG wire for small installations and 250 mm^2 (5 × 10^5 circular mils) for large installations. If this system is then developed into a grid-type network, it will approach the ideal.

2. EARTH GRID

Grid systems usually extend over the entire installation, and they may extend some distance beyond the property boundaries. They consist of conductors buried a minimum of 152 mm (6 in.) in the ground or stone fill to form a network of squares. The size of the squares will vary with the expected voltages, but cable spacings of 3 to 3.7 m (10 to 12 ft) are commonly used (see *SN 2(1)* and *MIL-STD-188-124*). All cable crossings should be securely connected to all equipment and structural steel work. In rocky ground, where driven electrodes are impractical, it is sometimes more economical and desirable to use a grid system in place of buried strips. In this case, the cables are usually buried at a depth of 0.3 or 0.6 m (1 or 2 ft). Where bedrock is near the surface, or where sand is encountered, the soil may be very dry and of high resistivity; therefore, it is necessary to have a grid of considerable size. Under such conditions buried metal strips, wires, or cables offer the most economical solution. Since the effectiveness of this type of electrode for lightning discharges is a function of its inductance, the use of a number of well-spaced shorted strips in parallel is preferable to one or more long strips. The depth at which the strips are buried is not critical. Tests by the Bureau of Standards have shown that the decrease in resistance from the minimum depth to the practicable maximum (about 0.5 to 1 m (18 to 36 in.)) is only about 5% (based on uniform soil resistivity). Similarly, the effect of conductor size is extremely small.

SUB-NOTE 2(1) One Example of a Grounding Grid



2.1 MAIN OBJECTIVES

The main objectives of a properly designed ground grid (or other main grounding system) are (1) to provide the lowest economically feasible ground resistance in the path of the expected fault current to ground, and (2) to hold the potential, induced by the fault current (over the area to be protected) within safe margins.

3. DIFFICULTY IN APPLYING PHYSICAL CONCEPTS

It is difficult to apply exact physical concepts to the variety of shapes and combinations. For complex forms it is impractical to express in analytical terms the boundary conditions for the equipotential surface of the ground conductors. The task of finding an accurate analytical solution is unrewarding because of the vagueness of soil resistivity measurements. The resistivity, often changing erratically, varies not only with the seasons, but also locally over the horizontal extensions of relatively confined areas and in vertical direction with the different strata. So, even if an accurate analytical solution could be found for the geometrical design, the computed resistance could be relied on only with certain reservations.

REO: ASD/AFCC

4. CALCULATION OF GROUND RESISTANCE

Since a high degree of accuracy in the end result, i.e., the absolute value of ground resistance, is not attainable, deviations from a pure mathematical approach may be tolerated. For the purpose of selecting the best arrangement and for preliminary comparisons, the approximate method presented here furnishes results that are sufficiently accurate for practical purposes. The resistance to infinite ground of an intermeshed network of the form depicted in *SN 2(1)* can be written as:

$$R = \frac{\rho}{\pi L}\left(\log_e \frac{2L}{a'} + \frac{K_1 L}{\sqrt{A}} - K_2\right) \quad \text{(Eq 1)}$$

Where:

R = ground resistance of ground grid mesh (ohms)

ρ = soil resistivity (ohm-centimeters)

L = total length of all connected conductors (centimeters)

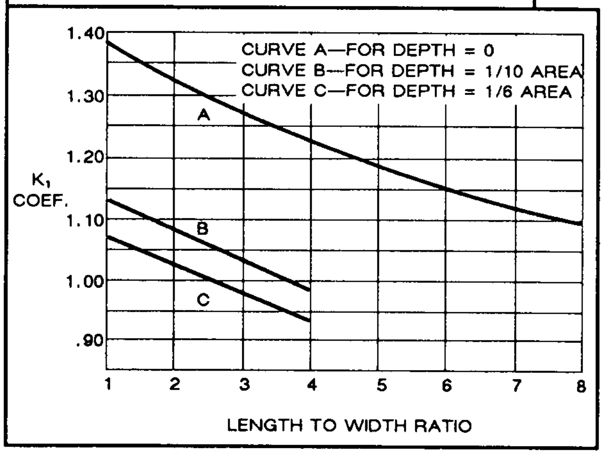
a' = ($a \times 2z$) for conductors buried at depth of z centimeters, or (a) for conductors on earth surface; 2a is diameter of conductor (centimeters)

A = area covered by conductors (square centimeters)

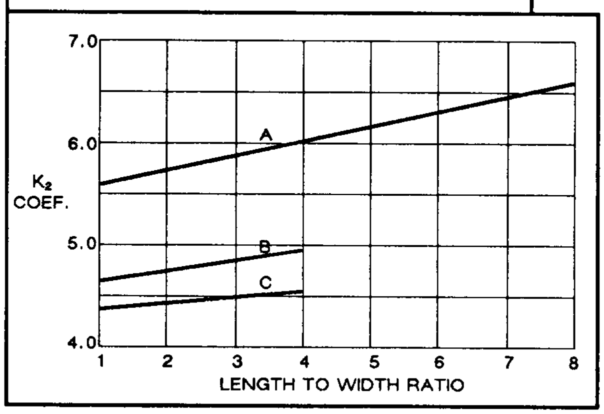
K_1, K_2 = coefficients, see *SN 4(1)* and *SN 4(2)*.

The coefficient K_1 in the above equation is obtained from the expression for the resistance of a horizontal thin plate. With L increasing toward infinity, Eq 1 approaches this value. Curve A in *SN 4(1)* shows the plotted coefficients K_1 for square and rectangular plates at earth surface; curves B and C show the coefficient K_1 for plates buried at different depths. They are based on tests which provide data for plates of length to width ratios up to 1:4. Curves B and C are presented here primarily for comparison. In most practical cases, grids or rod beds are buried to a sufficient depth so the coefficients K_1 for the surface level hold with sufficient accuracy. At worst they may produce values that are somewhat high and thus are on the safe side. Coefficients K_2 have been calculated for loops encircling areas of the same shape and depth and are given in *SN 4(2)*. For configuration and depths different from the ones presented in *SN 4(1)* and *SN 4(2)*, the corresponding coefficients K_1 and K_2 may be developed accordingly.

SUB-NOTE 4(1) Values of Coefficient K_1 as a Function of Length to Width Ratio X of Area



SUB-NOTE 4(2) Values of Coefficient K_2 as a Function of Length to Width Ratio X of Area



4.1 IRREGULAR MESH

It is assumed that equally close results will be obtained for oblong or even irregular meshes. In the derivation, the density factor $L/\sqrt{A}$ was entered so the results should be unaffected by irregularity in the distribution of the total conductor length over the area.

5. FACTORS AFFECTING GRID RESISTANCE

The resistance of a grounding grid decreases with an increase in the area enclosed, an increase of wire diameter used, and the depth to which the grid is buried. When the depth of the grid is of the same order of magnitude as the diameter of the wire, the resistance is quite high but as the depth is increased, the resistance decreases exponentially. Variation of resistance with the size of the wire is of a similar nature, except for the fact that very thin wires are rarely used and therefore ranges where variations are rapid are seldom encountered.

6. GRID RESISTANCE

The following points should be borne in mind when considering the resistance in designing a grounding grid:

a. The area enclosed by the grid should be as large as possible. If further decrease in resistance is desired, criss-cross conductors should be added. However, the number of meshes need not exceed 16 in an economical design.

b. The diameter of the wire is determined by thermal rather than by electrical considerations. Tubing may be advantageously used instead of wire.

c. The depth to which the grid is buried is determined by the nature of the soil. The grid should be buried as deeply as possible without involving too much expense in excavation.

7. MEASUREMENT OF EARTHING NETWORKS

See *MIL-HDBK-419* and *MIL-STD-188-124* for information on measurements of earthing subsystems. The fall-of-potential measurement method should always be used.

DESIGN NOTE 5E2 — EXTERNAL AIRCRAFT GROUNDING

1. INTRODUCTION

Install an adequate number of ground jacks so that all grounding cables required during fueling, weapons handling, or other servicing equipment can be connected. The total number of jacks to be used should be determined after an analysis of system requirements. The following can be used as a guide:

a. Earth-Grounding Jacks. Install one jack for a grounding cable to connect to an earth ground rod. The cable should be in place until there is intent for flight.

b. Refueling Grounds. Install a grounding jack at each gravity fuel inlet plus one for connecting a grounding wire from the fueler to the aircraft. A jack is not required for single point nozzles.

c. Oxygen Servicing Grounds. See *Para 5c.*

d. Other Servicing Grounds. Install additional grounding jacks, as determined by analysis, for other servicing, maintenance, or checkout equipment.

e. Weapons Grounds. Install grounding jacks (as necessary) at locations convenient for use in handling of weapons or other explosive devices. A jack may be necessary near each pylon or other attachment or loading point.

2. GROUNDING HARDWARE

Use the following requirements for grounding hardware:

a. Grounding Cables. Fabricate grounding cables according to *MS27574.*

b. Grounding Plug. The only part approved for connecting grounding cables to aircraft is the plug shown in *MS3493* which is a new stainless steel design. The old brass plug and the alligator clips are inadequate.

c. Grounding Jacks. Comply with *MS90298.*

d. Grounding Clamps. For connection to earth-grounding rods, use only clamps that comply with *MIL-C-83413.*

e. Streamer Warning. Install *MS51700-36* warning streamers according to *MS27574.*

3. INSTALLATION OF JACKS

Mount ground jacks on structure so that resistance to ground is less than 0.0025 ohm. Comply with *MS33645* for other installation requirements.

4. MARKING OF GROUNDING JACKS

When surface temperatures are less than 107°C, use decals that conform to *MS27606.* When surface temperatures exceed 107°C, paint the ground symbol with material according to *MIL-M-25047* (see *MS33645*).

5. GROUNDING OF SUPPORT EQUIPMENT

Use the following guidelines for grounding of support equipment:

a. Do not ground or install grounding wires on mobile electrical power equipment.

b. Fuelers, oil servicing, and other support equipment handling flammable materials require one grounding wire to connect to an earth ground and a second one to connect to the aircraft.

c. Oxygen servicing of support equipment requires one grounding wire to connect to an approved earth ground. Redundancy is achieved by use of hoses that are designed to be electrically conductive.

d. Engine covers, jacks, towbars, lock pins, chocks, and similar support equipment do not require a grounding wire.

REO ASD/ENACE

SECT 5F SHIELDING

SECTION 5F SHIELDING

DN 5F1 - INTRODUCTION

DN 5F2 - ABSORPTION LOSS (A)

DN 5F3 - REFLECTION LOSS

DN 5F4 - THIN METAL K FACTORS

DN 5F5 - SEAMS

DN 5F6 - RF GASKETS

DN 5F7 – NONSOLID SHIELD

DN 5F8 – ENCLOSURES

DESIGN NOTE 5F1* INTRODUCTION

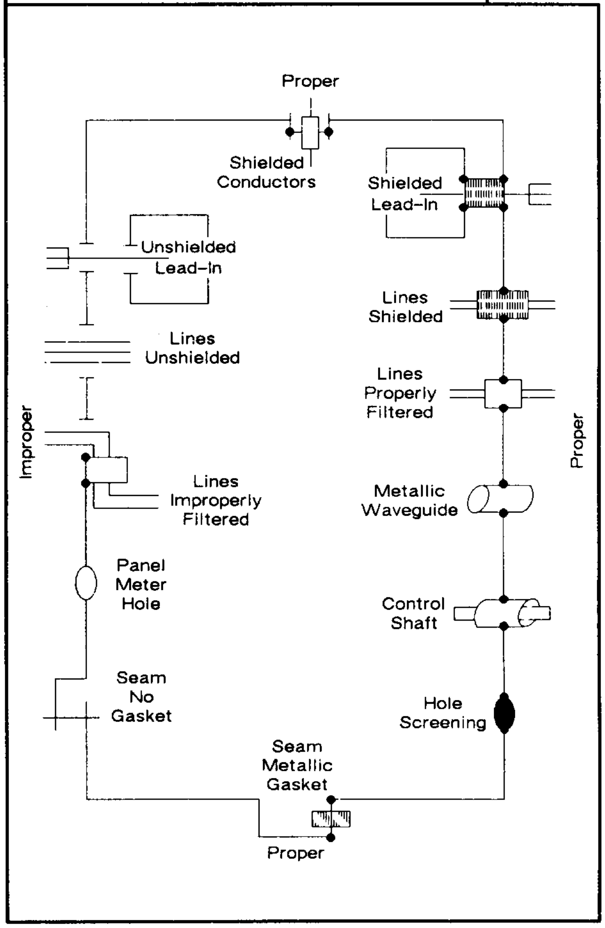
1. GENERAL

The purpose of an interference and susceptibility control specification is to provide the electromagnetic interference (EMI) engineer with the design limits he requires in the determination of shielding requirements. The system engineer should be ready to take advantage of all inherent shielding the system may have to offer. Items such as aircraft or missile skins, building walls, partitions, ship hulls, etc., may be used to advantage. The shielding effectiveness afforded by these portions of the system may be used to reduce limit requirements or to relax shielding requirements. Likewise, equipment within a console or rack may benefit from the inherent shielding of that rack. Consider carefully the impact of corrosion control requirements on shielding.

2. INTERFACES

If it were not for the many mechanical and electrical interfaces required in an aerospace system, the shielding problem would be reduced to choosing a proper shield material and applying a simple box concept. Since each interface degrades the shield to some degree, the selection and implementation of techniques to provide continuity at these interfaces is important. *Sub-Note 2(1)* illustrates some of these interfaces.

SUB-NOTE 2(1) Typical Shielded Compartment Discontinuities (Proper and Improper)

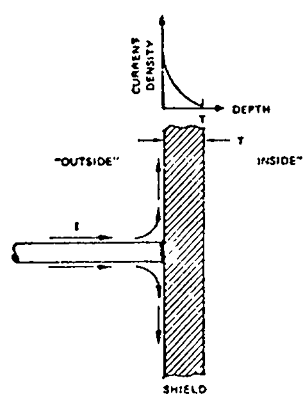


REO: ASD/ENACE
*Extracted in part from *Ref 668*. This Design Note extensively revised 31 Jan 91.

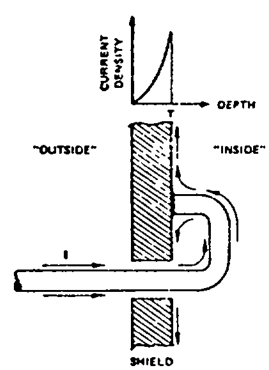
2.1 ILLUSTRATING EMI CURRENT FLOW*

When a current carrying conductor is attached to a shield, the current flows on the surface of the shield. This phenomenon, illustrated in *SN 2.1(1)a*, is a manifestation of the skin effect in conductors. It is important in application of the shielding topology because it permits interference current on the conductors to be diverted to the outside surface of the shield. When the conductor is brought through the shield as shown in *SN 2.1(1)b* and terminated to the inside surface, the conductor current is injected and/or radiated on the inside of the shield where it may interact with internal components. If transient current is very large, such as EMP, any ground conductor can be terminated on the outside of the shield or barrier and regenerated on the inside by conduction. By offsetting the external and internal ground as illustrated in *SN 2.1(2)*, this transient current can be minimized. Welding the terminals prevents holes or openings in the shield. *Sub-Note 2.1(3)* gives several examples of shielding topology with proper, compromising, and improper methods of shielding and how these currents can be restricted.

SUB-NOTE 2.1(1) EMI Current Flow

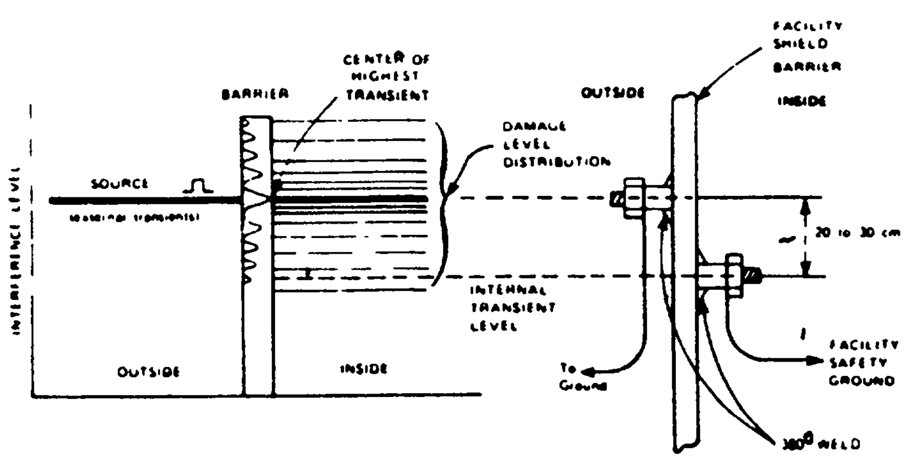


a. Confinement of conductor current to "outside" surface by skin effect.



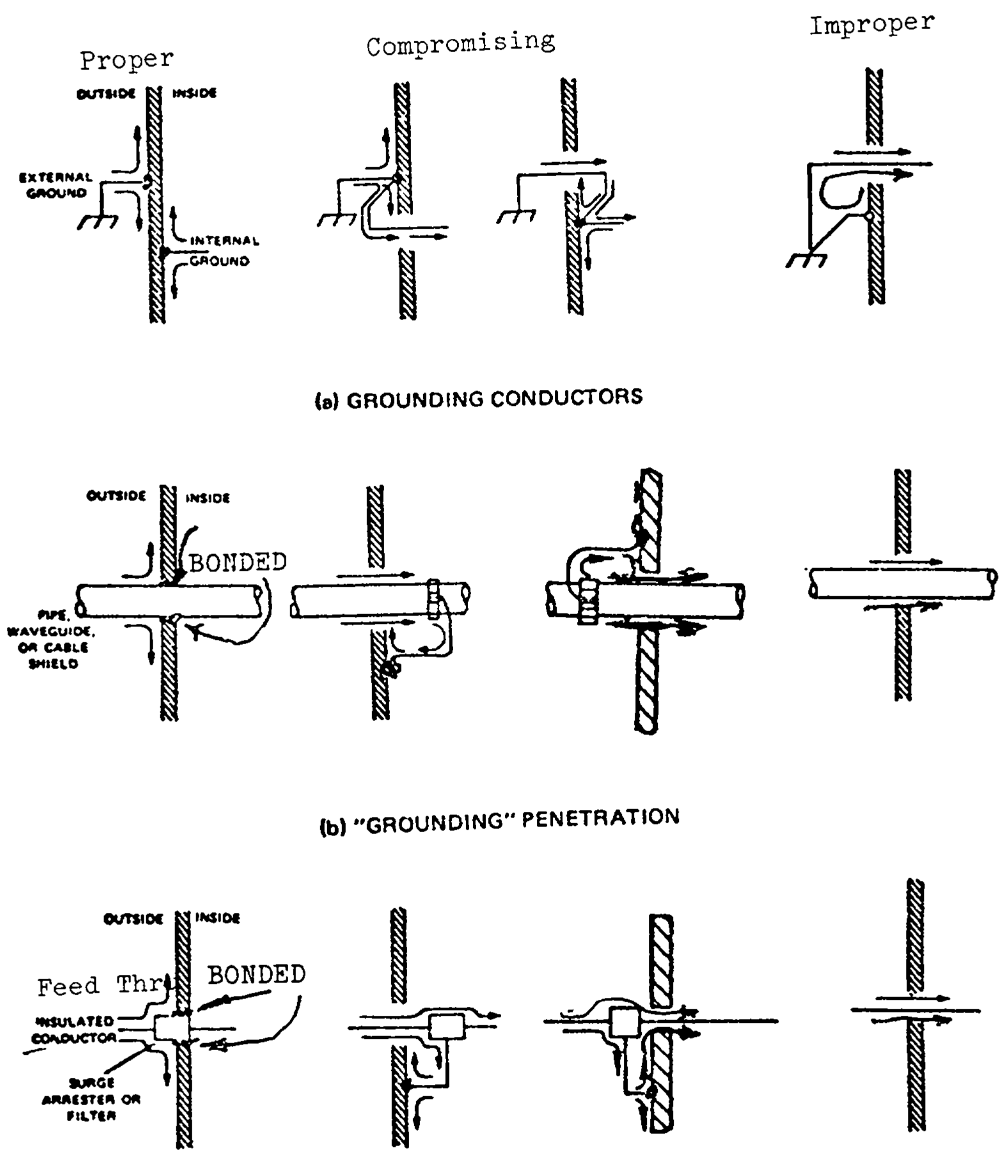
b. Conductor current injected on the "inside" of a shield.

SUB-NOTE 2.1(2) Offsetting External and Internal Ground to Minimize Transient



*Copyrighted in part from *Ref 659*.

SUB-NOTE 2.1(3) Shielding Topology



(a) GROUNDING CONDUCTORS

(b) "GROUNDING" PENETRATION

(c) INSULATED PENETRATION

3. SHIELDING EFFECTIVENESS (SE)

Shielding effectiveness is defined as the total attenuation of radiated RF electromagnetic energy realized when the energy attempts to pass through a barrier. It is an insertion loss, expressed in dB attenuation, and can be generalized as follows:

$$SE = R + A + K \quad \text{(Eq 1)}$$

Where:

R = Reflection loss for both sides in dB

A = Absorption loss in the wall material in dB

K = Correction factor for waves reflecting inside wall in dB. This factor is insignificant for metal walls of enough practical thickness to support their own weight. See *DN 5F4* for Thin Metal K Factors.

3.1 CHARACTERISTICS

In general, the absorption losses (A) are low and rise to high levels with rise in frequencies (see *SN 3.1(1)*). The reflection losses can be of three different natures, depending upon the impedance of the incident wave; the electric field R_e, the plane wave R_p, and the magnetic field R_h.

4. SHIELDING GUIDANCE

Shielding guidance is contained in *SN 4(1)*.

SUB-NOTE 3.1(1) SE Characteristics

FREQUENCY	SHIELDS IMPEDANCE	A	R_e	R_h	$SE_e = A + R_e$	$SE_h = A + R_h$
LF	Low	Low	High	Low	High	Low
HF	High	High	Low	High	High	Very High

Where E field is High Z and H field is Low Z

SUB-NOTE 4(1) Guidance for Shielding

1. Design shielded wires and enclosures to provide maximum shielding efficiency.
2. Use a minimum number of joints, seams, gasket seals, and openings.
3. Use conductive material for gasket seals.
4. Compress all RF gaskets.
5. Use a minimum number of inspection plates, adjustment holes, and screened ventilation parts.
6. Check equipment enclosure for RF leaks through:

   Meters
   Toggle switches
   Indicator lamps
   Fuse holders
   Handles
   Access doors
   Any other such openings

7. Electrically bond screens and honeycomb material to its frame.
8. Whenever possible, electrically bond all discontinuities.
9. Shield each radiation source.
10. Ensure shielding interfaces with the other EMC disciplines.

DESIGN NOTE 5F2* ABSORPTION LOSS (A)

1. INTRODUCTION

The absorption loss can be calculated by the following formula:

Wall absorption loss

$$A = 3.338 \times 10^{-3}\, T\sqrt{f\sigma\mu} \text{ in dB} \qquad \text{(Eq 1)}$$

Where:

T = Wall thickness in mils

f = Frequency in Hertz

σ = Material conductivity relative to copper

μ = Material magnetic permeability, vacuum = 1

1.1 SHIELDING MATERIAL

The choice of material for shielding purposes depends primarily on the type and degree of shielding performance desired. *Sub-Note 1.1(1)* gives the conducitivity (σ) and permeability (μ) of various metals used for shields and enclosures. Shielding effectiveness can be calculated by the equations and nomographs of *SN 2(1)* and *DN 5F3.* In some cases shielding effectiveness provided by a shield must be 60 dB or better.

2. NOMOGRAPH CALCULATION

Sub-Note 2(1) aids the designer in determining, for various magnetic and nonmagnetic materials, the penetration or absorption loss at a chosen frequency. Given a desired amount of absorption loss at a known frequency, determine the required thickness for a known metal.

a. Locate the frequency on the F scale and the desired absorption loss on the A scale. Place a straightedge across these points and locate a point on the unmarked scale. (Example: A = 10 dB, F = 100 kHz).

b. Pivot the straightedge about the point on the unmarked scale to various metals noted on the $\mu \times \sigma$ scale and the point on the unmarked scale will give the required thickness on the T scale. (Example: for copper T = 0.23 mm (9.2 mils), for commerical iron T = 0.13 mm (5.2 mils)).

c. The absorption loss graph can also be used in reverse of the above order.

3. SE AT LOW FREQUENCIES

Although the shielding effectiveness due to the absorption loss at low frequencies drops off considerably, this is of little consequence since the configuration is not likely to be an efficient receiving aperture at these frequencies.

SUB-NOTE 1.1(1) Electrical Properties of Shielding Materials (Part I)†

MATERIAL (NONMAGNETIC)‡	CONDUCTIVITY σ	MATERIAL (NONMAGNETIC)‡	CONDUCTIVITY σ
Aluminum	0.61	Magnesium	0.378
Beryllium	0.1	Monel	0.04
Brass	0.26	Phosphor-Bronze	0.18
Cadmium	0.235	Platinum	0.17
Copper(Anneald)	1.0	Silver	1.06
Copper(Harddrawn)	0.96	Stainless Steel	0.0284
Gold	0.7	Tin	0.15
Lead	0.08	Zinc	0.29

†This Sub-Note was extracted in part from Ref 1447 © and was prepared by Dr Leslie Radnay, Sr, Consultant, R&B Enterprise

‡For nonmagnetic shielding materials, $\mu = 1$ for all frequencies Therefore, the value σ is the same for $\sigma \times \mu$ and σ/μ

REO: ASD/ENACE

*The nomograph and explanation have been extracted from *Ref 1428*

SUB-NOTE 1.1(1) Electrical Properties of Shielding Materials (Part II)†

MATERIAL (MAGNETIC)	FREQUENCY (Hz)	CONDUCTIVITY σ	PERMEABILITY μ	$\sigma \times \mu$	σ/μ
Conetic*	0 to 1 k	0.0304	25 115	764	1.2×10^{-6}
Hypernick	0 to 1 k	0.035	4 529	159	7.7×10^{-6}
Iron (Commercial)	0 to 150 k	0.044	54.1	2.4	8.1×10^{-4}
Iron (Purified)	0 to 150 k	0.17	1 000	170	1.7×10^{-4}
	1M	0.17	700	119	2.4×10^{-4}
	3 M	0.17	600	102	2.8×10^{-4}
	10 M	0.17	500	85	3.4×10^{-4}
	15 M	0.17	400	68	4.3×10^{-4}
	100 M	0.17	100	17	0.0017
	1 G	0.17	50	8.5	0.0034
	1.5 G	0.17	10	1.7	0.017
	10 G	0.17	1.0	0.17	0.17
Mumetal	0 to 1 k	0.03	19 833	595	1.5×10^{-6}
Ni-Fe 50	0 to 1 k	0.12	3 162	380	3.8×10^{-5}
Netic (Blue)	0 to 1 k	0.1116	570	63.6	2.0×10^{-4}
Netic (Special)	0 to 1 k	0.1263	440	55.6	2.9×10^{-4}
Netic S3-6	0 to 1 k	0.1263	1 000	126	1.3×10^{-4}
Nichrome	0 to 1 k	0.02	18.2	0.364	0.0011
Nickel	0 to 1 k	0.2	100	20	0.002
Permalloy 4/79	0 to 1 k	0.03	20 667	620	1.45×10^{-6}
Permalloy 45	0 to 1 k	0.04	2 450	98	1.6×10^{-5}
Permalloy 78	0 to 1 k	0.035	2 692	94	1.3×10^{-5}
Primag 40*	0 to 1 k	0.0116	1 700	19.7	6.8×10^{-6}
Primag 90*	0 to 1 k	0.33	780	257	4.2×10^{-4}
Si-Fe 4%	0 to 1 k	0.0247	425	10.5	5.8×10^{-5}
Si-Fe 4% (Oriented)	0 to 1 k	0.11	4 787	527	2.3×10^{-5}
Steel (Cold Rolled)	0 to 200 k	0.17	224	38	7.6×10^{-4}
	1 k	0.17	212	36	8.0×10^{-4}
	6 k	0.17	153	26	1.1×10^{-3}
	8 k	0.17	147	25	1.16×10^{-3}
	10 k	0.17	135	23	1.26×10^{-3}
	15 k	0.17	97	16.5	1.75×10^{-3}
	20 k	0.17	86	14.6	1.97×10^{-3}
	30 k	0 17	59	10	2.88×10^{-3}
	40 k	0.17	49	8.3	3.47×10^{-3}
Steel (Galvanized)	0 to 1 k	0.1766	227	40	7.7×10^{-4}
Steel (Hot rolled)	0 to 1 k	0.1603	160	25.6	0.001
Steel (Terne)	0 to 1 k	0.1517	157	23.8	9.7×10^{-4}
Supermalloy	0 to 1 k	0.029	100 000	2900	2.9×10^{-7}

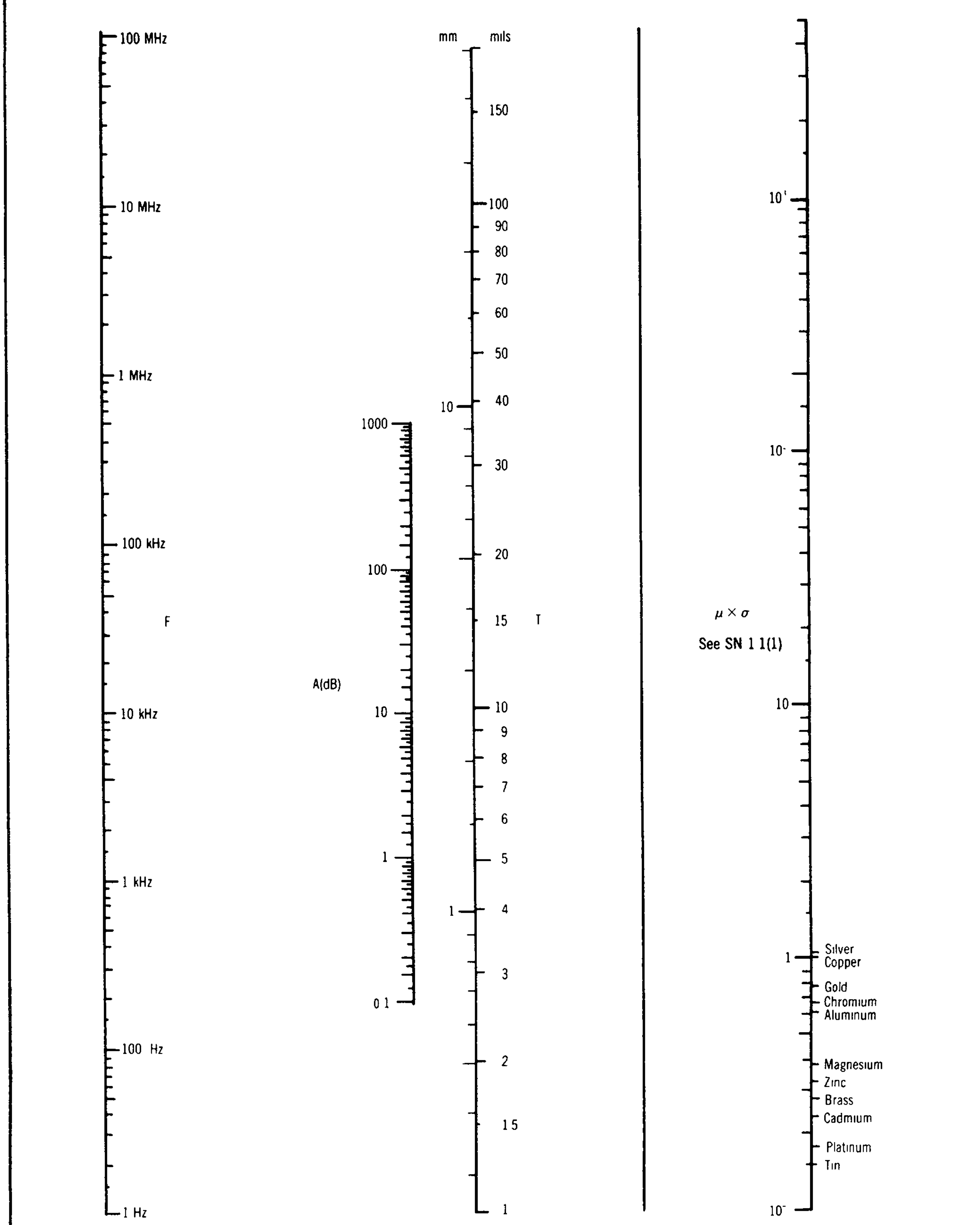
*Values given hold for magnetic induction between 3.2 and 159.2 A/m, above 318.4 A/m the permeabilities at 1 kHz are as follows:

Primag 40 48 000
Primag 90 60 000

NOTE Inquire at the manufacturers of magnetic materials for permeabilities and other magnetic properties (saturation, etc.) if used above 1 kHz! Permeabilities generally decrease with increasing frequencies. The minimum permeabilities of some materials at undefined frequencies are:

Conetic	3000		
Netic (Blue)	240		
Netic (Special)	125		
Netic (S3-6)	220		
Primag 40	1300.	above 318.4 A/m	1500
Primag 90	560	above 318.4 A/m	3000

SUB-NOTE 2(1) Absorption Losses (A)



DESIGN NOTE 5F3* REFLECTION LOSS

1. INTRODUCTION

As an electromagnetic wave propagates from free space (or air) into another medium, such as a metallic barrier, the wave impedance will change suddenly and reflection will occur at the boundary of the two media.

2. PLANE WAVE SHIELDING

For plane waves, shielding magnetic material provides the best absorption loss (since $\mu >> \sigma$ at a given thickness T) while good conductors provide better reflection loss ($\sigma >> \mu$). To calculate reflection loss for plane waves the following equation or *SN 2(1)* can be used.

$$R_p = 168.2 + 10 \log \frac{\sigma}{\mu f} \text{ in dB} \qquad \text{(Eq 1)}$$

In determining plane wave reflection loss R_p:

a. Locate a point on the σ/μ scale for one of the metals listed. If the metal is not listed, compute σ/μ and locate a point on the numerical scale.

b. Place a straightedge between the σ/μ scale and the desired frequency on the f scale.

c. Read the plane wave reflection losses from the R_p scale.

3. ELECTRIC FIELD SHIELDING

The electric field that exists close to the radiating antenna is high in impedance and is more in keeping with the nature of the radiating elements within an equipment group. The reflection loss for the high impedance wave can be calculated with the following equation or from the nomograph *SN 3(1)*:

$$R_e = 353.6 + 10 \log \frac{\sigma}{f^3 \mu D^2} \text{ in dB} \qquad \text{(Eq 2)}$$

Where:

D = Distance from radiating element to shield in inches

Both R_e and R_h can be computed using the following steps:

a. Locate a point on the σ/μ scale for one of the metals listed. If the metal is not listed, compute σ/μ and locate a point on the numerical scale.

b. Locate the distance between the energy source and the shield on the "D" scale.

c. Place a straightedge between D and σ/μ and locate a point on the blank scale.

d. Place a straightedge between the point on the blank scale and the desired frequency on the f scale.

e. Read the reflection loss from the R_e or R_h (*SN 3(2)*) scale.

f. By sweeping the f scale while holding the point on the blank scale, R_e or R_h versus frequency can be obtained.

4. MAGNETIC FIELD SHIELDING

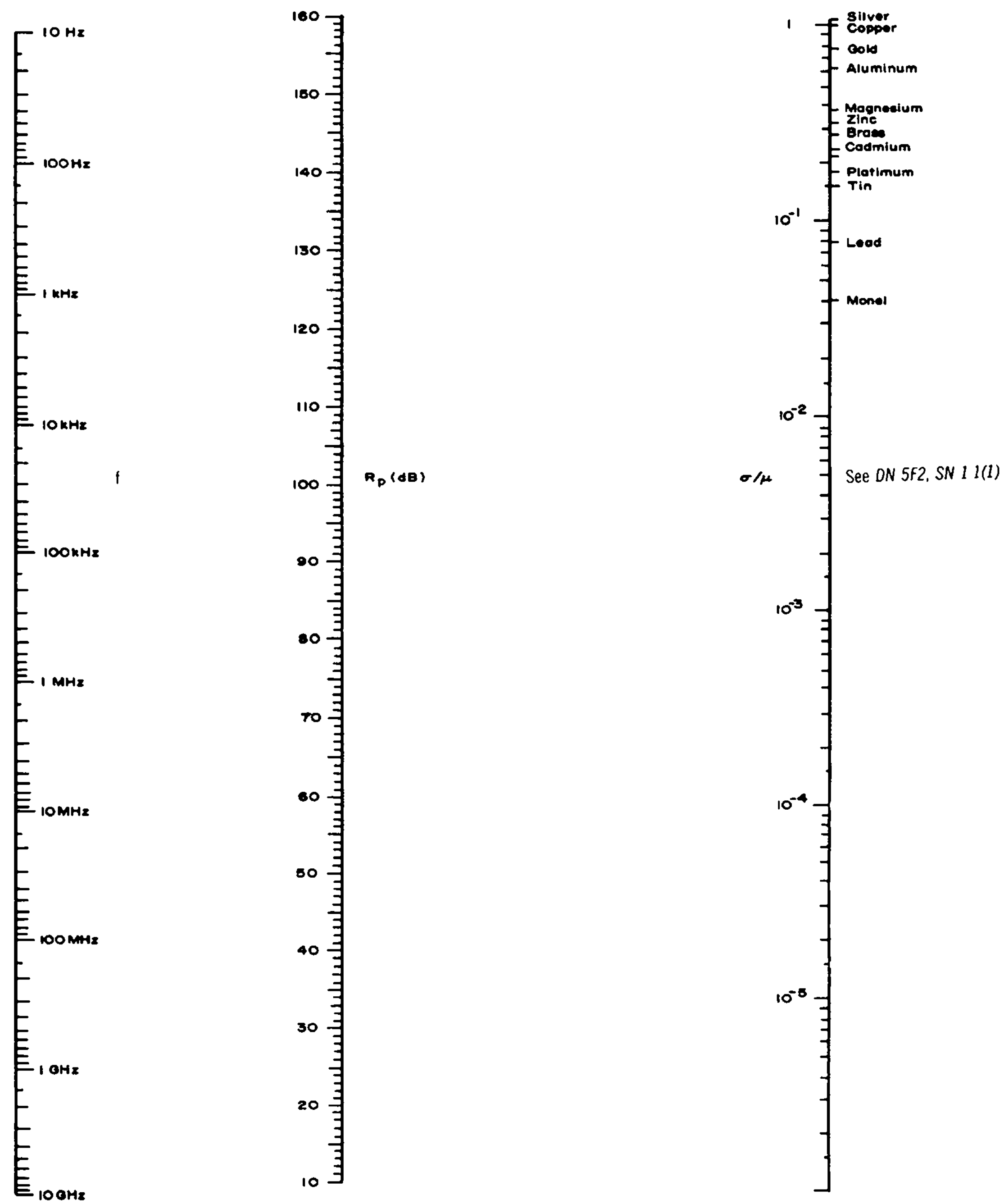
The magnetic field is known as a low impedance field. Magnetic field shielding may best be achieved through the use of magnetic material such as mumetal, permalloy, steel, etc.

$$R_h = 20 \log \left[\frac{0.462}{D} \sqrt{\frac{\mu}{f\sigma}} + 0.136D\sqrt{\frac{f\sigma}{\mu}} + 0.354 \right] \text{ in dB} \qquad \text{(Eq 3)}$$

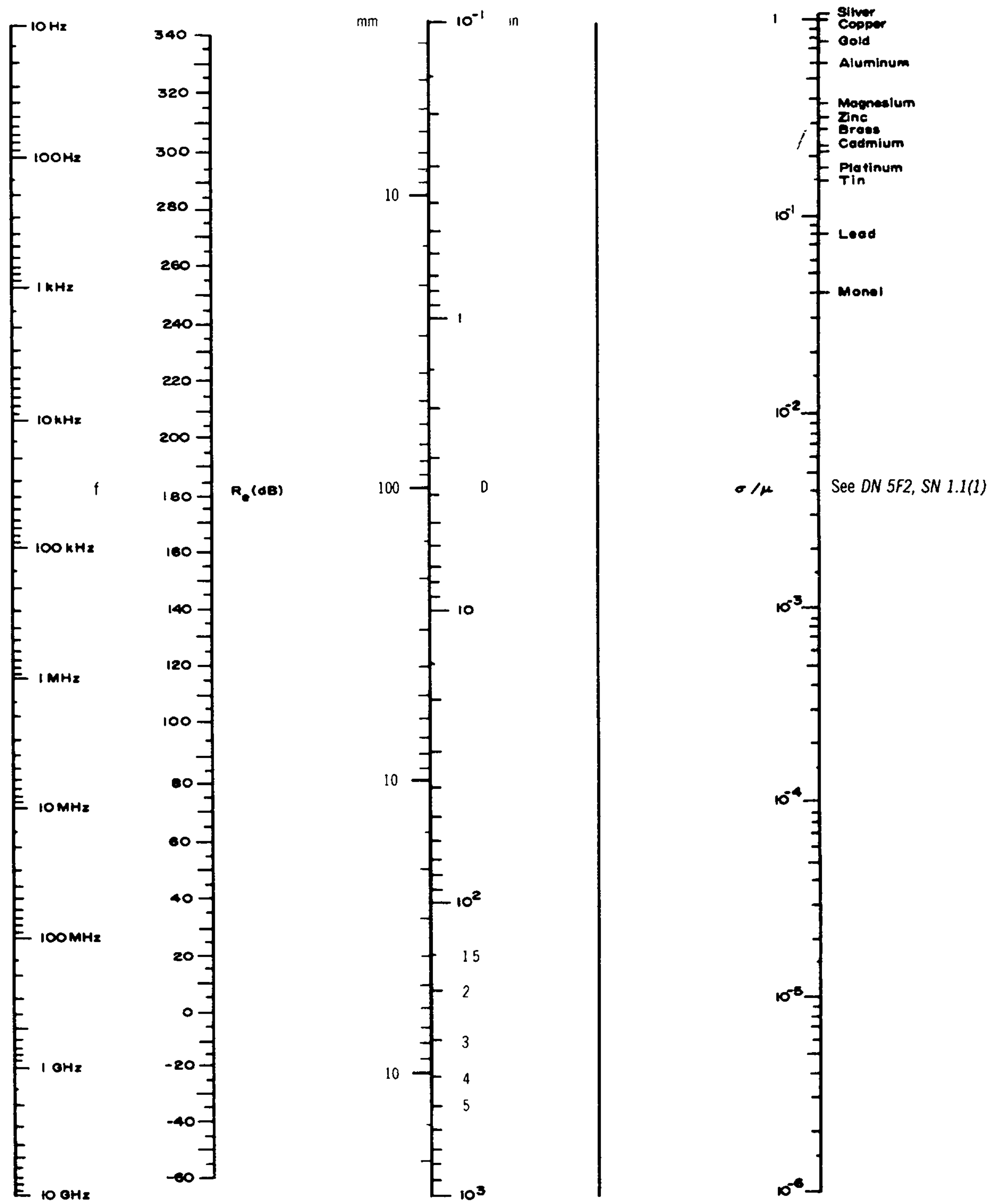
Use the nomograph *SN 3(2)* for calculating reflection loss for magnetic fields.

REO: ASD/ENACE
*The nomograph and explanation have been extracted from *Ref 1428*.

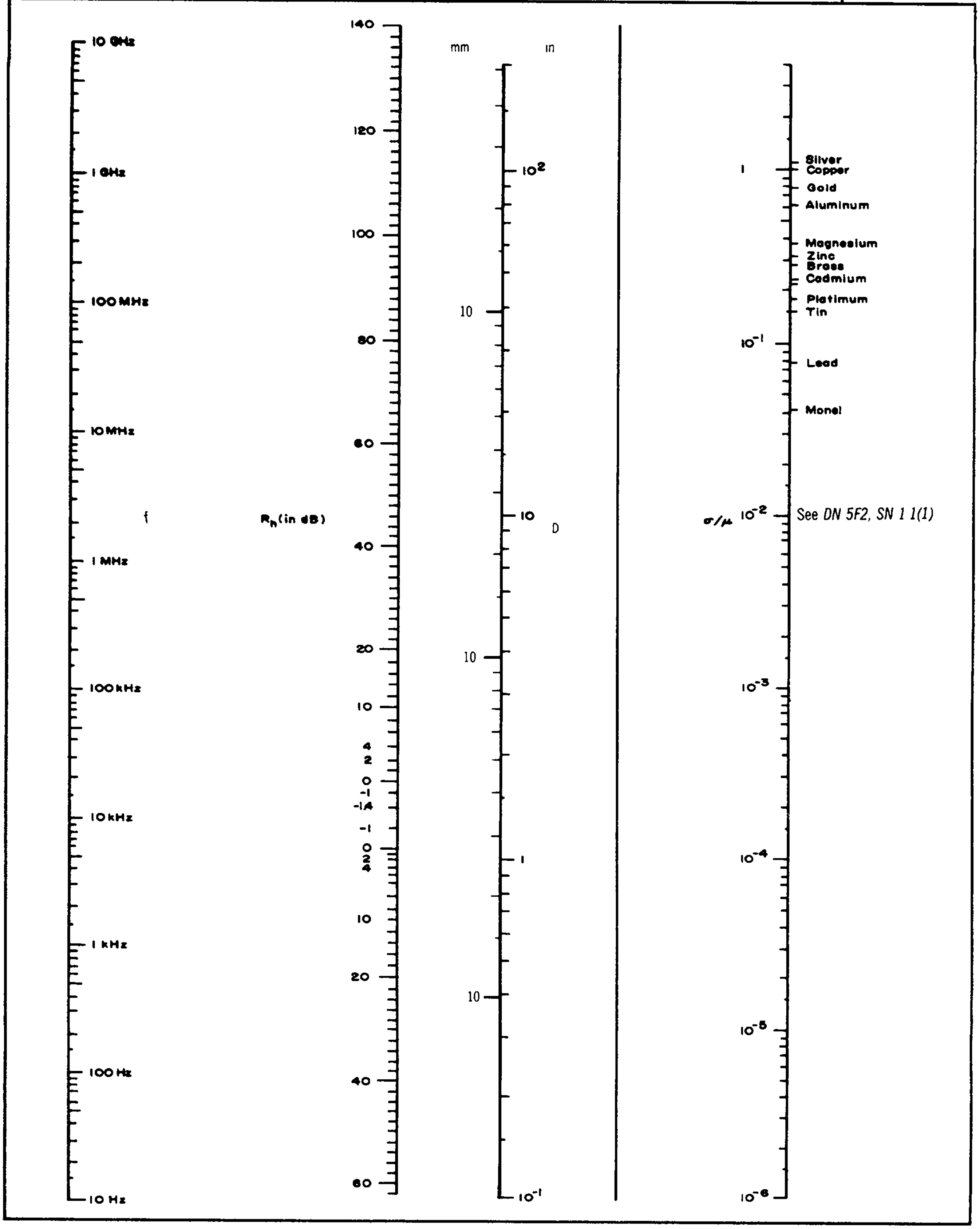
SUB-NOTE 2(1) Plane Wave Reflection Losses R_p



SUB-NOTE 3(1) Electric Field Reflection Losses R_e



SUB-NOTE 3(2) Magnetic Field Reflection Losses R_h



DESIGN NOTE 5F4 THIN METAL K FACTORS

1. INTRODUCTION

Constant K is the correction factor for thin material in decibels. The K factor is usually insignificant when absorption losses are greater than 10 dB. *Sub-Note 1(1)* gives approximate values of K for thin metals. *Sub-Note 1(2)* is obtained by plotting data given in *SN 1(1)* for copper magnetic field shielding. From this type of graph, any K correction factor can be calculated between 60 Hz and 1 MHz.

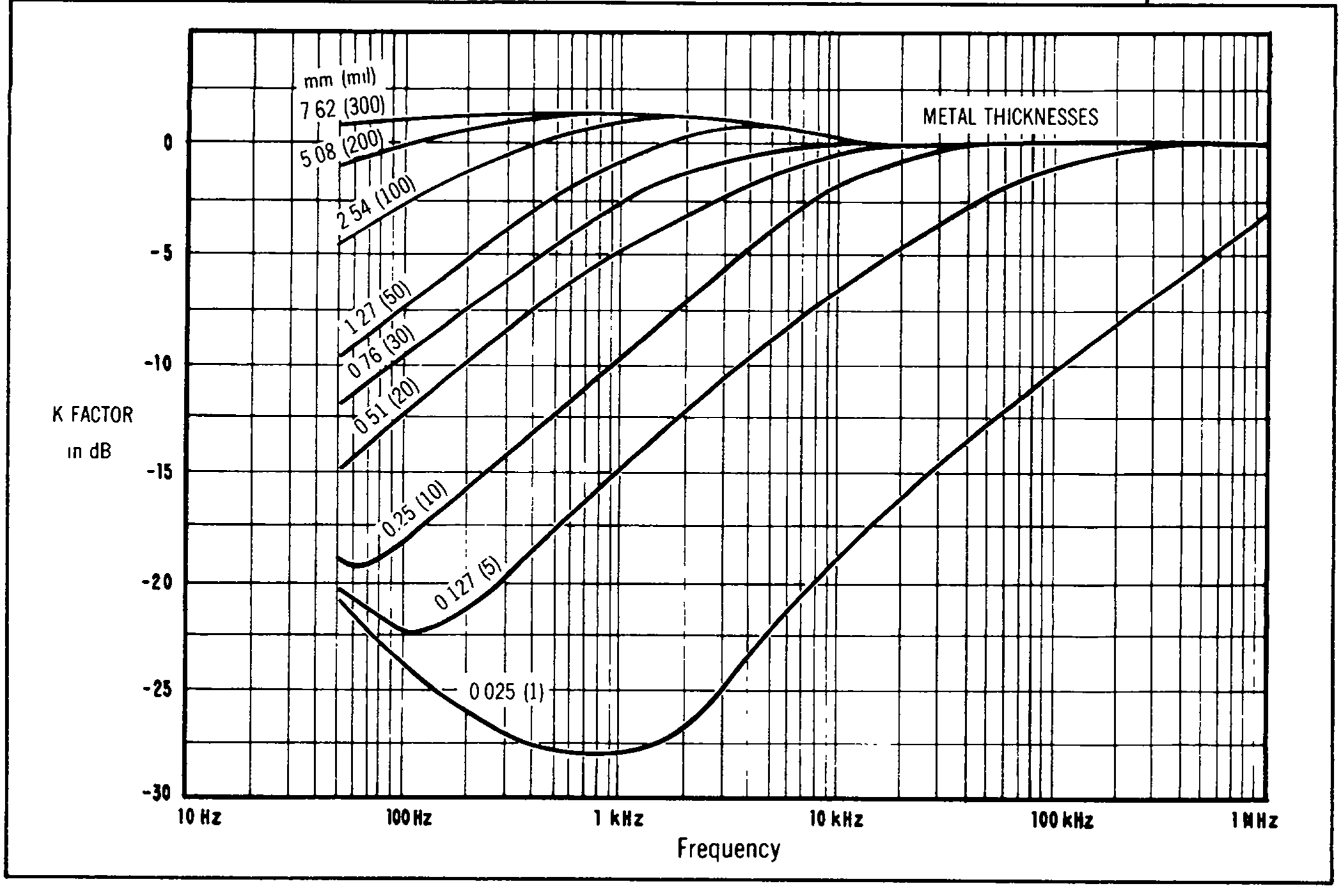
SUB-NOTE 1(1) K Correction Factors in dB for Solid Metal Shield*

	Shield Thickness mm (mils)	60 Hz	100 Hz	1 kHz	10 kHz	100 kHz	1 MHz
Magnetic Fields Copper (μ = 1, σ = 1)	0.025 (1)	-22.22	-24.31	-28.23	-19.61	-10.34	-2.61
	0.127 (5)	-21.30	-22.07	-15.83	- 6.98	- 0.55	+0.14
	0.25 (10)	-19.23	-18.59	-10.37	- 2.62	+ 0.57	-
	0.51 (20)	-15.35	-13.77	- 5.41	+ 0.13	- 0.10	-
	0.76 (30)	-12.55	-10.76	- 2.94	+ 0.58	-	-
	1.27 (50)	- 8.88	- 7.07	- 0.58	-	-	-
	2.54 (100)	- 4.24	- 2.74	+ 0.50	-	-	-
	5.08 (200)	- 0.76	+ 0.05	-	-	-	-
	7.62 (300)	+ 0.32	+ 0.53	-	-	-	-
Electric Fields and Plane Waves Copper (σ = 1, μ = 1)	0.025 (1)	-41.52	-39.31	-29.38	-19.61	-10.33	-2.61
	0.127 (5)	-27.64	-26.46	-15.82	- 6.96	- 0.55	+0.14
	0.25 (10)	-21.75	-19.61	-10.33	- 2.61	+ 0.57	-
	0.51 (20)	-15.99	-13.92	- 5.37	+ 0.14	- 0.10	-
	0.76 (30)	-12.73	-10.73	- 2.90	+ 0.58	-	-
	1.27 (50)	- 8.81	- 6.96	- 0.55	+ 0.14	-	-
	2.54 (100)	- 4.08	- 2.61	+ 0.51	-	-	-
	5.08 (200)	- 0.62	+ 0.14	-	-	-	-
	7.62 (300)	+ 0.41	+ 0.58	-	-	-	-
Magnetic Fields Iron (μ = 1000, σ = 0.17)	0.025 (1)	+ 0.95	+ 1.23	- 1.60	- 1.83	-	-
	0.127 (5)	+ 0.93	+ 0.89	- 0.59	-	-	-
	0.25 (10)	+ 0.78	+ 0.48	+ 0.06	-	-	-
	0.51 (20)	+ 0.35	+ 0.08	-	-	-	-
	0.76 (30)	+ 0.06	- 0.06	-	-	-	-
	1.27 (50)	-	-	-	-	-	-
Electric Fields and Plane Waves Iron (μ = 1000, σ = 0.17)	0.025 (1)	-19.53	-17.41	- 8.35	- 1.31	-	-
	0.127 (5)	- 6.90	- 5.17	+ 0.20	-	-	-
	0.25 (10)	- 2.56	- 1.31	+ 0.36	-	-	-
	0.51 (20)	+ 0.16	+ 0.54	-	-	-	-
	0.76 (30)	+ 0.58	+ 0.42	-	-	-	-
	1.27 (50)	+ 0.13	-	-	-	-	-

*Extracted from *Ref 108*

REO ASD/ENACE

SUB-NOTE 1(2) Graph of K Correction Factor for Copper Magnetic Field



DESIGN NOTE 5F5* SEAMS

1. INTRODUCTION

Good bonding technique is needed to obtain a seam that is electromagnetically tight. Radio frequency (RF) interference leakage problems primarily stem from improperly bonded seams. Slits which result in gaps and degrade the shielding effectiveness are most commonly produced by poor spot welds or poorly spaced fasteners such as screws or rivets. A detailed study of the bonding technique is given in *Sect 5D.*

2. CONSTRUCTION OF SEAMS

Several configurations for seams between two metallic members within an aerospace system are shown in *SN 2(1).* The preferred seam is a continuous weld around the periphery of the mating surfaces. The type of weld is not critical, provided the weld is continuous.

2.1 OVERLAPPING SEAM

An acceptable alternative technique is the overlap seam shown in "D" of *SN 2(1).* In an overlap seam, all nonconductive materials must be removed from the mating surfaces before the surfaces are crimped, and the crimping must be performed under sufficient pressure to ensure positive contact between all mating surfaces. *Sub-Note 2.1(1)* summarizes, in order of preference, techniques for implementing permanent or semipermanent seams.

2.2 RF IMPEDANCE

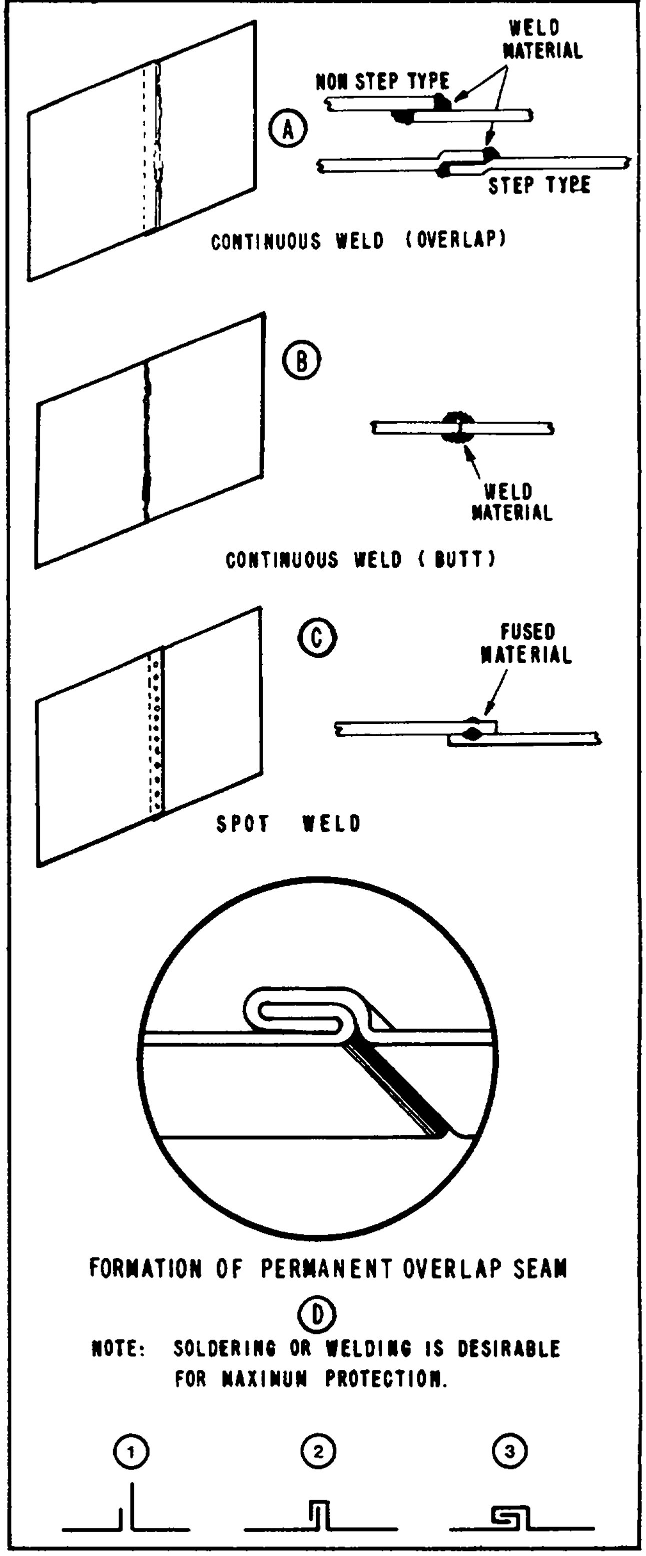
Regardless of the type of seam used, the RF impedance of the seam must not differ appreciably from that of the materials being joined. If the RF impedance of the seam is relatively high, RF voltages can develop across the seam from skin currents, permitting RF energy to enter the shielded enclosure. It is sometimes necessary to use continuous welding of seams to ensure shielding effectiveness.

2.3 CONSIDERATIONS

Seams that are properly bonded will provide a low impedance to RF current flowing across the seam. Wherever possible, mating surfaces of metallic members within an aerospace system should be bonded together by welding, brazing, sweating, swaging, soldering, or metal-forming. To assure adequate and properly implemented bonding techniques, observe the following recommendations.

a. All mating surfaces must be cleaned before bonding.

SUB-NOTE 2(1) Panel Seam Configurations

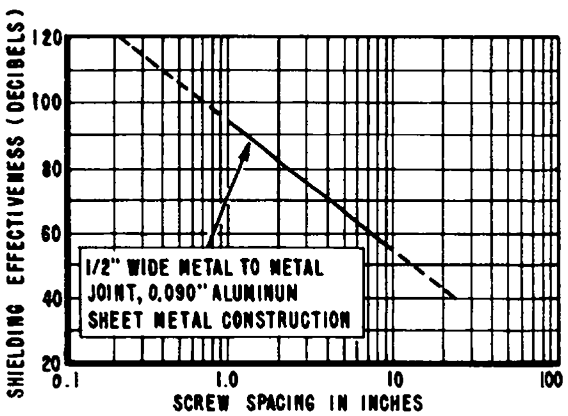


REO _ ASD/ENACE

*Extracted in part from *Ref 668*

SUB-NOTE 2.1(1) Types of Seams in Order of Preference		
PREFERENCE	**TYPE OF SEAM**	**REMARKS**
1	Continuous weld	Best RF seam
2	Spot weld	Space weld joints less than 51 mm (2 in.) apart
3	Crimp seam	Use strong and lasting crimping pressure; pressure is maintained by spot welding

SUB-NOTE 2.3(1) Shielding Effectiveness Versus Screw Spacing



25 4 mm = 1 in.

b. All protective coatings having a conductivity less than that of the metals being bonded must be removed from the contact areas of the two mating surfaces before the bond connection is made. (The conductivity of coatings, such as anodizing materials, should be verified with the manufacturer whenever it is questionable.)

c. When protective coatings are necessary, design them so that they can be easily removed from mating surfaces. Since the mating of bare metal to bare metal is essential for a satisfactory bond, a conflict may arise between the bonding and finish specifications. It is preferable to remove the finish where compromising of the bonding effectiveness would occur.

d. Generally, protective metal platings such as cadmium, tin, or silver need not be removed. Coatings having poor conductivity destroy the effectiveness of a bond to produce a low impedance RF path.

e. Mating surfaces should be bonded immediately after protective coatings are removed to avoid oxidation.

f. The nonreplaceable portion of a bonded joint that must be formed by dissimilar metals should be a metal lower in the electromotive force series than its mate (see *SN 2(1)* of *DN 5D3*). When two dissimilar metals must be bonded, select metals that are close to one another in the electromotive force series.

g. Bolted sections may be used for temporary bonds. However, bolted sections could be bonded to ensure consistent contact pressure over an extended period of time. Shield material must be rigid enough to prevent buckling between contact points.

h. When bolts or rivets are used to make a bond, they should be applied first at the middle of the seam and then progressively applied toward the ends of the seam to prevent the mating surfaces from buckling. *Sub-Note 2.3(1)* is a plot of shielding effectiveness as a function of the spacing of the screws that fasten the two surfaces together. The shielding effectiveness of the joint depends on the number of screws per linear inch, the pressure of the contacting surface, and the cleanliness of the two mating surfaces.

i. When pressure bonds are made, the surfaces must be clean and dry before mating and then held together under high pressure to minimize the growth of oxidation due to moisture entering the joint, since the joint may not be 100% moisture-tight. The periphery of the exposed joint should then be sealed with a suitable protective compound and, whenever possible, one that is highly conductive to RF currents.

2.4 RF BONDS

When implementing bonding techniques, always remember that bonding straps do not provide a low impedance current path at RF frequencies. The important impedance exists at radio frequencies. There is little correlation between the dc resistance of a bond and its RF impedance. Even the measured RF impedance of bonds such as jumpers, straps, or rivets, is not a reliable indication of the bonding effectiveness in the actual installation. Conductive epoxies and pastes do not always produce sufficient RF bonds. Even when proved effective in given instances, they have been known to degrade RF shielding effectiveness under conditions of strain, pressure, and the passage of time.

DESIGN NOTE 5F6* RF GASKETS

1. INTRODUCTION

Where continuous welding or overlap seams cannot be employed, radio frequency (RF) gasket material may be used. Gasket matrial is inserted between the mating surfaces and a high pressure is maintained against the seam. It is essential to clean the mating surfaces thoroughly before inserting the gasket material.

2. CONSTRUCTION

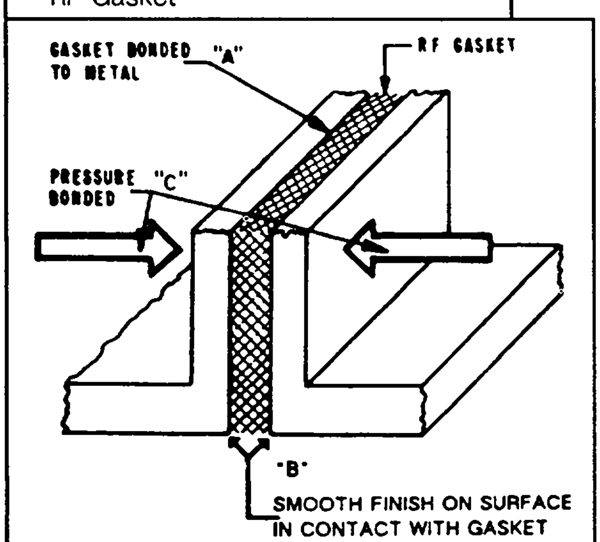
Sub-Note 2(1) illustrates an acceptable method of making a construction seam using RF gasket material. The features to be observed in figure are:

"A" - Gasket bonded to one metallic surface of the seam with conductive adhesive; surfaces cleansed of nonconductive material before application.

"B" - Metallic surface machined to smooth finish and all nonconductive materials removed.

"C" - Appropriate mechanical techniques (i.e., clamps, bolts, etc.) used to provide a high pressure on the RF gasket. The pressure must be nearly uniform along the entire length of the seam.

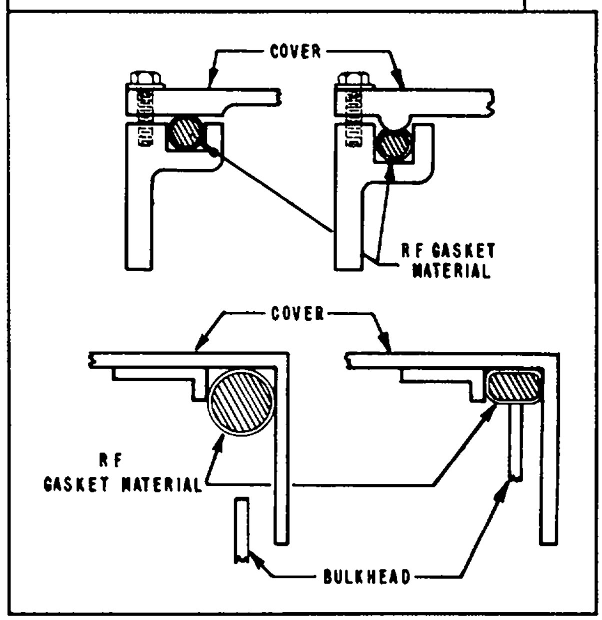
SUB-NOTE 2(1) Acceptable Method of Making Permanent Seam Using RF Gasket



3. CHARACTERISTICS

Sub-Note 3(1) illustrates acceptable methods of makng construction seams where sections must be removed and replaced for maintenance or loading and handling operations. *Sub-Note 3(2)* is a guide to RF gasket design and usage. *Sub-Note 3(3)* lists types of gasket material, citing advantages and disadvantages of each. *Sub-Note 3(4)* lists the three materials most frequently used for RF gaskets.

SUB-NOTE 3(1) Covers with Gaskets



3.1 CORROSION RESISTANCE

In *SN 3(4)*, the first comparison is on the basis of corrosion resistance, with the first column indicating intrinsic corrosion resistance and the second indicating compatibility with aluminum. Since RF gaskets are frequently butted against aluminum flanges, and since most are not made from aluminum (due to the tendency of noncon-ductive aluminum oxide to form readily), a galvanic corrosion potential exists when RF gasketed aluminum flanges are placed in service, especially in salt fog environments. In addition to the recommendations for corrosion resistance given in *SN 3(4)*, the following design guidelines should be followed whenever possible:

a. Provide positive sealing to prevent moisture from reaching the flange-gasket interface.

REO: ASD/ENACE
*Extracted in part from *Ref 668*.

SUB-NOTE 3(2) RF Gasket Design and Usage	
GASKET CONSIDERATION	DETERMINED BY
Material	Corrosion resistance, mechanical wear, resilience, compression set, GRF properties, and aging characteristics
Form	Attachment methods, force available, other gasketing functions, joint unevenness, and space available
Thickness	Class of joint, joint unevenness, force available, and RF level

SUB-NOTE 3(3) Types of RF Gaskets		
GASKET TYPE	ADVANTAGES	DISADVANTAGES
Knitted Wire Mesh (Monel, *tin-plated copper-clad steel, or aluminum)	Excellent attenuation below 1 GHz; bites through thin nonconductive oxides; highly compressible under modest closure forces; withstands EMP-induced current pulses.	Subject to severe permanent set; attenuation falls off rapidly above about 1 GHz; does not provide moisture seal (unless bonded to elastomer gaskets); tends to shed wire particles at cut ends.
Beryllium-Copper Spring Fingers (straight or spiral construction)	Good-to-excellent attenuation at high and low frequencies; highly deformable under modest closure forces; provides wiping contact action; available with *tin, silver, or gold plating.	Subject to permanent creasing and set; subject to breakage of individual fingers; does not provide moisture seal (unless bonded to elastomer gasket). Sensitive to sulfides, ammonia compounds, hydrogen embrittlement and stress corrosion cracking.
Conductive Elastomers (silicone or fluorosilicone elastomers filled with pure silver, silver-plated copper, silver-plated aluminum, or silver-plated glass particles)	Excellent attenuation, especially at high frequencies; provides inherent moisture/pressure sealing; hollow extrusions are highly compressible under low closure forces; can be precision-molded; some versions provide excellent corrosion resistance against aluminum (silver-plated-aluminum filled); good long-term aging if properly manufactured.	Limited to continuous operating temperatures of 125 to 200°C; some versions (pure silver or silver-plated-copper-filled) cause galvanic corrosion of aluminum if outside edges are not sealed in salt spray environments; some versions (silver-plated-glass-filled) lose their conductivity during vibration, long-term compression, or EMP environments; poor long-term aging if improperly manufactured.
*Tin-plating should be used only when approved by a material specialist.		

SUB-NOTE 3(4) Comparison of Common RF Gasket Materials

MATERIAL	CORROSION RESISTANCE		CONDUCTIVITY		MECHANICAL	
	Intrinsic	Against Aluminum	Intrinsic	With Surface Film	Compression Set	Conformability
Monel Mesh	1	3	3	1	3	2
Tin/Copper/Steel Mesh	2	2	1	1	3	2
Aluminum Mesh	3	1	1	3	3	2
Beryllium-Copper Fingers	2	2	2	2	2	2
Pure Silver Elastomer	2	3	1	2	1	1
Silver-Copper Elastomer	2	2	2	2	1	1
Silver-Aluminum Elastomer	2	1	2	2	1	1

In order of preference: best = 1 poor = 3

b. Treat flanges with a protective conductive finish (such as *MIL-C-5541* Class 3 chromate conversion coating).

c. Prime outboard edges and paint them with a protective, nonconductive paint. Where possible, allow this paint to intrude about $^1/_{16}$ to $^1/_8$ in. into the gasketed portion of the flange.

d. Locate fastener holes within or outboard of moisture sealing gasket.

e. Avoid designs which create sumps where moisture will collect and remain.

The relationship of galvanic corrosion resistance is indicated in *SN 3.1(1)*. Best corrosion resistance is achieved by using materials that are in close proximity on the list. For example, nickel plating on aluminum, or tin plating on copper would be poor selections.

3.2 CONDUCTVITY

Gasket materials should be ranked according to their conductivity with surface films rather than by their intrinsic conductivity, because surface corrosion films may form which can greatly reduce the actual conductivity of an RF gasket. See *SN 3(4)*.

3.3 MECHANICAL PROPERTIES

The most important mechanical properties of RF gaskets are compression set and conformability. Materials with a low compression set function effectively for longer periods of time and after repeated opening/closing cycles. Materials which conform most intimately to flange surface irregularities provide highest levels of attenuation. These properties are ranked as shown in *SN 3(4)*.

4. BONDING CHARACTERISTICS OF GASKETS

Design Note 5D2, Para 7.2, gives some of the bonding characteristics of RF gaskets.

5. CORROSION CONTROL

For information on design techniques to minimize corrosion when using RF gaskets, see *NAVMAT P 4855-2 Design Guidelines for Prevention and Control of Avionic Corrosion.*

SUB-NOTE 3.1(1) Grouping of Metals and Alloys

ANODIC **GALVANIC SERIES (SEA WATER)**

High Potential End ↕ Low Potential End

- Magnesium Alloys
- Beryllium
- Zinc
- Galvanized Steel
- Aluminum Alloys
- Chromium
- Gallium
- Cadmium
- Mild Steel
- Wrought Iron
- Indium
- Low-Alloy Steels
- Cast Iron
- Low-Alloy Cast Iron
- 4—6% Cr Steel
- Ni Cast Iron
- 12—14% Chromium Steel and 25—30%
- Lead-Tin Solders
- 16—18% Chromium Steel
- Austenitic Cr-Ni Stainless Steel
- Austenitic Cr-Ni-Mo Stainless
- Lead
- Tin
- Manganese Bronze
- Naval Brass
- Cobalt
- Nickel
- Inconel (13% Cr, 6.5% Fe, Bal Ni)
- Yellow Brass
- Admiralty Brass
- Aluminum Bronze
- Red Brass
- Antimony
- Copper
- Silicon Bronze
- Nickel Silver
- 70-30 Copper Nickel
- Titanium
- Monel
- Composition G Bronze (88% Cu, 2% Zn, 10% Sn)
- Composition M Bronze (88% Cu, 3% Zn, 6.5% Sn, 1.5% Pb)
- Silver Solder
- Nickel (Passive)
- 70-30 Nickel Copper
- Stainless Steels (Passive)
- Silver
- Palladium
- Gold
- Rhodium
- Platinum
- Carbon

CATHODIC

Extracted from *NAVMAT P 4855-2*.

DESIGN NOTE 5F7* NONSOLID SHIELD

1. INTRODUCTION

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 employed if an enclosure must be transparent (e.g., a meter face) or ventilated.

2. WOVEN MATERIAL

Since there is no precise means of calculating the shielding effectiveness (SE) of woven materials, the EMC designer is referred to literature for the attenuation characteristics of the various materials and configurations. Often, the exact situation may not be treated sufficiently; therefore, the designer must perform measurements to validate the shielding effectiveness and the configuration intended for use in the aerospace system.

2.1 CHARACTERISTICS

In general, the SE of woven materials for radiated fields decreases with increasing frequency, and the SE increases with the density of the weave. In the induction field where the magnetic component is large, the SE increases with frequency, with the density of the woven material, and with the permeability of the material.

2.2 SHIELDING EFFECTIVENESS (SE) OF WIRE MESH

Sub-Note 2.2(1) shows the magnetic field shielding effectiveness for three sizes of copper mesh. Because of the variation in commercial meshes and screens, verify use by testing. Extensive data on a number of different screen materials and mesh sizes are presented in *Ref 62, Chap 2, Sect IV.*

3. SE CALCULATIONS FOR PERFORATED SHIELDS

The graphs and nomographs (*SN 3(1)* through *SN 3(8)*) are taken from *Ref 473*©. The factors which define the SE of perforated shields are:

$$SE = A + R + B + K_1 + K_2 + K_3$$
(Eq 1)

Where:

SE = Shielding effectiveness, decibels

A = Aperture attenuation or absorption loss

R = Aperture reflection losses

B = Correction factor for aperture reflections

K_1 = Correction factor for the number of openings per unit square

K_2 = Correction factor for conductor penetration at low frequencies

K_3 = Correction factor for coupling between closely spaced shallow holes.

The SE for perforated shields can be calculated by using *SN 3(1)* through *SN 3(8)* and *Eq 1*. All parameters must be calculated in the same units (metric or nonmetric).

3.1 PERFORATED SHIELD EQUATIONS

The following six factors are used to compute the performance of the perforated shields:

a. Aperture attenuation (A) in decibels:

$A_c = 32\ L/D$ for circular apertures
(Eq 2)

$A_r = 27.3\ L/W$ for rectangular apertures
(Eq 3)

Where:

L = Aperture length

W = Greatest rectangular aperture width

D = Circular aperture diameter

The A factor represents attenuation (at frequencies below cutoff) as the wave passes through an aperture. For rectangular openings, W is the dimension perpendicular to the incident field.

b. Aperture reflection losses (R) in decibels:

$R = 20 \log [J/4 + 1/2 + 1/4J]$
(Eq 4)

Where:

J = Z_a/Z_w, the ratio of the aperture characteristic impedance to the impedance of the incident wave as listed in *SN 3.1(1)*.

OPR: ASD/ENACE
*Extracted in part from *Ref 473*©. (Courtesy of R.B. Cowdell)

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

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

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

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

And:

f = Frequency, Hz

r = Signal source to shield distance, mm (in.)

μ = Material permeability; see *DN 5F5, SN 1(1)*.

ϵ = Dielectric constant

Reflection losses are an interaction between the impedance of an incident wave and the waveguide, hence, the resulting charts for electric (e), magnetic (m), and plane wave (p) fields incident upon circular or rectangular shaped apertures.

c. Correction factor for aperture reflection losses (B) in decibels:

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

(Eq 5)

B is correction factor to reflection losses when A is less than 10 dB.

d. Correction factor (K_1) in decibels for openings per unit square:

$$K_1 = -10 \log an$$

(Eq 6)

Where:

a = Hole area, square centimeter (square inch)

n = Number of holes per square centimeter (square inch).

This factor is to be used for all perforated shields. The amount of power transferred through a perforated shield is a function of the number of openings.

e. Correction factor (K_2) for conductor penetration at low frequencies in decibels.

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

(Eq 7)

For screening, substitute c_w for d^2 for perforated sheets.

Where:

σ = Material conductivity

c_w = Conductor width between holes

d = Wire diameter

K_2 can be used for all screen-type perforated shields. This factor assumes that the waveguide depth for screens is equal to the wire diameter. At low frequencies, the skin depth becomes comparable to the radius of the wire and a considerable loss in shielding effectiveness occurs. The results of testing were plotted and an empirical equation derived to yield K_2.

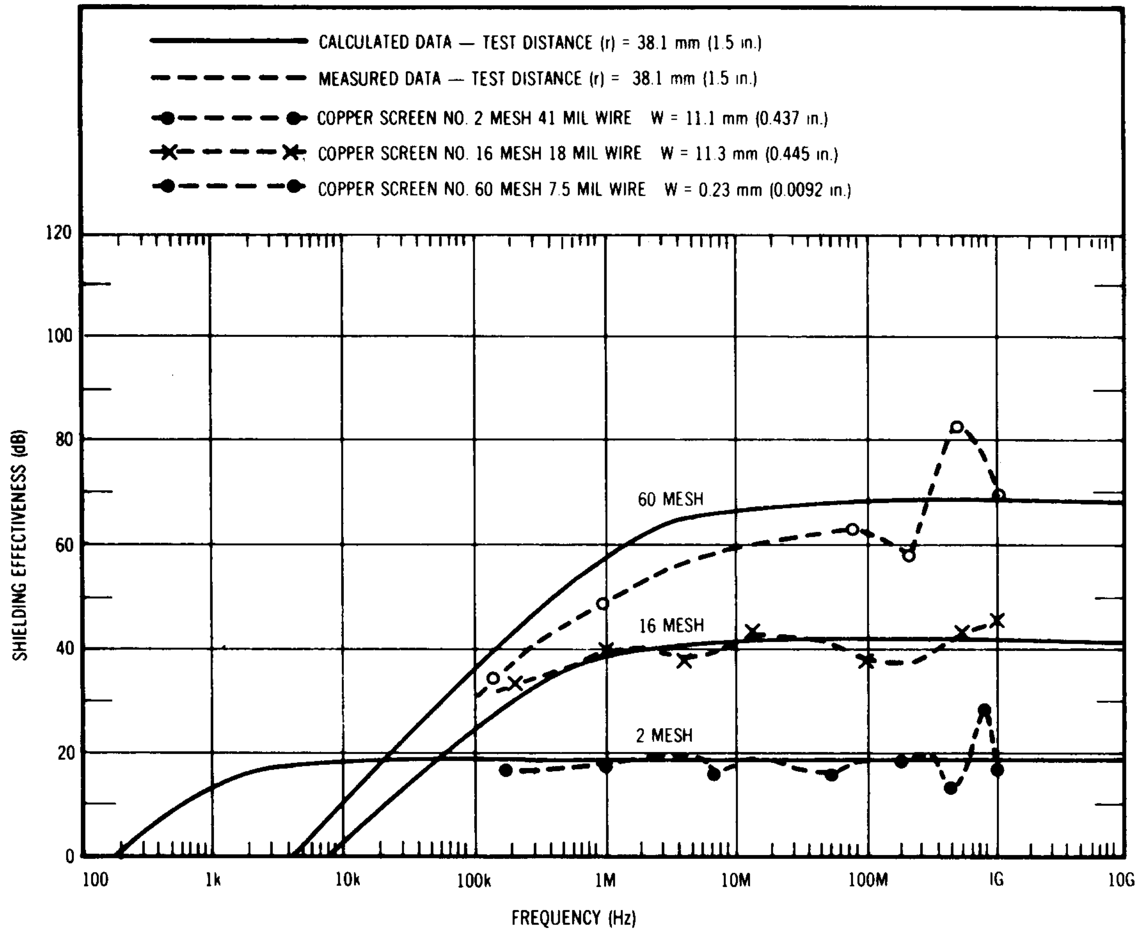
f. Correction factor (K_3) for coupling between closely spaced, shallow holes in decibels.

$$K_3 = +20 \log [1/\tanh(A/8.686)]$$

(Eq 8)

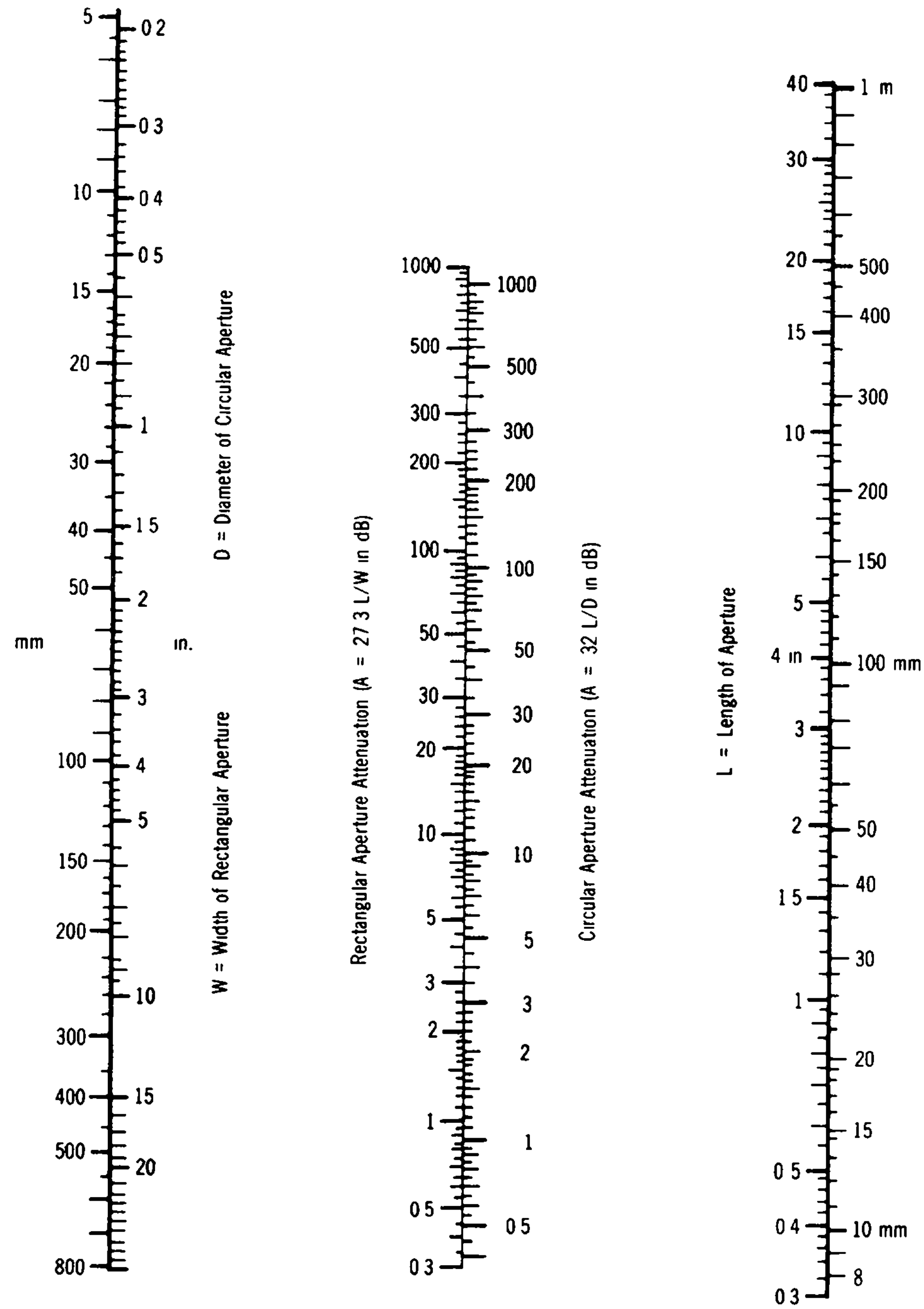
Shielding effectiveness has been found to increase when holes are closely spaced and the opening depth is small compared to hole size.

SUB-NOTE 2.2(1) Magnetic Field Shielding Effectiveness vs Frequency for Copper Wire Mesh*



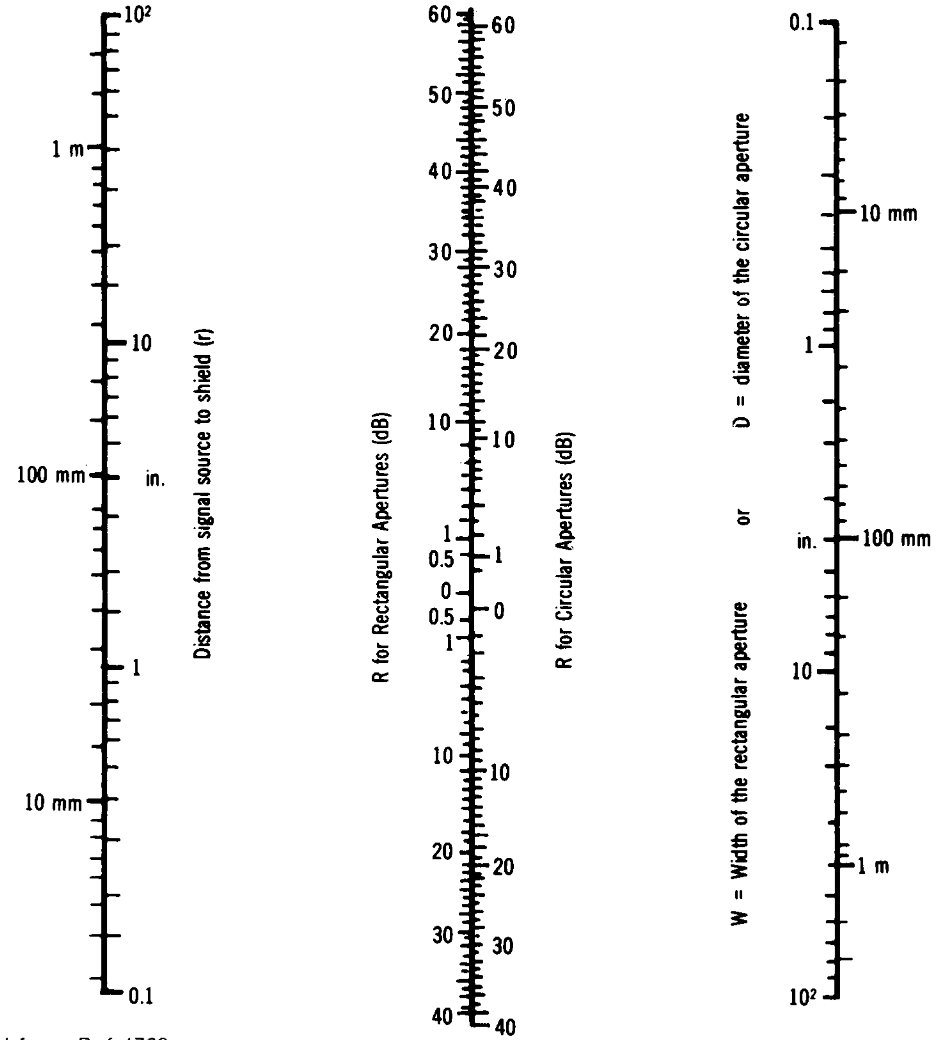
*Extracted in part from *Ref 473*©

SUB-NOTE 3(1) Aperture Attenuation (A)*



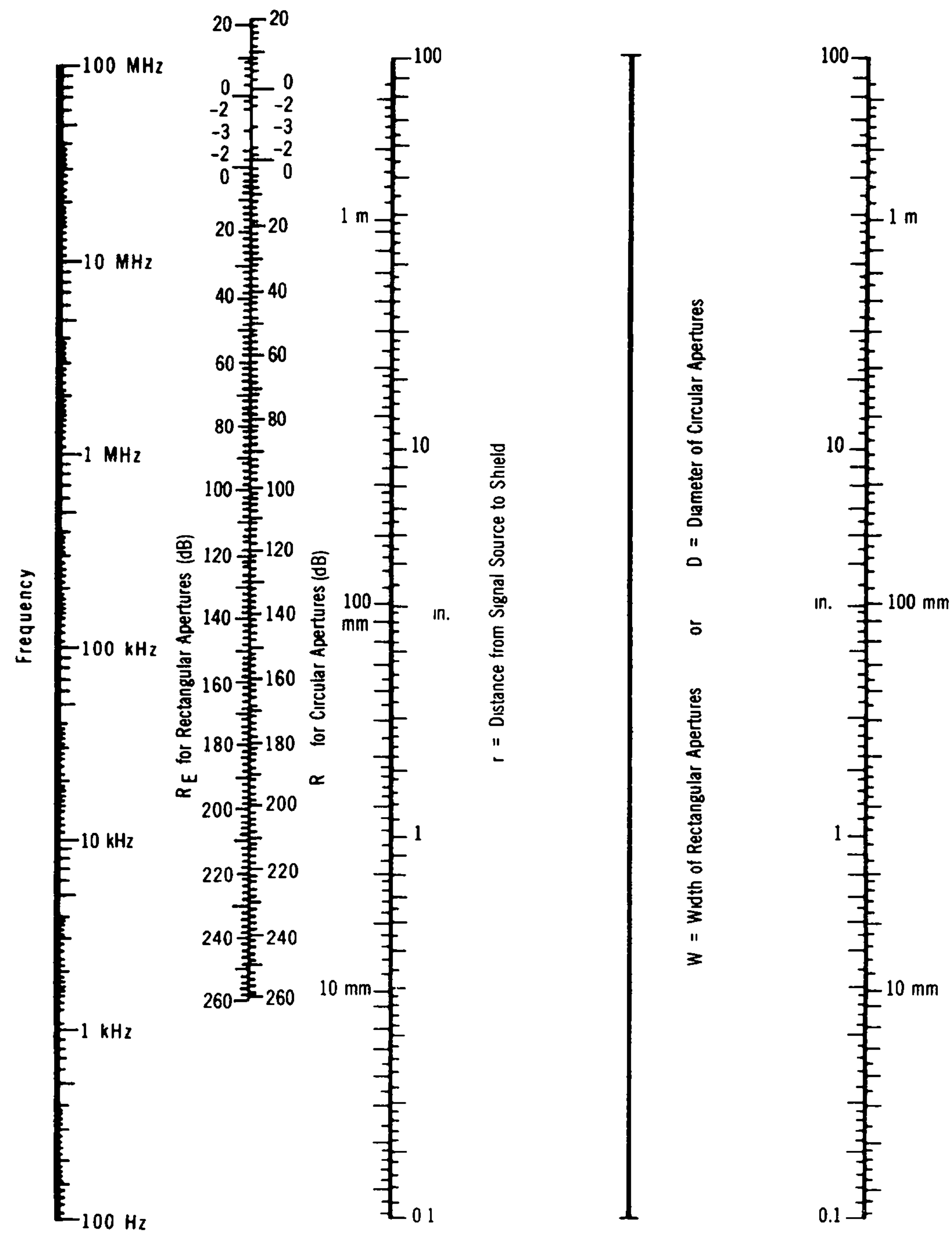
*Extracted from *Ref 473*©

SUB-NOTE 3(2) Aperture Reflection Losses (R_h) for Magnetic Fields*



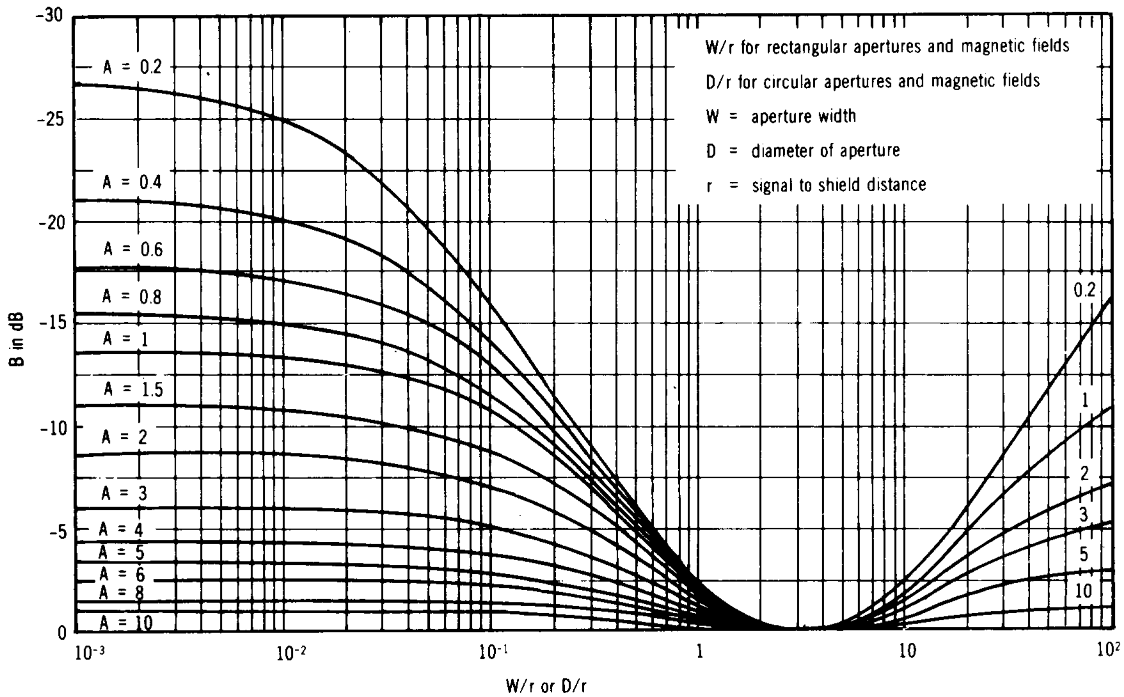
*Extracted from *Ref 473*©

SUB-NOTE 3(3) Aperture Reflection Losses (R_e) for Electric Fields*



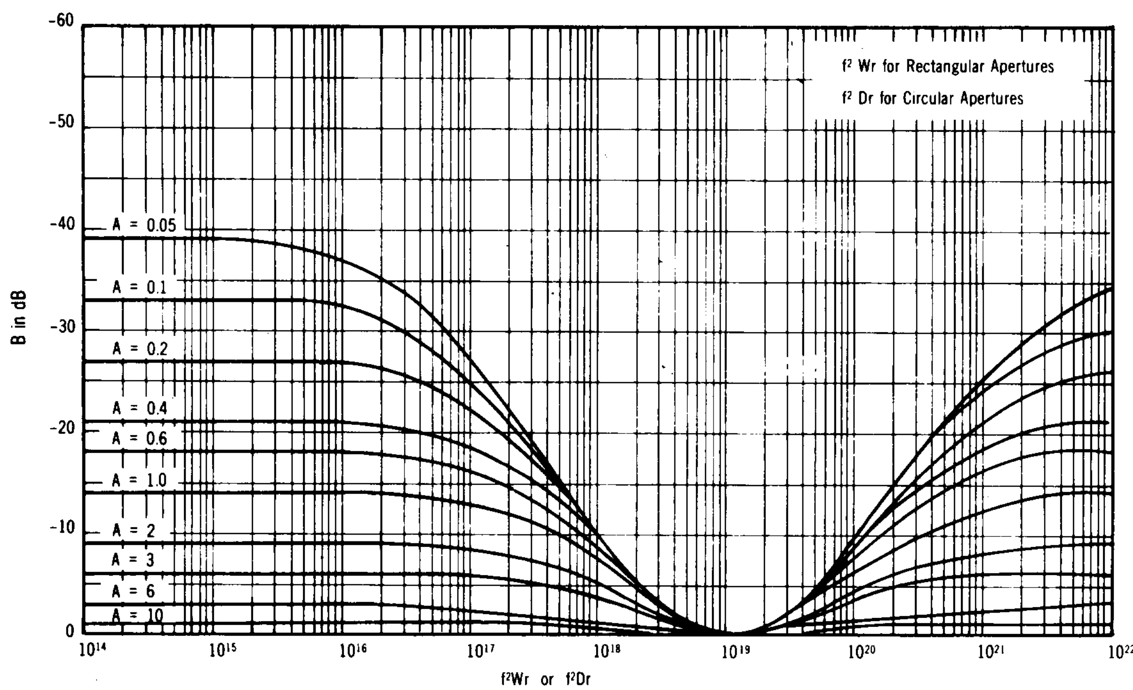
*Extracted from *Ref 473*©

SUB-NOTE 3(4) Table for Computing Secondary Reflection for Magnetic Fields*



*Extracted from *Ref 473*©

SUB-NOTE 3(5) Table for Computing Secondary Reflection Losses for Electric Fields*



*Extracted from *Ref 473*©

3.2 SAMPLE PROBLEMS

To demonstrate the use of nomographs and charts, *SN 3.2(1)* identifies the variables required to compute the factors of *Eq 1*.

a. *Example 1.* A 610-mm (24-in.) square honeycomb panel, made of cold-rolled steel, which has 5220 openings and the following dimensions:

L = 28 mm (1.1 in.)

D = 9.5 mm (0.375 in.)

r = 508 mm (20 in.)

n = $5220/(610)^2$ = 0.014 holes/mm^2 or $5220/(24)^2$ = 9.06 holes/in.^{2}

Problem: Compute the shielding effectiveness against incident magnetic fields located 508 mm (20 in.) from the panels between the frequencies of 10 Hz to 10 MHz.

Solution:

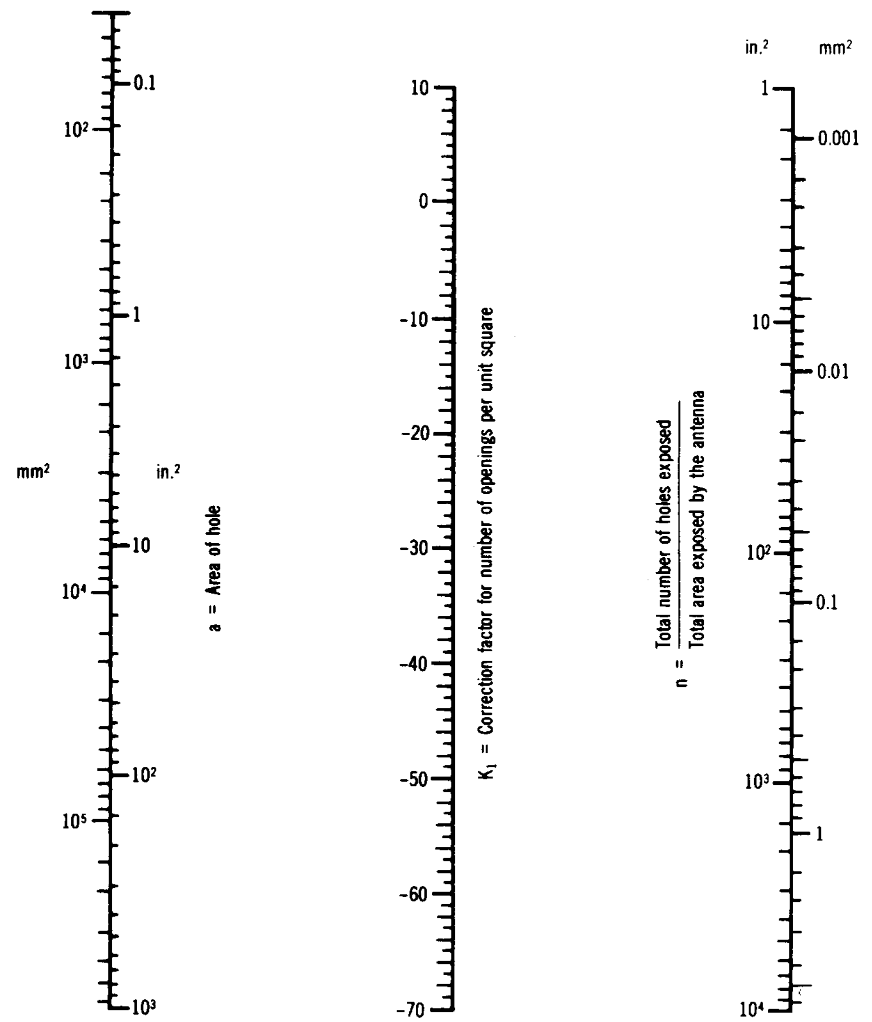
(1) From *SN 3(1)*, A = 94.5 dB for L = 28 mm (1.1 in.), D = 9.5 mm (0.375 in.)

(2) From *SN 3(2)*, R_h = 35.5 dB for r = 508 mm (20 in.), D = 9.5 mm (0.375 in.)

(3) From *SN 3(4)*, B = 0 since A > −10 dB

(4) From *SN 3(6)*, K_1 = 0 for a = 71 mm^2 (0.11 in.^{2}), n = 0.014 holes/mm^2 or 9.06 holes/in.^{2}

SUB-NOTE 3(6) Correction Factor for the Number of Holes per Unit Square (K_1)*



*Extracted from *Ref 473*©

(5) From *SN 3(7)* for 10 Hz < f < 10 MHz

f(Hz)	K_2(dB)	f(Hz)	K_2(dB)
10	−89	10k	−21.0
100	−66	100k	−3.5
1k	−43	1M	−0.2

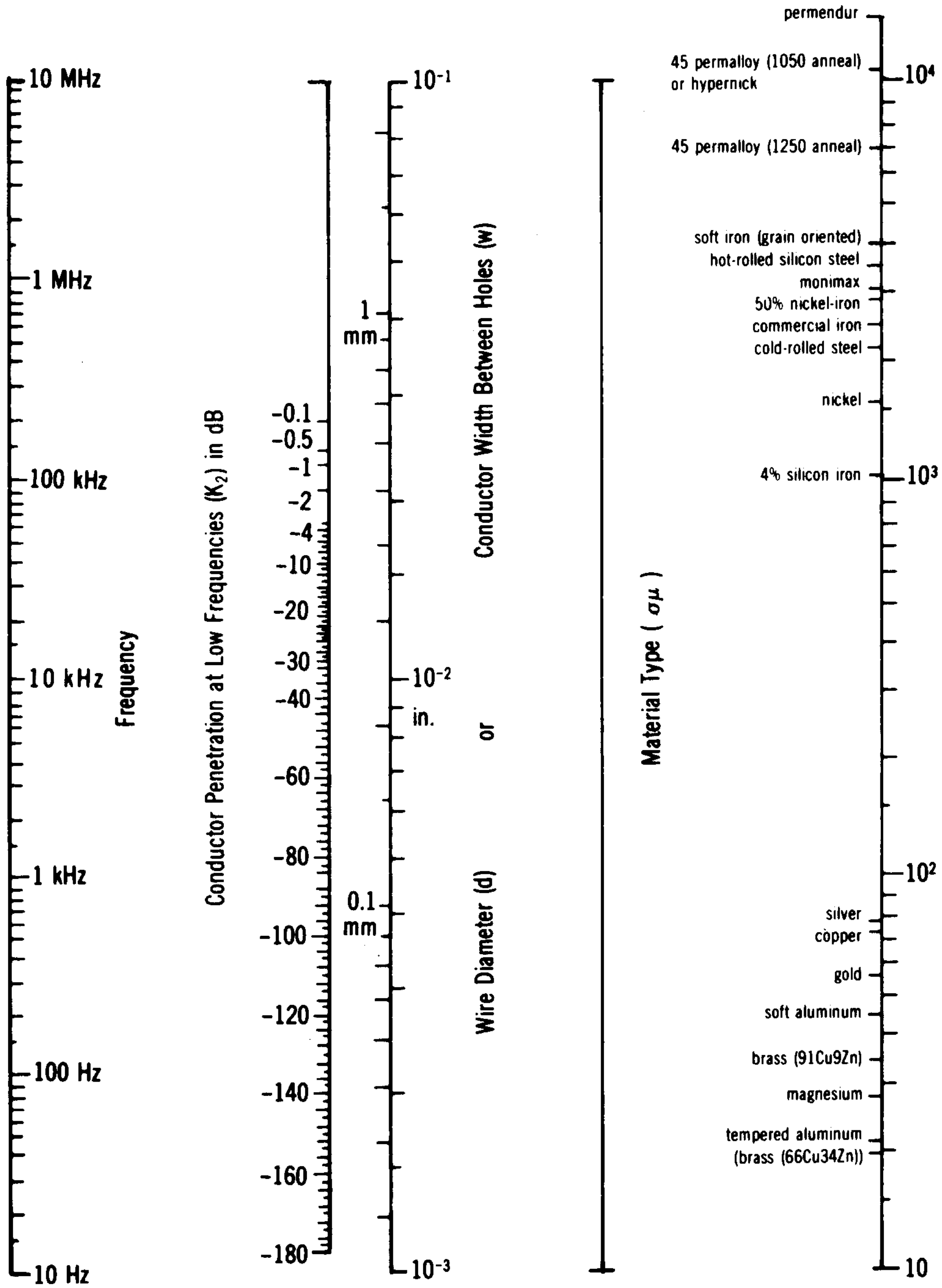
(6) From *SN 3(8)*, K_3 = 0 for A > 20 dB.

From the above, the factors for A, R_h, and K_2 are added to obtain the shielding effectiveness required (B, K_1, and K_3 were all zero). The results of this computation are shown in *SN 3.2(2)*.

b. *Example 2*. Comparing the performance of ferrous and nonferrous honeycomb. An interesting comparison can be made by changing only the material type in *Example 1* to copper. Examination of *SN 3.2(2)* shows that only K_2 will be affected. The new factors for K_2 are computed from *SN 3(7)* for copper and 10 Hz < f < 10 MHz.

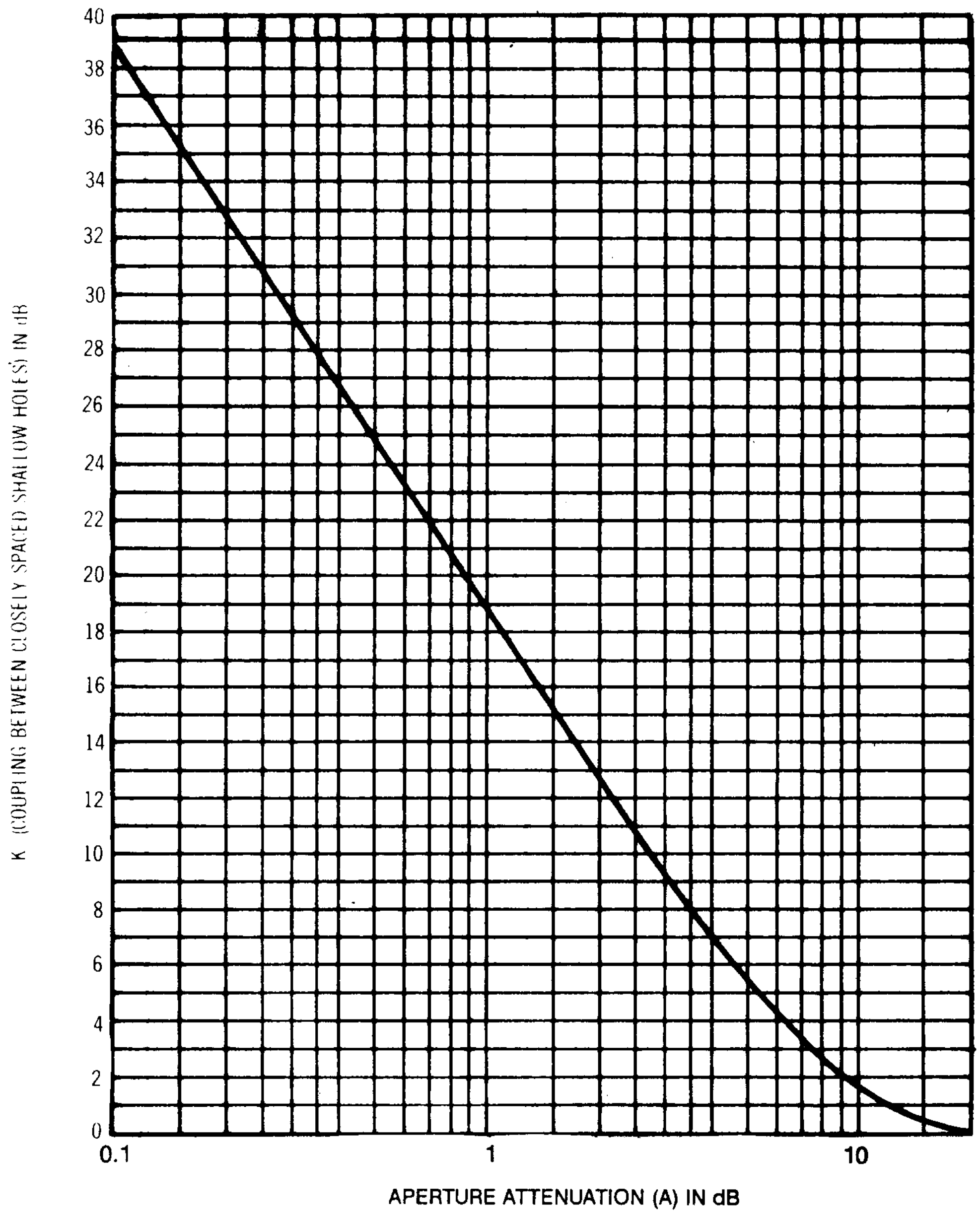
Adding the factors for A and R_h from above to K_2 for copper, yields a second curve as shown in *SN 3.2(2)*. The change from copper to cold-rolled steel resulted in a loss of 32 dB below approximately 100 kHz. The shielding effectiveness of copper finally approaches that of cold-rolled steel above 10 MHz.

SUB-NOTE 3(7) Correction Factor for Conductor Penetration at Low Frequencies (K_2) *



*Extracted from *Ref 473*©

SUB-NOTE 3(8) Chart for Computing the Correction Factor for Coupling Between Closely Spaced Holes (K_3)*



*Extracted from *Ref 473*©

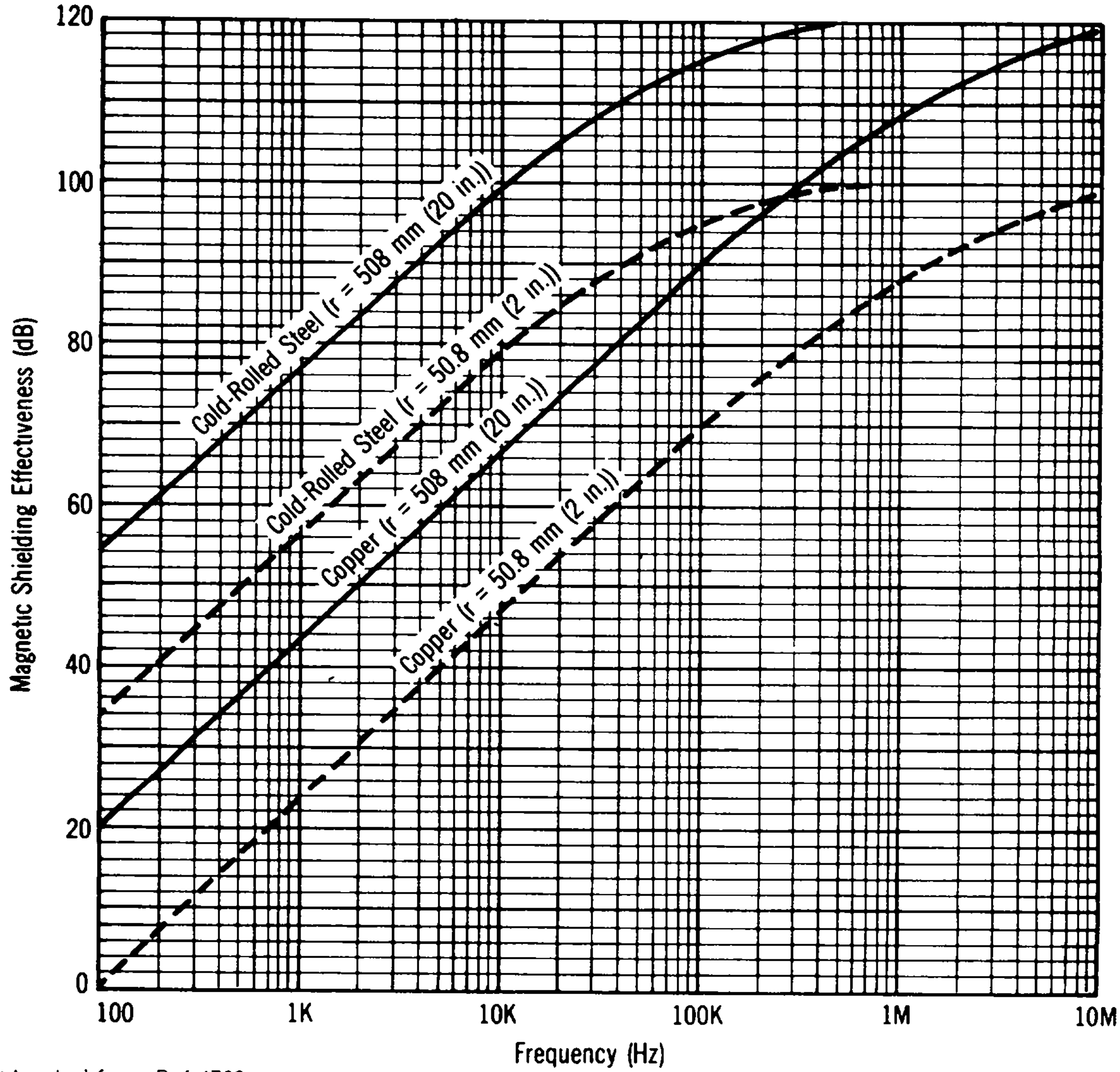
SUB-NOTE 3.1(1) Aperture Characteristic Impedance Equations

Aperture Type	Incident Field	
	Magnetic	Electric
Rectangular	$W/\pi r$	$-9 \times 10^{-20}\ Wf^2r$
Circular	$D/3.682r$	$-7.68 \times 10^{-20}Df^2r$

SUB-NOTE 3.2(1) Identification of Variables Required for Computing Shielding Effectiveness

Sub-Note	Factor	Required Variables
3(1)	A	L, D or W
3(2)	R_h	r, D or W
3(3)	R_e	r, f, D or W
3(4)	B_h	r, W or D, A
3(5)	B_e	r, W or D, f, A
3(6)	K_1	a, n
3(7)	K_2	f, material type ($\sigma\mu$)
3(8)	K_3	A

SUB-NOTE 3.2(2) Computed Magnetic Field Shielding of Copper and Cold-Rolled Steel Honeycomb*



*Extracted from *Ref 473*©

c. *Example 3.* The effect of changing test distance (r). Another interesting comparison can be made by repeating *Examples 1* and *2*, changing only the source-to-shield distance (r) from 508 to 50.8 mm (20 to 2 in.). Examination of *SN 3.2(1)* shows that B_h still equals zero. From *SN 3(2)* the new reflection loss factor (R_h) is 15 dB for r = 50.8 mm (2 in.) and D = 9.5 mm (0.375 in.). The overall performance of both copper and cold-rolled steel honeycomb is thus degraded by 35.5 dB - 15 dB = 20.5 dB as shown in *SN 3.2(2)* by simply placing the source of energy 457.2 mm (18 in.) closer to the panels.

3.3 COMPUTED AND MEASURED RESULTS

The measured and computed magnetic shielding effectiveness of seam-welded stainless steel honeycomb with circular cells is compared in *SN 3.3(1)*. A, R_h, and K_2 were used to compute performance (B_h, K_1, and $K_3 = 0$). The computed and measured performance of screened materials is presented in *SN 2.2(1)*. It is important that good conductivity be maintained between strands to ensure high performance. For No. 2 copper screen with

r = 3.8 mm (0.15 in.)

d = 1.1 mm (0.043 in.)

W = 11.1 mm (0.437 in.)

L = 1.1 mm (0.043 in.)

the following was computed:

A = 2.7 dB

R_h = 10 dB

B_h = -4.5 dB

K_3 = 10.2 dB

and K_2 can be computed for copper. Because of low A values the effect of B_h and K_3 are important.

For 16-mesh copper screen the following parameters were used:

r = 38.1 mm (1.5 in.)

d = 0.457 mm (0.018 in.)

W = 1.15 mm (0.0455 in.)

L = 0.457 mm (0.018 in.)

Calculated data was approximately 6 dB higher than measured levels. This design approach can be used to compute electric, magnetic, or plane wave shielding effectiveness for the following cases:

a. Waveguide below cutoff filters (honeycomb).

b. Perforated solid panels (with any number of holes).

c. Screen materials.

Information presented herein is principally theoretical. An effort has been made to demonstrate the accuracy of the classical and the accompanying factors.

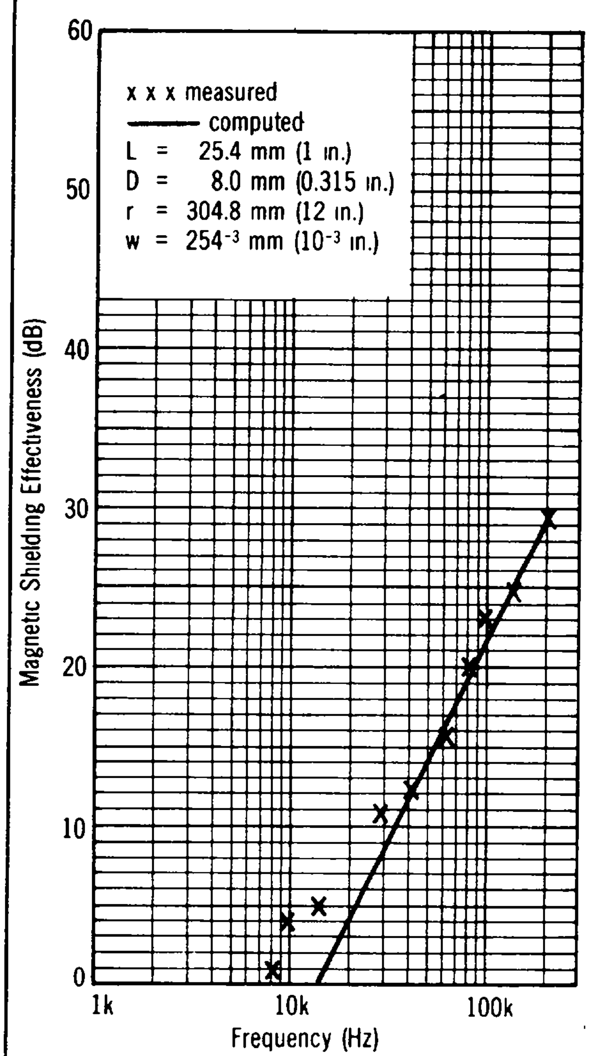
4. PERMANENT APERTURES

Permanent apertures are those holes or discontinuities in an aerospace system housing which cannot be shielded by a metal cover. Openings for ventilation or control shafts, apertures for panel-mounted meters, exposed connector pins, and exhaust nozzles are common examples.

4.1 HONEYCOMB MATERIALS

Where shielding, ventilation, and strength are required and weight is not a critical condition, honeycomb panels may be used. The SE of honeycomb panels is based on, and predicted by, the attenuation properties of waveguides operated below cutoff. It is a function of the size and length of the waveguide and the number of waveguides in the panel. *Sub-Note 4.1(1)* indicates the SE of a honeycomb panel constructed of steel with 3.1-mm ($^1/_8$-in.) hexagonal openings 12.7 mm ($^1/_2$ in.) long.

SUB-NOTE 3.3(1) Magnetic Field Shielding of Stainless Steel Honeycomb*



*Extracted from *Ref 473*©

SUB-NOTE 4.1(1) Shielding Effectiveness of Hexagonal Honeycomb Made of Steel

FREQUENCY	SHIELDING EFFECTIVENESS
(MHz)	(dB)
0.1	45
50	51
100	57
400	56
2200	47

4.2 SHIELDING OF METERS

Acceptable methods of shielding apertures for meters or other panel-mounted readout devices are illustrated in *SN 4.2(1)*.

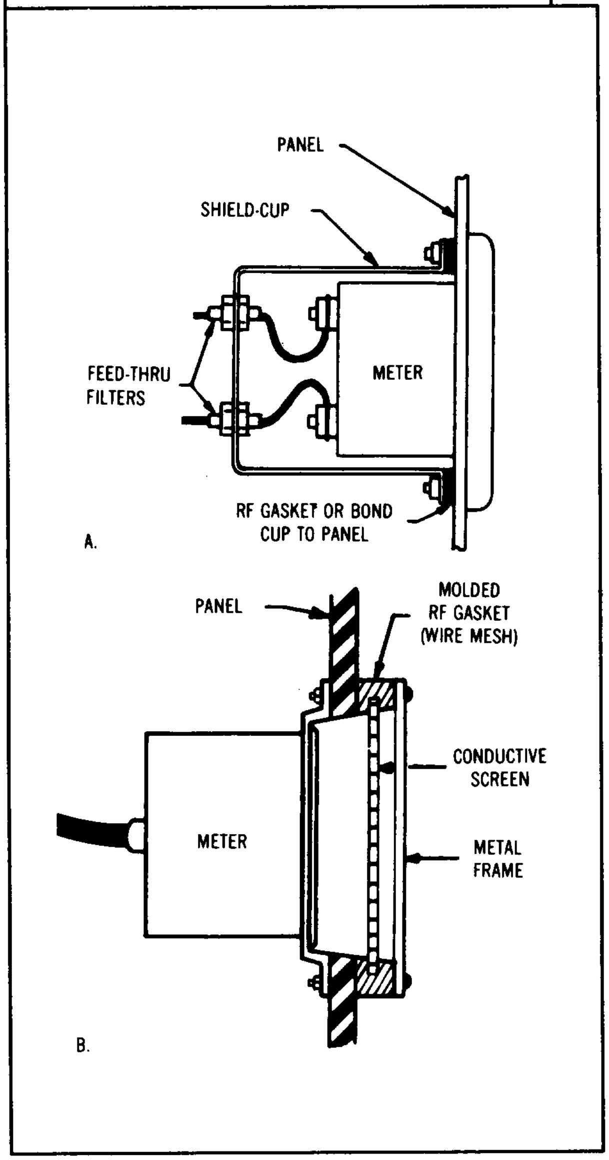
4.3 MOUNTING OF SCREENS

Where the use of waveguide materials is impractical or otherwise undesirable, as in large ventilating holes, substantial attenuation of radiated electromagnetic energy can be obtained by covering the aperture with a wire screen or mesh. Number 22, 15-mil copper wire screen will provide about 50-dB attenuation to electric and magnetic fields at frequencies between 1 MHz and 1 GHz. *Sub-Note 4.3(1)* shows an acceptable technique for mounting a wire screen over an aperture. A similar mounting technique can be used in installing circular and rectangular waveguide materials.

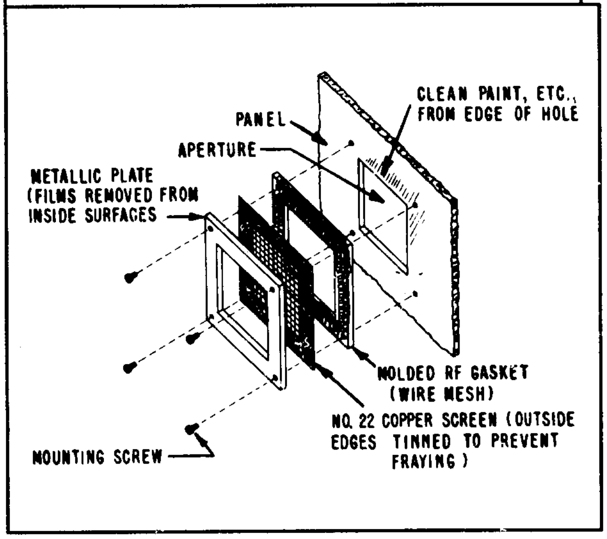
4.4 APERTURE WAVEGUIDE ATTENUATORS

One method of minimizing the degradation of SE is to design small aperture to act as effective waveguide attenuators. *Sub-Note 4.4(1)* illustrates how a necessary hole can be designed into a circular waveguide with a nonmetallic control shaft that passes through the panel. The cutoff frequency for a waveguide is the lowest frequency at which propagation occurs without attenuation. Below cutoff, the attenuation is a function of guide length and frequency. An aperture in a shielding enclosure designed as a waveguide operating below cutoff for the dominant mode or lowest propagating frequency can achieve theoretical shielding efficiencies in the range from 80 to 100 dB. The depth of the aperture determines the amount of attenuation realized and the diameter of individual openings determines the cutoff frequency.

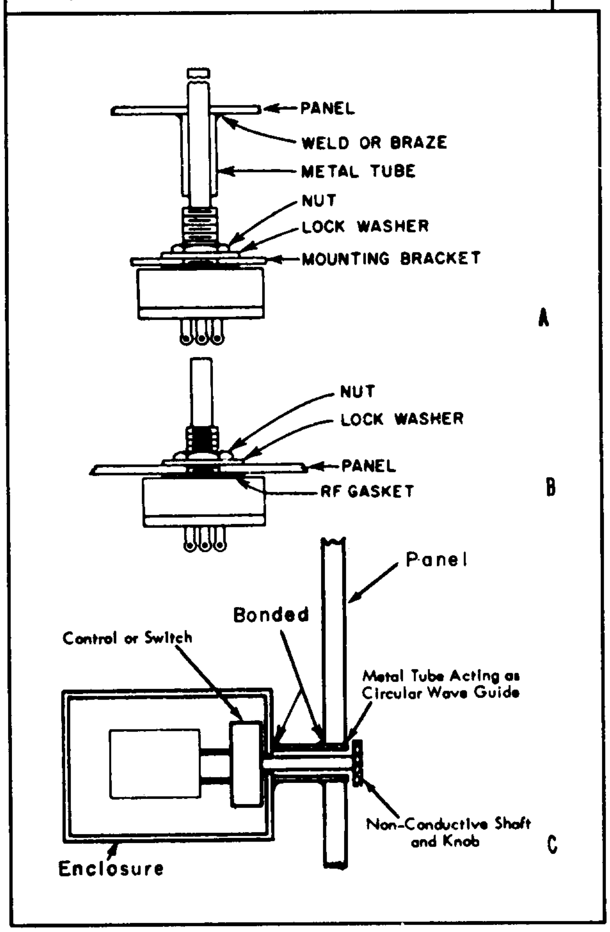
SUB-NOTE 4.2(1) Acceptable Methods of Shielding Panel-Mounted Meters



SUB-NOTE 4.3(1) Method of Mounting Wire Screen Over a Large Aperture



SUB-NOTE 4.4(1) Acceptable Use of Circular Waveguide in a Permanent Aperture for Control Shaft



4.4.1 WAVEGUIDE SE. A hole may take the form of a rectangular or a circular waveguide. The lowest cutoff frequency (fo) of the hole can be determined by use of the following expressions:

For a rectangular waveguide:

$$f_o = \frac{150 \text{ m (or 5900 in.)}}{W} \text{ in MHz}$$

(Eq 9)

For a circular waveguide:

$$f_o = \frac{176 \text{ m (or 6920 in.)}}{D} \text{ in MHz}$$

(Eq 10)

Assuming $f_o \geq 10f$ (when f is the frequency in MHz), the attenuation (A) of circular and rectangular waveguides of length (L), respectively, may be approximated within a 2% error by the following formulas:

For circular waveguides:

$$A = 32 \text{ L/D in dB}$$

(Eq 11)

For rectangular waveguides:

$$A = 27.3 \text{ L/W in dB}$$

(Eq 12)

For 100-dB attenuation in a circular waveguide, the length of the waveguide must be three times the diameter of the waveguide.

5. TEMPORARY APERTURES

Temporary apertures include access panels or removable metallic sections within aerospace systems. These panels or sections cannot perform a shielding function when opened or removed. If it is necessary for apertures to be opened in RF fields, design the interior circuits, components, and cables to preclude interference.

5.1 FINGER STOCK

Design 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. Metallic mesh or fingers between the mating surfaces achieve the best bond. When metallic fingers are used, 5 to 10 grams of pressure per finger should be applied to the mating surfaces.

5.2 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.

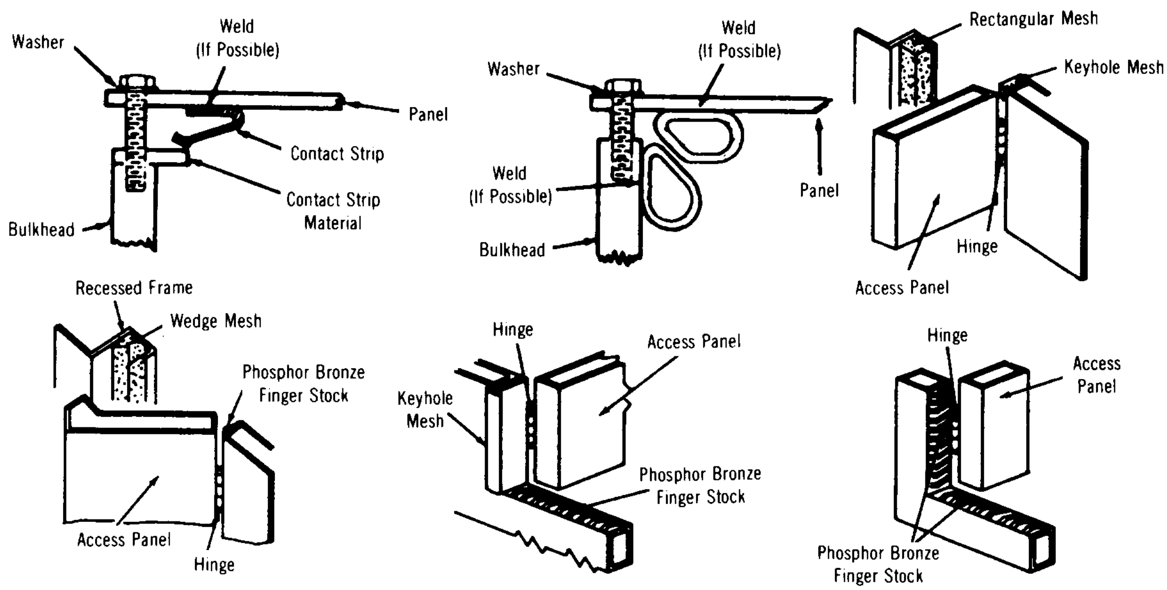
5.3 APPLICATION OF SHIELDING

Sub Note 5.3(1) illustrates acceptable methods of applying shielding materials around the sides of hinged access panels. The mesh used in these applications should be a square cross section from 13 to 25 mm (0.5 to 1 in.) on a side. Also, appropriate mechanical locking devices must be used on access panels to maintain a minimum of 138-kPa (20-lbf/in.^{2}) pressure between the edges of the panel and the mesh or fingers.

5.4 ARRANGEMENT OF 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 set 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. Keep finger stock and mating surfaces clean and free of corrosion. Ensure contact fingers and mating surfaces are not painted or in any way reduce the bonding integrity. A light film of noncorrosive conductive lubricant can be used on fingers, but ensure bonding integrity.

SUB-NOTE 5.3(1) Acceptable Close Contact Strips for Temporary Apertures



DESIGN NOTE 5F8 ENCLOSURES

1. INTRODUCTION

Where possible, use internal walls and compartments to limit propagation of interference within the case. Design lead entry and exit as follows:

a. Isolate leads likely to be noisy (such as power leads) from other leads, or if connectors are used employ separate connectors.

b. Power input circuit configuration should complement the power and power grounding system into which the equipment will be integrated. Do not ground a power return lead internally if the total system follows the wired power return concept. Do not use a sensing device or transducer that uses the shield for signal return in a system or subsystem having balanced symmetrical input circuits.

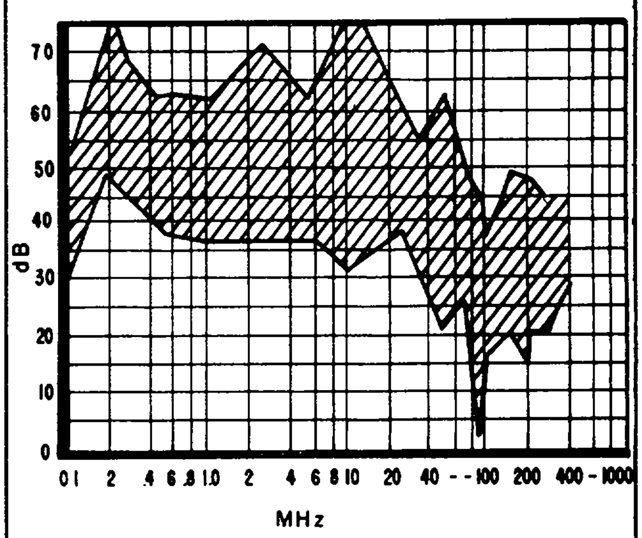
2. SYSTEM ENCLOSURE

The fuselage or hull of an aircraft or missile affords an efficient shield against outside interference fields and greatly attenuates the radiation of internal fields. Calculate the degree of shielding afforded by the fuselage skin with the same equations used for compartment calculations in *DN 5F2* and *5F3*. Maintain strict control of the bonding of doors and access cover plates to obtain calculated attenuation. The preferred method of bonding is a clean bare metal contact between mating surfaces. The surfaces should be smooth and free of dents and distortions. Where dimensional tolerances, sealing requirements, or other mechanical requirements preclude or unduly compromise the conditions necessary for a good bond, the bond may be maintained by the use of conductive gaskets or spring finger stock. Radio frequency gaskets and spring finger stock which are resilient and conductive can be obtained completely fabricated, or they can be made from commercially available materials. See *SN 2(1)* for shielding effectiveness of typical aircraft.

2.1 ANTENNA LOCATIONS

Antenna locations are generally controlled by the required antenna pattern. The location and orientation of the antenna's radiating elements to the conducting fuselage influence the effective radiating pattern to such an extent that functional considerations generally rule.

SUB-NOTE 2(1) Shielding Effectiveness of a Typical Aircraft



However, from the interference aspect much can be done to assure a compatible location. Due to the high shielding effectiveness of an unbroken fuselage skin, fields inside the vehicle will be low if there are no compromises of skin conductivity in the area of the antenna. Ensure that preventive design features include:

a. No doors or access holes in the antenna area

b. Skin and fairings made of highly conductive material such as aluminum

c. Skin and fairing joints, laps and seams of clean bare metal to metal contact

d. Antenna leads of coaxial or waveguides

e. Coaxial shields at ground potential at point of exit.

3. ENCLOSURES FOR TESTING OF ELECTRONIC EQUIPMENT

MIL-E-8881 covers shielded enclosures and screened rooms which will provide specified degrees of attenuation from external electromagnetic fields between the frequencies of 100 kHz and 20 GHz. The enclosure is used for testing and alignment of electronic equipment and other such related purposes.

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SECTION 5G FILTERING

DN 5G4 - Contd

DN 5G5 - TRADE-OFF FACTORS

DESIGN NOTE 5G1* INTRODUCTION

1. GENERAL

Filters provide a very effective means for the reducing and suppressing of EMI. They attenuate undesired electromagnetic signals while passing the desired ones. The application of a filter in a subsystem requires careful consideration of a variety of trade-off factors such as insertion loss, impedance, power handling capability, signal distortion, tunability, cost, weight, size, and rejection of undesired signals. There are many textbooks on filters and filtering. *References 591* and *592* are typical examples. Design filters to meet the requirements specified in *MIL-F-15733*, *MIL-F-18327*, and *MIL-F-25880*, or as specified by the procuring activity. The method of insertion-loss measurement is given in *MIL-STD-220*.

2. FILTER NETWORK

An electrical filter can be defined as a network of resistors, inductors, and capacitors, or any combination thereof. It offers comparatively little opposition to certain frequencies or to direct current while blocking the passage of other frequencies. The design of filters is an art as well as a science since so much depends on the judgment and techniques used by the filter design engineer. The purpose of this Section is to assist the design engineer in the solution of interference suppression problems on a scientific basis and thus avoid the pitfalls which are almost certain to be encountered in choosing values of elements on a trial-and-error basis.

3. TYPES OF FILTERS

Filters are classified according to the band of frequencies to be transmitted and attenuated such as: low pass, high pass, band pass, and band reject. *Sub-Notes 3(1)* and *3(2)* show typical examples of the various types of filters and their attenuation curves.

3.1 INSERTION LOSS (IL) EQUATIONS

In most instances, interference-suppression filters are low-pass devices,

Let $R_I = R_L = R$ (see *SN 3(1)*)

Insertion loss (IL) in decibels (dB) is defined as:

$$IL = 20 \log\left(\frac{E_1}{E_2}\right) \quad \text{(Eq 1)}$$

or

$$IL = 10 \log\left(\frac{E_1}{E_2}\right)^2 \quad \text{(Eq 2)}$$

Where:

E_1 = load voltage without filter in the circuit

E_2 = load voltage with filter in the circuit

For the L-type low-pass filter of *SN 3(1)*

$$IL = 10 \log\left[\frac{(2-\omega^2 LC)^2 + \left(\omega CR + \frac{\omega L}{R}\right)^2}{4}\right] \quad \text{(Eq 3)}$$

For the π-type low-pass filter of *SN 3(1)*

$$IL = 10 \log\left[(1-\omega^2 LC)^2 + \left(\frac{\omega L}{2R} - \frac{\omega^3 LC^2 R}{2} + \omega CR\right)^2\right] \quad \text{(Eq 4)}$$

For the T-type low-pass filter of *SN 3(1)*

$$IL = 10 \log\left[(1-\omega^2 LC)^2 + \left(\frac{\omega L}{R} - \frac{\omega^3 L^2 C}{2R} + \frac{\omega CR}{2}\right)^2\right] \quad \text{(Eq 5)}$$

4. REDUNDANT FILTERING

Redundant filtering is a result of uncoordinated efforts by two or more separate design groups. This usually occurs when each black box of a subsystem is required to meet an interference control specification irrespective of its cable tie location or its final installation location. Economy measures, the use of already designed equipment in a new system, and schedule constraints can also result in redundant filtering. Certainly, trade-offs must be made between these factors. However, there is no substitute for a well thought-out System EMC Control Plan, well ahead of the design of the subsystem, which minimizes filtering of interconnecting leads. For example, both a switch and a motor would probably be filtered at their inputs when shielded leads between the devices would possibly be a more economical, reliable approach. When several hundred leads are involved in a complex system, redundant filtering must be guarded against carefully. However, one precaution should be observed when

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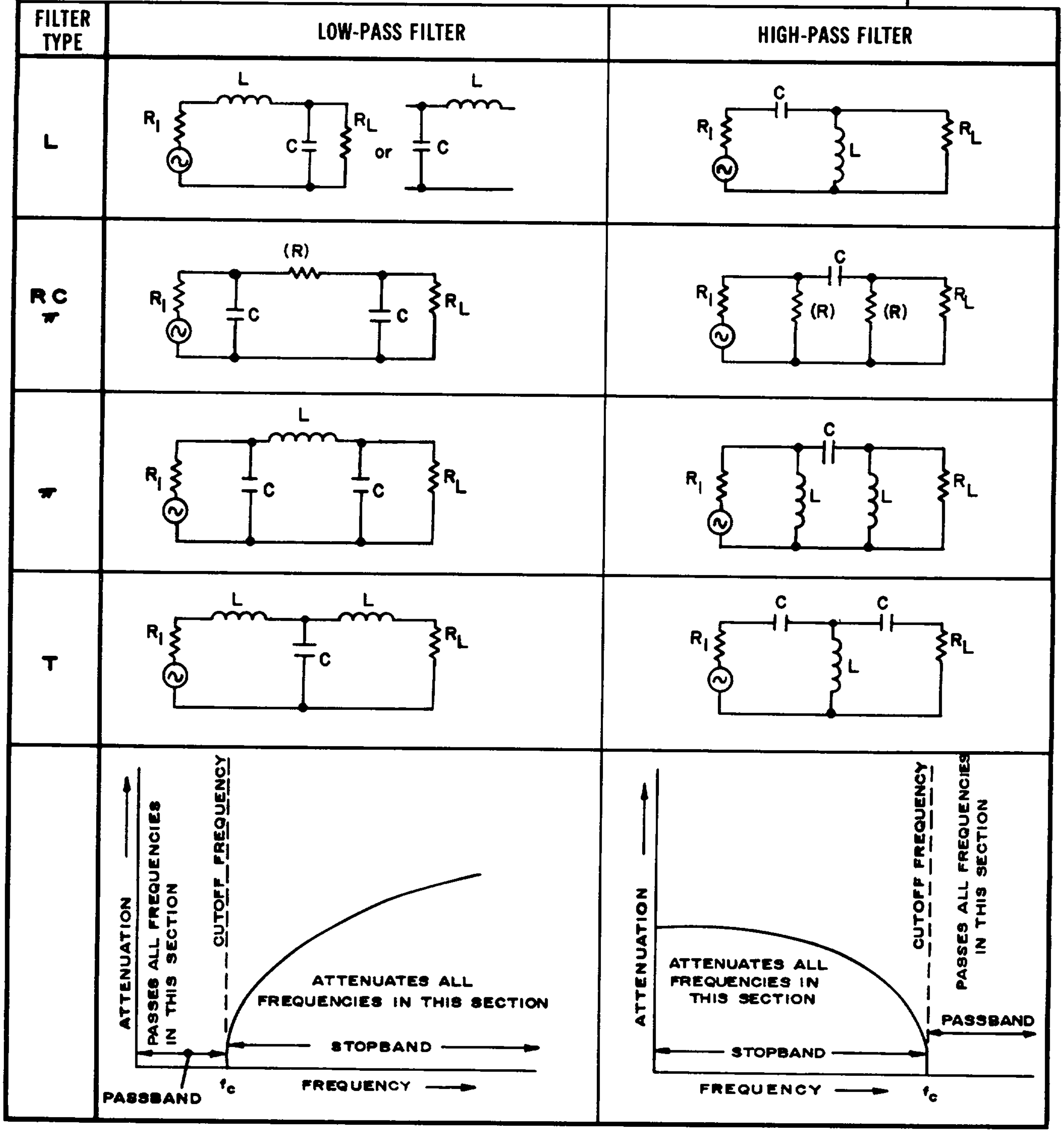
*Extracted in part from *Ref 62*©.

SUB-NOTE 3(1) Low- and High-Pass Filter Configuration



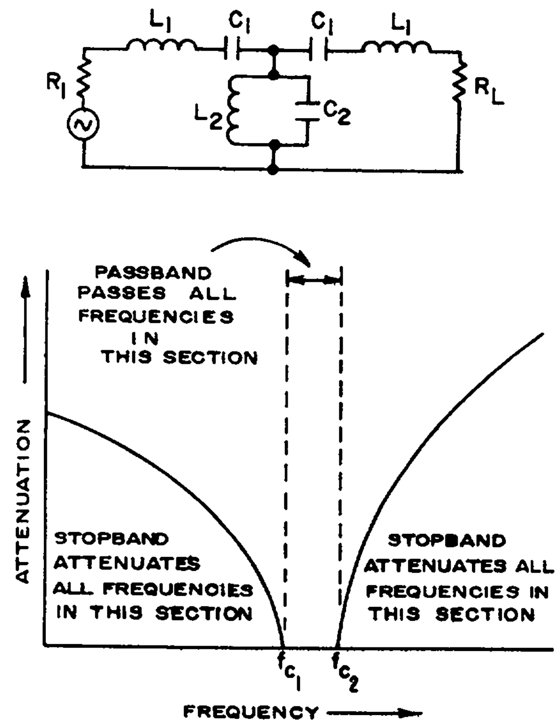
considering the reduction of redundant filters; equipment at both ends of the cable must be able to withstand interference levels passed in both directions.

5. FILTERING GUIDANCE

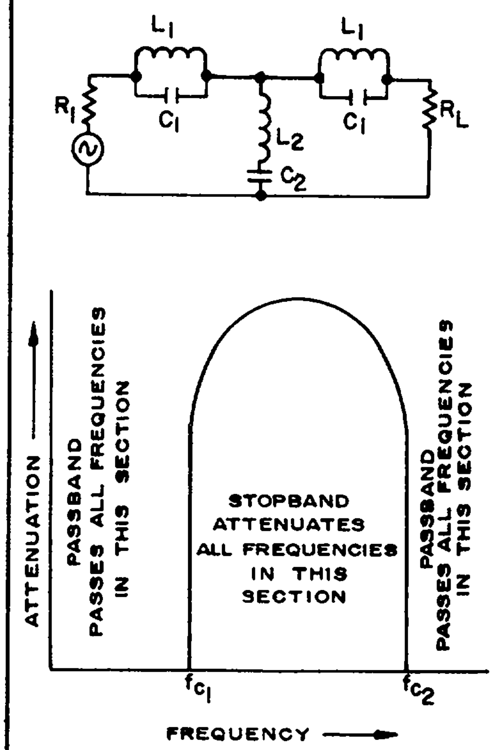
Filtering guidance is contained in *SN 5(1).*

SUB-NOTE 3(2) Band-Pass and Band-Reject Filter Configuration	
BAND-PASS FILTER	**BAND-REJECT FILTER**

BAND-PASS FILTER



BAND-REJECT FILTER



SUB-NOTE 5(1) Guidance for Filtering
1. It is best to filter the interference sources.
2. Suppress all spurious signals.
3. Design nonsusceptible circuits.
4. Ensure that the filter elements interface with other EMC elements.

DESIGN NOTE 5G2* INSERTION LOSS ELEMENT CALCULATIONS

1. INTRODUCTION

A method of calculating insertion loss is through the use of Craig Charts. These Craig Charts are constructed in accordance with *MIL-STD-220* in which source and load impedances are both 50 ohms ($R_I = R_L = 50\Omega$).

2. SINGLE-ELEMENT FILTERS

The equations for the insertion loss (IL) of a single series inductor *(SN 2(1))* and a single shunt capacitor *(SN 2(2))* are the same.

$$IL\ (dB) = 10 \log (1 + F^2) \qquad \text{(Eq 1)}$$

Where:

$F = f/f_o = \omega/\omega_o$ = normalized frequency

f_o cutoff frequency $\omega_o = 2\pi f_o$

For the inductor:

$$\omega_o = 2R/L \text{ or } L = 2R/\omega_o$$

For the capacitor:

$$\omega_o = 2/RC \text{ or } C = 2/R\omega_o$$

Equation 1 has only one mode of response, which is presented in *SN 2(3)*.

2.1 CRAIG CHART FOR SINGLE-ELEMENT FILTERS

Sub-Note 2.1(1) gives the relationship between element value and insertion loss for a single-element filter.

STEP 1

To find the insertion loss at any frequency for a given shunt capacitance, do the following:

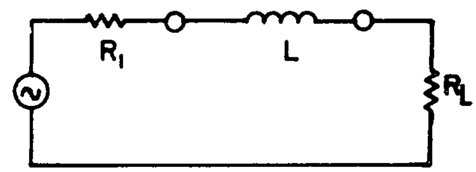
a. Place a straightedge so that it lies parallel to the sloping guide lines and intersects the given value of capacitance on the C scale. The straightedge now lies along the insertion loss characteristic for that ideal element.

b. At any frequency along the abscissa, read insertion loss in dB along the ordinate.

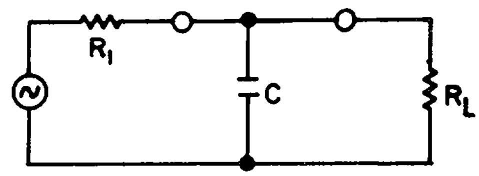
STEP 2

To find insertion loss at any frequency for a given series inductance, do the same as above, but use the L scale instead of the C scale.

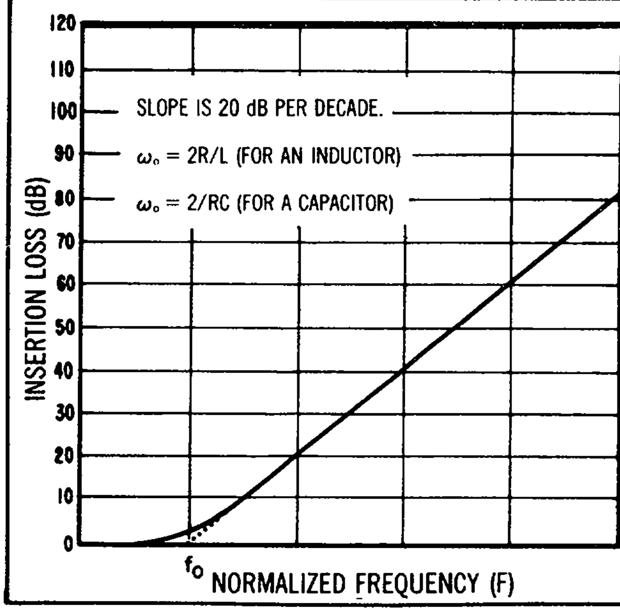
SUB-NOTE 2(1) Single Series Inductor



SUB-NOTE 2(2) Single Shunt Capacitor



SUB-NOTE 2(3) Response Mode of Single-Element Filter



STEP 3

To find the amount of shunt capacitance required to produce a desired amount of insertion loss at a given frequency, do the following:

a. Place a straightedge so that it lies parallel to the guide lines and pass it through the desired amount of insertion loss at the given frequency.

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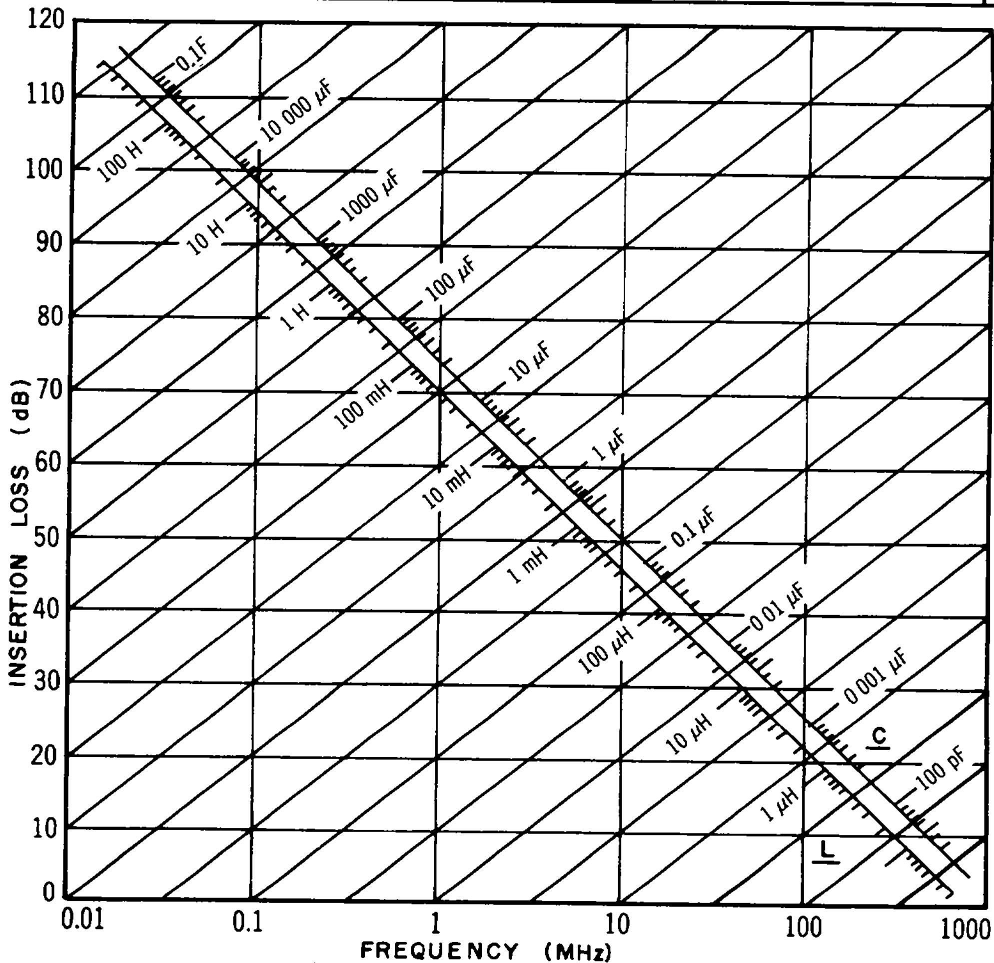
*Extracted in part from *Ref 557*©

SUB-NOTE 2.1(1) Craig Chart I: For Computing Single-Element Filters



b. Read the required capacitance on the C scale.

STEP 4

To find the amount of series inductance required to produce a desired amount of insertion loss at a given frequency, proceed as above, but use the L scale instead of the C scale.

3. TWO-ELEMENT (L) FILTERS

Equation 2 represents two modes of response, see *SN3(1)* of *DN 5G1* for the L network filter.

$$IL\ (dB) = 10 \log (1 + F^2D^2/2 + F^4) \qquad (Eq\ 2)$$

Where:

$\omega_o = \sqrt{2/LC}$

$D = \frac{1-d}{d}$ = constant function of d

$d = L/CR^2$ = damping ratio

$L = 2/\omega_o^2C$ (any value of d)

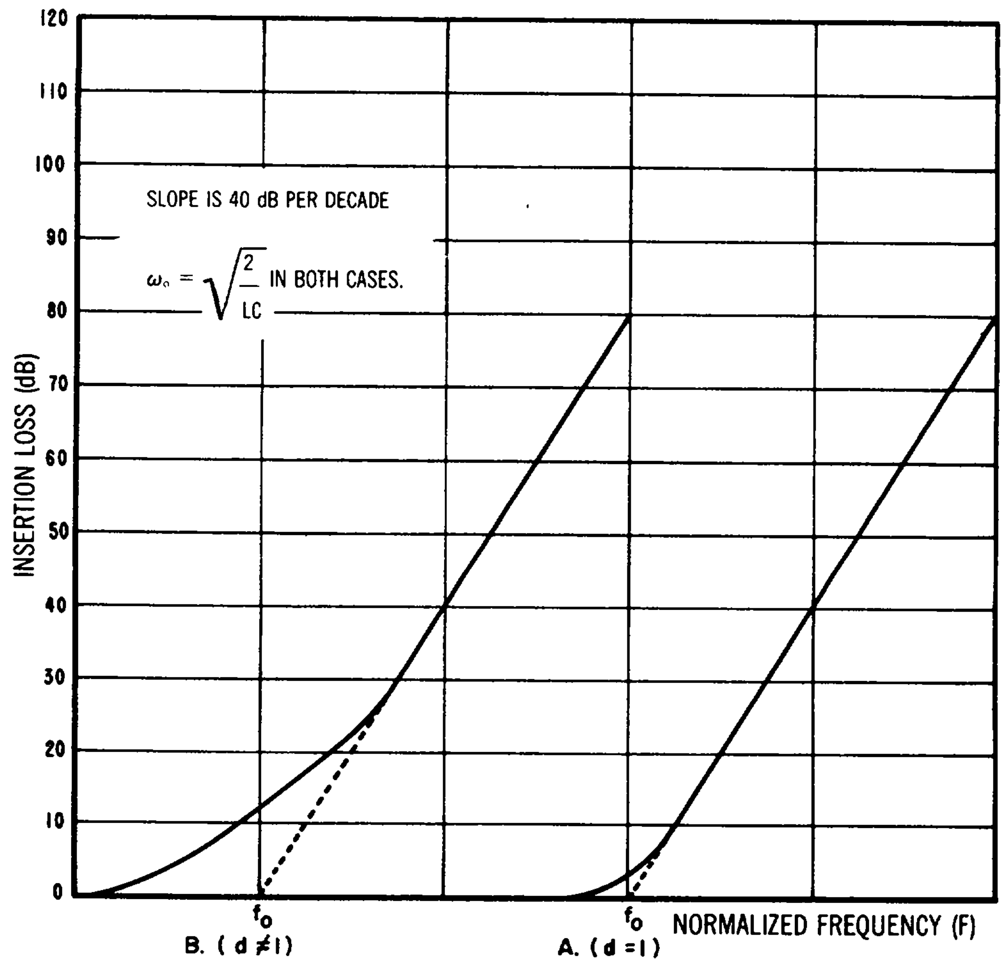
$L = \sqrt{2}R/\omega_o$ (only if d = 1)

$C = 2/\omega_o^2L$ (any value of d)

$C = \sqrt{2}/R\omega_o$ (only if d = 1)

When d = 1, the response is shown by curve A in *SN3(1)*. This is referred to as the ideal (Butterworth) response curve. When d ≠ 1, the response is shown by curve B in *SN 3(1)*. This is the nonideal response. Values of d less than one result in insertion loss curves identical to those obtained when d is greater than one. That is, insertion loss for d = n is equal to insertion loss for d = 1/n, for a two-element filter. It can also be shown that the insertion loss of a two-element filter is not changed when the L is transposed so that the source and load terminals are turned around as shown in *SN 3(1)* of *DN5G1* for L-type filters.

SUB-NOTE 3(1) Response Modes of Two-Element Filters



3.1 CRAIG CHART II-A

Sub-Note 3.1(1) represents the relationship between cutoff frequency (f_o) and insertion loss for an ideally damped two-element filter. It is based on *Eq 2* with d set equal to one.

STEP 1

To find the insertion loss of an ideally damped L section at any frequency when f_o is known, do the following:

a. Place a straightedge so that it lies parallel to the guide lines and pass it through the known cutoff frequency. The straightedge now lies along the insertion loss characteristic for the ideally damped L section having that cutoff frequency.

b. At any frequency along the abscissa, read the insertion loss in dB along the ordinate.

STEP 2

To find the cutoff frequency (f_o) required to produce a desired amount of insertion loss at a given frequency with an ideally damped L section, do the following:

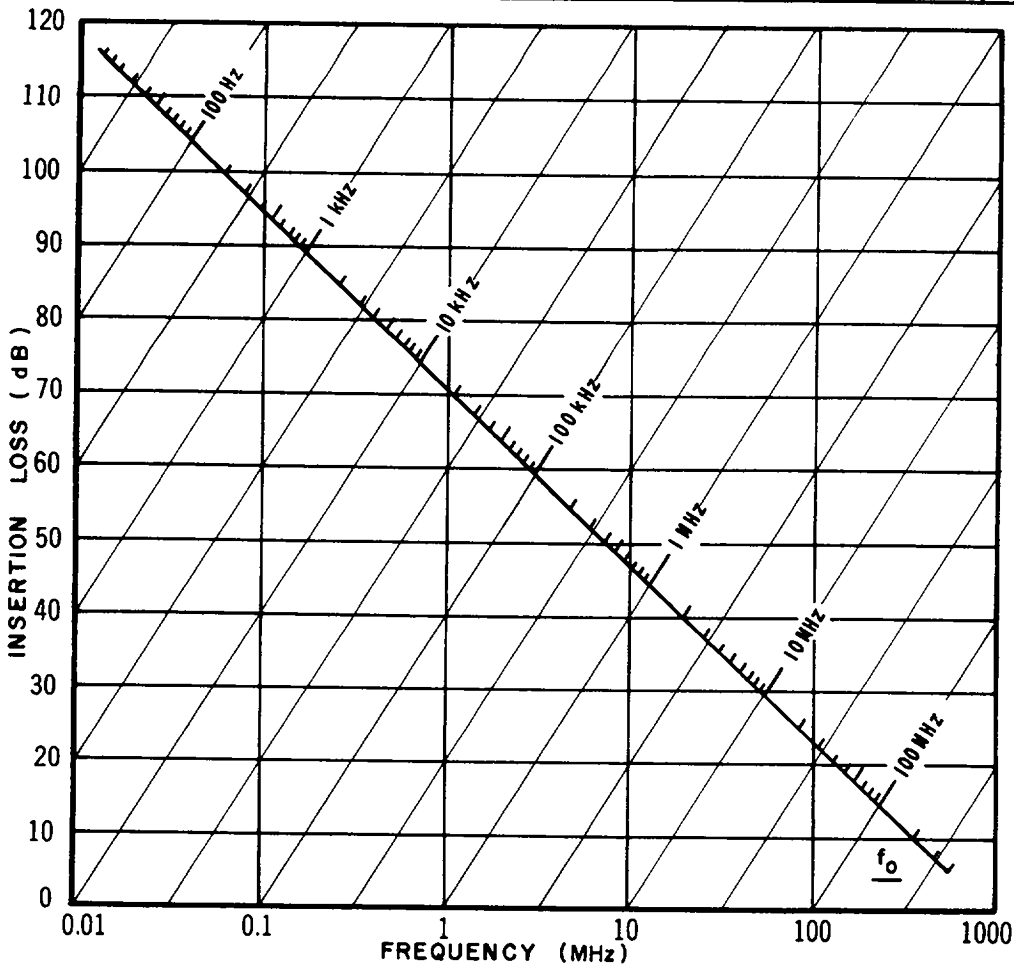
a. Place a straightedge so that it lies parallel to the guide lines and passes through the desired insertion loss at the given frequency.

b. Read the cutoff frequency on the f_o scale.

3.2 CRAIG CHART II-B

Sub-Note 3.2(1) represents the insertion loss characteristic for the nonideally damped two-element filters. It is based on *Eq 2* with d variable. To find the insertion loss of a nonideally damped L section at any frequency when the cutoff frequency (f_o) and the damping ratio (d) are known, do the following:

SUB-NOTE 3.1(1) Craig Chart II-A: For Computing Two-Element Filters



a. This chart is normalized for $f_o = 1$; thus, divide the frequency of insertion by the known f_o to determine the normalized frequency of interest.

b. Locate the characteristic for which d is equal to the known damping ratio. Read the approximate value of d which is not shown.

c. At the normalized frequency of interest, read the insertion loss in dB.

3.3 CRAIG CHART II-C

Sub-Note 3.3(1) represents the relationship between the inductance, capacitance, cutoff frequency, and the damping ratio for the two-element filters. It is based on the notation under *Eq 2.*

STEP 1

To find the cutoff frequency and the damping ratio for a given inductance and capacitance, do the following:

a. Place a straightedge so that it passes through the known L and C values.

b. Read the cutoff frequency (f_o) on the center scale.

c. The damping ratio slope line which lies parallel to the straightedge indicates the damping ratio. Note that the point at which the straightedge intersects the damping ratio scale is irrelevant; the "d" slope lines parallel to the straightedge determines the damping ratio. See example in *Para 4.8.*

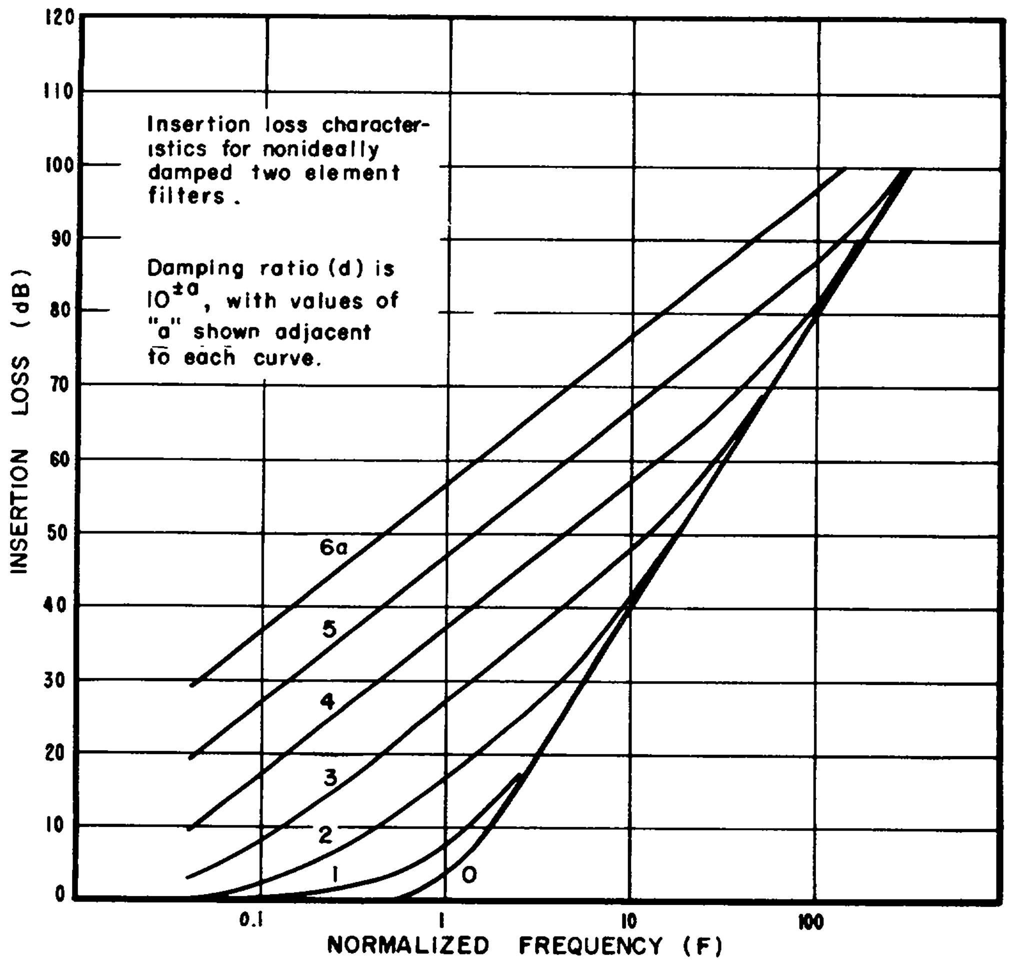
STEP 2

To find the circuit elements required to produce a desired cutoff frequency at a given damping ratio, do the following:

a. Place a straightedge so that it passes through the desired cutoff frequency and lies parallel to the given damping ratio line.

b. Read the inductance and capacitance on the L and C scales.

SUB-NOTE 3.2(1) Craig Chart II-B: For Computing Two-Element Filters



4. THREE-ELEMENT FILTERS

Equation 3 for insertion loss is the same for both the T and π network (*SN 4(1)*).

$$IL\ (dB) = 10 \log (1 + F^2D^2 - 2F^4D + F^6) \qquad (Eq\ 3)$$

Equation 3 has three modes of response. *Sub-Note 4(2)* curve A shows d = 1. This is the ideal (Butterworth) response curve. Curve B shows when d is greater than one, the overdamped response mode. Curve C shows when d is less than one, the underdamped response mode. The hump in curve C has a maximum value of:

$$IL\ (dB) = 10 \log (1 + 4D^3/27) \qquad (Eq\ 4)$$

At the frequency where:

$$F = \sqrt{\frac{D}{3}}$$

The minimum point falls at the frequency where:

$$F = \sqrt{D}$$

The value of insertion loss at the minimum point is 0 dB for ideal components. For real components the depth of this d is determined by the quality factor (Q) of the circuit at that frequency; the severity of the dip increases as Q increases.

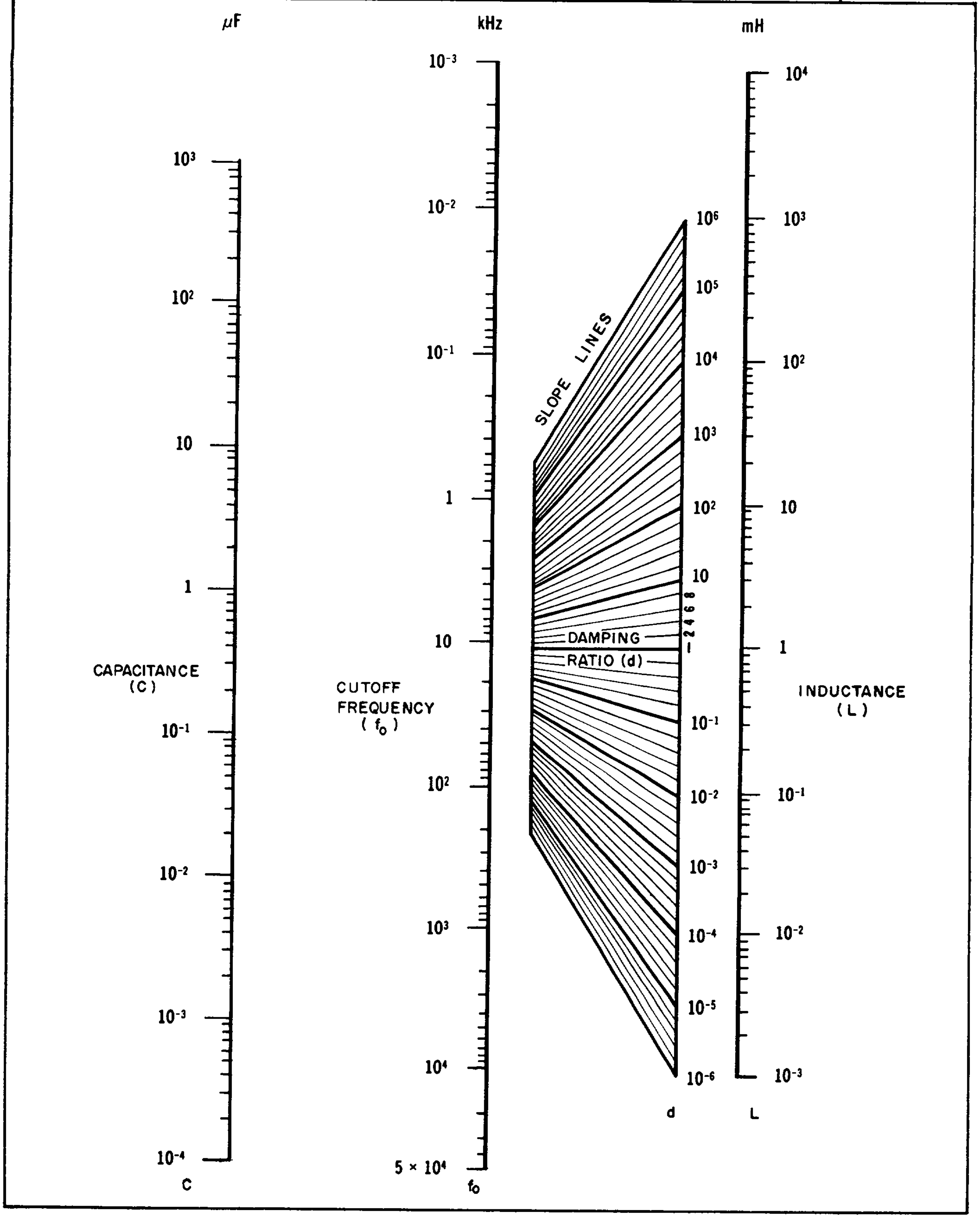
4.1 CRAIG CHART III-A

Sub-Note 4.1(1) represents the relationship between insertion loss and cutoff frequency for ideally damped T and π networks. It is based on *Eq 3* with d = 1. This chart is used in the same manner as Craig Chart II-A (*Para 3.1*).

4.2 EXAMPLES

The insertion loss at 150 kHz for an ideally damped three-element filter which has a cutoff frequency of 45 kHz will be 30 dB according to this chart. The cutoff frequency

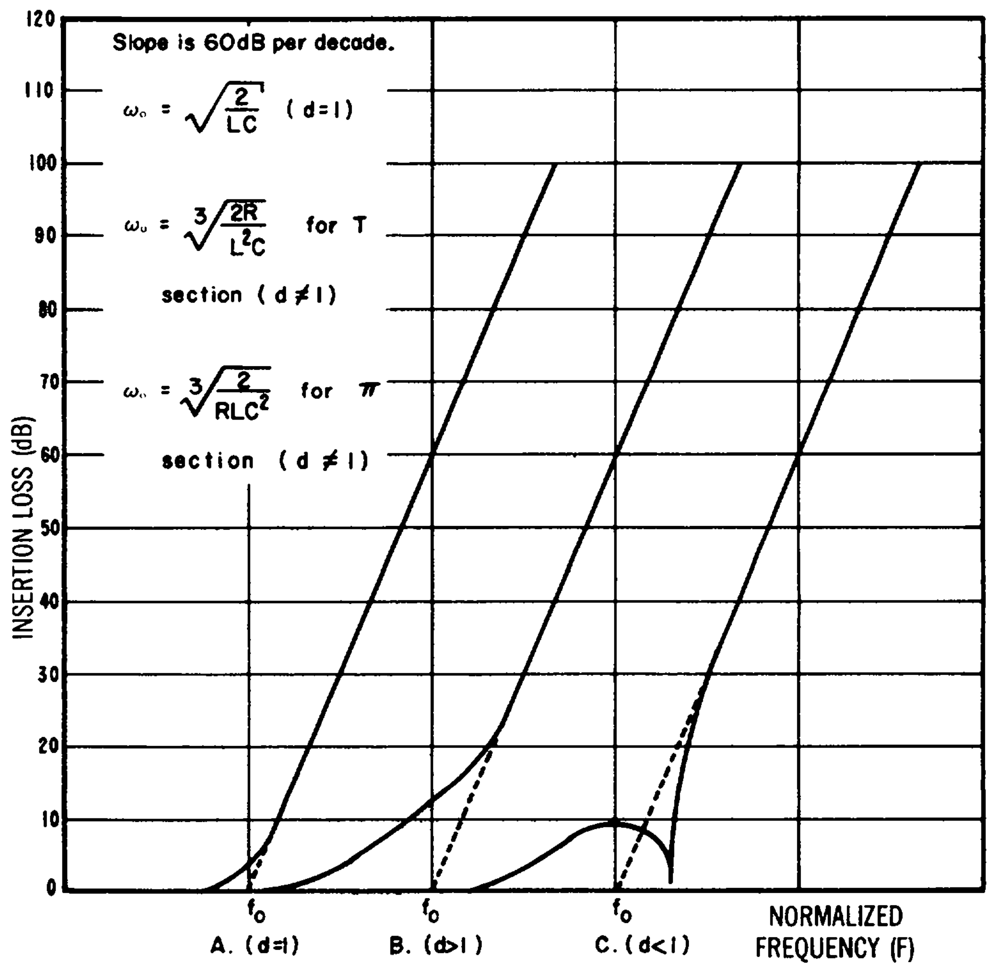
SUB-NOTE 3.3(1) Craig Chart II-C: For Computing Two-Element Filters



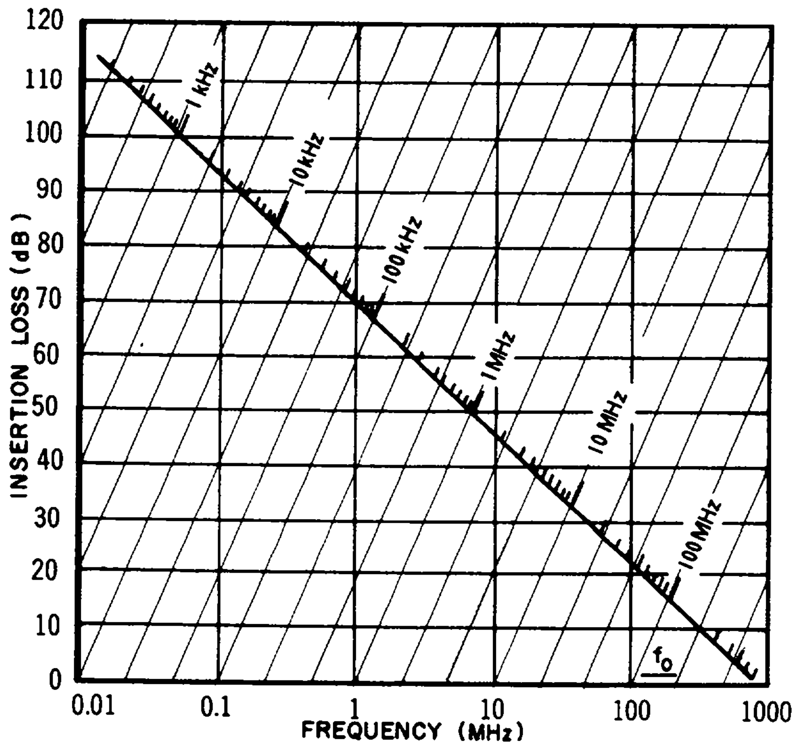
SUB-NOTE 4(1) T and π Filter Network Notations

FILTER NOTATIONS		
T NETWORKS	**π NETWORKS**	**REMARKS**
$\omega_o = \sqrt[3]{2R/L^2C}$ $L = \sqrt{2R/\omega_o^3C}$ $C = 2R/\omega_o^3L^2$	$\omega_o = \sqrt[3]{2/RLC^2}$ $L = 2/RC^2\omega_o^3$ $C = \sqrt{2/RL\omega_o^3}$	any value of d
$\omega_o = \sqrt{2/LC}$ $L = R/\omega_o$ $C = 2/R\omega_o$	$\omega_o = \sqrt{2/LC}$ $L = 2R/\omega_o$ $C = 1/R\omega_o$	only if d = 1
$d = R^2C/2L$ $D = \frac{1-d}{\sqrt[3]{d}}$	$d = L/2CR^2$ $D = \frac{1-d}{\sqrt[3]{d}}$	

SUB-NOTE 4(2) Response Modes of Three-Element Filters



SUB-NOTE 4.1(1) Craig Chart III-A: For Computing Three-Element Filters



required to produce 42 dB at 150 kHz with an ideally damped three-element filter will be 30 kHz.

4.3 CRAIG CHART III-B

Sub-Note 4.3(1) represents the insertion loss characteristic of overdamped T and π networks. It is based on *Eq 3* with d limited to values greater than one. This chart is used in the same manner as Craig Chart II-B (*Para 3.2*).

4.4 EXAMPLES

The insertion loss at 40 kHz for a three-element filter has a cutoff frequency of 80 kHz and a damping ratio of 1×10^3 will be 34 dB according to Craig Chart III-B. The insertion loss at 200 kHz for a three-element filter which has a cutoff frequency of 50 kHz and a damping ratio of 2×10^2 will be approximately 46 dB.

4.5 CRAIG CHART III-C

Sub-Note 4.5(1) represents the insertion loss characteristic of underdamped T and π networks. It is based on *Eq 3* with d limited to values less than one. This chart is used in the same manner as Craig Chart II-B.

4.6 EXAMPLES

The insertion loss at 10 kHz for a three-element filter which has a cutoff frequency of 50 kHz and a damping ratio of 1×10^{-4} will be 13 dB according to Craig Chart III-C. The insertion loss at 230 kHz for the above filter is right at the "dip" point, and the insertion loss is 0 dB for ideal elements. For real elements the insertion loss depends on the Q of the elements at 230 kHz, the better the Q the deeper the dip.

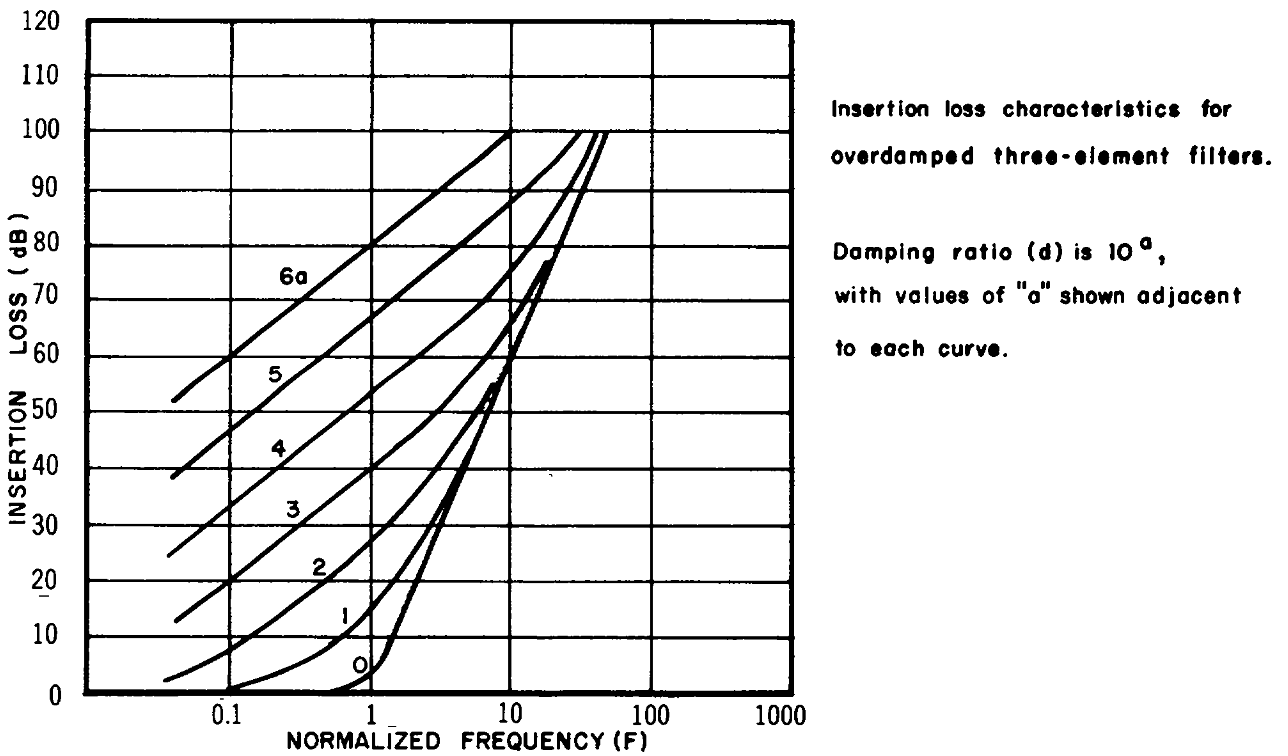
4.7 CRAIG CHART III-D FOR T NETWORKS

Sub-Note 4.7(1) represents the relationship between inductance, capacitance, cutoff frequency, and damping ratio for T network filters. It is based on *Eq 3* and the notations for the T networks. This chart is used in the same manner as Craig Chart II-C (*Para 3.3*). The value of inductance read on the L scale is the value of each inductor in the circuit; no doubling or halving is necessary.

4.8 EXAMPLES

The value for L and C for a T section with a cutoff frequency of 500 Hz and a damping ratio of 10 will be L = 7.5 mH and C = 60 μF according to *SN 4.7(1)*. The value

SUB-NOTE 4.3(1) Craig Chart III-B: For Computing Three-Element Filters

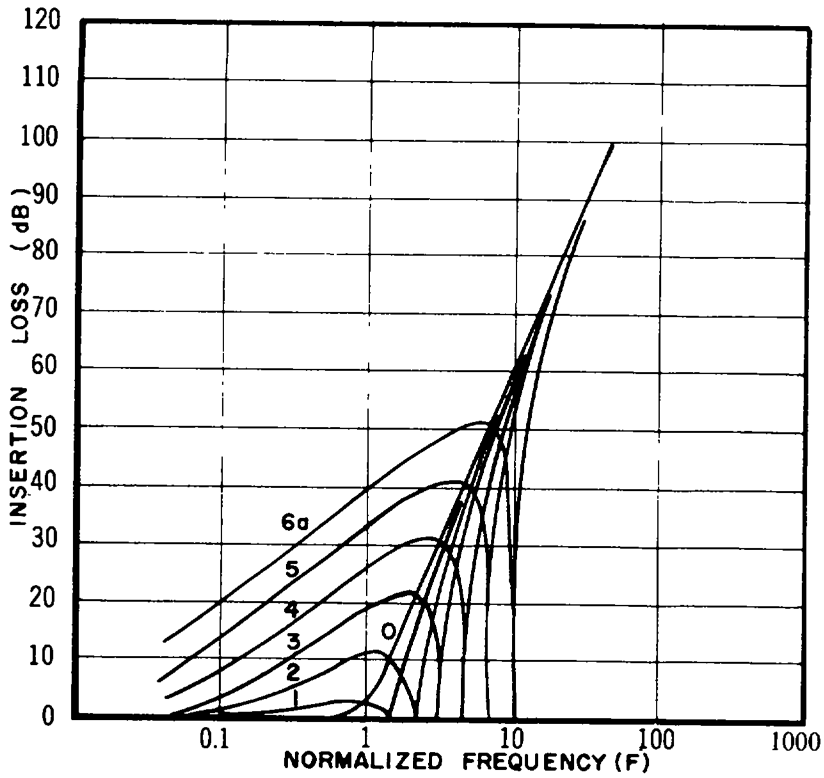


of C and d for a cutoff frequency of 10 kHz and an inductance of 100 μH will be C = 45 μF and d = approximately 8×10^2 as illustrated on *SN 4.7(1)*.

4.9 CRAIG CHART II-E FOR π NETWORKS

Sub-Note 4.9(1) represents the relationship between inductance, capacitance, cutoff frequency, and damping ratio for π network filters. It is based on *Eq 3* and the notations for the π network. This chart is used in the same manner as Craig Chart II-C (*Para 3.3*). The value of capacitance read on the C scale is the value for each capacitor in the circuit; no doubling or halving is required.

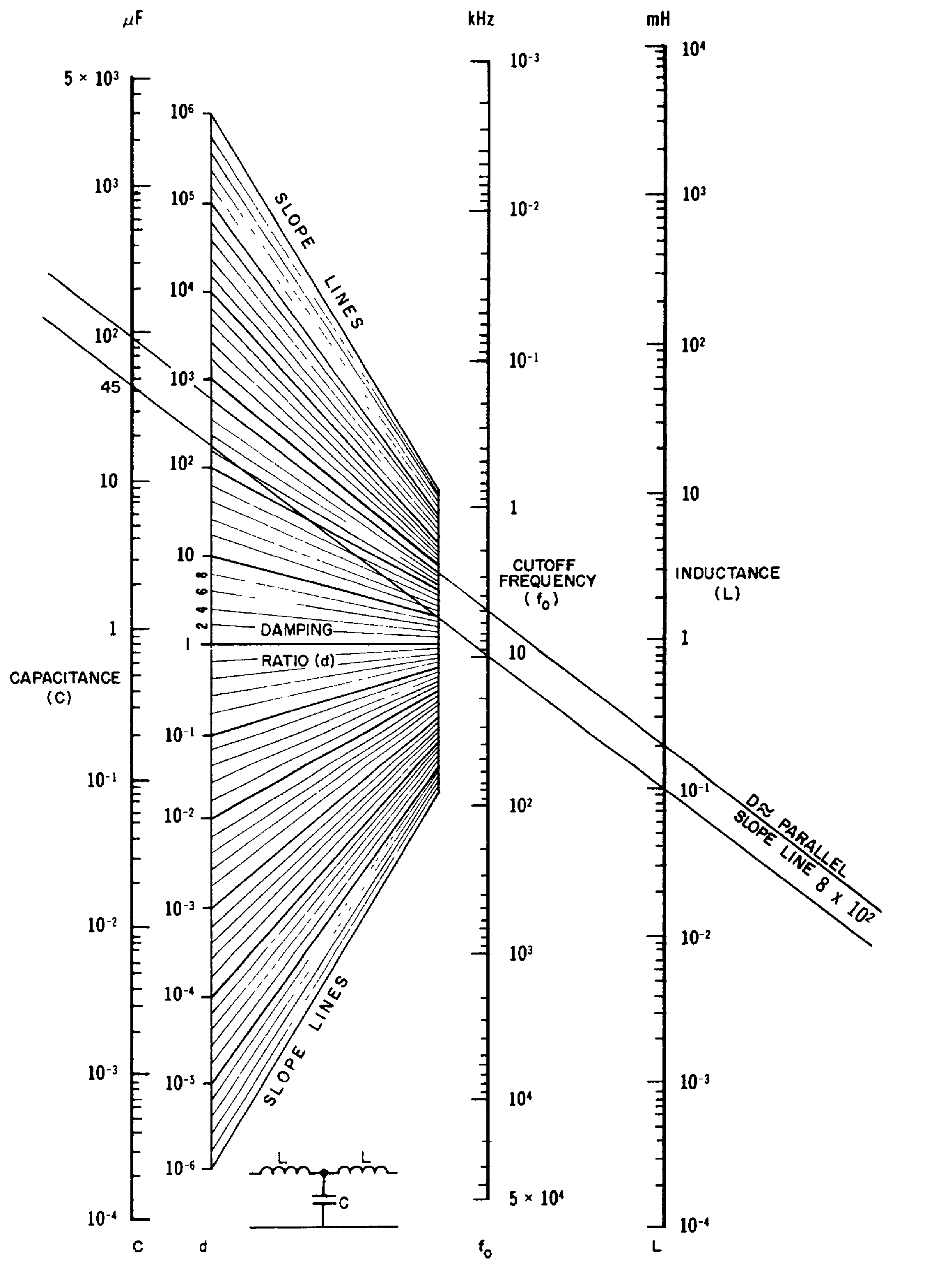
SUB-NOTE 4.5(1) Craig Chart III–C: For Computing Three-Element Filters



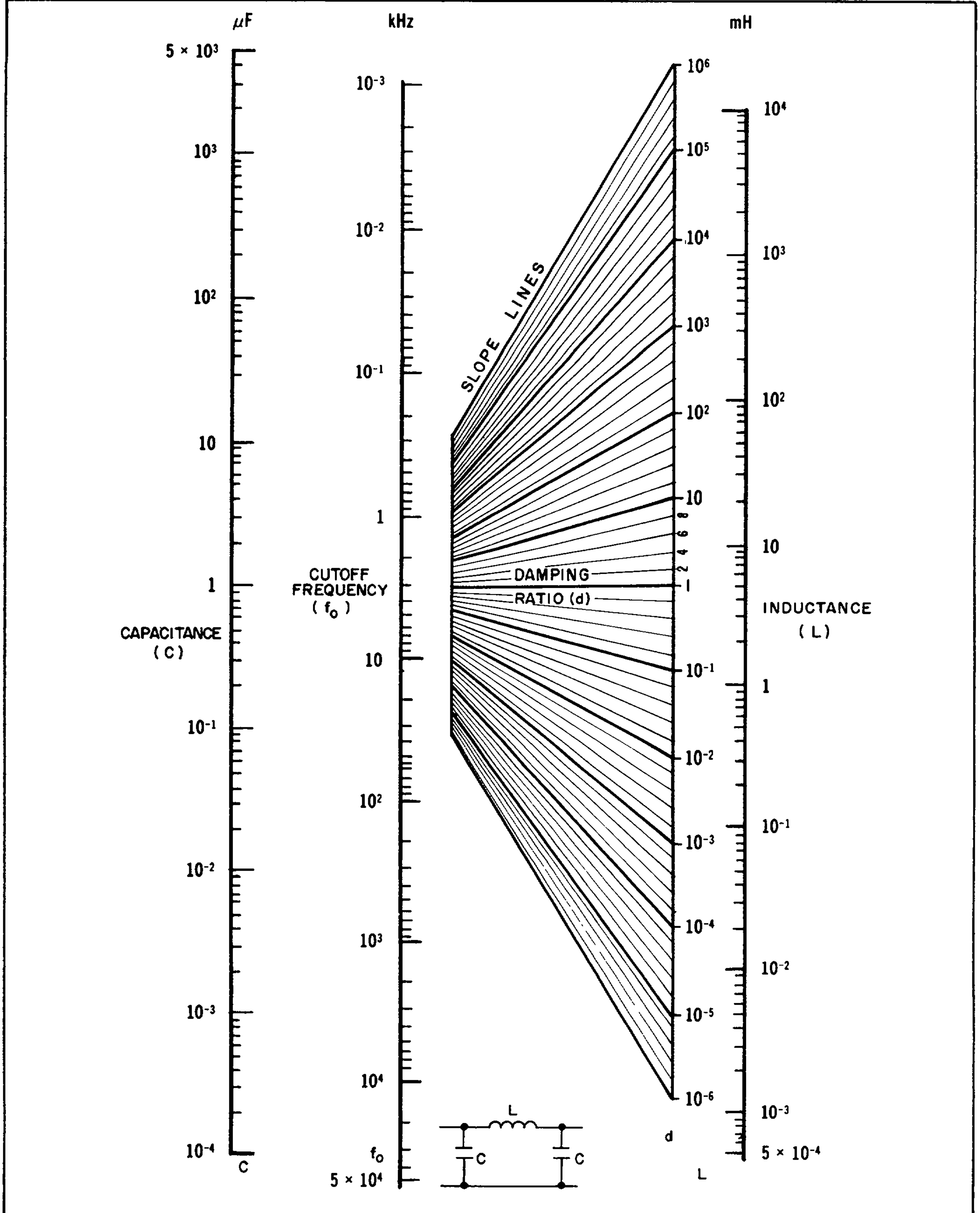
Insertion loss characteristics for underdamped three-element filters.

Damping ratio (d) is 10^{-a}, with values of "a" shown adjacent to each curve.

SUB-NOTE 4.7(1) Craig Chart III-D: For Computing T Filters



SUB-NOTE 4.9(1) Craig Chart III-E: For Computing π Filters



DESIGN NOTE 5G3 LOSSY TRANSMISSION LINE FILTERS

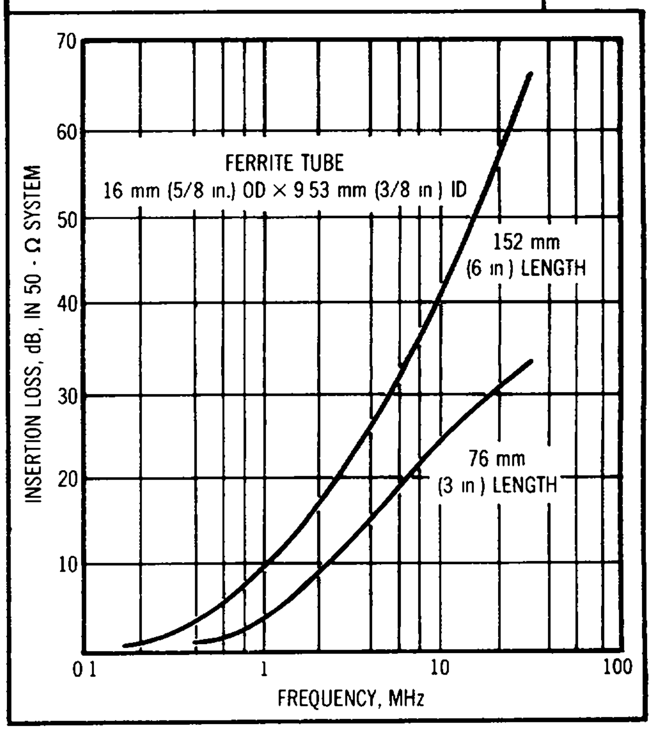
1. INTRODUCTION

The usual π or T filters, intended for broadband interference filtering, are generally composed of lossless, or very nearly lossless, inductive capacitive lumped elements. Such filters cannot dissipate energy within their rejection range; they merely reflect it, reroute it, or transform it so that, under certain conditions, it may reappear elsewhere as an undesirable signal or interference. For any configuration of lossless circuit elements of a filter, there may be found, for any frequency, a load impedance for which the filter will transmit to the load the maximum energy available from the source. Given the proper source and load impedances, insertion of a lossless filter may actually increase the energy delivered to the load; or the filter, in that circuit at that frequency, might have negative insertion loss. Similarly, the application of a filter composed of lossless lumped elements may also, under proper circuit impedance conditions, increase the voltage or current at the load. Unlike carefully designed laboratory circuits used for insertion loss measurements, where sources and load impedances are fixed at exactly 50 Ω resistance, the impedances that a filter sees in most practical power line applications are extremely variable with frequency ranging from very high or very low resistance to nearly minus or plus infinity reactance. In a practical application, it is not unlikely that at one or several frequencies within the range over which the filter is expected to be effective, the circuit impedances will cause a critical lowering of the filter's insertion loss. These impedances may even render the insertion loss altogether negative. Demonstrations of this effect have been observed where the application of a reactive filter to a line carrying interference has actually resulted in more, rather than less, interference voltage appearing on the line beyond the point of application. This deficiency, inherent in all filters composed of lossless elements, has led to the investigation of a dissipative type of filter that takes advantage of the loss versus frequency characteristic of dielectric materials such as ferrites.

2. DISSIPATIVE FILTER

The dissipative filter is a short length of ferrite tube with conducting silver coatings deposited in intimate contact on the inner and outer surfaces to form the conductors of a coaxial transmission line. The line becomes extremely lossy: that is, it has high attenuation-per-unit-length in the frequency range where either electric or magnetic losses, or both, become large and increase rapidly with frequency. *Sub-Note 2(1)* illustrates a typical insertion loss versus frequency curve for a lossy ferrite tube transmission line filter. Dissipative filters of this type are necessarily low pass and the large field of application is general purpose power line filtering.

SUB-NOTE 2(1) Lossy Ferrite Tube Filter Insertion Characteristics



REO ASD/ENACE

DESIGN NOTE 5G4* TRANSMITTER-RECEIVER FILTERS

1. INTRODUCTION

It is virtually impossible to collocate modern, high power transmitters and sensitive receivers in a communication, command, control, and intelligence (C^3I) environment without degradation to some required capability. A general technique used to reduce transmitter broadband noise and spurious outputs and improve receiver adjacent channel performance is the addition of some type of filter. The filter may be designed into the radio or added externally between the radio and its antenna. Receiver degradation caused by collocated transmitters is a problem recognized since the early days of radio. The use of solid-state technology in modern military communications equipment has, in many cases, made the problem more severe. The low noise crystal oscillator has been replaced by the relatively noisy digital synthesizer. The narrow-band vacuum tube amplifier has been replaced by solid state devices that cover several octaves of bandwidth. Vacuum tube receivers have given way to solid state receivers with inferior interference handling capability. High "Q" mechanically tuned receiver preselectors are being replaced by varactor tuned filters which not only have less selectivity, but generate additional distortion due to their nonlinearities. The use of existing fixed tuned communications with advanced modulation techniques such as pseudo-random code spread spectrum, frequency hopping, or hybrid techniques to enhance the anti-jam capability of essential communications further complicates the collocation problem. The anti-jam communications requirement dictates the need for high power frequency hopping filter technology to supplement the normal fixed tuned or electromechanically tuned filters available off-the-shelf.

2. TRANSMITTER FILTERS

There are several design techniques that can be used to reduce the broadband noise and spurious outputs of modern solid-state transmitters. First, a high-level, ultra-low noise synthesizer can be used. Improvements of 15 to 30 dB in transmitter noise floor and spurious output levels have been demonstrated in the 225-400 MHz band using this technique. Second, improved grounding, bonding, and shielding techniques are very important. It has been shown that proper techniques can reduce spurious signals by 10 to 15 dB. Significant spurious signals have been traced to power supply switching frequency harmonics in solid-state transmitters. All power supply leads should be heavily filtered, and the power supply module should be physically located as far as possible from the transmitter audio/modulation stages. Also, conetic material should be used for the power supply enclosure rather than steel. Third, broadband noise and spurious outputs can be significantly reduced by introducing electronically tuned tracking filters at low-level stages. A similar technique using electromechanically tuned filters was used in the previous generation of vacuum tube radios. These filters usually employ varactor diodes as the tuning element and care must be taken to ensure they are not driven nonlinear. *Sub-Note 2(1)* presents a summary of fixed and electromechanically tuned filters and current state-of-the-art in electronically tuned filters which may be used between a radio set and its antenna to reduce the magnitude of transmitter broadband noise and spurious outputs, and improve adjacent channel receiver performance. Detailed information regarding these filters may be obtained from RADC/RBCT, Griffiss AFB NY 13441-5700.

REO: RADC/RBCT
*This Design Note extensively revised 31 Jan 91.

SUB-NOTE 2(1) Summary of Transmitter Filter Characteristics (Sheet 1 of 2)

TYPE	CLASSI-FICATION	APPLICABLE FREQUENCY RANGE (Hz)	~ POWER CAPABILITIES (W)	~ PASSBAND LOSS (dB)	~ STOP BAND ATTENUATION (dB)	TUNING H/S	SPURIOUS
Electronically Tuned Filter	Band Pass	225-400 MHz	30, 100% AM 120 Peak	2-4	3 Pole	500	None
Electronically Tuned Filter	Band Pass	225-400 MHz	100	3-4	2 Pole	500	None
Electronically Tuned Filter	Band Pass	350-400	100/100 W*	2-3	2/1 Pole	500	None
Electronically Tuned Filter	Notch	240-252	1000	80 (Notch)	3	500	None
Electronically Tuned Filter	Band Pass**	240-252	20 Mw	1	3 Pole	500	None

* Filters are a frequency-tracked set for power amplifier input/output use.
** Receiver preselector

3. RECEIVER FILTERS

Filters play a very important role in receiver design. The designer should consider utilizing filters in the RF and IF sections of a receiver to insure adequate interference rejection.

4. PRESELECTOR FILTERS

Preselector filters are seldom included in either communication or radar receivers in the design stage but this does not preclude their use. More liberal use of preselector filters would aid in the rejection of much interference that is present without them. Cavity resonators are sometimes used in VHF and UHF communications, as well as radar receivers. However, a major disadvantage of cavity resonators is they cannot be made rapidly tunable, so they cannot be used for systems that must either change frequency rapidly or on a pulse-to-pulse basis. *Sub-Note 4(1)* presents a summary of preselector filters.

5. IF FILTERS

The IF amplifier in a receiver provides the dual function of providing amplification and selectivity. From an interference standpoint, it is necessary that the IF amplifier be operated in a linear manner and that high selectivity be provided. Some of the means of achieving selectivity include the use of mechanical filters, crystal filters, sideband selectors, Q-multipliers, delay line controlled amplifiers, and automatic variable selectivity. A summary of IF filter characteristics is presented in *SN 5(1)*.

SUB-NOTE 2(1) Summary of Transmitter Filter Characteristics (Sheet 2 of 2)

TYPE	CLASSIFICATION	APPLICABLE FREQUENCY RANGE (Hz)	SPECIFIC DESIGN FREQUENCY (Hz)	~ POWER CAPABILITIES (W)	~ PASSBAND LOSS (dB)	~ STOP BAND ATTENUATION (dB)	TUNING	SPURIOUS
				NON-MICROWAVE				
Resonant LC Circuits	Either Band Pass or Reject	Up to ~100 MHz	—	500 kW	1	30	Mech.	Few
SRI HF Filter	Band Pass	Up to ~100 MHz	8–15 MHz	20 kW	0.3	60	Mech. 8–15 MHz	Few
SRI VHF Filter	Band Pass	Up to ~500 MHz	300 MHz	5–10 kW	0.3	80	Mech.	Few
				MICROWAVE-REFLECTIVE				
Coupled Resonators	Band Pass	Above 1 GHz	—	20% of waveguide	0.1	40	Mech	Many
SRI Three Cavity Resonator	Band Pass	Above 1 GHz	1.25 to 1.35 GHz	1–9 MW	0.3	30–60	Mech.	Many
Serrated* Ride Waveguide	Band Pass	Above 1 GHz	—	Less than waveguide	0.1	40	Set	Few
Waffle Iron	Band Pass	Above 1 GHz	1.25 to 1.35 GHz	1–4 MW	0.1	>40	Set	Few
Strip* Line	Band Reject	200 to 1000 MHz	250 MHz	50 MW	0.1	>50	Set	Few
				MICROWAVE-DISSIPATION				
General Leaky Wall	Band Pass	Above 1 GHz	—	80% of waveguide	0.25	40	Set	Few
Straight* Wall	Low Pass	Above 1 GHz	3 GHz Cutoff	80% of waveguide	0.5	10–30	Set	Few
Offset* Wall	Low Pass	Above 1 GHz	3 GHz Cutoff	80% of waveguide	0.5	20–40	Set	Few
Serpentine Wall*	Low Pass	Above 1 GHz	3 GHz Cutoff	80% of waveguide	2	5–55	Set	Many
Circular Leaky Wall	Low Pass	Above 1 GHz	4.68 MHz Cutoff	80% of waveguide	0.5	25–45	Set	Few
Circular* Side Waveguide	Low Pass	Above 1 GHz	3 GHz Cutoff	10–20 kW	0.5	>18	Set	Few
Coaxial* Leaky Wave	Low Pass	1–3 GHz	1.7 GHz Cutoff	140–280 kW	0.3	15–40	Set	Few
General Directional Coupler	Low Pass	Above 1 GHz	—	80% of waveguide	0.3	30	Set	Few
Transfer* Coupler	Low Pass	Above 1 GHz	3 GHz Cutoff	80% of waveguide	0.2	6	Set	Few
Ferrite Filters	Band Reject	Above 1 GHz	—	Low	0.1	>30	Set or Elect.	Few
Leaky Wall Wiregrid*	Mode Filter	Above 1 GHz	—	80% of waveguide	TE_{10} Mode 0.1	TE_{20}, TE_{30} 30	Set	—
Periodic Filter	Band Pass	Above 1 GHz	7 GHz	500 kW peak	1.4	>50	Set	None

*Experimental models only—not commercially available.

SUB-NOTE 4(1) Receiver Preselector Filter Characteristics

TECHNIQUES	CLASSIFICATION	FREQUENCY RANGE (Hz)	FRACTIONAL BANDWIDTH (%)	PASSBAND INSERTION LOSS (dB)	STOP BAND ATTENUATION (dB)	TUNING	SPURIOUS TRANSMISSION CHARACTERISTICS
LC Resonant Circuits	Band Pass or Reject	Up to ~200 MHz	2	1 to 2	>30	Tunable over wide range	Medium
Spiral Inductance Tuner	Band Pass	200 to 400 MHz	1 to 2	~2	>30	Tunable over wide range	Medium
Helical Resonator	Band Pass	200 to 400 MHz	0.4	1.5	>50	5 to 1 range	Medium
Butterfly Resonator	Band Pass	100 to 1000 MHz	0.5	~2	>40	5 to 1 range	Poor
Butterfly Resonator	Band Reject	100 to 1000 MHz	0.2	1 to 2	26 to 44	2 to 1 range	Poor
Bridged Tee Filter	Band Reject	Up to 1000 MHz	0.01	~3	60 to 100	Difficult and critical	Good
Cavity Resonator	Band Pass	200 to 3000 MHz	0.2	1 to 2	>50	—	Medium
Coaxial Cavity Resonator	Band Pass	100 to 3000 MHz	0.2	~1.5	~60	—	Good
Ferrite Resonator	Band Pass	2 to 7 GHz	0.2	~2	~40	Elec.	Medium
Ferrite Resonator	Band Reject	2 to 7 GHz	0.5	~0 5	10 to 15	Elec	Medium
Backward Wave Amplifier	Band Pass	2 to 4 GHz	0.5	-20	20	Elec	Poor
Modified Hybrid	Band Reject	500 to 4000 MHz	—	~2	13 to 40	Less than an octave	Medium
Waveguide Cavity Resonator	Band Pass	1 to 30 GHz	0.2	~0.5	~60	—	Good
Waveguide Cavity Resonator	Band Reject	1 to 30 GHz	~0.1	~0.3	~60	—	Good
Diode Up Converter	Band Pass	Broad	—	-12	40	Elec.	Excellent

SUB-NOTE 5(1) IF Amplifier Filter Characteristics

TECHNIQUE	RANGE OF AVAILABLE FREQUENCIES (Hz)	Q	SPURIOUS RESONANCES	OUT OF BAND REJECTION	OTHER COMMENTS
Mechanical Filters	60 kHz to 500 kHz	10^4 to 10^6	Few	High	No adjustment other than initial matching
Crystal Filters (bridge type)	20 kHz to 150 MHz	10^4 to 10^7	Many	High	None
Q Multiplier	Very wide at least 80 kHz to 100 MHz	10^4	Few	High	May be unstable if large multi-plication is required.
Delay Line Controlled Amplifier	Up to 300 MHz	Variable (up to 10^4)	Few	Variable	Provides gain in addition to selectivity.
Negative Feedback Amplifier	Up to 300 MHz	High	Few	High	None
Automatic Variable Selectivity	Up to 300 MHz	Variable	Few	Varies	IF bandwidth can be varied for optimum.
Lumped Constant	Up to ~ 200 MHz	Medium	Few	Varies	None

6. ELECTRONICALLY TUNED FILTER DESIGN

High levels of transmitted noise and spurious signals from high power broadband solid-state transmitters and power amplifiers in frequency agile communications equipment severely degrade the EMC performance of collated equipment. Recent development efforts have resulted in design methods applicable to UHF and lower frequencies permitting filtering of the signal source to reduce the interfering signals while maintaining compatibility with fast hopping requirements. A description of the basic characteristics of these electronically tuned filters is presented in this design note.

6.1 BASIS OF OPERATION

There are two basic types of electronically tuned filters presently used. The first, varactor tuned filters, is used primarily in RF receiver front-ends and other locations where high power handling is not required. The second filter type, PIN diode switch tuned filters, has recently been developed for applications where RF power handling capabilities of less than 1 W to 1000 W are required with fast tuning speeds. Although various schemes have been used, the switch tuned filters generally use high power PIN diodes to switch reactive elements (capacitors, inductive loops) into a resonant RF cavity structure to vary the operating center frequency. Because discrete values of reactance are controlled by the PIN diodes, the filter tunes in individual steps rather than continuously over a frequency band. Control of the filter center frequency is accomplished by selecting a predetermined tuning reactance by forward-and reverse-biasing the proper group of PIN diodes. This tuning scheme permits non-sequenced, direct tuning to any desired frequency within the overall range of the filter. The PIN diodes used to control the filter tuning network can have very high RF power ratings, permitting high power filter operation without operating components in nonlinear regions.

6.2 CHARACTERISTICS AND TRADE-OFFS

The basic performance characteristics and trade-offs affecting the selection of performance parameters for PIN diode switch tuned filters are listed in this section.

6.2.1 TUNING SPEED. Tuning speed for the PIN diode switch tuned filters is set by the switching speed of the PIN diodes and their associated driver circuits. The slow switching diodes typically used to enhance the RF performance of the filter are the primary limiting factor in tuning speed. Center frequency tuning time is independent of the frequency span covered in a single tuning network. Typical tuning speeds of less than 100 μs have been obtained, with 50 μs achieved with more elaborate tuning network drivers, and 20 μs achievable with a substantial increase in driver circuit complexity. These measurements reflect results obtained for UHF filters using the slowest switching diodes readily available.

6.2.2 HOPPING RATE. Selection of the filter hopping rate is dependent primarily on the tuning speed and desired dwell time at the tuned frequency. The selection of faster hopping rates increases the primary power consumption of the filter because of charging currents for the RF bypassing capacitors with the high voltages used in the PIN diode circuits. Higher output rated reverse bias supplies are required as the hopping rate increases. During static or non-hopping use, the reverse bias power required is very low (less than 0.5 W). Higher hopping rates also increase the difficulty of internal EMI control required to prevent the filter itself from becoming an interference source.

6.2.3 TUNING RANGE. The center frequency tuning range covered by an electronically tuned filter is a function of the total reactance change switched in the tuning network and the location of the tuning network within the filter cavity. Each most-significant tuning bit added to a filter (even though it may consist of multiple tuning elements) doubles the reactance change available for tuning. Full octave tuning ranges have been achieved in a single filter with a single tuning element array. Wider ranges are possible but may require elaborate internal cavity configuration switching. In general, as the tuning range required increases, complexity (and cost) of the filter increases, insertion loss increases (for bandpass filters), and it becomes more difficult to tune to higher frequencies (because of increased stray reactance). For multiple-pole notch filters, structure limitations require either limited tuning ranges or a scheme to vary the resonator-to-resonator coupling.

6.2.4 TUNING RESOLUTION. The tuning resolution required in a switch tuned filter is closely related to the operating bandwidth and the tuning range selected. Since the filter tunes in discrete steps across the selected tuning range, sufficient resolution must be provided to avoid gaps in the band coverage. While tuning range is increased by adding more-significant tuning bits, resolution is improved by adding less-significant bits. Specification of excessive resolution increases cost because of added driver circuits required and increases the stray reactance of the tuning network. Usually, added less-significant tuning bits are included in a tuning network to permit tracking between resonators in a filter to be performed electronically. These bits also help improve resolution and tuning accuracy. When specified, resolution should be stated as a minimum frequency step size rather than as a number of bits desired because resolution available varies across a tuning range and can be modified through design to match variations in filter bandwidth.

6.2.5 BANDPASS SHAPE. In general, electronically tuned cavity filters have similar response passbands to mechanically tuned or fixed frequency cavity filters. Filters with bandpass or band-reject shapes based on Butterworth, Chebychev, etc., low-pass prototype filters are possible. Butterworth response filters are generally used as a starting point for most designs because of advantages in loss versus bandwidth trade-offs. Further, the high inherent accuracy of fixed reactance switching present in switch tuned filters permits multiple-pole filters to be easily tracked. This characteristic allows filters with greater selectivity to be practically implemented and tuned over wide ranges. As with other transmission-line filter implementations of lumped element filters, switch tuned filters have secondary responses located above the primary passband. In addition to responses related to the cavity resonator structure, circuit resonances within the tuning networks at high frequencies cause multiple secondary responses. In filters built to date, all secondary responses have been above the tuning range of the filter and have not been harmonically related to the tuned frequency. For applications where secondary above-band responses may cause interference, a low-pass filter may be required at the switch tuned filter output. Such a filter can be incorporated into the filter cavity structure to form a single, integrated unit.

6.2.6 BANDWIDTH. Of the performance parameters describing an electronically tuned filter, operating bandwidth and selectivity bandwidths have major impacts on the design and operation of the filter. In addition to the frequency rejection required to resolve the EMC problem under consideration, selection of the filter bandwidth must also take into account the resulting insertion loss obtained, tuning resolution required, RF power handling requirements, and complexity (and cost) of the resulting assembly. For Butterworth shape factor bandpass filters, the rejection-bandwidth characteristic is expressed as

$$X\ (\text{dB}) = 10 \log\left[1 + \left(\frac{BW_X\ \text{dB}}{BW_3\ \text{dB}}\right)^{2n}\right] \quad \text{(Eq 1)}$$

Where:

X = filter rejection in dB
n = number of filter poles
BW = bandwidth at specified rejection

Sub-Note 6.2.6(1) contains a list of bandwidth ratios for Butterworth 2 to 6 pole filters. Because of loss limitations in the electronic tuning networks, the filter 3 dB bandwidth should be maximized to minimize insertion loss and permit high power handling. To achieve sufficient rejection for EMC control, the number of poles can be increased to maximize the switch tuned filter skirt selectivity without encountering the tracking problems of mechanically tuned or varactor tuned filters. However, as the number of poles increases, the filter becomes larger, more complex, and requires tight controls of inter-resonator coupling to achieve a smooth passband response across a wide tuning range. A parameter describing the bandwidth of a filter is the loaded Q, defined as

$$Q_L = \frac{f_o}{BW} = \frac{\text{Center Frequency}}{\text{3 dB Bandwidth}} \quad \text{(Eq 2)}$$

when the filter is driven from a matched generator into a load (50Ω in most systems). The electronically tuned filters built to date have a relatively constant loaded Q versus frequency rather than constant bandwidth. Therefore, the 3 dB bandwidth is much narrower at the low end of a wide tuning range than the high end. This characteristic should also be considered when determining filter requirements.

SUB-NOTE 6.2.6(1) Filter Selectivity Ratios

Bandwidth Ratio (dB)	2 Pole Filter	3 Pole Filter	4 Pole Filter	5 Pole Filter	6 Pole Filter
3/.05	1.69	1.42	1.30	1.23	1.19
40/3	10.00	4.64	3.16	2.51	2.15
50/3	17.78	6.81	4.22	3.16	2.61
60/3	31.62	10.00	5.62	3.98	3.16

6.2.7 INSERTION LOSS. As previously described, many potential factors impact the insertion loss of a switch tuned filter. Since the electronically tuned filter replaces a mechanically tuned cavity filter in many applications, direct comparisons are made between desired performance levels and present capability. However, in all cases, the electronically tuned filter will have higher insertion loss than a fixed tuned or mechanically tuned cavity filter, all other performance parameters being equal. This is obvious from the fact that losses are present just from introducing the tuning components into the cavity structure. Therefore, some performance trade-off (usually either bandwidth or insertion loss) must be made. The prediction of final insertion loss in an electronically tuned filter is very difficult and depends on many factors. These include bandwidth, number of poles, power handling requirements, tuning range, tuning resolution, filter cavity size, accuracy of filter coupling, tuning element losses, and primary power limitations. Ultimately, these loss factors impact the unloaded Q of the filter resonators. Unloaded Q (the ratio between energy stored and energy dissipated with no external loads, or the resonator bandwidth with the source and load resistance removed) can be used to predict insertion loss of bandpass filters using the expression:

$$\text{insertion loss} = 20 \log (C_n d_k + 1) \text{ dB} \quad \text{(Eq 3)}$$

Where:

C_n = $a_1 a_0$ = first term of the transfer function polynomial
d_k = $Q_{L\ TOT}/(Q_{unl}/\text{pole})$
$Q_{L\ TOT}$ = overall filter loaded Q
Q_{unl}/pole = unloaded resonator Q per resonator.

Sub-Note 6.2.7(1) contains C_n factors for Butterworth filters of 2 to 6 poles (or resonators). An expression for the ultimate depth of a notch filter, taking into account limited resonator unloaded Q, is:

$$(L_A)_{\omega_0} = 20 \sum_{n=1}^{N} \log (g_n D_n) + 10 \log (g_0 g_{N+1}/4) \text{ dB} \quad \text{(Eq 4)}$$

Where:

$(L_A)_{\omega_0}$ = notch depth at the tuned center frequency
N = number of poles
g_n = nth element value of low-pass prototype
D_n = $\omega'_1 w\, Q_{unl}$
ω'_1 = low-pass prototype cutoff frequency = 1
w = fractional bandwidth = $1/Q_L$
Q_{unl} = unloaded Q of the nth resonator

As a guide in determining approximate loss achievable, *SN 6.2.7(2)* contains typical unloaded Q factors achieved for UHF band filters for various total tuning ranges. However, as mentioned earlier, each particular filter requirement should be analyzed in detail to determine appropriate trade-offs to optimize insertion loss performance.

6.2.8 RF POWER HANDLING. The switch tuning concept of electronically tuning a filter has inherent high power handling capability. Filters handling 1000 W at UHF frequencies have been successfully built and tested. Power handling limits are set by the normal factors of cavity size, tuning element voltage and current ratings, and implementation of the tuning scheme within the cavity. Because of the close relationship between insertion loss and dissipation rating of the tuning elements, filters expected to handle very high power levels may require bandwidth trade-offs to permit component ratings to be met. Intermodulation distortion performance of the filter also influences design decisions on the placement and operating levels of the filter tuning network. Filters with third-order intercept point performance of +80 dBm to over +100 dBm have been tested. This level of performance can be particularly useful in collocation or multicoupler applications.

6.2.9 POWER SUPPLY REQUIREMENTS. Electronically tuned filters require internal power supplies to bias the switching PIN diodes and drive control and monitoring circuits. Power requirements are directly proportional to the number of filter poles, number of tuning elements, and hopping rate of the filter. The filter also tends to require greater primary power as more tuning elements are turned on (at lower frequencies in the tuning band) and with filters that are designed for absolute minimum insertion loss. Internal supplies require careful filtering to avoid coupling signals into the RF handling circuits of the filter. Regulation of absolute voltage levels is not particularly critical since the major power users are the switching PIN diodes, which are only forward- or reverse-biased. High voltages (over 500 V) and high current levels (several amps) are used to bias each diode in high power filters. Total dissipation is low, however, since power requirements for diode bias are low.

6.2.10 FILTER SIZE AND WEIGHT. Electronically tuned filters have size and weight characteristics similar to mechanically tuned or fixed tuned cavity filters using a similar cavity implementation. Although some additional space is required for the electronic PIN diode driver circuits, RF decoupling circuits, and internal power supplies, certain implementation techniques also reduce the cavity size required (as compensation for the stray reactance introduced into the filter cavity by the electronic tuning network). As in any cavity filter, an increase in cavity volume yields a higher unloaded Q for the cavity.

6.3 EXAMPLE FILTERS

Several examples of built and tested filters and parameters described in this design note are listed in *SN 6.3(1)*. Note the filters listed are experimental models intended to show certain characteristics for different applications and do not generally represent optimum trade-offs for all uses. However, this data does provide an indication of the range of filters and performance parameters achievable.

SUB-NOTE 6.2.7(1) Butterworth Filter Coefficients (C_n)

n	C_n
2	1.41
3	2.00
4	2.61
5	3.24
6	3.86

SUB-NOTE 6.2.7(2) Typical Resonator Unloaded Q-UHF Filters

Tuning Range (MHz)	Unloaded Q Range	Nominal Loaded Q	Comments
225-400	350-375	100	2 pole 100 W filter
350-400	450-500	100	2 pole 100 W filter
350-400	200-500	40	1 pole 1000 W filter
240-252	600-750	80	5 pole notch filter - small cavity
240-252	800-950	80	5 pole notch filter - large cavity

SUB-NOTE 6.3(1) Typical Experimental Model Filter Performance

Filter Performance Parameter		A(1)	B(1)	C	D	E
Tuning Speed	(μS)	60	60	70	50	100
Hopping Rate	(per sec)	200	200	300	2000	200
Tuning Range	(MHz)	350-400	350-400	240-252	225-400	225-400
Tuning Resolution	(Max-MHz)	2	0.20	0.20	2	4
Bandpass Shape		1 pole	2 pole	5 pole	2 pole	2 pole
Classification		Bandpass	Bandpass	Notch	Bandpass	Bandpass
Bandwidth	(MHz)	7-9	2.8-4.0	3.0	2.2-4.0	16-25
Insertion Loss	(dB)	0.9-1.5	2.5-3.0	80 typ	2.5-3.0	2.5-3.8
RF Power Handling	(W)	1000	100	30 W CW at f_0	100	20
Power Supply	(W-max) (V)	175 (2)	175 (2)	115 V, 400 Hz-178 28 V DC-154	200 (2)	20
Size		(3)	(3)	$1^1/_2$ ATR	19'' Rack $3^1/_2$'' Tall	40 cu in.
Weight	(lb)	N/A	N/A	75	N/A	N/A

Notes: (1) Filters A and B are a frequency-tracked set.
(2) Lab supplies used.
(3) Unit not packaged.

DESIGN NOTE 5G5 TRADE-OFF FACTORS

1. INTRODUCTION

When designing or selecting a filter, a number of parameters must be considered. This design note will give these parameters.

2. IMPEDANCE MATCHING

The elements of the filter must be chosen so the impedance network matches the line into which it is inserted. This is especially true of transmission lines so the filter does not impair the normal function of the equipment at both ends of this line.

3. VOLTAGE RATING

Consider the voltage rating on the filter used on power lines. *MIL-STD-704* specifies the limits within which electrical power subsystems operate. Under some conditions the voltage may deviate by a large amount from the normal line voltage. In addition, short duration (10 μs) pulse up to 600 V may be on the power circuits, both ac and dc. The filter voltage ratings must be sufficient to provide reliable operation under the extreme conditions shown in *MIL-STD-704.*

4. VOLTAGE DROP

Determine the maximum allowable voltage drop through the filter and design accordingly. Ensure the voltage drop caused by a filter does not exceed the total drop permitted by *MIL-STD-5088*.

5. CURRENT RATING

Current rating should be for the maximum allowable continuous operation of the filter. Calculate the current rating for filter elements, such as capacitors, inductors, and resistors. Whenever possible, the current rating of filters should be consistent with the current rating of the wire, circuit breakers, or fuse with which the filter will be used. A filter with a higher current rating than the circuit in which it is installed will often add to the weight and space penalty. A filter with a lower rating is a safety hazard. The safety factor used in rating filters should also be consistent with those used for other circuit components.

6. FREQUENCY

Consider both the operating frequency of the circuit and the frequency to be filtered (attenuated). In general, do not use sharp filters to reject the power frequencies. If such a filter is required, its rejection characteristic must be wide enough to provide adequate attenuation over the power frequency deviation specified in *MIL-STD-704.*

7. INSULATION RESISTANCE

The insulation resistance of the filter may vary during the life of the filter. Determine the maximum allowable variation of this resistance for proper filter operation.

8. ELECTROLYTIC CAPACITORS

Electrolytic capacitors are sometimes used in low-pass filters. The dissipation factor increases, and the capacitance decreases with age on the wet-type electrolytic capacitor. An RF bypass capacitor should be placed across the output of dc supplies to filter out any high-frequency interference which may be present. The high dissipation factor or series resistance within the wet electrolytic capacitor makes it a poor filter for RF. Do not use wet electrolyte in airborne applications. If space is at a premium and the working voltage of the circuit is low, a solid type tantalum capacitor with a low-dissipation factor subject to testing may be used.

9. GROUND LEADS

Ground leads on capacitors and filter enclosures should be as short as possible for RF interference filtering. Capacitors having metal cases with grounding studs or mounting clamps provide leadless grounds. Feed-through capacitors and filters are grounded through the metal case and mounting flange.

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10. SIZE AND WEIGHT

Size and weight can be the deciding factor in some filter applications. When space is at a premium, adding or subtracting various filter elements may reduce the size and weight of the filter.

11. ISOLATING AND SHIELDING

Isolating and shielding is the key to good filtering. A filter network may be placed in a shielded enclosure or metal case and grounded by the methods explained in *Para 9*. See *SN 1(1)* in *DN 5D4* and *SN 2.1(3)* in *DN 5F1* for methods of mounting and installing filter networks.

12. TRANSMISSION-LINE FILTERS

Transmission-line filters can be the lossy type or one of the four types of filters explained in *DN 5G1*. These filters are completely shielded in a case and are usually terminated with an input and output coaxial connector.

13. FILTERS IN CONNECTOR CONTACTS

Miniature filters can be constructed into a single-pin contact and placed in a multipin connector receptacle. This connector consists of a group of low-pass filters for the isolation and suppression of RF.

SECT 5H SUMMARY OF BASIC EMC DESIGN

SECTION 5H SUMMARY OF BASIC EMC DESIGN

DN 5H1 - EMI SUMMARY LIST

DESIGN NOTE 5H1 EMI SUMMARY LIST

1. INTRODUCTION

The material presented in *SN 1(1)* is provided as a convenient reference for reviewing the electromagnetic interference (EMI) aspects of equipment design or installation. It was prepared by the Lockheed Missile and Space Company for the Agena system. It is divided into seven subject areas. This guide can be used by designers and engineers when designing or installing equipment.

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SUB-NOTE 1(1) EMI Summary List

CIRCUITS TO BE SHIELDED AND FILTERED

Have any of the following EMI producing circuits been filtered?

a. Chopper
b. Converters
c. Inverters
d. Relays
e. DC motors
f. Switches
g. Clock or timing circuits with fast rise time or high repetition circuits
h. Other circuits

Have transformer-rectifier (TR) outputs been filtered? Was the transformer electrostatically shielded?

Have any components with inherent shielding been used, such as cupreous tuning inductors?

Has bandpass filtering been used on transmitter outputs or receiver inputs?

What type of electromagnetic field is being shielded against, E field or H field? Is the shielding material suitable for this type of field for the frequency range of interest?

Have decoupling capacitors been used on internal power connections?

Have any feed-through capacitors been used for internal connection of circuits? Or, as bulkhead-mounted headers?

Have shielded subassemblies been used in the equipment?

Have RF chokes and inductors been used to confine the RF energy to the desired circuits?

Were parts of internal chassis used to obtain shielding?

Have waveguide-below-cutoff techniques been used for chassis openings, such as tuning adjustments or air cooling?

Have low-level or susceptible circuits been physically separated from EMI producing circuits within an enclosure?

Have toroids been used to minimize the leakage field of inductors? Have inductors been cross-oriented to minimize coupling?

METHODS OF ELIMINATING SPURIOUS EMANATIONS AND RESPONSES

Are components being operated in linear rather than nonlinear regions, if possible?

Are crystal-controlled circuits being used? Has the best choice of multiplier stages been made?

Have crystal filters, bandpass filters, tank circuits, tuned stages, and other narrow-band devices been used?

Have RF trap circuits been used for known or expected spurious outputs or responses?

Have circuits been used which inherently discriminate against creation or passage of certain harmonics, such as push-pull outputs of amplifiers, balanced mixer-ring coupler combinations, or other hybrid circuits of a similar nature?

Have circuits of balanced or symmetrical design been used?

Have diodes or other biasing devices been used to establish definite minimum or maximum actuation levels for circuits?

Have coincidence circuits, time-delay circuits, or similar logic circuits been used?

Have circuits utilizing coded inputs or outputs been used?

Has filtering been done at subsystem levels, especially multiplier stages?

Have RF circuits been decoupled from power supplies?

Have short-lead lengths been used in RF circuits? Has internal wire routing been controlled?

Has physical and electrical isolation of circuits potentially capable of producing or of being susceptible to spurious energy been achieved?

Are internal subassemblies shielded and filtered to prevent undesired modulation?

Have components and devices been chosen to minimize frequency drift or random modulation due to temperature, aging, vibration, etc.?

Are potentially susceptible circuits sufficiently shielded against external RF fields, including low-frequency magnetic fields?

Have special precautions been taken to prevent responses at receiver image frequencies?

Have shielded antenna inputs been used?

Have operating frequencies been chosen to avoid conflicts with known existing frequencies or their harmonics?

Have the proper or excessive power levels of generated frequencies been used, such as the local oscillator stages or receivers or multiplier and output stages of transmitters?

Has circuitry (other than RF) of receivers and transmitters, such as power connections, telemetry connections, and monitoring points, been controlled to prevent RF coupling to other circuits?

Have any special methods been used to avoid spurious modes of operations of circuit elements, such as klystrons and oscillators?

METHODS OF ELIMINATING SPURIOUS RESONANCES

Have short-lead lengths been used for all components, especially capacitors in RF circuits?

Has damping been used in circuits capable of oscillation?

Have feed-through capacitors been used for interstage coupling and isolation, and for power input connections to RF circuitry?

Have waveguide-below-cutoff techniques been used for all required openings in enclosures?

Has the number of enclosures, openings been minimized?

Have critical dimensions been avoided, considering the enclosure or subenclosure as an RF cavity?

Have tuning methods which minimize nodes or harmonic generation been used?

Have all feedback loops been designed to prevent oscillation under worst-case conditions?

Has high-power and low-power stage of units been isolated?

Is the proposed enclosure bonding adequate at the known critical radio frequencies?

Have component tolerances been controlled to prevent frequency drift, mode switching, etc., due to temperature, aging, etc.?

Have RF components been used throughout RF stages, (i.e., have components been used that are not self-resonant in the intended frequency range (unless desired))?

Have special circuits which discriminate against spurious resonance been used?

METHODS OF OBTAINING CONTINUOUS SHIELDING ON EQUIPMENT USING PRESSURE OR HERMETIC SEALS

Has the enclosure been mechanically designed to assure sufficient pressure between mating parts?

Has chassis been mechanically designed to minimize the number of openings and open leakage?

Has each opening in enclosure been analyzed to determine the need for gaskets, waveguide-below-cutoff techniques, screening, etc.?

Has the minimum attenuation needed by the enclosure been evaluated?

Are openings and attenuation consistent? (Item 3 above applies to radiation through the opening in the enclosure and Item 4 above refers to radiation through the metallic portion of the enclosure.) Leakage will normally determine minimum overall enclosure leakage, except at low frequencies.

Do the mating surface pressure, area, finish, or tolerances degrade the expected attenuation of the enclosure seams?

Have dissimilar metals been used in the enclosure? Is this compatible with the expected environment?

If RF gaskets have been used, is the design adequate to optimum pressure, class of joint or seam, choice of gasket mounting, size of gasket, attenuation of gasket, etc.?

Are subenclosures properly attached to main enclosure?

What are the expected internal and external fields and expected frequencies?

THICKNESS OF CASE MATERIAL REQUIRED TO PROVIDE ADEQUATE SHIELDING IN HIGH POWER RF EQUIPMENT

Are there expected internal and external RF fields and frequencies? What is the physical location of the equipment to other equipments?

Is the enclosure thickness adequate to attenuate the expected fields to a tolerable level? Is the thickness and weight excessive?

Is the estimated added attenuation provided by shielded subenclosure?

Is composite shielding provided by enclosure, subenclosure, waveguide-below-cutoff openings, gasket seams, screened openings or normal mating surfaces?

Does associated external cabling degrade the required attenuation levels?

SELECTION OF INTERFERENCE-FREE COMPONENTS TO BE USED WITH OTHER COMPONENTS

Are diodes or other suppression components being used across relay coils?

Are RC circuits being used across switch or relay contacts?

Are solid-state switches being used instead of mechanical switches?

Are capacitors being used directly across dc motor brushes?

Are electrostatically shielded transformers being used?

Are matched diodes being used in balanced mixers?

Are toroids or other low leakage field inductors being used?

Are nonself-resonant components, such as feed-through capacitors, being used?

Are bulkhead-mounted components being used?

Are crystal filters being used?

Are twisted pair, twisted triad, or shielded wire being used?

Is balanced-circuit design being used?

Are diodes or other bias devices being used to establish definite maximum or minimum actuation levels?

Are connectors being used as inherent parts of filters?

Are separate connectors being used for sensitive and EMI producing circuits?

Are crystals being used as frequency sources?

Are selective waveguide or coaxial components, such as diplexers, being used?

Are lossy line techniques being used to attenuate harmonics?

Are temperature-compensated components being used to minimize drift, etc.?

Are components being operated in linear regions?

Are limiting devices, such as diodes, being used?

Are dc blocks being used?

OTHER PERTINENT INFORMATION

Are there any special type circuits which intentionally or unintentionally eliminate or minimize EMI? Examples might be blanking circuits, time-sequencing circuits, disabling circuits, bridge or differential type of circuits, balanced input circuits, possibly AGC, AFC, and AVC circuits.

Is there any bonding information that has not been previously covered?

Is there any circuit uniqueness due to special signal or modulation characteristics?

Is there any antenna data that could be included which could influence the EMI characteristics of transmitters or receivers?

Is there any sharing of antennas? or time sharing? or switching of antennas? If so, has it been proved feasible?

Are there any transmission line or antenna devices present, such as RF isolation, whose losses or bandwidth would be pertinent?

Have sources of primary power been fully covered? Are there any usual characteristics of primary or secondary power sources?

Is there any circuit redundancy which might affect EMI control?

Have the most susceptible circuits been identified? Have the greatest EMI producing circuits been identified?

CHAP 6 TEST PROCEDURES AND EQUIPMENT

CHAPTER 6 TEST PROCEDURES AND EQUIPMENT

SECT 6A TEST METHODS AND TESTING

SECTION 6A TEST METHODS AND TESTING

DN 6A1 - STATISTICAL TESTS FOR ELECTROEXPLOSIVE INITIATORS

DESIGN NOTE 6A1*

STATISTICAL TESTS FOR ELECTROEXPLOSIVE INITIATORS

1. INTRODUCTION

The statistical test methods commonly applied to electroexplosive initiators (EEI) in determining direct current (dc) sensitivities are evaluated for the following objectives:

a. Can dc no-fire, mean-fire, and all-fire levels be used to estimate radio frequency (RF) sensitivities?

b. Is the statistical method utilized in determining dc sensitivities usable in RF sensitivity measurements?

c. Is the statistical test method used to establish dc sensitivities consistent?

d. Can the statistical test methods be improved, particularly with regard to obtaining the desired result with fewer number of samples (hence, lower cost)?

Design Note 3D6 contains additional EEI information.

1.1 SAMPLE SIZE, RELIABILITY REQUIREMENTS, AND COST CONSIDERATIONS

Sample size and reliability requirements are closely connected with the problem of EEI reliability estimation. As reliability requirements get higher, the number of parts allocated to prove the reliability should increase proportionately. However, experience has proved that this is not always the case. Where the individual unit cost is high, there have been cases where the sample size for reliability testing has actually been decreased at the higher reliability levels. It is understandable that the budget conscious engineer resists allocating large numbers of expensive parts to be destructively tested in sensitivity testing. However, if the mission of the EEI is sufficiently important to warrant a high reliability and confidence level, an expenditure of the necessary number of parts to demonstrate the reliability is justified. The direct demonstration of a 99.5% or better response at 95% confidence of an EEI to a given stimulus is often too costly in material, time, and manpower to be seriously considered. It would require the firing of nearly 600 items without a failure. Similarly, it requires the successful functioning of over 2300 EEI to establish a simple functional reliability of 99.9% at a confidence level of 90%.

2. EVALUATION OF TEST METHODS

The various methods for testing EEI are briefly summarized here.

2.1 BRUCETON METHOD

The most frequently used method for determining the dc sensitivity of electric initiators is the Bruceton (or up and down) test. The Bruceton test is carried out using test levels which are computed from an estimated standard deviation of stimulus levels. A methodology is followed advancing to the next lower stimulus level if a firing occurs, or to the next higher level for a no-fire. For making studies around the 50% response level, the test is most often highly acceptable and advantageous. When estimates beyond the 75% response level are made by the Bruceton method, difficulties can be anticipated. For example:

a. The Bruceton method gives a poor estimate of the standard deviation. Even Bruceton tests of 100 samples will often underestimate the true standard deviation by 50% or more.

b. Since most all data are collected between the 25-75% response levels, long extrapolations must be made to the no-fire or all-fire points along a curve which is usually unknown. Though the test is widely used and its theory well established, the theory is based upon a large number of samples; a minimum of 200 is recommended. The test is widely used in the United States on much smaller samples, often as low as 25 and seldom over 50. The Bruceton test, therefore, accurately determines median firing level. However, extrapolation to the no-fire and all-fire points is not reliable, primarily because it does not give a good estimate of the standard deviation, even if the distribution is assumed to be normal. The standard deviation is usually underestimated, thus rating EEI as safer than they really are at the rated firing current.

2.2 THE PROBIT METHOD

The Probit method is particularly well suited to the situation in which it is difficult to change the stimulus level by predetermined amounts. The Probit method generally requires more parts to produce the same results than other more efficient methods of sensitivity testing. A basic assumption is that the method is based upon normalcy of the variate being tested.

2.3 THE RUN DOWN METHOD

This method was developed at the Naval Ordnance Laboratory, White Oak, MD. The method assumes a very conservative EEI probability distribution (log logistic) and generates test data further out on the distribution curve than does the Bruceton test. The Run Down

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*Extracted in part from Ref 661.

method requires 200 parts to establish fire or no-fire (380 parts for both) to a reliability of 99.0%. See *Ref 1435* for more information on this subject.

2.4 THE NONPARAMETRIC TESTING METHOD

All sensitivity testing methods previously discussed are parametric methods. They depend critically upon the assumption of various parameters. The outcome of the test is directly related to the degree of accuracy with which the original assumptions are verified. Thus, there is a built-in restriction on the tests which can cause serious errors if ignored. The nonparametric tests are completely different. They do not depend upon the assumption of any particular distribution or parameter of a distribution. There are some requirements which must be met but these are very easy to satisfy. Most existing nonparametric testing methods suitable for sensitivity testing are variations of the Robbins-Monro method.

2.4.1 ROBBINS-MONRO METHODOLOGY. The actual estimate of the no-fire level by the Robbins-Monro method is nearly independent of the actual firing probability distribution of the population. No assumption is made about distribution curves, although very highly skewed distributions give rather odd results for finite numbers of samples. The starting points and initial step sizes are more important than distribution. It is assumed that the no-fire level desired is the stimulus that will fire not more than 0.5% with a 95% confidence level. Other levels may be found by substituting the desired level for α (α must be expressed as a decimal fraction).

2.4.2 ROBBINS-MONRO EQUATION. The basic equation for the Robbins-Monro method is

$$X_{n+1} = X_n + A_n(\alpha + Y_n) \qquad \text{(Eq 1)}$$

Where:

X_{n+1} = the value of the independent stimulus variable (current, etc.) to be used in the next trial.

X_n = the variable value used in the last trial.

α = the proportion of successes desired, $0 < \alpha < 1$.

Y_n = 1 if the last trial resulted in a success.

Y_n = 0 if the last trial resulted in a failure. A success has occurred if the EEI fired.

A_n = $\sigma/2^{n'}$ (a function selected for desired convergence properties).

σ = the approximate standard deviation of the sample. It need not be known accurately. Bruceton data, even for a few tries, are quite good.

n' = starts at 0 and increases by 1 for every success.

X_1 = the initial stimulus level and should be set to the average value plus 2σ if Bruceton data are available. (This is for a fire test.)

X_n = approaches the level that has the fractional response α if Y_n is 1 for a positive response and A_n is a series such that

(1) $\sum_{n=1}^{\infty} A_n = \infty$

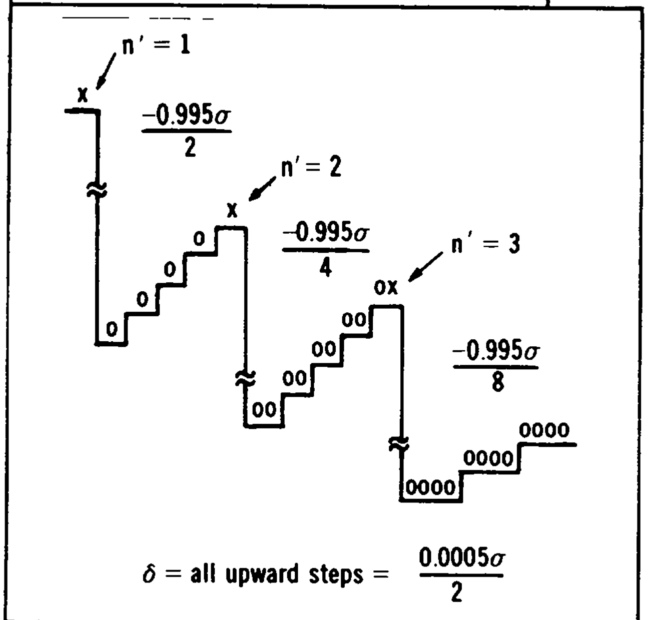
(2) $\sum_{n=1}^{\infty} (A_n)^2$ = some finite number

(3) $A_n > 0$

The condition in (1) above ensures that there is enough mobility in the series to get to the proper region. The condition in (2) above, a finite number, ensures convergence. This result is independent of the actual frequency distribution in the sample. Simulation tests using random numbers with the series $X_n = C/n$ indicated that the convergence to the proper region is quite slow. Continued research led to the series $X_n = C/2^{n'}$ where n′ was only changed when a squib fired. This series showed excellent results if C is approximately equal to σ. In fact, if 100 samples were tested, the formula $X_{101} - \sigma$ failed to be less than the true value of 0.5%, firing only once in 2000 times. If only 50 samples are used, the results are not quite as good as for 100, but the number of instances of $X_{50} - \sigma$ exceeding the true value was less than 5%. The essence of the scheme is that one is led by the series to a region in which, for every one that fires, $1/\alpha$ (200 for 0.5% firing level) do not fire. This is because the step size for each fire is $(1 - \alpha)/\alpha$ times as great as for the no-fire steps. Thus, for an α −0.005, the step downward following a fire is almost 200 times as great as the step upward after a no-fire. The steps decrease by a factor of two for each fire so that a good estimate may be reached fairly rapidly.

2.4.3 PROCEDURE. For a fire test, the initial increment is 0.005σ following a no-fire ($n' = 0$) and $-0.995\sigma/2$ following a fire ($n' = 1$). The basic increment is halved each time there is a success. Since $0.005\sigma/2^{n'}$ can become quite small, the following plan can be used. As the accuracy limit (δ) of the equipment to set stimulus increments is reached, the increment can be held constant at δ, but the number of tries at each level must be doubled following each fire. *Sub-Note 2.4.3(1)* is an example. If the original guess is quite high, fires will occur rather frequently at first. If the original guess is quite low, possibly none will fire.

SUB-NOTE 2.4.3(1) Typical Test Level Sequence for Fire Test



3. DIVISION OF SAMPLES

Because of the desirability of starting with reasonable values of x_1 and σ, some information about them is necessary. If no previous information is available, the samples should be divided approximately as shown in *SN 3(1)* (if the objective is a no-fire level). Sample sizes of less than 60 are not recommended. The last stimulus level (current) used in the run is the best estimate of the level that will cause the fractional response σ. No practical formula for an estimate of the reliability has been achieved. In an experimental approach, however, it has been found that at the 0.005 level, the estimate obtained minus one standard deviation is as great as, or greater than, the true value of the 0.005 level in about 999 out of 1000 series with 100 samples even though the distribution in many cases was quite skewed. The figure to quote as the no-fire level is the last current tried minus the standard deviation found in the Bruceton test.

SUB-NOTE 3(1) Division of Samples

Total Specimen	Bruceton	Robbins-Monro
150	30	Remainder
100	24	76
60	16	44

4. CONCLUSIONS

The following conclusions regarding sensitivity testing of EEI were reached:

a. Direct current no-fire, mean-fire, and all-fire levels can be used qualitatively as estimates for RF sensitivities. In general, RF powers required for firing (at the most susceptible frequencies) exceed those of corresponding dc levels.

b. The statistical method used in dc sensitivity testing could be used in RF sensitivity testing, but it results in an expensive test program if a number of devices are fired (in a Bruceton manner, for example) at each desired frequency and in each desired firing mode. Such statistics, if gathered, also are hardly worth the effort and cost involved, when trying to determine general RF characteristics.

c. The statistical method used to establish dc sensitivities is not consistent. Bruceton data is extrapolated into reliability and confidence regimes where it is totally inapplicable. This occurs because the cost of direct demonstration of statistical reliabilities specified is prohibitive. It seems that reasonable firing probabilities and confidence limits should be established; i.e., the firing statistics for an EEI used to release stores from a manned aircraft need not be tested and qualified as stringently as those used in an intercontinental ballistic missile (ICBM).

d. Statistical methods can be improved. The Robbins-Monro method for accurately determining no-fire levels was developed to where this level can be accurately determined at a much lower sample size than previously expected.

5. SENSITIVITY TESTING

The Jet Propulsion Laboratory has had considerable success in requiring nondestructive testing of EEI (prior to any sensitivity firings) using the thermal time constant bridge circuit. This technique allows abnormalities in thermal capacity, thermal resistance, and thermal time constants to be recognized. This test identifies bridgewire weld conditions, intimacy of contact between bridgewire and pyrotechnic material, etc., and thereby covers the primary constituents contributing to no-fires or duds. It appears plausible that such testing combined with carefully controlled limited firing tests would be far more constructive than gross firing tests alone.

SECTION 6B TEST EQUIPMENT

DESIGN NOTE 6B1*

GENERATION OF HIGH-LEVEL RADIATED SUSCEPTIBILITY FIELDS

1. INTRODUCTION

This Design Note presents methods of fabricating devices for generating high-level RF fields for susceptibility testing.

2. PARALLEL PLATE LINES

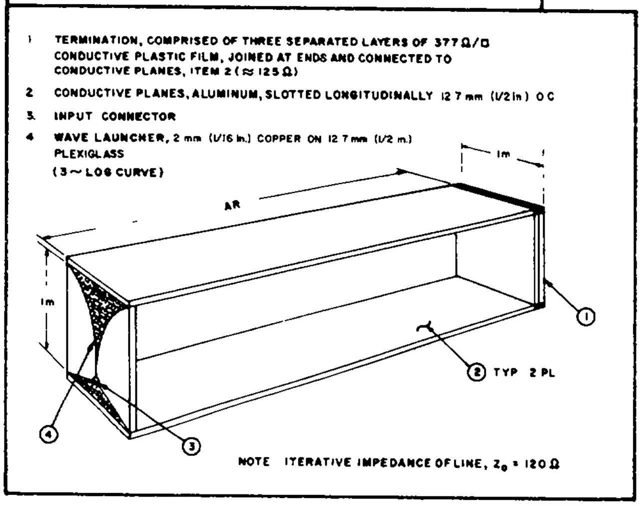
Sub-Notes 2(1) thru *(3)* show construction of a state-of-the-art parallel plate line. This design incorporates the following features and improvements:

a. The longitudinal slots in the parallel plates prevent transverse current and help to maintain the transverse electromagnetic wave (TEM) mode of propagation.

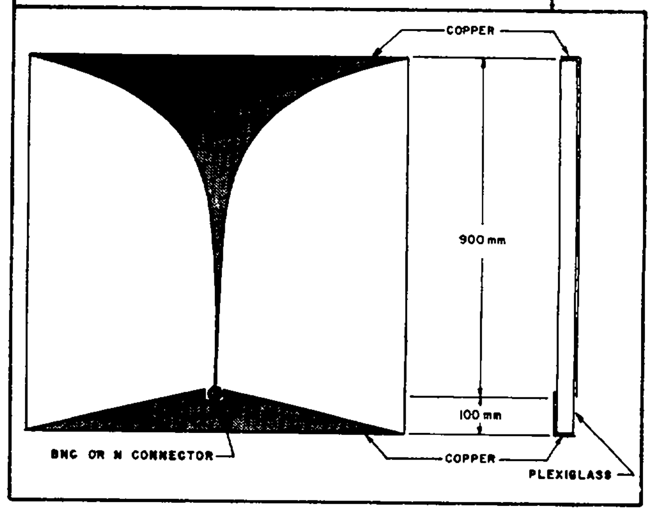
b. The termination reduces coupling between the end of the line and the shielded room wall. Each layer of conductive plastic (377 Ω/□) reduces the energy passing through by 6 dB/layer so that coupling is reduced by 36 dB for the 3 layers.

c. The input is designed as a wave launcher rather than a matching section. The shape of the launcher has been determined empirically to minimize variations of wave

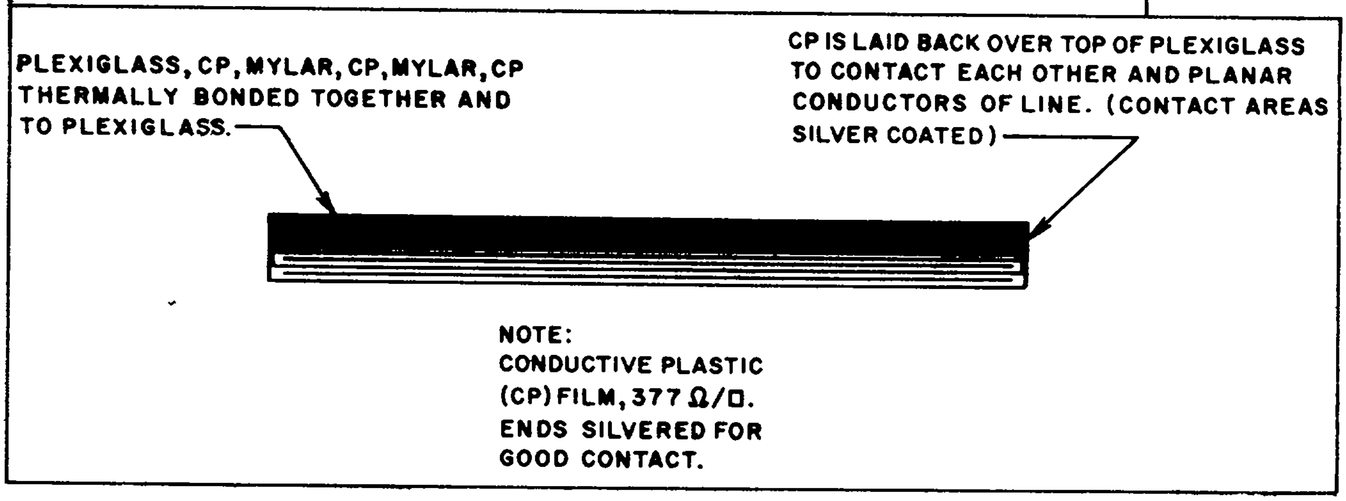
SUB-NOTE 2(1) Parallel Plate Line



SUB-NOTE 2(2) Wave Launcher Detail



SUB-NOTE 2(3) Termination Detail



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*Paragraphs 1, 2, and 3 contributed by EMI Consultants Incorporated.

front homogeneity at the sending end. The input is suitable for low-impedance (4 Ω) spike generators or conventional 50-Ω signal sources.

2.1 GROUNDING

Investigations have indicated that grounding the bottom plate to the ground plane along its entire length creates a nonuniform field, concentrated along the grounded side. It is recommended that the bottom plate be grounded only at the termination, over the entire width of the bottom plate.

2.2 RF POWER

The parallel plate line will accept 250 W continuously. *Sub-Note 2.2(1)* indicates the typical RF power required to generate a 10 V/m field. Each line should be calibrated individually.

3. TRANSMISSION LINE

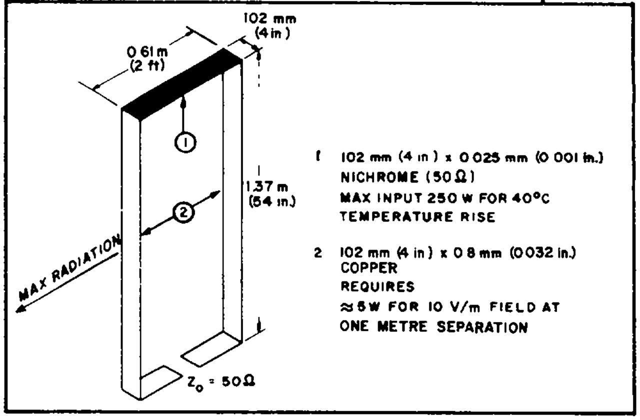
Sub-Note 3(1) illustrates the "electrical" construction of a transmission line antenna. Framing, bracing and supports are not shown. This antenna will accept 250 W continuously.

4. METHOD FOR LONG-WIRE ANTENNA

This method is applicable for establishing high values of field intensity in the 0.014 to 30 MHz range. Test apparatus consists of the following:

a. Two vacuum tube voltmeters (VTVM).

SUB-NOTE 3(1) Transmission Line Antenna



b. RF signal generator capable of 1 V output into a 100-Ω load.

c. A dc resistance bridge.

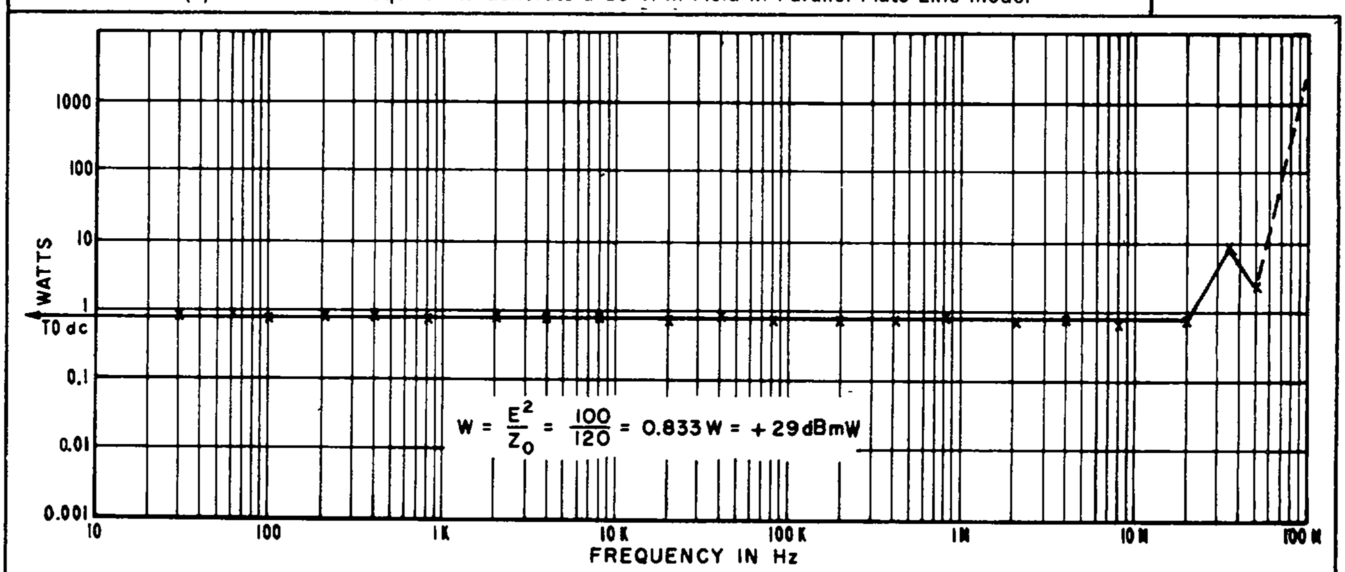
d. Assortment of resistors from 100 to 1000 Ω ("non-inductive") of adequate power dissipating capability.

e. Wire—#12 copper.

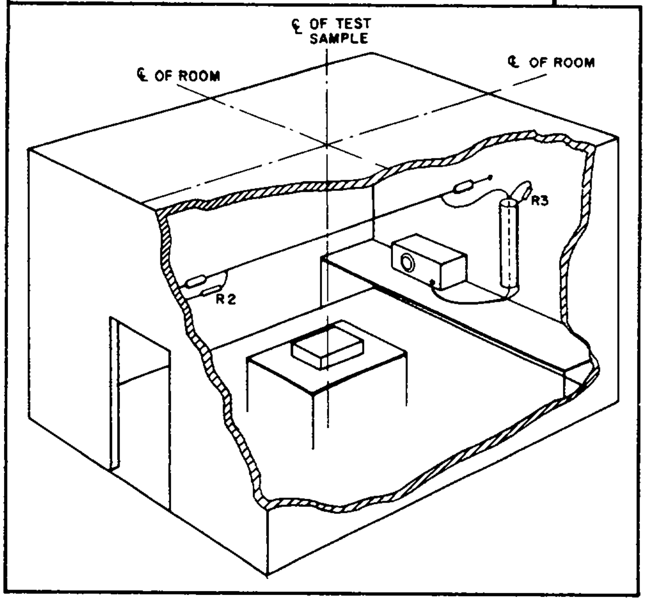
4.1 TEST SETUP

The test setup is as indicated in *SN 4.1(1)*. The horizontal line is located at the longitudinal center of the shielded enclosure at a distance from the ceiling equal to between 1/4 to 1/3 the height of the room. The line is drawn taut on insulators. A "noninductive" resistance equal to the characteristic impedance of the line is located at the far end from the signal generator. A concentric feeder line

SUB-NOTE 2.2(1) RF Power Required to Generate a 10 V/m Field in Parallel Plate Line Model



SUB-NOTE 4.1(1) Typical Screen Room Setup for Long-Wire Antenna



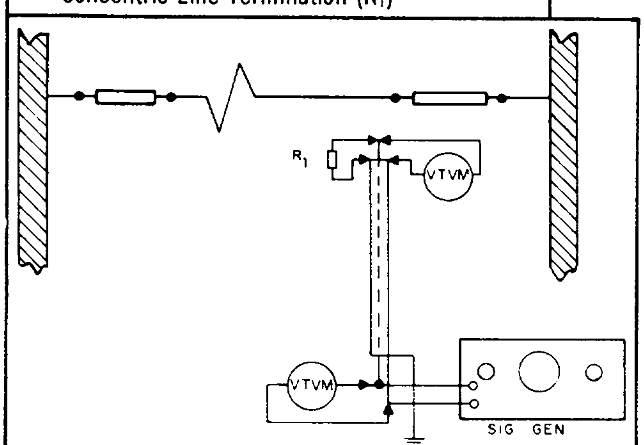
(copper tubing with #16 wire supported in center) extends from the input end of the line down to the terminals of a signal generator. The signal generator output is connected to the concentric line input; the signal generator ground and the concentric line tubing (lower end) is connected to the shield.

4.2 LINE TERMINATIONS

Line terminations consist of the following.

4.2.1 CONCENTRIC LINE. Disconnect long line from top of concentric feeder line. Connect the vacuum tube voltmeters as shown in *SN 4.2.1(1)* but omit the temporary termination R_1 until a desirable test frequency has been found. Adjust the generator frequency so that it resonates line as at 1/4 wave system. This point will be indicated by a dip in the output calibrating meter on the signal generator or by maximum voltage at top of tubing for constant input. This voltage may be read with the VTVM connected as shown in *SN 4.2.1(1)*. This frequency at which the concentric tube is electrically 1/4 wave length long is the one at which the greatest stepup at the end of the line will occur and, therefore, will give the most sensitive indication of correct termination. A frequency near this resonant frequency may be used if the line absorbs too much energy from the generator. Connect R_1 temporarily at top end of concentric line between center wire and pipe. The final value of this resistor is to be determined by "cut and try" methods; its approximate value may be obtained from the formula for finding characteristic impedance of a concentric line:

SUB-NOTE 4.2 1(1) Test Setup to Measure Concentric Line Termination (R_1)



$$Z_0 = R_1 = 138 \log \frac{d_2}{d_1} \text{ in ohms}$$

Where:

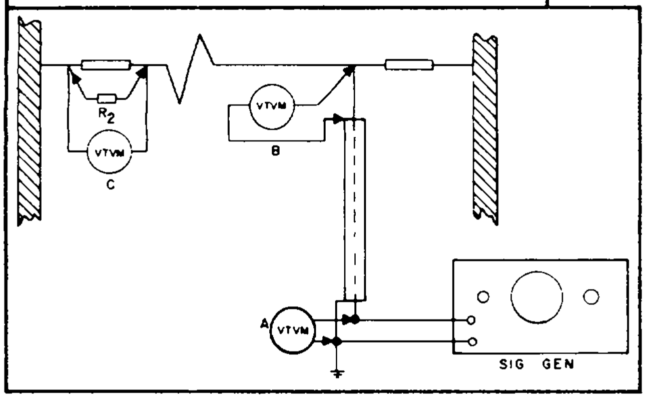
d_2 = inside diameter of pipe

d_1 = outside diameter of central conductor

For a specific case of 25mm (1 in.) tube and #14 wire the value is approximately 150 Ω. Across this resistor—R_1—connect a VTVM. At the input end of the tubing near the generator connect the other VTVM (see *SN 4.2.1(1)*); with the generator set at zero output, adjust the voltmeters for zero reading. With input to concentric tubing raised to 1 or 2 V, the meters will read the same if the selected R_1 is correct termination for the system. If the voltage at the top end of tubing is higher than the voltage at the lower end, the termination is too high a value (and conversely). By successive trials, a value of resistance can be found which will terminate the line properly. Several resistors in parallel or series combinations may be used to get the required value if a single resistor of correct value cannot be found. Successive lower frequencies should then be tried and should result in identical readings on the two meters if everything is in order. This termination can now be disconnected and measured on a dc resistance bridge, the value being recorded as R_1.

4.2.2 TERMINATION OF HORIZONTAL LINE. With the termination of the concentric line removed, connect the end of the horizontal line to the center wire of the tubing (see *SN 4.2.2(1)*). With the voltmeters in positions A and C and temporary termination R_2 (approximated with following equations) removed, the frequency at which the system is 1/4 wave long is found as in *Para 4.2.1*. This frequency is to be used in the following accurate determination of R_2. The following equations

SUB-NOTE 4.2.2(1) Test Setup for Finding the Exact Value of R_2



can be employed to determine an approximate value for R_2

Case 1 Wire is much closer to ceiling than to floor:

$$Z_0 = 138 \log \frac{4D}{d} \text{ in ohms}$$

Where:

D = distance from wire to ceiling, mm (in.)

d = diameter of wire 2.05 mm (80.81×10^{-3} in.) for #12 wire

Case 2 Distance of wire to ceiling is greater than 1/3 room height:

$$Z_0 = \left[138 \log \frac{h}{d}\right] + 5$$

Where:

h = height of screen room, mm (in.)

d = diameter of wire, mm (in.)

For finding the exact value of R_2, the voltmeters are connected in positions B and C (see *SN 4.2.2(1)*); proceed as in *Para 4.2.1* to find the correct termination. Once the voltmeters read the same or within 0.1 volt of one another for several frequencies, the termination may be removed, measured on a bridge and replaced permanently as part of the system. Record termination value as $R_2 = Z_L$, the characteristic impedance of the line, to be used later in calculation of final concentric line feeder termination and attenuation constant.

4.2.3 MATCHING HORIZONTAL LINE TO THE CONCENTRIC TUBE FEEDER. The termination found in *Para 4.2.2* is the correct value for the single wire horizontal line alone and will be the impedance one would "see" looking in the end opposite to that termination. However, this resistance is not the correct value for proper termination of the top of the concentric line. Since the termination of the concentric line at this point is of concern, a resister may be put in as a termination, which, in parallel with the impedance presented by the horizontal line, will give the value of resistance determined in *Para 4.2.1* as the correct termination of the concentric line. The formula for finding this resistance is the usual one for finding values of parallel resistance combinations.

$$R_3 = \frac{R_1 \times R_2}{R_2 - R_1}$$

Where:

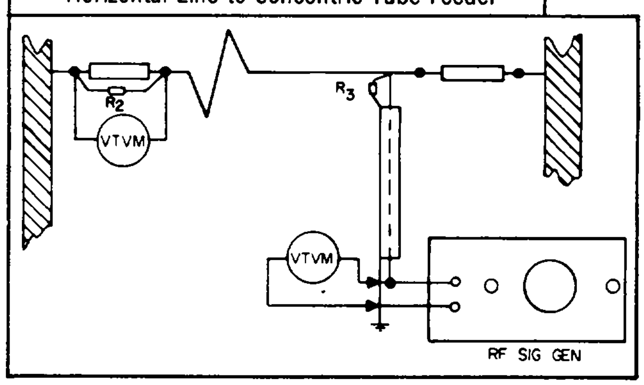
R_1 = Termination for concentric line from *SN 4.2.1(1)*

R_2 = Termination for horizontal line from *SN 4.2.2(1)*

R_3 = Termination which must be put across the top end of concentric line as indicated in *SN 4.2.3(1)*.

After both terminations have been placed in system (see *SN 4.2.3(1)*), a final check should be made to see if the voltages at the bottom end of concentric line and far end of horizontal line remain substantially the same over a frequency range from 14 kHz to 15 MHz.

SUB-NOTE 4.2.3(1) Test Setup for Matching Horizontal Line to Concentric Tube Feeder



4.3 DETERMINING FIELD STRENGTH

The attenuation constant (K) relates voltage at point A of *SN 4.3(1)* to the field strength at a known distance from the transmission line. Since:

$$E = 2.36 \times 10^3 \frac{E_L}{Z_L} \times \left(\frac{1}{d} + \frac{1}{2d_1 - d} - \frac{1}{2d_2 + d}\right)$$

(CONTINUED)

$$\text{and } \frac{1}{K_d} = \frac{2.36 \times 10^3}{Z_L} \left(\frac{1}{d} + \frac{1}{2d_1 - d} - \frac{1}{2d_2 + d} \right)$$

Therefore:

$$\frac{1}{K_d} = E$$

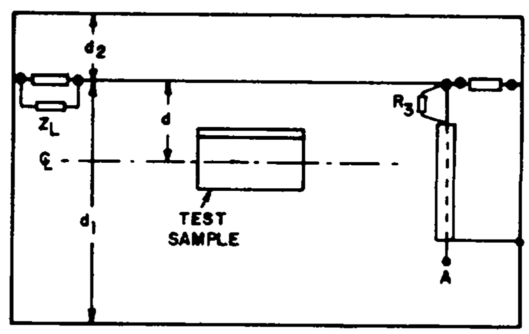
Where:

E	=	Field strength at known distance (μV/m)
E_L	=	μV into line at point A (*SN 4.3(1)*) from a signal generator
Z_L	=	Characteristic impedance of line (ohms)
d, d_1, d_2	=	Distances (in.) as indicated in *SN 4.3(1)*

K_d is a constant and, for a standard test distance d, in a given room can always be used to determine field strength in microvolts per metre in terms of the generator input in microvolts.

For example: If this constant ratio is found to be 5, then to obtain a field strength at the test sample of 1 V/m the signal generator input will be set at 5 V. Calculations should be checked by actual measurement of the field.

SUB-NOTE 4.3(1) Test Setup for Determining Field Strength



DESIGN NOTE 6B2 — EMI INSTRUMENTATION CHARACTERISTICS

1. INTRODUCTION

This Design Note gives the recommended EMI instrumentation characteristics. All EMI instrumentation panel markings will conform to the International System of Units (SI). Avoid using dBm as it is not an authorized SI unit.

2. EMI INSTRUMENTATION INSTRUCTION MANUAL

The EMI Instrumentation Instruction Manual should contain detailed instructions for each test method and the criteria found in *SN 2(1)*.

3. INSTRUMENTS POWERED BY BATTERIES

Comply with the following for all instruments containing batteries:

a. If batteries must be replaced, serviced or recharged periodically, the front panel will have a place to record the next servicing date and action. The surface provided for marking the date and action shall have a long life.

b. If rechargeable batteries are used, provide an indicator to show the operating time available for use until recharging is required. In addition, make provisions to either quickly change the internal batteries or operate from an external battery pack. Design the equipment so that batteries can be changed in 60 seconds or less.

4. SEMIAUTOMATIC CHARACTERISTICS

All instruments intended for laboratory use should have provisions for semiautomatic operation with the following minimum requirements.

4.1 IF OUTPUT

Make the IF signal available for external use. The pick-off point may be "pre or post IF" or both. A signal output of at least 0.1 V is recommended.

4.2 DETECTOR CHARACTERISTICS

A detector is required that provides signal processing for interface with X-Y recorders. This will usually require a detector that samples the signal, retains the sample in a memory until the recorder records the peak, and then dumps the memory. Nominal characteristics recommended are:

SUB-NOTE 2(1) EMI Instruction Manual Information
Application of correction factors and specification limits to the graph paper
Characteristics of required accessories
Checkout information (verification of acceptability of data)
Control settings
Helpful hints
Identification of narrow and broadband interference
Identification of spurious responses
Interpretation of results
Measurements of transients
Preparation of graph paper
Reproduction of calibrated paper
Safety precautions
Test setups
Use of IF monitors

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a. Detector charge time:

$$\text{Charge Time} \leqslant \frac{1}{2\ (\text{Impulse Bandwidth})}$$

or 0.3 μs, whichever is less.

b. Detector discharge time: such that the stored signal in the memory is not less than 0.25 dB below true peak value, when signal is dumped. (Typical discharge times are 50 to 100 seconds).

c. Initiate a new "hold" interval if a signal is detected within the sample time greater than the signal in the memory.

d. The hold time should be adequate to permit the X-Y recorder to reach full signal response.

e. The detector circuits should limit the number of signals to be recorded to about 394/m (10/in.). (This is a resolution of about 1% as measured on the graph paper.) If the instrument has a greater resolution, record the maximum signal in each 1% interval.

f. A scan time not greater than 60 seconds per octave is recommended. (This is based on a recorder writing speed of 0.38 m/s (15 in./s), the above resolution requirement, and a 127 × 229 mm (5 × 9 in.) space for recording data.) Sometimes adjustments are necessary if a faster X-Y recorder is used, if a greater resolution is feasible, or if the data space is different.

g. If additional scan times are provided for other uses, provide hold and dump times for each speed. It is preferred that the same control switch both scan times and detector constant.

h. It is preferred that no provisions be included for quasipeak.

i. If more than one detector function is provided, clearly mark the function to be used for X-Y recording.

j. Include provisions in the detector for measurement of spikes, and other short duration interference. Design the memory circuit to store the signal so that the recorder can reach maximum signal level. Design for measurement of spikes in a nonscanning mode.

5. INSTRUMENT BANDWIDTHS

A minimum of three different bandwidths is recommended, selectable from the instrument panel—one to be at least twice the size of the other. It is preferred that five bandwidths be available, with a logarithmic relationship.

6. OTHER INSTRUMENTATION CHARACTERISTICS

Recommended minimum and desired values of instrumentation characteristics are shown in *SN 6(1)*.

7. MODIFICATION OF OLDER EMI EQUIPMENT

Some older EMI equipment do not have the minimum capabilities required. The procuring activity may approve the use of such equipment provided that modifications for its output monitoring, X-Y recording, scan detectors, and adequate sensitivity are accomplished.

SUB-NOTE 6(1) Instrumentation Characteristics

CHARACTERISTICS	MINIMUM ACCEPTABLE VALUE	DESIRED VALUE	REMARKS
Attenuator Accuracy	±1 dB	±0.1 dB	
Impulse Bandwidth Accuracy	±15%	±5%	
Meter Tracking	±2 dB	±0.5 dB	
Reserve Gain	10 dB	30 dB	
X-Y Output Linearity	5%	1%	
Audio Response	±6 dB	±1 dB	50 Hz to 15 kHz
Linearity of meter	±2 dB	±0.5 dB	Variation from straight line
Measurement Accuracy, NB	±2 dB	±0.5 dB	Measured on X-Y recorder w/calibrated graph paper (NB and BB)
Measurement Accuracy, BB	±2 dB	±0.5 dB	
Antenna Terminal Conducted	+10 dB	-10 dB	*MIL-STD-461* limit is the reference (Antenna Terminal Conducted through Spurious Response)
Conducted Interference	+10 dB	-10 dB	
Conducted Susceptibility	-10 dB	+10 dB	
Cross Modulation	+10 dB	-10 dB	
Intermodulation	+10 dB	-10 dB	
Radiated Interference	+10 dB	-10 dB	
Radiated Susceptibility	-10 dB	+10 dB	
Spurious Response	+10 dB	-10 dB	
Spike Susceptibility	-6 dB	+20 dB	
Dynamic Range	40 dB	100 dB	1/
VSWR	2.0	1.1	2/
Frequency Accuracy	2%	0.5%	3/
Power Line Regulation	±1 dB	0 dB	4/
Variation of Impulse BW	20%	1.0%	5/
Pulse Response	±3 dB	±0.5 dB	6/
Impulse Generator Accuracy	±1 dB	±0.25 dB	7/
Sensitivity, Broadband	-6 db	-40 dB	8/ (Broadband and Narrowband)
Sensitivity, Narrowband	-6 dB	-40 dB	
Measurement Accuracy, Spikes	±5 dB	±0.5 dB	9/

1/ Without changing attenuators and coupling with spurious response requirement

2/ Measure on minimum attenuator setting (Ref to 50 ohms)

3/ Measure on instrument dial and X-Y recorder with calibrated graph paper

4/ Measure change in instrument response when changing from minimum to maximum rated line voltages, and from maximum to minimum

5/ Over each frequency band at different levels

6/ Response to Pulse width (0 1 to 50 μs) PRF 5 to 10 000 pps

7/ Must be referenced to rms of equivalent sine wave Calibration referenced to peak value will be grounds for rejection of instrument

8/ Ref is to most stringent limit in *MIL-STD-461* and *MIL-STD-462* for all tests for which the instrument can be used

9/ Measured on X-Y recorder in scanning mode

CHAP 7 LIGHTNING AND STATIC ELECTRICITY

CHAPTER 7 LIGHTNING AND STATIC ELECTRICITY

SECT 7A - LIGHTNING

SECT 7B - STATIC ELECTRICITY

SECT 7C - LIGHTNING TESTING

SECTION 7A LIGHTNING

DN 7A1 - LIGHTNING STRIKE PHENOMENA

DN 7A2 - PREVENTIVE DESIGN

DN 7A3 - LIGHTNING TEST FACILITIES

DN 7A4 - ROTARY WING AIRCRAFT SUSCEPTIBILITY

DESIGN NOTE 7A1 LIGHTNING STRIKE PHENOMENA

1. LIGHTNING ENVIRONMENT

The exact mechanism of generating natural lightning has been the subject of many theories. However controversial the theories may be, there is little or no disagreement that lightning is hazardous for aerospace systems and that most systems must include lightning provisions. There is no known technology to prevent lightning strikes to aircraft. Aircraft will encounter cloud-to-ground, inter-cloud, and intracloud lightning strikes. The nature of the strike and the physical configuration of the aircraft will determine the point of strike and damage incurred. Quantitative information on the electrical characteristics of the different types of strikes is basic to lightning protection design.

2. LIGHTNING STRIKE CHARACTERISTICS

Sub-Note 2(1) is a review of cloud-to-ground lightning strokes. The review shows that for 95% of lightning strikes the peak lightning current exceeded 14 kiloamperes (kA), 50% exceeded 30kA, and 5% of the strokes were in excess of 80 kA.

2.1 PRESTRIKE PHASE

Lightning is typically originated by a stepped leader which develops from the cloud toward the ground or toward another charge center. As a lightning stepped leader approaches an extremity of the vehicle, high electrical fields are produced at the surface of the vehicle. These electric fields give rise to other electrical streamers which propagate away from the vehicle until one of them contacts the approaching lightning stepped leader as shown in *SN 2.1(1)*. Propagation of the stepped leader will continue from other vehicle extremities until one of the branches of the stepped leader reaches the ground or another charge center. The average velocity of propagation of the stepped leader is about 1 m/µs and the average charge in the whole stepped leader channel is about 5 coulombs (C).

2.2 HIGH PEAK CURRENT PHASE

The high peak current associated with lightning occurs after the stepped leader reaches the ground and forms the return stroke of the lightning flash. This return stroke occurs when the charge in the leader channel is suddenly able to flow into the low impedance ground and neutralize the charge attracted into the region prior to the stepped leader's contact with the ground. The return stroke is in the range 10-30 kA. Higher currents are very common with a peak current of 200 kA representing a severe stroke. Reliable measurements are few but there is evidence peak currents can exceed 500 kA. The current in the return stroke has a fast rate of change, typically about 10-20 kA/µs and rarely exceeding 100 kA/µs. Typically the current decays to half its peak amplitude in 20-40 µs.

2.2.1 INTERMEDIATE AND CONTINUING CURRENT PHASES. The total charge transported by the lightning return stroke is relatively small—a few coulombs. Most of the charge is transported in two phases of the lightning flash following the first return stroke. The first is an intermediate phase in which currents of a few thousand amperes flow for a few milliseconds. The second is a continuing current phase in which currents of the order of 200-400 A flow for times varying from about 0.1 to 1 second. The maximum charge transferred in the intermediate phase is about 20 C and the maximum charge transported during the total continuing current phase is about 200 C.

2.3 RESTRIKE PHASE

In a typical lightning event there will be several high current strokes following the first return stroke. These occur at intervals of several milliseconds as different charge pockets in the cloud are tapped and their charge fed into the lightning channel. The peak amplitude of the restrikes is typically about one half that of the initial high current peak. The continuing current in which the major portion of the lightning charge is transported links these various successive return strokes or restrikes.

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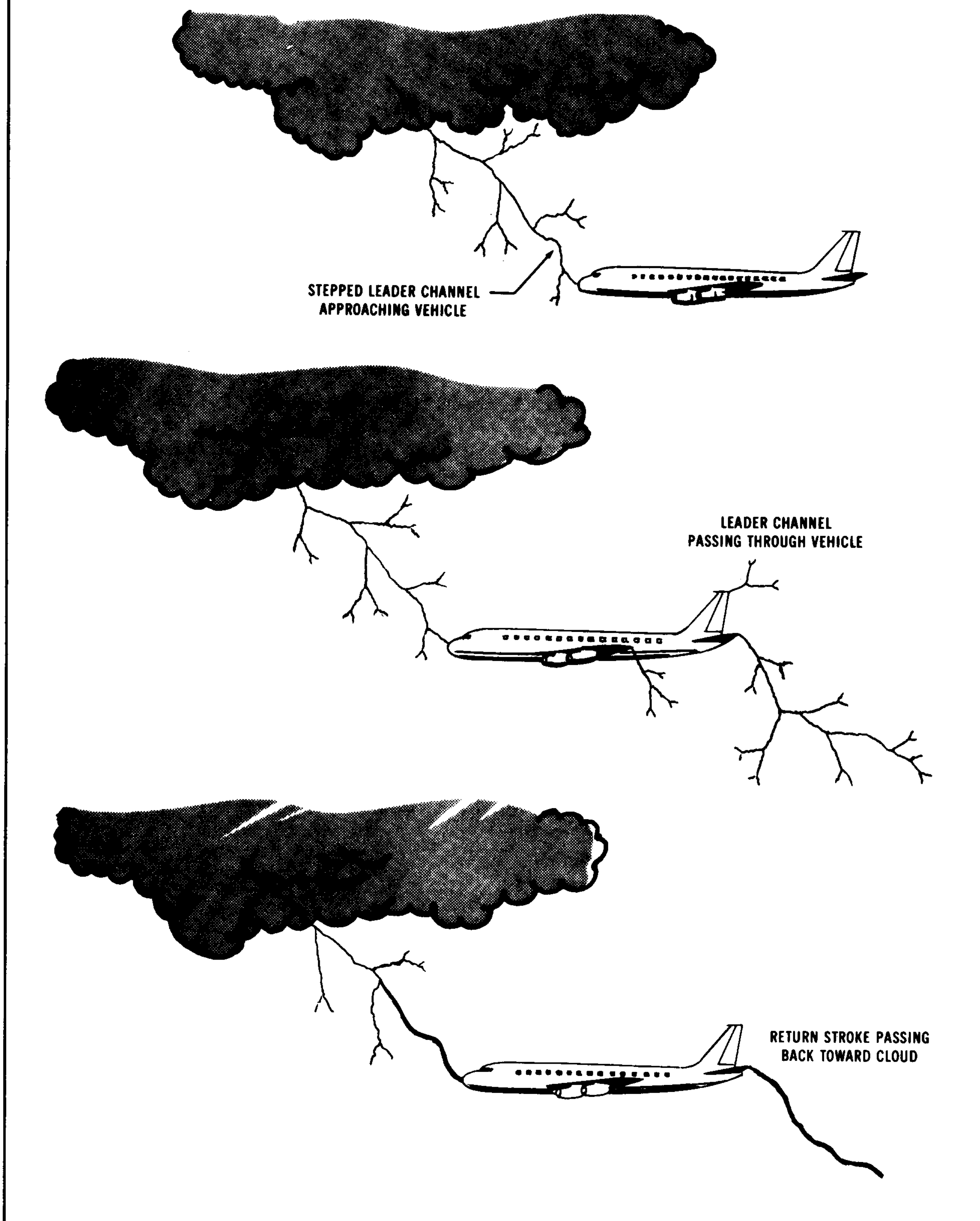
SUB-NOTE 2(1) Data from Review of Cloud-to-Ground Strokes

PARAMETER	Percent of lightning strikes exceeding listed value		
	95%	50%	5%
Peak Lightning Current (kA) (minimum 2 kA)			
Negative first strokes and flashes	14	30	150
Negative following strokes	4.6	12	30
Positive flashes (no following strokes)	4.6	35	250
Charge - Coulombs (C)			
Negative first strokes	1.1	5.2	24
Negative following strokes	0.2	1.4	11
Negative flashes	1.3	7.5	40
Positive flashes	20	80	350
Impulse charge (C)			
Negative first strokes	1.1	4.5	20
Negative following strokes	0.22	0.95	4.0
Positive flashes (only one stroke)	2.0	16	150
Time to Peak Current (μS)			
Negative first strokes	1.8	5.5	18
Negative following strokes	0.22	1.1	4.5
Positive flashes	3.5	22	200
Maximum dI/dt(kA/μs)			
Negative first strokes	5.5	12	32
Negative following strokes and flashes	12	40	120
Positive flashes	0.20	2.4	32
Time to Half-value on Wavetail (μs)			
Negative first strokes	30	75	200
Negative following strokes	6.5	32	140
Positive flashes	25	230	2000
Integral (I^2dt) (A^2s)			
Negative first strokes and flashes	6.0×10^3	5.5×10^4	5.5×10^5
Negative following strokes	5.5×10^2	6.0×10^3	5.2×10^4
Positive flashes	2.5×10^4	6.5×10^5	1.5×10^7
Time intervals between negative strokes (ms)	7	33	150
Duration of flashes (ms)			
Negative (including single stroke flashes)	0.15	13	1100
Negative (excluding single stroke flashes)	31	180	900
Positive flashes	14	85	500

2.4 TYPICAL SEVERE WAVEFORMS

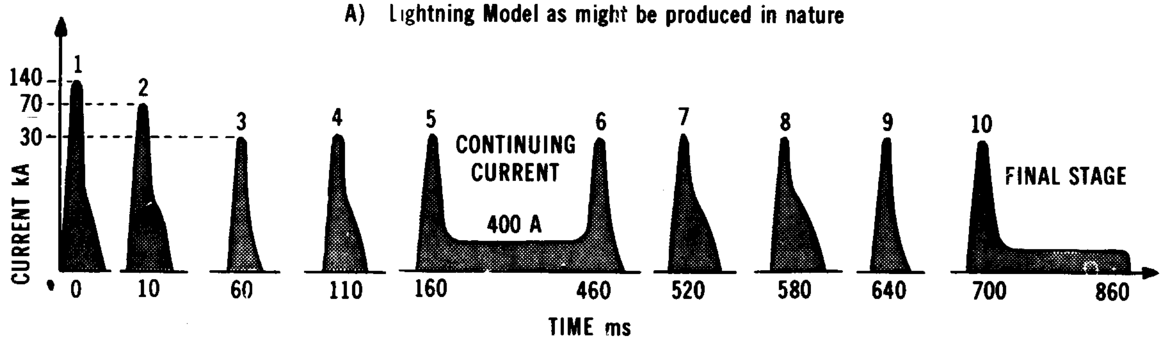
Sub-Note 2.4(1) shows a typical representative lightning current waveform model. Determination of the effects produced by such a lightning model in the laboratory is difficult due to inherent facility limitations. Accordingly, for simulation of the effects of lightning and for laboratory qualification testing vehicle hardware, simplified models of lightning have been defined and are described in *DN 7C2*.

SUB-NOTE 2.1(1) Lightning Striking an Aircraft

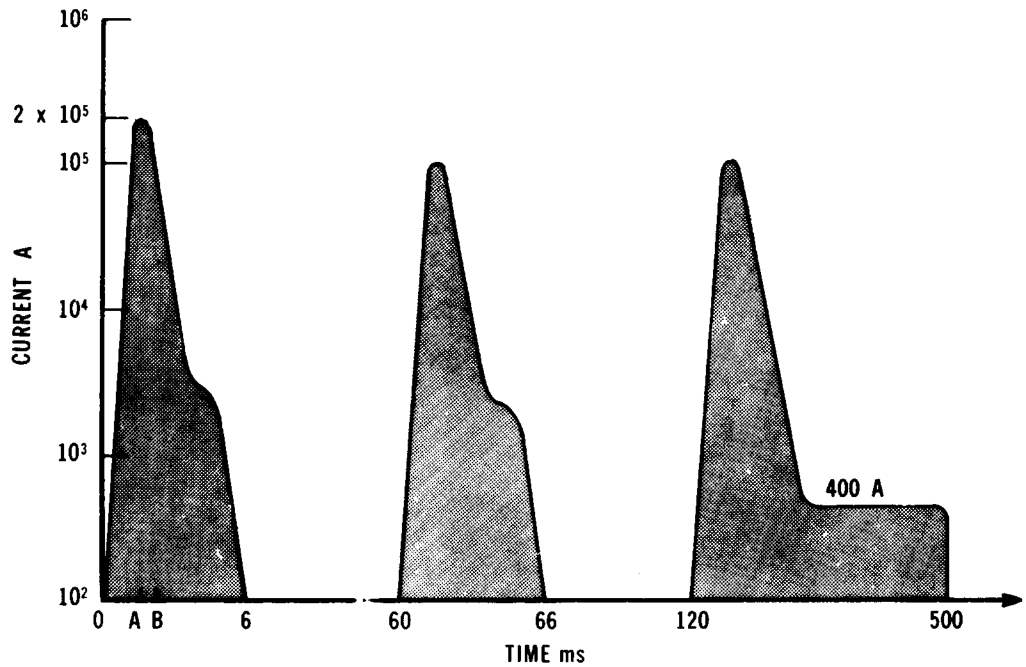


SUB-NOTE 2.4(1) Typical Lightning Current Waveforms

A) Lightning Model as might be produced in nature



B) Lightning Model as might be employed for a laboratory test



A = TIME TO PEAK CURRENT = 1.5 μs
B = TIME TO HALF VALUE = 40 μs

3. STRIKE PHENOMENA

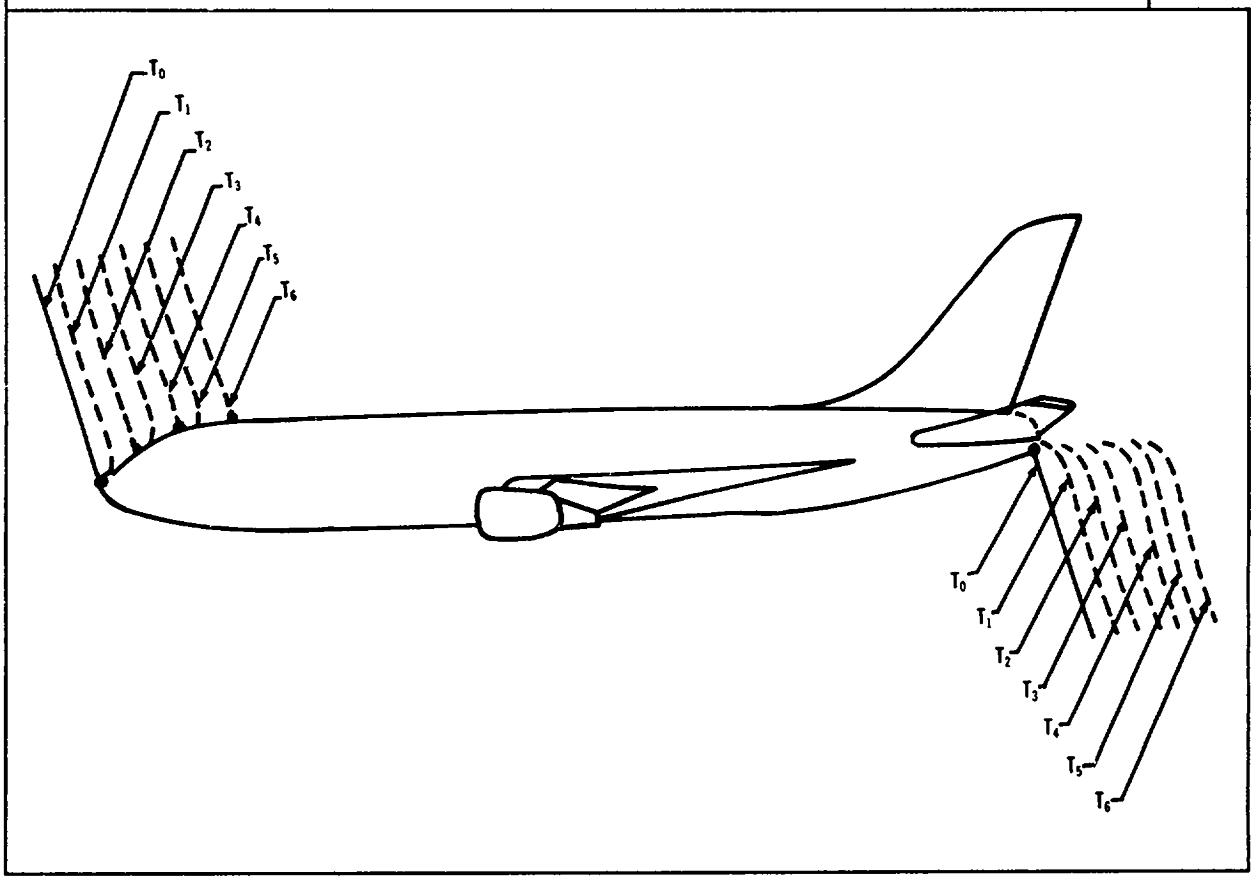
3.1 INITIAL ATTACHMENT

The lightning will enter the aircraft at one or more attachment points and leave at exit points. There will always be at least one entrance point and one exit point. It is not possible for the vehicle to store the electrical energy of the lightning in the capacitive field of the vehicle and so avoid an exit point. These initial attachment and exit points are at the extremities of the vehicle and include the nose, wing tips, elevator and stabilizer tips, protruding antennas, and engine pods or propeller blades. Lightning can also attach to the leading edge of swept wings and some control surfaces.

3.2 SWEPT STROKE PHENOMENA

The lightning channel is somewhat stationary in space while it is transferring electrical charge. When a vehicle is involved it becomes part of the channel. Due to the speed of the vehicle and the length of time that the lightning channel exists, the vehicle moves through the lightning channel. Thus, the lightning channel appears to sweep back over the surface as illustrated in *SN 3.2(1)*. As the sweeping occurs, the lightning channel will dwell at various surface locations for different periods of time. Since surface heating at a point depends on the arc dwell time at that point, the amount of damage depends upon the type of material and the surface finish. When the lightning arc has been swept back to one of the trailing edges it may remain attached at that point for the remaining duration of the arc. An initial exit point occurring at a trailing edge would not be subjected to any swept-stroke action. The significance of the swept-stroke phenomenon is that portions of the vehicle that would not be targets for the initial entry and exit point of a lightning arc may be involved in the lightning process as the arc is swept backward across the vehicle.

SUB-NOTE 3.2(1) Swept Stroke Phenomena



4. EFFECTS ON AEROSPACE VEHICLES

The threats to which lightning exposes aerospace vehicles and the effects which should be reproduced through laboratory testing with simulated lightning waveforms can be divided into physical effects and electromagnetic effects. The physical effects of lightning are the burning and eroding, blasting and structural deformation caused by lightning, as well as the high pressure shock waves and magnetic forces produced by the associated high currents. The electromagnetic effects are those resulting from the electromagnetic fields associated with lightning and the interaction of these electromagnetic fields with equipment in the aircraft. Hazardous effects can be produced by lightning that does not directly contact the aircraft. In some cases, both physical and electromagnetic effects may occur to the same component. An example would be a lightning strike to an antenna which physically damages the antenna and also sends damaging voltages into the transmitter or receiver connected to that antenna.

4.1 PHYSICAL EFFECTS

The nature of the particular physical effects associated with lightning depends upon the structural component involved and the particular lightning current transfer phase.

4.1.1 BURNING AND ERODING. The continuing current phase of a lightning stroke can cause severe burning and eroding damage to vehicle structures. The most severe damage occurs when the lightning channel dwells or hangs on at one point of the vehicle for the entire period of the lightning arc. This can result in holes of up to a few centimeters in diameter on the aircraft skin.

4.1.2 VAPORIZATION PRESSURE. The high peak current phase of the lightning transfers a large amount of energy in a short period of time (several microseconds). This energy transfer can result in vaporization of material. In a confined area the high pressure created may be of sufficient magnitude to cause structural damage.

4.1.3 MAGNETIC FORCE. During the high peak current phase of the lightning, the flow of current through sharp bends or corners of the aircraft structure causes extensive magnetic flux interaction. In certain cases, the resultant magnetic forces can twist, rip, distort, and tear structures away from rivets, screws, and other fasteners. These magnetic forces are proportional to the square of the lightning current.

4.1.4 FIRE AND EXPLOSION. Fuel vapors and other combustibles may be ignited in several ways by lightning. During the prestrike phase high electrical stresses around the vehicle produce streamers from the aircraft extremities. The design and location of fuel vents determines their susceptibility to streamer conditions. If streamers occur from a fuel vent in which flammable fuel air mixtures are present, ignition may occur. If this ignition is not arrested, flames will propagate into the fuel tank area and cause a major fuel explosion. The flow of lightning current through vehicle structures during the high peak current phase can cause sparking at poorly bonded structure interfaces or joints. If such sparking occurs where combustibles such as fuel vapors are located, ignition may occur. Lightning attaching to an integral tank skin may also burn holes in the tank or heat the inside surface sufficiently to ignite any flammable vapors present. Other combustibles, such as hydraulic fluid or ethelyne glycol, may be released and ignited.

4.1.5 MECHANICAL SHOCK. The air channel through which the lightning propagates is nearly instantaneously heated to a very high temperature. When the resulting shock wave impinges upon a surface it may produce a destructive overpressure and cause mechanical damage.

4.2 ELECTROMAGNETIC EFFECTS

Damage or upset of equipment by currents or voltages is defined as electromagnetic effects, even though the currents or voltages may arise as a result of a direct lightning arc attachment to a piece of external electrical hardware. An example would be a wing tip navigation light. If lightning shatters the protective glass covering or burns through the metallic housing and contacts the filament of the bulb, current will be injected into the electrical wires running from the bulb to the power supply bus. This transient may burn or vaporize the wires or cause breakdown of insulation and damage to other electrical equipment.

4.2.1 EFFECTS ON VEHICLE. Even if the lightning does not contact wiring directly, it will set up changing electromagnetic fields around the vehicle. The metallic structure of the vehicle does not provide a perfect Faraday cage electromagnetic shield and therefore some electromagnetic fields can enter the vehicle, either by diffusion through metallic skins or direct penetration through apertures such as seams and windows or other nonmetallic sections. If the fields are changing with respect to time and link electrical circuits inside the vehicle, they will induce transient voltages and currents into these circuits. These voltages are hazardous to avionic and electrical equipment. Voltages and currents may also be produced by the flow of lightning current through the resistance of the aircraft structure.

4.2.2 EFFECTS ON PERSONNEL. One of the most troublesome effects on personnel is flashblindness. This invariably occurs to a flight crew member looking out of the vehicle in the direction of the lightning. The resulting flashblindness may persist for 30 seconds or more, rendering the crewmember temporarily unable to use his eyes for flight or instrument reading. Serious electrical shock may be caused by currents and voltages conducted via control cables or wiring leading to the cockpit from control surfaces or other hardware struck by lightning. The shock varies from mild to serious and may be sufficient to cause numbness of hands or feet, disorientation, confusion, or unconsciousness. This can be quite hazardous in high performance aircraft, particularly under the thunderstorm conditions during which lightning strikes generally occur. Shock can also be induced on flight crews under dielectric covers such as canopies by the intense thunderstorm electric fields. This generally occurs without puncture of the dielectric covering.

DESIGN NOTE 7A2 PREVENTIVE DESIGN

1. INTRODUCTION

Protection from lightning hazards is often overlooked in designing aerospace systems. Systems have been lost or severely damaged because of a lack of lightning protection. Design the system and subsystem to prevent lightning currents from entering the vehicle.

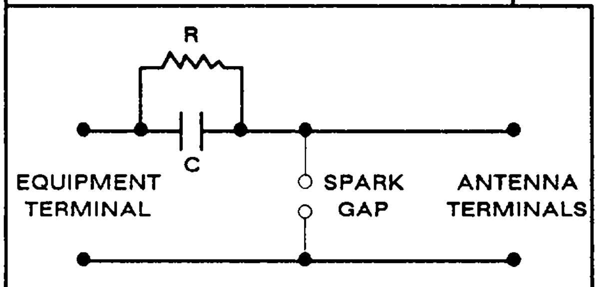
2. RADOMES AND CANOPIES

Design radomes and canopies to have a dielectric strength of at least 300 kV/m (100 kV/ft) of flash over path, and equip them with diverter strips. Improperly protected radomes and canopies will often be shattered by a lightning strike. Thoroughly evaluate and test radomes that are important to flight safety. See *DN 7A6* for information on radome lightning protection.

3. LIGHTNING ARRESTERS

Install lightning arresters (*MIL-A-9094*) on antenna terminals with considerable care as they do not provide complete protection. *Sub-Note 3(1)* is a typical circuit of an arrester. A high voltage transient appears at the equipment terminal which is equal to the spark gap setting. Since gaps are often set at 10 to 30 kV, this transient is intolerable for equipment using field-effect transistors (FET), integrated circuits, etc. Secondary protection must be provided to adequately protect equipment. Insulate exposed terminals on lightning arresters to avoid possible shock hazards.

SUB-NOTE 3(1) Arrestor Circuits



R IS BLEEDER RESISTANCE.
C IS TYPICALLY 10 TIMES THE ANTENNA CAPACITANCE.

4. INSULATED SECTIONS

Insulated sections, such as fiberglass, require lightning protection. Such sections are especially vulnerable to lightning damage when used at wing tips or other extremities of the aircraft. Diverter strips or ribs often provide adequate protection.

5. EXTERNAL STORES AND PODS

External stores mounted under the wing are in a relatively safe position but additional protection may be required if a high degree of safety is necessary. Stores or pods mounted on or near the wing tips are very vulnerable, and protective devices are always necessary.

6. PROBLEM OF FUEL IGNITION

One of the following conditions must exist to cause ignition of fuel:

a. Explosive mixture

b. Ignition source to start explosion.

As for an explosive mixture, this can form over JP-4 fuel at temperatures of -37 to 10°C (-35 to 50°F) and at altitudes of 0 to 6.1 km (0 to 20 000 ft.). The high energy source can be either an electric spark or a compression wave, caused by nearby lightning. See *DN 3B5* for additional information on electrical ignition.

6.1 ENERGY LEVEL

To ignite an explosive mixture, 0.2 mJ is sufficient. A person walking on a rug can cause a spark of 15 mJ energy. (The energy level available in a lightning strike transfers hundreds of million joules in one strike.) Energy levels of pressure waves created by lightning need further investigation. As a yardstick, the following practical experience of the Lightning and Research Institute is quoted: "A pressure wave caused by a 100 000 A lightning stroke is insufficient to produce ignition of an explosive mixture at a distance of 0.3 m (1 ft) or more from the lightning." (This is not to imply the ionization associated with the strike would not produce ignition.) Superficial comparison of energy levels will show the electric spark is by far the greatest problem. Pressure waves are of concern only in direct strikes to fuel vents or other open spaces with explosive mixtures.

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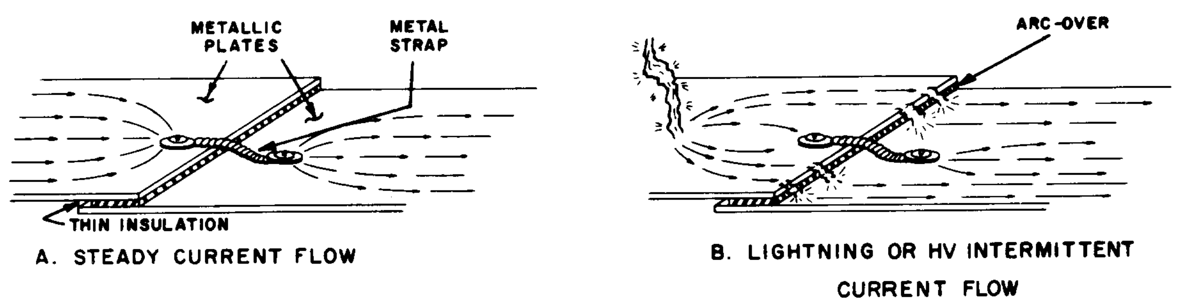
6.2 FUEL VAPORS

The need for ventilation of spaces where fuel vapor may form due to leaks (space around fuel tanks) has been proved. Skin discontinuities can provide sufficient sparking for ignition, if in the immediate vicinity of the lightning strike. Where ventilating is impractical, it is very important to provide electrically sound skin seams.

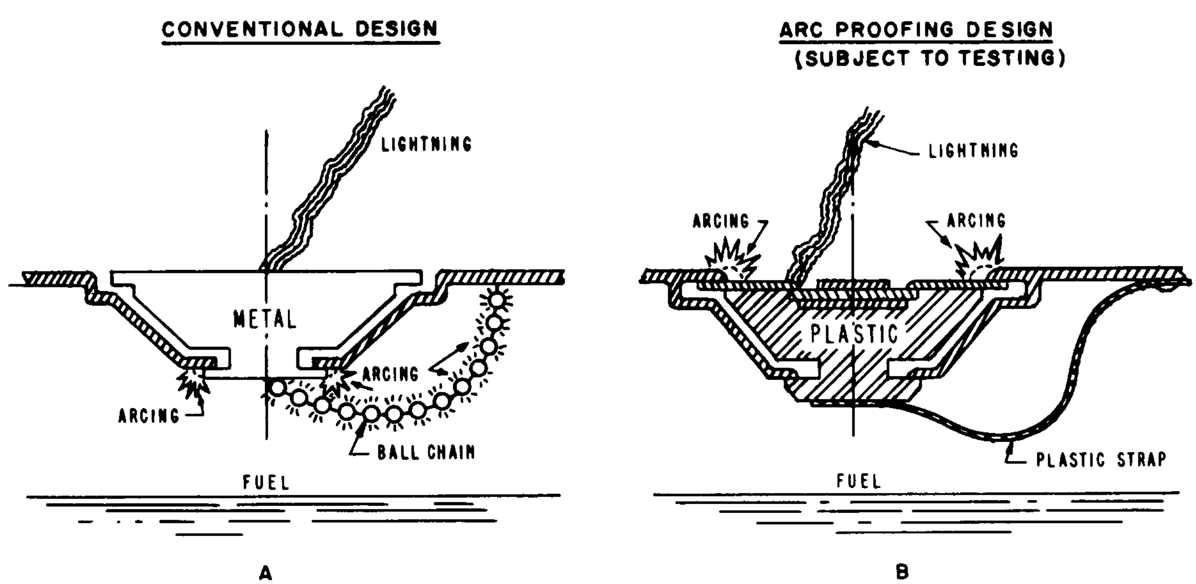
6.3 FILLER CAPS

How grounding works for steady-state current and does not work for lightning is illustrated in *SN 6.3(1)*. The inductive voltage, opposing current path curvature, prevents the lightning current from deviating to the bonding link. It is easier for lightning to go through the small air gap than to deviate to the grounding link. *Sub-Note 6.3(2)* shows a conventional filler cap. When struck by lightning it can produce sparking inside the fuel tank. *Sub-Note 6.3(2)* also shows an idealized design for a safe fuel cap. The basic idea is to produce a good peripheral, metal-to-metal contact on the outside of the fuel tank. Filler caps are equally applicable to drain pumps, fuel metering probes, and access doors. The problem is greatly alleviated if the openings which lead to the fuel tanks are covered by the aircraft skin with suitable access provisions in the skin.

SUB-NOTE 6.3(1) Comparison of Current Flow



SUB-NOTE 6.3(2) Safe Fuel Tank Cap



6.4 FUEL HAZARDS

Electrically bond fuel vents to the vehicle structure and locate them in areas of low strike probability. Design fuel tank caps so sparking cannot take place inside the tanks. Use armor skin to protect thin aluminum panels over fuel areas. Do not route fuel gauge wiring with wires leading to entry points. Carefully evaluate flame arresters, used to protect fuel vents, for possible hazards due to icing.

7. PROBLEMS OF EXTERNAL WIRING

Artificial lightning strikes to navigation lights, anti-collision lights, etc., will result in destruction of the lights. Usually the socket of the light and the baseplate provide a sufficient path for the lightning current, which will not travel along the wire for a long distance. Nevertheless, wires of pitot tube heating, navigation lights, etc., bring a part of the lightning potential inside the forward cabin. Much depends on the length of the wire and its position inside the wire bundle and the routing of the wire bundles. For example, a direct strike to the fuel gauge wire, close to the fuel probe, could result in sparking inside the fuel probe in the tank. For this reason all wiring should be inside the aircraft skin, a skin which is continuous.

8. POINTS OF ENTRY

Protect all points at which lightning can enter the aircraft with lightning arresters or an equivalent device. Examples of entry points are navigation lights, antennas, pitot tubes, and windshields. Masts, booms, or other objects protruding from the aircraft also require protection.

9. CONTROL SURFACES

Control surfaces and flaps require bonding jumpers if the resistance across the joints or hinges is greater than 0.01 ohm.

10. INDUCED VOLTAGES

Line transients caused by lightning strikes cause considerable damage to electronic equipment every year. Even with proper protection, 500 V surge voltages can appear on antenna leads and internal wiring. Protect equipment that can be damaged by short duration spikes by the use of metal oxide varistors or other suitable components.

11. BLINDING EFFECTS

The temporary blinding effects of streamers, St. Elmo's fire, or other discharge that occur before, during, or after a lightning strike can be reduced if the external surface of the windshield has a conductive surface.

12. CORROSION CONTROL

Be cautious in the use of wet rivets, faying surface sealants, encapsulated fasteners, and similar corrosion control techniques that increase the dangers of lightning strikes.

13. BONDING JUMPERS

Do not use soldered terminals on bonding jumpers that must carry lightning current. Most crimped connectors are satisfactory though some cannot withstand the mechanical stresses. Test the jumpers with simulated strokes to verify design adequacy.

14. TESTING

Testing on full scale samples in exact production configuration is always necessary when the safety of the vehicle is involved. Examples of equipment requiring such testing are nose radomes, lightning arresters, fuel vents, and caps.

15. INSULATED MATERIAL

Whenever the use of insulated rivets and insulating tapes is mandatory, a test program should be initiated to find out what effect the material has on the ability of the fuselage to carry load and lightning currents. Suitable precautions must be taken to ensure good electrical bond. Some remedies could be:

a. Limit the use of insulating rivets and tapes to the floating portion of the fuselage, but keep the upper portion of it electrically continuous and move all the grounding points to the upper portion of the fuselage.

b. Review the skin integrity, under simulated lightning strikes, whenever discontinuity is suspected in areas carrying fuel or where fuel vapors may accumulate.

16. GROUND FACILITIES

Use *ANSI/NFPA 78-1975* and *MIL-STD-1542* to provide lightning protection for ground facilities.

17. PRIME CONSIDERATIONS

When designing systems/equipment, apply the following:

a. Keep lightning currents on the outside of the vehicle.

b. Guide lightning currents around or over nonmetallic sections.

c. All conductive paths for lightning currents, including the skin, must be low inductive, low resistance, and have no sharp corners or bends.

18. RECOMMENDATIONS

Use the following protective techniques to protect aircraft in a lightning environment:

a. Fuel Systems. Ensure adequate skin thickness (0.080 in. minimum) is used on fuel tanks and in the vicinity of fuel bay areas and fuel vapor areas. Internal bladder or self-sealing tanks are not vulnerable to lightning. Install fuel vents in areas of low electrical gradients and flush with the skin. Protect the vent with a flame suppressor. Apply *MIL-F-38363*, *MIL-C-38373*, and *FAA Circular 20-53* in designing fuel subsystems. Locate fuel tank access doors where they are not likely to be struck by lightning or on the bottom of the tank where they will normally be covered by fuel. If this is not possible, provide a metal-to-metal contact around the doors and test to ensure safety. Consider using a nitrogen fuel tank inerting system where space and weight can be allocated. Another method of protection is use of polyurethane foam in the fuel tanks. For additional information contact ASD/ENFEF, Wright-Patterson AFB OH 45433-6503.

b. Pitot Booms. Ensure the boom is adequately grounded to structure and tested to meet the requirements of *MIL-B-5087*. Do not use metallic tubing for the data lines.

c. Radomes. Arrange metal conductors to provide lightning protection and minimum radar interference. If lightning protection cannot be provided, design the radome to meet damage tolerance requirements. Contact ASD/ENFSS, Wright-Patterson AFB OH 45433-6503, for additional information.

d. Advanced Composite Materials. Boron, graphite, and glass fiber reinforced plastics behave differently when struck by lightning. Glass fiber reinforced plastics are not electrical conductors and are damaged by pressure effects. Boron and graphite fiber reinforced plastics have some electrical conductivity and are damaged by the current flow in the fibers. One method of effective lightning protection for boron and graphite fiber reinforced plastics is plasma sprayed or flame sprayed aluminum. Silver paint is moderately effective, giving protection at 50 to 75 kA for a 0.076-mm (3-mil) coating. These forms of protection are subject to erosion damage with resulting maintenance problems. A developmental lightning protective coating for boron and graphite fiber reinforced plastics is aluminum wire fabric, which provides protection for 200 kA at one-fourth the weight of plasma sprayed or flame sprayed aluminum. Another form of lightning diversion and erosion protection is sheet aluminum, stainless steel, or titanium adhesively bonded to the structure. This form of protection has proved to be more durable in areas of high erosion.

19. BIBLIOGRAPHY

The following documents are recommended as sources of lightning information:

a. L. C. Walko, *Test Technique for Measuring Lightning-Induced Voltages on Aircraft Electrical Circuits*. Final Report. Jan 73. Lewis Research Center, Aerospace Safety Research and Data Institute, Cleveland OH 44102. Describes a transient analyzer used to measure lightning induced voltages on aircraft electrical circuits.

b. Cianos and Pierce, *A Ground-Lightning Environment for Engineering Usage*. SRI Project 1834. Aug 72. Stanford Research Institute. Surveys and colligates information on the physical characteristics of lightning and shows how to use the data to estimate the lightning sensitivity of equipment.

c. *Space and Planetary Environment Criteria Guidelines for Use in Space Vehicles*. NASA TM X-64627 (Revision). Nov 71. Marshall Space Flight Center AL 35812. Provides information on natural environments in interplanetary space, terrestrial space, cislunar space, moon, Venus, Mercury, Mars, Jupiter, and other planets. Electromagnetic radiation, charged particles, and a spacecraft charging are discussed.

d. *Analysis of Apollo 12 Lightning Incident*. MSC-01540. Marshall Space Flight Center AL 35812. Explains the triggering mechanism, permanent and temporary effects, and imposed restrictions on future launches.

e. Buser, Kauninger, and Gumeiner, *Controlled Helicopter Discharge*. ECOM 3575 (DTIC No. AD 745 102). May 72. A water spray technique for discharging helicopters is discussed.

f. Glen E. Daniels, *Atmospheric Electricity Criteria Guidelines for Use in Aerospace Vehicle Development*. NASA TN D-6901, Marshall Space Flight Center AL 35812. Includes results of studies for atmospheric electricity protection of launch vehicles as a result of the Apollo 15 incident.

20. AIRBORNE SYSTEM PROTECTION

Guidance for airborne system protection is contained in *SN 20(1)*.

SUB-NOTE 20(1) Guidance for Airborne System Protection

1. Do radomes have adequately tested diverter strips?
2. Does radome have conductive coating on outside surfaces?
3. Has attachment hardware for radome been tested?
4. Have electrical bonding provisions for radome been tested, and have quality controls been established?
5. Have protective devices and shielding been effectively used on wiring under radome?
6. Has a pressure relief been designed into radome in event wiring or components are vaporized?
7. Have metallic protection strips been installed on canopies to protect crew?
8. Have protection strips been tested for lightning current capacity and to ensure the ejection is not degraded?
9. Has electrical bonding of canopy protection been adequately tested?
10. Does canopy have an adequately high puncture voltage?
11. Have applied corrosion control techniques been tested to be lightning-compatible?
12. Have lightning-protected fuel tank caps been used?
13. When "wet wing" fuel tanks are used, is metallic skin thickness adequate for lightning currents?
14. Have bonding jumpers been used to obtain electrical continuity around sealed fuel tank joints?
15. Have external fuel tanks been designed with adequate and properly tested protection?
16. Have *MS25083* (or equivalent) bonding jumpers been used where required for lightning protection?
17. Have bonding jumpers been installed so that they cannot be exposed to a direct arc?
18. Have *MIL-A-9094* (or equivalent) arresters been used for each antenna (including UHF)?
19. Has secondary protection been installed to eliminate the inherent 10 000-volt spike from *MIL-A-9094* or equivalent arresters?
20. Has all electrical wiring that extends outside of the skin been protected with spark gaps or other protective devices?
21. Has all wiring going into fuel tanks been adequately electrically isolated, shielded, and physically separated from wiring which might carry induced energy from lightning strike?
22. Have fuel vents and ejection mechanisms (dumps) been tested for electrical conductivity and installed at safe locations?
23. Have all control surfaces and hinges had bonding jumpers installed or tests run to prove jumpers are not needed?
24. Have diverter rods or other protection been provided for external stores?
25. Has the air intake for jet engines been tested against the blast effect of lightning strikes?
26. Have all crew stations been tested to verify that the crew cannot be subjected to hazardous induced energies?
27. Have rotor blades and associated controls been tested to demonstrate safety?
28. Have all nonmetallic structures been tested to demonstrate flight safety? (No flights should be accomplished until this testing has been satisfactorily completed.)
29. Have nonmetallic hoses been used for the air data lines?
30. Has electronic equipment been protected from line transients by metal oxide varistors or other suitable components?

DESIGN NOTE 7A3 — LIGHTNING TEST FACILITIES

1. INTRODUCTION

Individual laboratory lightning tests for new design prototypes, or modification of old designs, are essential to check the successful application of general lightning protection principles. There are numerous examples where apparently unimportant production modifications were proven to be hazardous.

2. IN-HOUSE FACILITIES

An inexpensive facility is described in *Ref 556* which uses a simple Marx-type high-voltage impulse generator and other components. It is suitable for preliminary development testing, eliminating unsuccessful designs, and making routine checks on production. The facility described permits simulation of high current, heavy charge transfer, streamering, and strong electromagnetic fields. It is useful for testing components such as fuel filler caps, bonding straps, access doors, and lightning arresters. In designing this type of facility, consider the danger involved and the task of training operators. Final evaluation tests cannot be performed with the facility described in *Ref 556,* but must be accomplished with more sophisticated test equipment.

3. COMMERCIAL TEST FACILITIES

Several commercial test facilities are available to conduct tests on components, scale models, full-size airborne vehicles, or at missile sites. These commercial facilities are capable of simulating complex waveforms and evaluating the many interrelated factors which can degrade the overall lightning protection design. Contact the procuring activity for additional information regarding such facilities.

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DESIGN NOTE 7A4* ROTARY WING AIRCRAFT SUSCEPTIBILITY

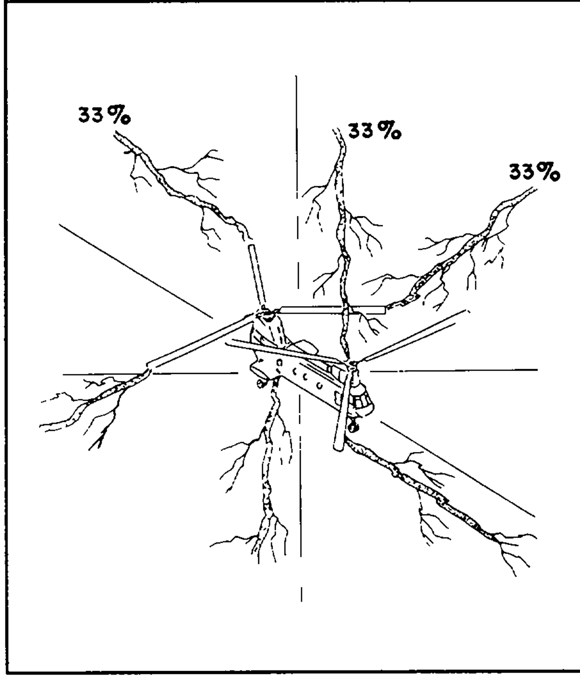
1. INTRODUCTION

Helicopter rotor blades are especially vulnerable to lightning because of the materials and construction techniques used. When lightning currents penetrate the blades, moisture, resins, glues, etc., are vaporized. The pressures associated with these vapors reach several hundred lbf/in.^{2}, which will rupture most blades. All-metal blades are less vulnerable but their skin is easily punctured and any bonded points could delaminate. The basic lightning protection requirements for all aerospace systems are stated in *MIL-B-5087*. These requirements are applicable to helicopters and rotor blades and must be part of all development effort.

2. DISTRIBUTION OF LIGHTNING STRIKES

The lightning leader follows an erratic path and the main strokes are approximately 16 to 32 km (10 to 20 mi) in length. The probability of a lightning strike is the same from all directions as illustrated in *SN 2(1)*. Sixty-six percent of these strikes would go through the rotor blades and 33% would go through the rotor head or blades and the lower portion of the fuselage. Statistics indicate aircraft are most frequently struck by lightning between altitudes of 1200 to 6000 m (4000 to 20 000 ft) with air temperature in the range of -5° to +5° C. The peak of 18% of the strikes occur at approximately 3000 m (10 000 ft). One strike could occur approximately every 2500 flight hours.

SUB-NOTE 2(1) Lightning Path Probability



3. PROTECTION OF THE BLADES AND THE ROTOR HUB

From the electrical point of view, three types of blades are considered:

a. Metal spar and metal trailing-edge boxes

b. Metal spar and plastic trailing-edge boxes

c. Nonmetallic blade with (1) plastic honeycomb fill, (2) metal honeycomb fill, or (3) boron or carbon filament composites.

3.1 NONMETALLIC BLADE WITH PLASTIC HONEYCOMB FILL

Once the main stroke occurs, an ionized channel is created through which several more strokes can occur, separated by approximately 500 µs. If a blade cuts through this channel, it will be "stitched" by lightning every 0.0005 second. In this time interval the blade, moving at 213 m/s (700 ft/s), can advance through the lightning channel approximately 102 mm (4 in.) between each successive stroke. Whether the lightning will "stitch" through the blade or circumvent it depends on:

a. Dielectric strength of the blade

b. Inductive voltage drop (E_L) of the circumventing path which depends on the circumvented path length (L) and the current rise (dI/dt).

$$E_L = -L\frac{dI}{dt}$$

3.1.1 TESTING. A test panel can be destroyed by a 50-kA discharge (which is below *MIL-B-5087* protection requirements) if the discharge passes through it. It appears that preventing lightning from entering the inside of the

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*Extracted in part from *Ref 12*®.

blade should be relatively easy. Thin metal strips, applied along the trailing-edge and across the blade chord at intervals of approximately 305 mm (12 in.), should prevent lightning from penetrating the surface and passing through the inside of the blade. This protection will have to be combined with a suitable dielectric strength of the scotchply skin. Metallic paint can also be used.

3.1.2 CORROSION OF LIGHTNING DIVERTER WIRES. Corrosion of metallic lightning diverter wires occurs rapidly within fiberglass rotor blades due to the hygroscopic (water-absorbing) nature of fiberglass skin. These wires cannot be replaced or repaired without destructive disassembly of the blades. Lightning diverters should be made from corrosion resistant materials or be isolated from moisture sources.

3.2 NONMETALLIC BLADE WITH ALUMINUM HONEYCOMB

Test panels and blade samples were tested extensively. When lightning reaches the metal honeycomb, destruction is less severe than in cases where phenolic honeycomb is used; nevertheless, a strike of approximately 100 000 A could produce an in-flight failure. The remedy is to prevent lightning from penetrating the surface and passing through the inside of the blade. This is impossible by simple applications of protective strips.

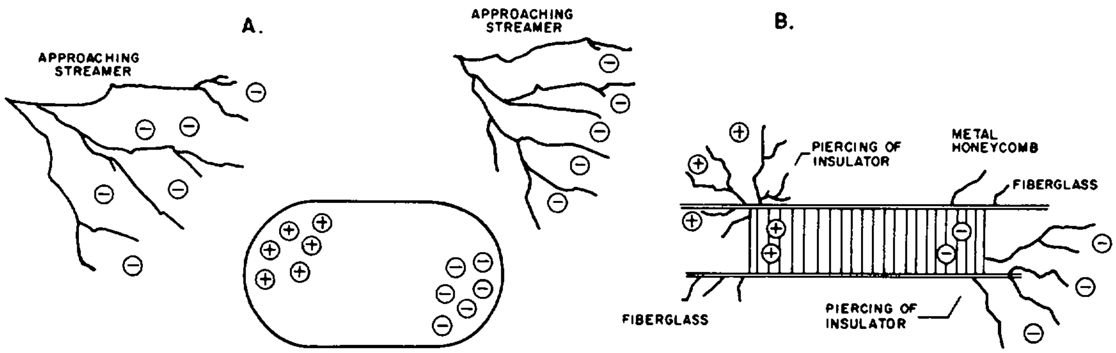
3.2.1 LIGHTNING ENTRY. When a leading streamer approaches the blade, the adjoining metal undergoes charge separation, as shown in *SN 3.2.1(1)A*. If the metal foil has sharp corners and edges (as in the case of cut aluminum honeycomb) secondary streamers will appear, as shown in *SN 3.2.1(1)B*. These streamers have sufficient voltage to pierce the fiberglass skin of the trailing-edge of the blade. Once this skin is pierced, lightning will pass through the inside of the blades. If the lightning current is in the order of 50 kA, delamination of approximately 152 mm (6 in.) in diameter will occur with no possibility of an in-flight failure. A current of 100 kA could cause destruction of honeycomb and delamination of an area 508 mm (20 in.) in diameter, which could result in an in-flight failure of the blades.

3.2.2 PREVENTIVE DESIGN. To prevent lightning from penetrating the surface and passing through the inside of the blade with electrically floating honeycomb, a schematic for protection has been developed as shown in *SN 3.2.2(1)*. *Sub-Note 3.2.2(1)A* shows the secondary streamers (originating on metal honeycomb edges) piercing the blade skin. The strike path goes through the honeycomb. *Sub-Note 3.2.2(1)B* shows electric bonding of the floating honeycomb to the trailing-edge. It extinguishes the streamers facing the trailing-edge, but does not affect the streamers facing the leading edge. The lightning path continues through the honeycomb. *Sub-Note 3.2.2(1)C* shows chordwise metal strips connecting the trailing and leading metal strips. The streamers facing the trailing-edge would be reduced to the point where it will be impossible to pierce the thick plastic near the blade spar. (Distance between chordwise strips has to be determined experimentally.) This type of protection needs confirmation by experiment on blade samples designed more or less on the principles shown in *SN 3.2.2(1)C*. The considerations apply to any metal floating electrically inside a plastic structure of the aircraft. Also see *DN 7A2* for information on preventive design.

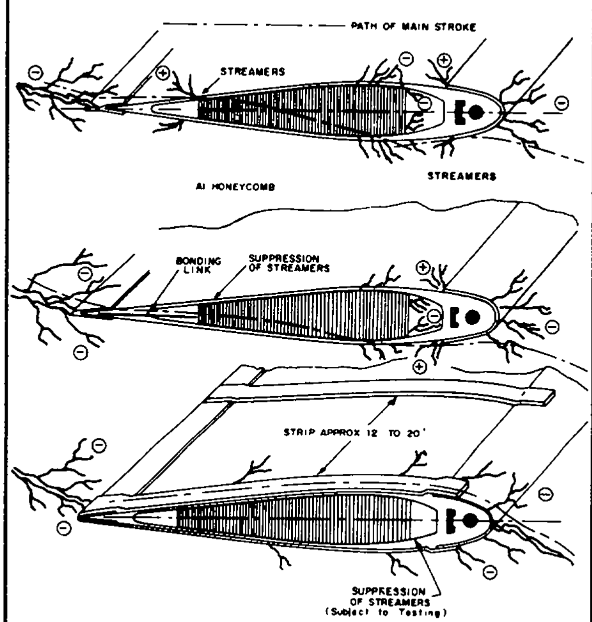
3.3 LIGHTNING STRIKES ON THE ROTOR HUB

Due to high contact pressures on the bearings of the blades and rotor hub, no additional bonding is required. Testing of pitch arm bearings, with 200 kA discharges, is recommended under minimum simulated bearing loading. Bearing damage without in-flight failure would be anticipated.

SUB-NOTE 3.2.1(1) Streamer Formation on Floating Honeycomb



SUB-NOTE 3.2.2(1) Protection of Floating Metal Honeycomb



4. PROBABILITY OF LIGHTNING STRIKES TO FUEL SYSTEM

Only 33% of lightning strikes will go through the fuselage. Only a small percentage of these will "stitch" from the blades to the upper portion of the fuselage where fuel vents, filler caps, and fuel gauge probes are located. It can be estimated that only 1 out of every 10 of the 33% lightning strikes that hit the helicopter vertically will hit the upper surface skin above the fuel tanks (1 hit approximately every 15 000 flight hours).

4.1 STREAMER PROBLEMS

Any lightning striking the helicopter will produce intense streamering. The energy of even a weak streamer is far above the ignition level of an explosive mixture. Problems caused by streamers are by far more common than those caused by a direct strike—approximately 1 intense streamering in every 2000 flight hours. (Weak lightning goes undetected in airline statistics, but produces streamers just the same.)

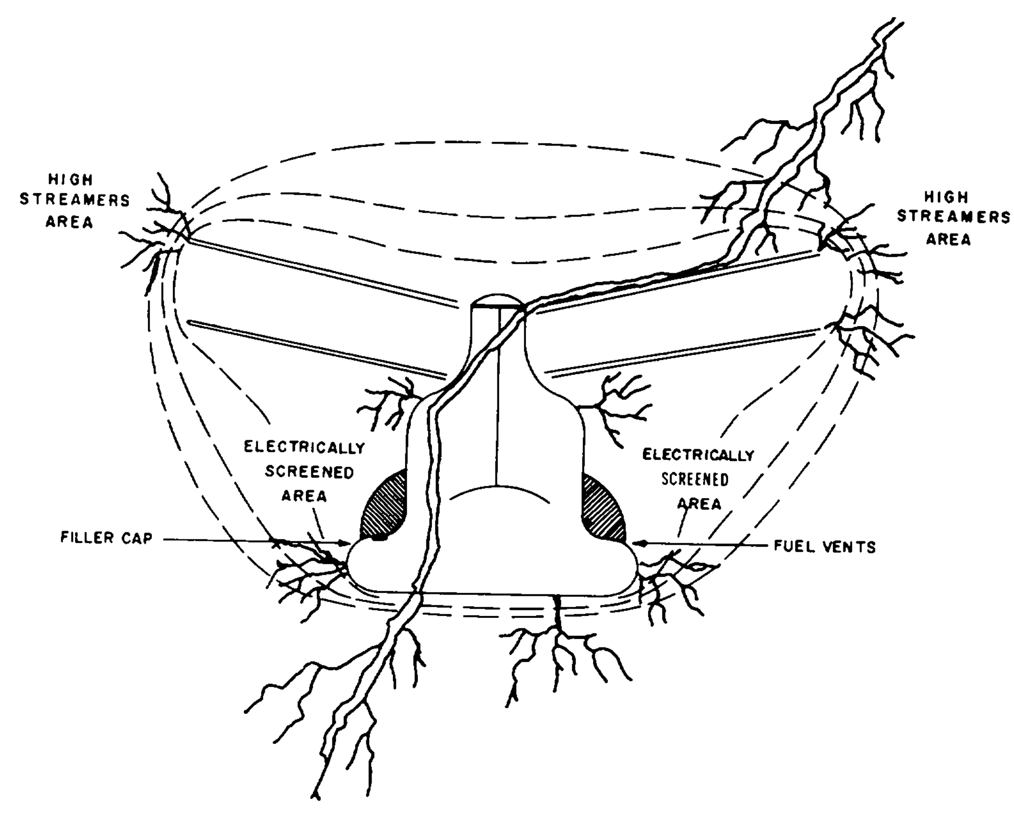
4.2 FUEL VENTING

Fuel venting presents special problems due to streamers. The direct strike is a greater problem depending on a particular design, but streamering has sufficient energy to ignite the explosive mixture in the fuel vents. *Sub-Note 4.2(1)* is an example of fuel vent location on a helicopter. The venting pipes of 25 mm (1 in.) diameter are located in the fold of the skin between fuel pontoons and fuselage skin. This is an excellent location to avoid direct strike and reduce streamering. Fuel jettison pipes should be located in points not likely to suffer from streamering and shielded from enough direct lightning paths.

5. ROUTING OF WIRES

To determine the problems lightning can cause when it hits external cables is very complicated. There is a possibility of (1) hazard to flight crews, (2) ignition of fuel, and (3) firing squibs of cable cutters and weapons. This will be especially true when carrying outside cargo and after provision of escape systems (cutting off rotor system and firing ejection seats). It is safe to recommend bypassing the problem by running all cables under the aircraft skin.

SUB-NOTE 4.2(1) Location of Fuel Vents and Filler Caps



DESIGN NOTE 7A5 STRIKE AND DAMAGE EXPERIENCE

1. INTRODUCTION

Aircraft are going to be struck by lightning at any point on the aircraft. The frequency of strikes will depend on the type of aircraft and its operational use. Experience shows that most damage caused by lightning strikes is minor, although lightning is capable of major damage or loss of the aircraft. The aircraft which have been lost have few or no lightning protection design features. With the use of new materials and the increase in size and complexity of modern aircraft, a major effort will be required to ensure mission-capable, safe aircraft. The statistical information on lightning strikes in this Design Note covers 1965–1970. Information on lightning problems affecting aerospace vehicles may be obtained from *Ref 60*. *Reference 187* presents lightning information from the standpoint of its relation to, and interaction with, aerospace vehicles and ground complexes.

2. STRIKE INCIDENCE

Comparison of the British commercial aircraft operating in Europe and the 1967 Air Force trainer aircraft reveals that the mean hours between aircraft strikes vary from one strike every 2400 hours to one strike every 500 000 hours. The large difference between aircraft lightning strikes can be caused by many different factors. There may be differences in (1) yearly thunderstorm activity, (2) geographic area; see *SN 2(1)* and *SN 2(2)*, (3) time of year; see *SN 2(3)*, (4) aircraft altitude; see *SN 2(4)*, (5) mission; see *SN 2(5)*, and (6) weather; see *SN 2(6)*.

3. LIGHTNING STRIKE ATTACHMENT TO AIRCRAFT

From Air Force incident data, a summary of typical attachment points is shown in *SN 3(1)* for various F-4 aircraft models. This data shows that aircraft configuration has a significant effect on attachment points.

3.1 LIGHTNING ATTACHMENT

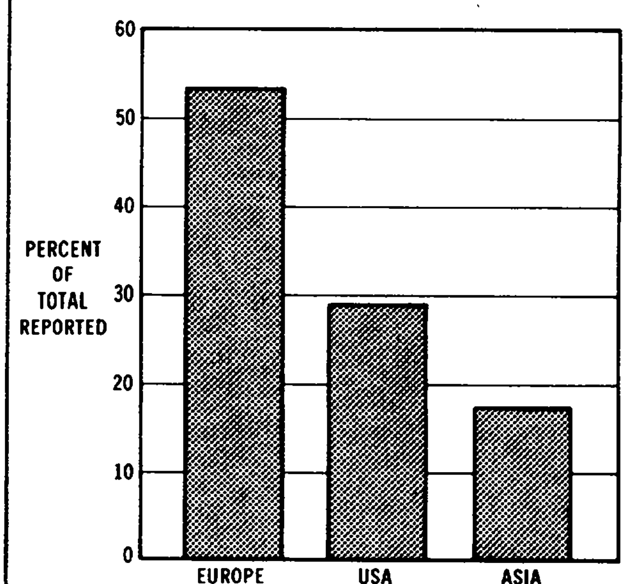
Aircraft surfaces can be divided into three segments with each having different lightning attachment and transfer characteristics. See *SN 3.1(1)*. These surface segments are:

Segment 1: Surfaces of the vehicle for which there is a high probability of direct lightning stroke attachment or exit. On initial attachment points there may be either low or high probability of hang-on.

Segment 2: Surfaces of the vehicle where there is a high probability of a swept stroke. A swept stroke surface may have either low or high probability of stroke hang-on.

Segment 3: Includes all other surfaces of the vehicle. There is a low probability of any direct attachment of the lightning arc; however, there will be substantial amounts of lightning current flowing between entry and exit attachment points.

SUB-NOTE 2(1) Total Lightning Strikes to Aircraft as a Function of Geography



(Does not Include any Reference to Hours of Flight Time or Type of Aircraft)

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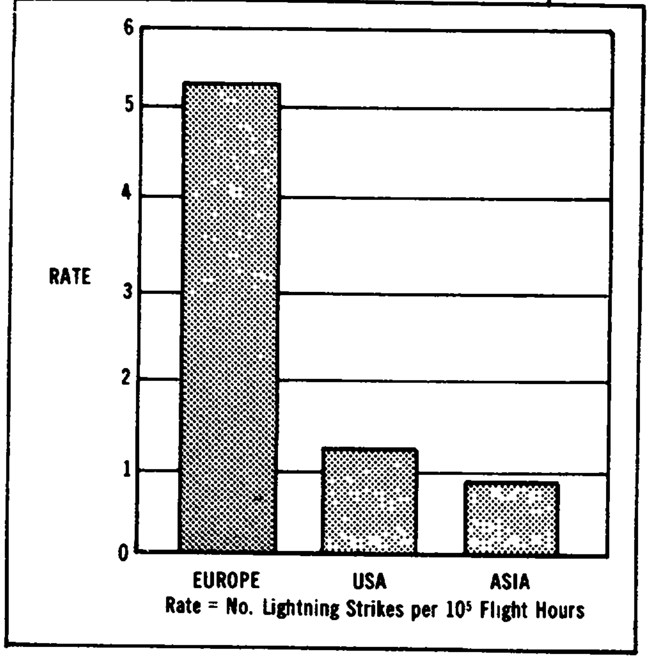
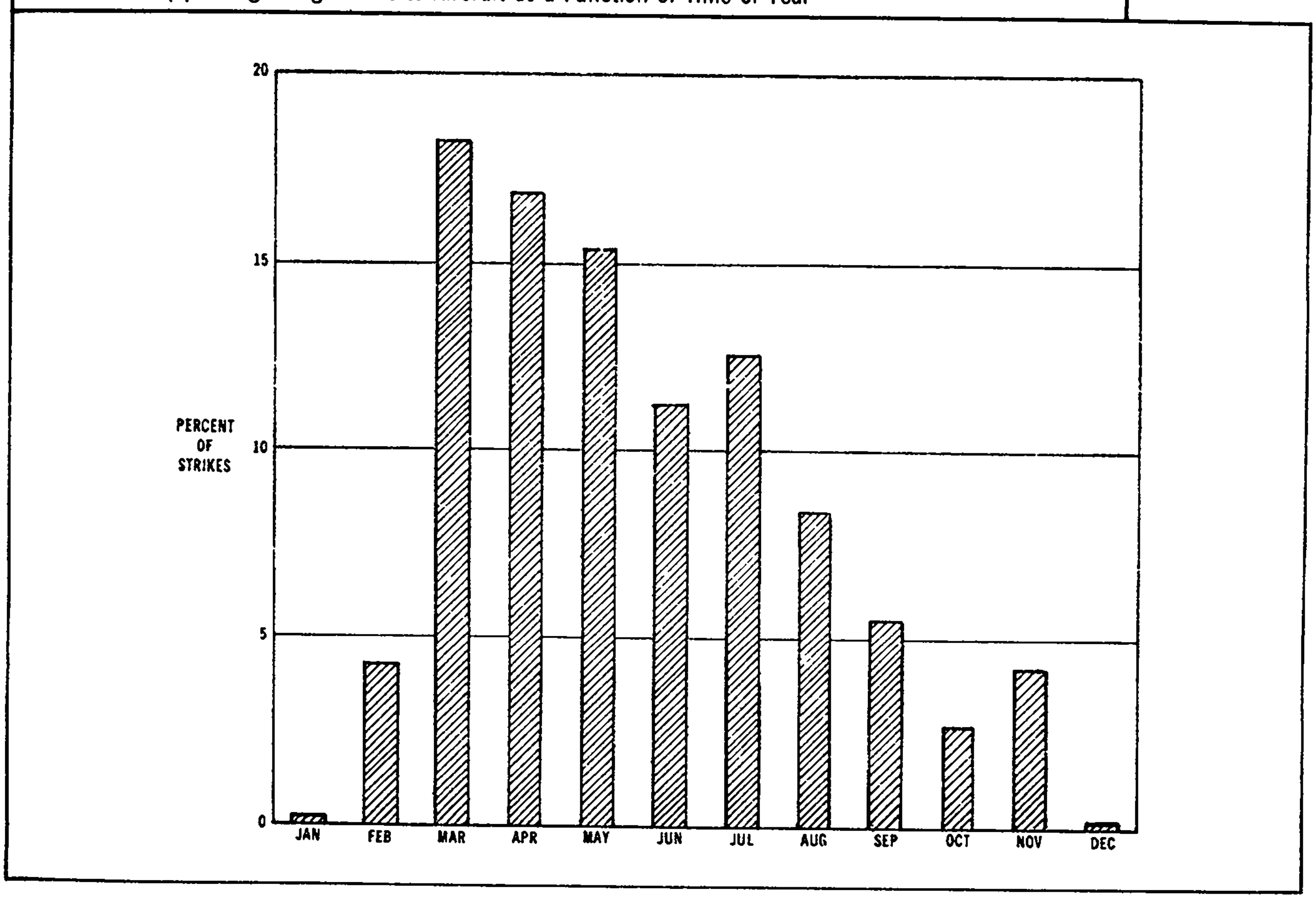
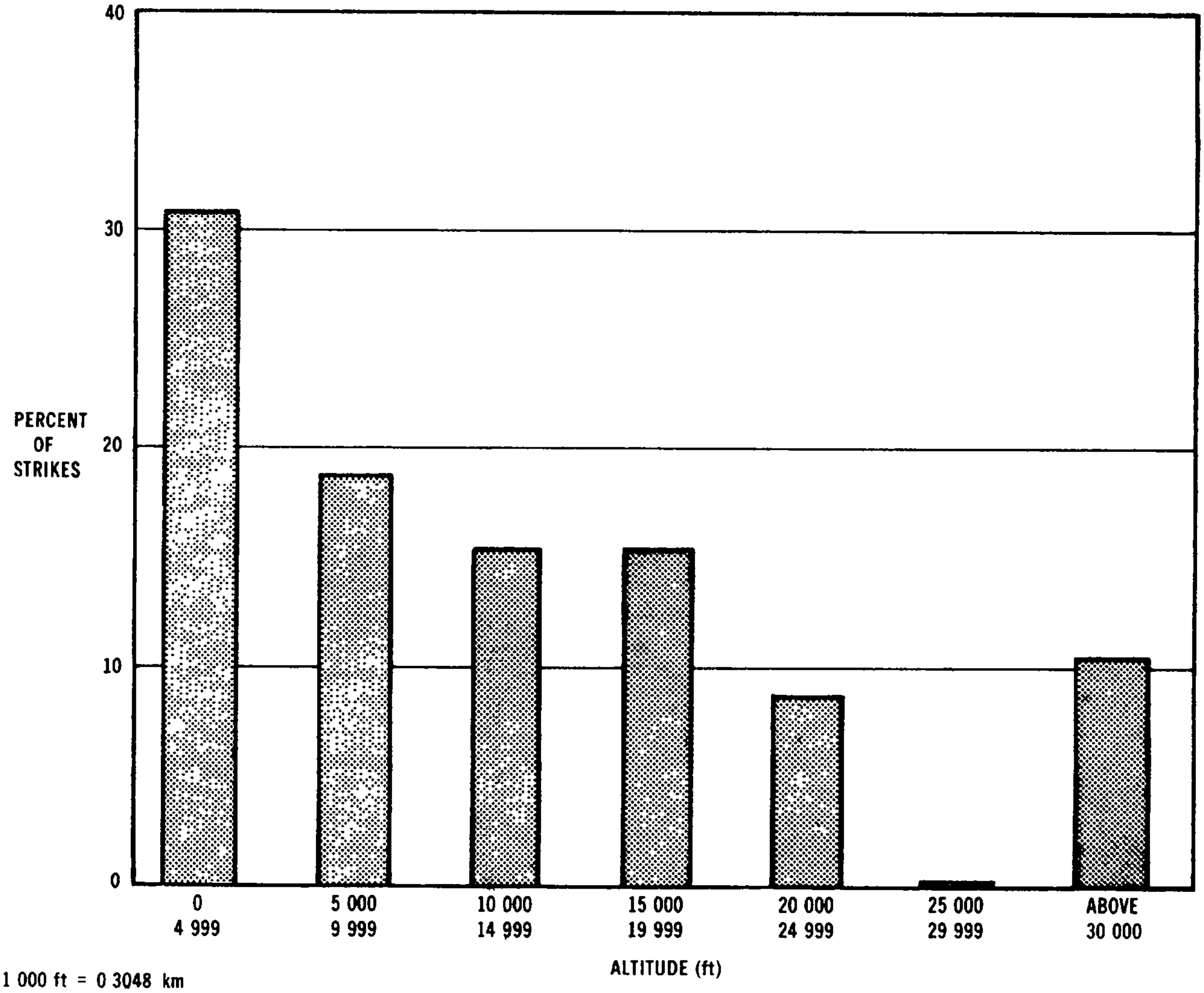
SUB-NOTE 2(2) Rate of Lightning Strikes to Aircraft as a Function of Geography



SUB-NOTE 2(3) Lightning Strikes to Aircraft as a Function of Time of Year

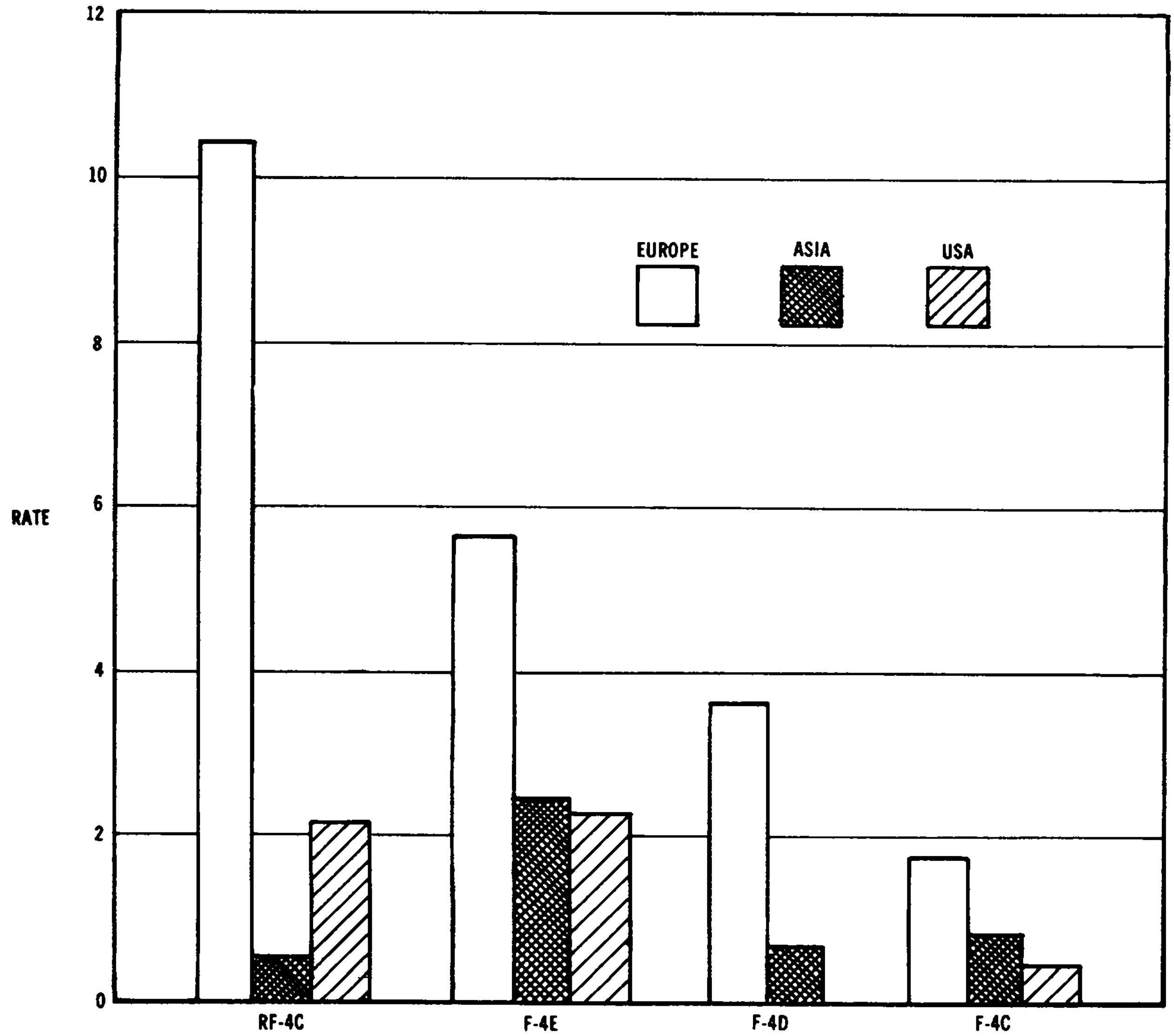


SUB-NOTE 2(4) Lightning Strike to Aircraft as a Function of Altitude Statistical Analysis



1 000 ft = 0 3048 km

SUB-NOTE 2(5) Rate of Lightning Strikes to the F-4 Aircraft



Rate = No. Lightning Strikes per 10^5 Flight Hours

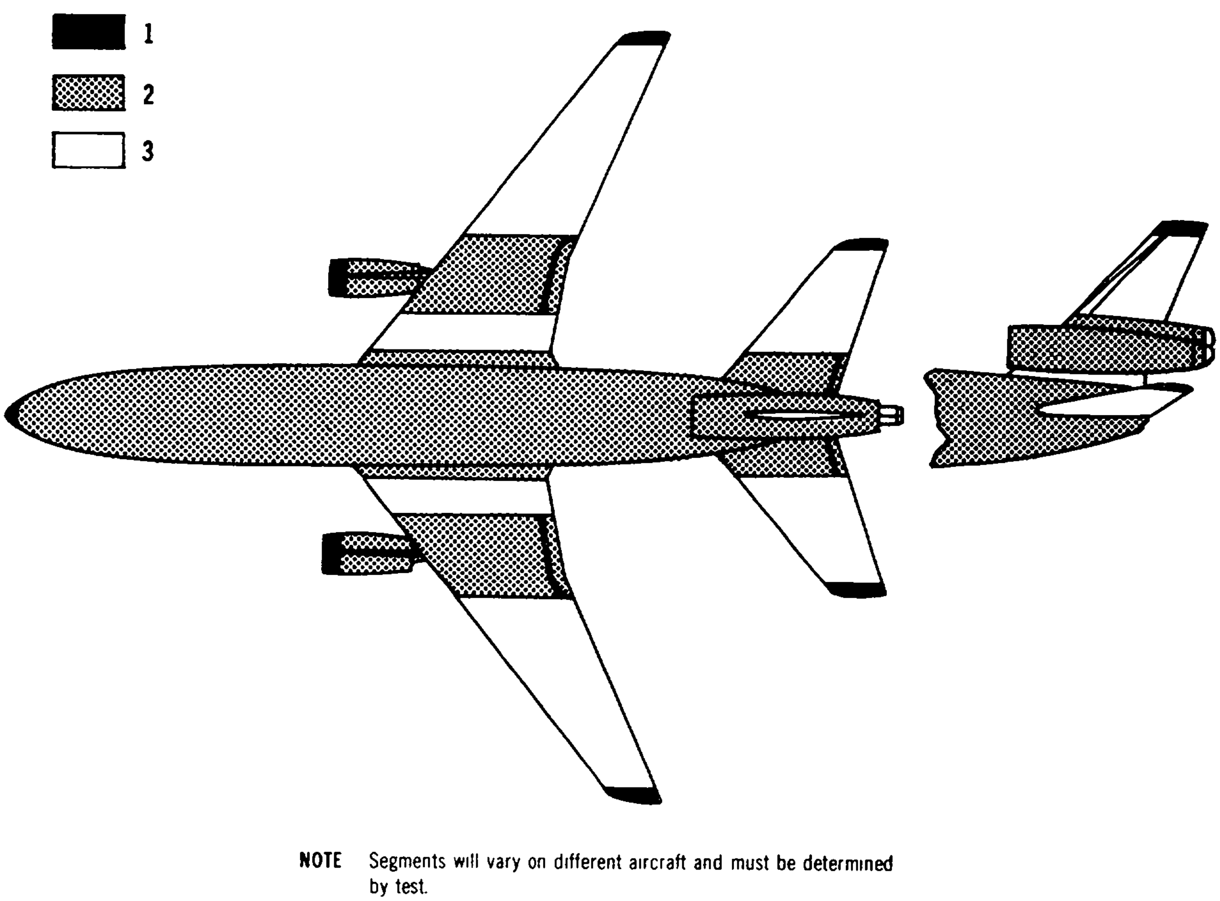
SUB-NOTE 2(6) Weather Associated With Lightning Strikes

CLOUDS	43% IN CLOUDS 57% ADJACENT TO CLOUDS 0% NO CLOUDS
ELECTRICAL ACTIVITY	19% LOCAL 19% NO 62% ADJACENT
RAIN	83% PRESENT 17% ABSENT

SUB-NOTE 3(1) Typical Lightning Strike Location

PERCENT OF STRIKES WHICH AFFECT A GIVEN LOCATION			
	RF-4C	**F-4E**	**F-4D**
PITOT MAST	76	63	—
RADOME	—	—	8
WING TIP	59	50	50
VERT FIN	35	0	17
POD	18	13	33
STABILATOR	29	19	33
FUSELAGE	6	6	8

SUB-NOTE 3.1(1) Typical Aircraft Lightning Strike Segments



NOTE Segments will vary on different aircraft and must be determined by test.

DESIGN NOTE 7A6 — RADOME LIGHTNING PROTECTION

1. INTRODUCTION

Lightning damage to aircraft radomes is generally considered to be an economic problem, but lightning damage to radomes for supersonic aircraft may seriously affect aircraft stability. The breakup of large sections of a radome may also affect the flight stability or damage adjacent areas. The lightning protection systems which have been developed include the use of graded resistance paint strips or aluminum paint for diverting discharges across the radome outer surface, the use of lightning diverter rods for locally diverting the discharge away from the radome, and the use of external conductors of various types. The conductor grids are used on the radomes of most US transport aircraft.

2. LIGHTNING PROTECTION

In evaluating the need for radome lightning protection, consider the effects of the total loss of the radome on aircraft safety. Evaluate the (1) flight stability, (2) hazards to the flight deck from the breakup and movement of the radar fragments over the aircraft, (3) engine ingestion of the radome fragments, (4) lightning energy surge coupling into the balance of the aircraft electrical system affecting control systems or other vulnerable electrical circuitry, (5) errors in airspeed indication, and (6) general hazards to aft sections of the aircraft from the radome fragments. The lightning protection technique is a separate problem for each type of aircraft.

3. FOIL CONDUCTOR

Aluminum foil strips provide protection for only one strike, but are inexpensive and easy to mount. The aluminum foil conductor must have a certain minimum mechanical strength as any breakage of the metallic conductors can result in severe UHF and VHF radio interference. The broken segments, being electrically isolated from the aircraft, are charged by precipitation particle impact and can sparkover as a spark gap transmitter to adjacent sections. The fundamental frequency of the sparkover interference is determined by the length of the isolated segment. The strip lengths used on most aircraft correspond to wavelengths in the UHF and VHF frequency range. As UHF and VHF frequencies are primarily for communications, this radio interference becomes a very serious problem. Conducting coatings are generally recommended for use over the entire radome surface to reduce precipitation charge buildup, subsequent streamering, and possible static puncture. The resistance coatings also shield the strips and greatly increase the severity of the precipitation charging conditions required to produce direct corona off the strips. The present practice is to use aluminum foil 9.5 mm (3/8-in.) wide and 0.076 to 0.2 mm (3 to 8 mils) thick. If the radome is thin, 12.7 mm (1/2-in.) tape or wider is preferable as it distributes the blast force over a wider area. The principal problem in the use of foil protection strips is adequate maintenance. Paint layers of over 0.25 mm (10 mils) can cause the differential expansion of the paint and metal to crack the conductors and can restrict the expansion of the exploding foil to cause implosion and severe damage to the radome. Thus, although the foil system is inexpensive to apply, has low drag, and can be field installed, the maintenance problems introduced by its use have resulted in a general trend back to the heavier solid aluminum conductors.

4. SOLID METAL CONDUCTOR

Solid metallic conductors arranged in a suitable pattern provide minimum interference with the radar operation and provide maximum protection. Heavier copper strips, or straps, do not require replacement but are more expensive, heavier, and must usually be factory installed. Solid conductors provide much better protection, especially for the very high lightning current. A mechanical force of about 3600 kg (8000 lb) for 100 μs is caused by a lightning current of 200 kA. Due to the very short time, the actual stress is roughly equivalent to 227 kg (500 lb) over a time of several seconds. These high forces require careful attention to the mechanical aspects of the protection design. The following recommendations are for solid conductors:

a. Cross sections of 3 by 10 mm (0.12 by 0.4 in.) are adequate for alloys 6061-T4, 6061-T6, and 2024-T3.

b. Attachment spacings of not more than 76 mm (3 in.).

c. If an inner conductor is used, adequate wire diameter must be required to carry the current.

d. Conductors to carry the current to the airframe require a minimum cross-sectional area of 25.34 mm (50 000 circular mils).

e. Testing of the design is mandatory, since apparently minor design and construction details are important to the mechanical strength.

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5. SPECIAL RADOME PROTECTION

For special radomes where transmission losses or other effects present particular problems, a combination of protection techniques can be used. For example, the use of aluminum paint enhances high voltage external sparkover across the radome surface and thus provides a measure of lightning protection with minor signal attenuation. The conventional protection strips for certain portions of the radome and the paint can be used as a protection system. Dielectric reinforcement can be used for certain portions of the radome where the radome dielectric strength is low. Acrylic insulation can be added inside the radome to certain portions particularly vulnerable to puncture. Thus, a combination of strips, external aluminum paint, and local dielectrics can protect this particular radome. As each radome installation presents entirely separate protection problems, it is generally desirable and often necessary to review all possible protection techniques.

6. SUPERSONIC AIRCRAFT RADOMES

For supersonic aircraft, the radome is generally used for supporting the pitot boom (air data probe) which extends well ahead of the aircraft. The pitot boom thus constitutes a very effective lightning diverter rod and may be expected to receive most of the strikes to the aircraft. For this reason, a thorough protection system is required because total radome loss affects flight stability, airspeed indications, possible severe damage to the forward bulkheads, and possible engine ingestion of broken-up parts. However, a conduit between the pitot boom and the aircraft fuselage can conduct the currents into the aircraft without introducing excessive voltage transients into the aircraft electrical system. Air Force experience shows excellent radome protection is provided by a pitot tube well bonded to the aircraft fuselage.

7. FLUSH RADOME PROTECTION

For large aircraft or high speed aircraft, it is very desirable to utilize radome protection systems which are flush with the external surface. The earlier foil protection strip systems did provide a nearly flush external surface but had undesirable characteristics. A new system uses flush external buttons connected to an internal bonding conductor leading to the aircraft frame. The system has obvious advantages from an aerodynamic standpoint. The disadvantage is that the internal bonding conductors are near the internal radar equipment. Inductive flashover may occur to internal equipment from a large lightning strike. This can also be a problem with conventional exterior radome protection; however, the dielectric strength of the radome does tend to prevent the inductive flashover. The flush protection buttons need an extremely rugged connection between the bolts which penetrate from the external radome surface and the bonding conductors which lead to the airframe. Tubing flattened to form a loop is used to connect the internal bonding wire to the inside of the button. This system has successfully passed currents of 200 kA. See *Ref 128*.

8. TEST PROCEDURES

The simple high current tests of radomes are not sufficient to determine the complete degree of protection. In addition to testing the adequacy of the protection conductor system to carry high currents, tests should be made with long high voltage arcs to determine if there is adequate coverage provided by the protection network. Also, high current rate of rise tests should be made to determine that no internal sparkover can occur to the radar equipment (see *DN 7C1, DN 7C3,* and *DN 7C4*).

9. SEGMENTED DIVERTER STRIPS

The new segmented diverter strip technology has attracted considerable interest because of improved radar transparency; however, recent tests have verified that disadvantages exist with these strips which were not identified during R & D testing. They are:

a. Certain lightning waveforms will not ionize the strips. When this occurs, the diverter strips are destroyed.

b. During high-coulomb tests, the intense heat destroys the strips and can cause damage to the radome.

c. The segmented strips can carry one or two high current-high energy lightning strokes, and then must be replaced.

d. When the segmented strips are installed on some conductive finishes, their effectiveness can be seriously reduced.

e. Rain erosion tests have shown the life of the strips to be only a few minutes in heavy rain.

f. Installation of the strips has proved to be difficult and field replacement at bases may not be feasible.

g. The segmented strips should not be used to protect air data probes installed on nose radomes.

9.1 PRECAUTIONS

It is recommended that any project office considering the use of the segmented strips take precautions to ensure that the problems listed in *Para 9* will not degrade the safety of the system. Do not use the segmented strips in any critical applications where destruction of the strips would leave the aircraft without lightning protection.

9.2 NATO REVIEW

The NATO Aircraft Lightning Protection Committee has reviewed the available test information and has determined that tests on segmented button diverter strips performed in the United Kingdom, France, Germany, and the United States have confirmed the problems discussed. Procurement organizations participating in NATO are being alerted to these problems so that necessary precautions can be taken to ensure aircraft safety.

10. METALLIC DEPOSIT DIVERTER STRIPS

A new metallic deposit diverter strip is now available. It consists of fine aluminum particles deposited on a flexible mylar substrate strip 12.7 mm (½ in.) wide. It has certain advantages over segmented diverter strips. They are:

a. It is compatible with higher frequency radars.

b. It can be installed easily at the field level.

c. It is economical in price.

d. It is very flexible and will lend itself to installation on curved surfaces.

The metallic deposit strips are very new and have not seen extensive use. They should be thoroughly tested in a laboratory to determine optimum placement and radar compatibility before a final design is established.

SECTION 7B — STATIC ELECTRICITY

DN 7B1 - INTRODUCTION

DN 7B2 - STATIC DISCHARGERS (PASSIVE)

DN 7B3 - EFFECTS OF P-STATIC ON NAVIGATION SUBSYSTEMS

DN 7B4 - STATIC ELECTRICITY CONSIDERATIONS FOR AIRCRAFT FUEL SYSTEMS

DESIGN NOTE 7B1*

INTRODUCTION

1. GENERAL

Static electricity can cause a number of problems that directly affect the safety of aerospace vehicles and their overall system effectiveness. Components such as transistors can be permanently damaged by a single static discharge.

1.1 DIFFERENCE BETWEEN LIGHTNING AND STATIC DISCHARGE

Since the difference between lightning and static discharge is sometimes confusing, a short recapitulation is presented below:

a. Lightning is a surge of static electricity between cloud and cloud or between cloud and ground. The aircraft happens to form part of this path. The voltage involved is in the order of hundreds of millions of volts; the transfer of charge, up to 600 C (currents of the order of 200 kA).

b. Static discharge is an electrical charge, generated on the aircraft leaving it in the form of a corona current (on the order of 100 μA) or as a spark to ground. The voltage generated can be between 40 kV to 1000 kV and the charge from 0.04 mC to 1 mC.

Lightning is approximately 10^6 times the order of magnitude of static discharge and can inflict mechanical damage on a helicopter or ignite its fuel. Static discharge can ignite the fuel or ammunition, cause radio interference, and possibly injure the cargo hook handler; but, as far as mechanical damage is concerned, static discharge is insignificant.

2. ATMOSPHERIC ELECTRICAL HAZARDS

Atmospheric electricity can cause a number of problems that directly affect the safety of aerospace vehicles and their overall system effectiveness. Atmospheric electrical phenomena causing problems that occur under similar weather conditions can be placed in three classes.

a. Precipitation static

b. Saint Elmo's fire

c. Lightning.

3. EFFECTS OF PRECIPITATION STATIC (P-STATIC)

Electrical interference caused by static electricity leaking off a vehicle is called P-Static. Effects which could result from precipitation static include possible failure of mission, mission abort, or just plain nuisance. For particularly susceptible equipments, such as in low frequency (LF) and medium frequency (MF) bands and shoran, a specific program is required. This inteference is broadband and has a continuous spectrum. It produces a rushing sound similar to amplified shot noise. The manned aircraft problem is severe because precipitation static occurs during storm conditions when the pilot must fly by instruments, voice, and radio navigation aids. The unmanned vehicle problem is also severe because the computing or control system has only limited capability to distinguish between noise and the desired signal. Loss of the vehicle is possible if frequency bands susceptible to precipitation static are used.

3.1 DIRECT CURRENT PATH TO GROUND

Any equipment connected to an antenna must have a dc path to ground so that static charge may bleed off. This path can be provided in the antenna, lightning arrester, coupler, transmit receive box or elsewhere.

4. SAINT ELMO'S FIRE

Saint Elmo's fire is a brush-like corona discharge from the propellers, wings, projecting parts, and windshields of aerospace vehicles. It does not cause damage to the vehicle but serves as a warning that the vehicle or the surrounding atmosphere is highly electrified and that lightning strikes may occur.

5. TRIBOELECTRIC CHARGING

Triboelectric charging is that phenomenon producing static electricity (P-static) by friction. This takes place when rain, ice crystals, dust, sand, and nuclear debris impinge on an isolated surface and charge it to a higher potential (either negatively or positively) than the circumjacent area. When the potential of the charged surface is high enough relative to the adjacent or surrounding areas, corona, sparking, or streamering occurs, thereby producing broadband radio frequency noise. This noise spectrum reaches from a few hertz to the gigahertz area and is very pronounced in the VHF and UHF bands (30–3000 MHz) on those high performance aircraft having plastic surfaces. Since an aircraft travels through the air, it literally drives itself against the offending particles. Rain and snow particles create a charge when they strike and bounce off a surface. Dust and sand create a charge when they strike. They often

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*Paragraphs 5 through 7.3 were extracted in part from *Ref 376*.

become imbedded in a surface. Triboelectric charging generally increases with speed, but beyond a certain point it begins to diminish. Unfortunately, the point where the decrease commences is higher than the speed of modern aircraft. At 1073 m/s (2400 mi/h), triboelectric charging by ice crystals is practically zero.

6. CROSSFIELD GRADIENT

Crossfield gradient charging occurs when an aircraft penetrates the charged atmosphere within or adjacent to atmospheric areas charged to different potentials. For example, the space between two clouds charged at different potentials contains a crossfield. An aircraft intercepting this field will transverse the gradient lines comprising the field and cause a charge to accumulate on the surface of the aircraft.

7. STATIC DISCHARGES

When an individual particle collides with a surface, it leaves a minute charge. The next particle also leaves a charge which adds to the first charge thereby creating a step increase. The charge increases until the surrounding air is ionized creating a path for a corona discharge, streamering, or sparking. The step increase often reaches its discharge potential in the order of 0.01 μs and discharges at an exponential rate throwing the charging into the VHF and UHF spectra.

7.1 CORONA

When a charge accumulates on an aircraft, the charge is relative to the surrounding air or to the adjacent but insulated aircraft sections. When the potential of the charge is high enough, relative to the surrounding air, ions are created which are swept away in the air-stream. Since ionized air is electrically conductive and electrostatic charges by nature are concentrated at extremities and at small curved or sharp surfaces (large fuselage surfaces disperse the charge), corona discharge occurs as a regular pulse train.

7.2 STREAMERING

When the charge on a nonmetallic aircraft surface is great enough, relative to surrounding metal portions of an aircraft, visible electrical discharges take place. In appearance they resemble miniature lightning strokes except that they are continuous.

7.3 SPARKING

Sparks develop between two metallic surfaces which are isolated as far as direct current is concerned and which are triboelectrically charged to different potentials. This is usually the result of difference in surface area. Sparking occurs when the dielectric strength of the media separating these surfaces is exceeded. Sparking creates noise in the VHF and UHF spectra.

DESIGN NOTE 7B2* STATIC DISCHARGERS (PASSIVE)

1. INTRODUCTION

Static dischargers are used to drain the accumulated electrical charge on an aircraft without generating excessive radio noise. Static dischargers permit a satisfactory solution of the P-static problem. They have no effect on the lightning problem and will neither protect an aircraft from lightning strikes nor reduce the probability of an aircraft being struck by lightning. However, when an aircraft is struck by lightning, improperly installed dischargers can actually increase the damage. See *MIL-S-9129* for additional information.

2. POINT OF CHARGE CONCENTRATION

The concentration of static charges is greatest at the trailing edges of the wing tips, and descends at the trailing tips of the vertical and horizontal stabilizers. On aircraft where the horizontal stabilizer is attached to the top of the vertical fin, the charge is similar to that of the wings. Static discharging devices attached at the points of charge concentration can be used effectively to draw off the charges and keep them reduced to a noninterfering level. It is recommended an extra discharger be installed on each trailing edge to ensure some protection in the event one of the dischargers is lost or becomes inoperative.

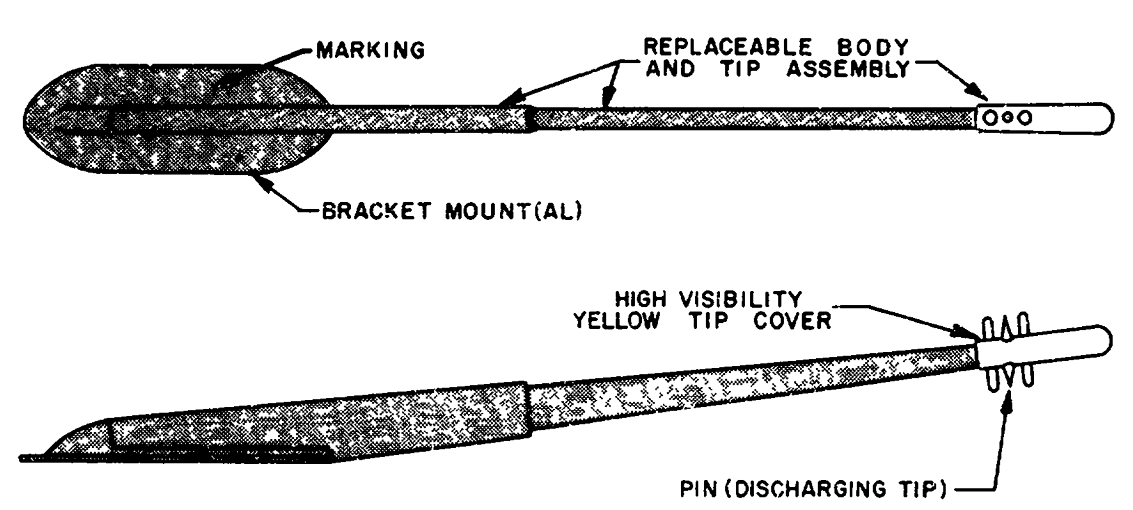
3. DESCRIPTION OF TYPES

There are (basically) two types of static dischargers, active and passive.

a. The active discharger uses circuitry to reduce the static charge on an aerospace vehicle. One type uses the thermionic emission principle to boil off excess electrons. It is adaptable to spacecraft since it is independent of airflow.

b. Passive types 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. See *SN 3(1)* for a passive type electrostatic discharger.

SUB-NOTE 3(1) Typical Electrostatic Discharger



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*Extracted in part from *Ref 376*.

4. INSTALLATION REQUIREMENTS

Install static dischargers at the points of static charge accumulation. Do not place dischargers closer than 0.3 m (12 in.) apart due to mutual shielding. Locate the outboard discharger as close to the tip of the airfoil as possible and the second discharger inboard approximately 0.3 m (12 in.). Place the third discharger inboard about 0.6 m (24 in.) from number two and use a 0.6-m (24-in.) spacing for the remainder of the dischargers. Mount the dischargers on structurally sound airframe members. If the mounting surface is nonmetallic, install metal interconnecting strips between the mounting location and the nearest metal surface. Ensure the surface preparation and treatment is compatible with the operational environment. See *DN 5D4, SN 1(4)*, for bonding requirements.

5. DC RESISTANCE

It has not been verified any correlation exists between dc resistance and RF noise quieting. When conducting dc resistance tests, consult each manufacturer for applicable resistance limits. A visual inspection of the discharger is recommended to determine when replacement is necessary. Also check for blunting of pins and erosion of conductive coatings. See *Ref 187* for additional information on discharger installation.

6. DISCHARGER CAPACITY

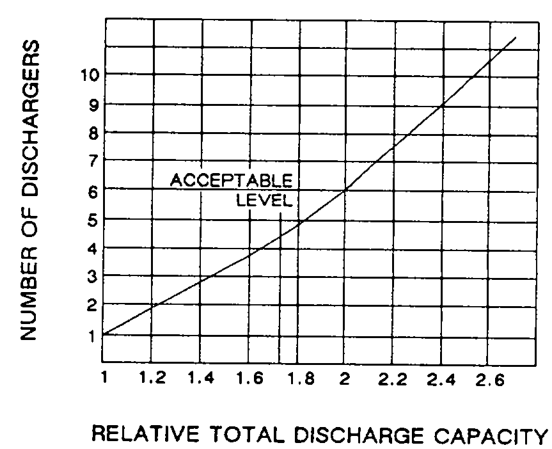
Studies have shown that five dischargers per trailing edge on commercial aircraft reduce static accumulation to an acceptable level of 1.75. Using this level as a base, the approximate number of required dischargers can be estimated by determining the relative total discharge capacity and applying it to the graph shown in *SN 6(1)* and vice versa. 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 =

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

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).

SUB-NOTE 6(1) Relative Total Discharge Capacity vs Required Number of Dischargers per Trailing Edge



* A minimum of two dischargers is recommended for redundancy on each trailing edge; see *Para 2*.

DESIGN NOTE 7B3 EFFECTS OF P-STATIC ON NAVIGATION SUBSYSTEMS

1. INTRODUCTION

Precipitation static can cause a deviation indicator, VHF Omnirange (VOR), Localizer (LOC), and Glide Slope (GS) equipment to present a false indication without showing a warning flag. P-static induces course errors in VOR receivers and causes misalignment in LOC and GS receivers. This Design Note describes some of the errors that can be induced in VHF navigation subsystems by P-static and suggests means of eliminating this phenomenon.

2. EFFECTS

By simulating P-static conditions encountered in enroute and approach flight profiles, it is possible to induce false course signals in VOR and localizer receiving systems without triggering a warning flag. In the presence of P-static, warning flags appear when the valid signal strength is weak. However, with a strong signal strength, as would be the case close in or on final approach, the flags do not appear with an erroneous course display. The course misalignment is not readily recognizable since the false course reading is often steady and can be centered by the omnibearing selector. The course misalignment, without a warning flag, is most likely to first occur at low corona discharge levels and at high VOR/LOC signal levels. Comparison of the two VOR indications in a cockpit is of doubtful value since both systems can be in error. It is possible to induce a 10° or more course error on a VOR display when the VOR signal equals 2 mV. A 10° error is equal to about a 1-km displacement at a distance of 6 km from a VOR facility. A full scale localizer on-course error can be obtained artificially by inducing corona currents from the skin of the airframe. A corona discharge is a dc pulse which can be at a steady or random rate. It is conceivable that the rates could be approximately 30, 90, or 150 Hz. The above effects have been demonstrated on all navigation equipment tested to date. The problem is apparently caused by shock excitation of the receiver tuned circuits.

3. INSULATING ANTENNAS

To reduce the adverse effects of P-static caused by tribo-electric charging on an aircraft, insulate exposed metal antenna components with polyethylene or other suitable material so they cannot come in contact with airborne particles of snow, rain, ice crystals, dust, sand, and nuclear debris. An insulated antenna also prevents a corona discharge directly from the antenna. The locations of the antennas are important. Since static charges concentrate on sharp points of an aircraft such as pitot tubes or trailing edge tips, locate antennas as far as possible from these areas. If antennas cannot be installed other than in the proximity of sharp edges or protrusions, prevent the adverse accumulations of static charging by using static discharge devices. Conduct periodic testing and maintenance on all polyethylene covered antennas since a small puncture may result from the concentration of electrostatic charges.

4. METALLIC AND NONMETALLIC AIRCRAFT STRUCTURES

Sparking occurs when metal surfaces are separated by a dielectric and become charged at different potentials. To prevent this, use adequate electrical bonding between metal sections to keep all metal parts at approximately the same potential. This bonding may not be suitable for lightning protection (see *DN 7A2, Para 6.3*). Also, streamering can develop between plastic materials and the adjacent metal areas when each is charged to a different potential (see *DN 7A4, Para 3.2*). Streamering may be overcome by shielding the nonmetallic areas with electrically conductive coatings that will keep the surfaces at approximately the same potential.

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DESIGN NOTE 7B4 — STATIC ELECTRICITY CONSIDERATIONS FOR AIRCRAFT FUEL SYSTEMS

1. INTRODUCTION

The Air Force has experienced explosions and fires caused by static electricity generated within the aircraft fuel system and fuel trucks. The accumulation of electrostatic charge in the handling of hydrocarbon fuels is a potential hazard. Modern military aircraft with high refueling velocities have intensified the electrostatic charge generation problems. The more recent use of reticulated foam in fuel tanks for explosion suppression has contributed to the static generation/discharge problem especially where high velocity fuel is permitted to impinge directly on the foam surface.

2. STATIC ELECTRICITY IN FUELS

Aviation turbine fuels such as JP-4, JP-5, or JP-8 are excellent electrical insulators and in the pure form would have resistivities in the range of 10^{16} Ω·cm. Trace impurities normally lower the resistivities to the range of 10^{14} to 10^{13} Ω·cm (that is, conductivities of 1 to 10 conductivity units (CU) or picosiemens per metre). These trace impurities also greatly increase the tendency of the fuel to become electrostatically charged. Both the conductivity of the fuel and its charging tendency are dependent upon ionizable impurities. Some ions may be at the molecular (i.e., dissolved) level and consequently highly mobile. The so-called electrical conductivity additives (antistatic additives) are of this type. Other ions may be of colloidal size with poor mobility. These could significantly increase the charging tendency of the fuel but would have little effect on the conductivity. Fuel becomes electrostatically charged whenever ion removal from or addition to the fuel occurs. Typically, filter-water separators in refueling units are excellent charge generating units. Also, very high flow velocities in pipes and hoses, fuel spraying or splashing from nozzles, and aeration of the fuel are high charging mechanisms. The electrical conductivity additives provide greatly increased fuel conductivity so that any charge generated can bleed (dissipate) rapidly, and safely, to ground. Such additives do increase electrostatic charging but normally allow the charge to rapidly bleed (dissipate) to ground. See *DN 3B5, Electrical Ignition of Combustible Mixtures.*

3. BONDING

Ensure that all plumbing meets the requirements of *MIL-B-5087* and *MIL-F-38363*. Ensure that there are no unbonded components or metal objects inside of the fuel tanks to act as charge collectors (unbonded conductive object). Ensure that the bonding jumpers are compatible with fuel and the metal to which they are attached. Also, see *MS25083* and *MIL-STD-889* for more details. All copper jumpers, and those aluminum jumpers with crimped terminals are prohibited; however, aluminum jumpers with brazed terminals are recommended.

4. DESIGN CONSIDERATIONS

Consider the following in the design of aircraft fuel systems:

a. Comply with bonding requirements noted in *Para 3* above.

b. Locate tank fuel inlets at or as close as possible to the bottom of the tank to ensure prompt submersion by fuel and with minimum misting, spraying, or foaming. Also, design the inlet to provide fuel discharge velocities of 10 ft/s or less and preferably to point downward or at a maximum of 45 degrees from horizontal. Piccolo tube (tube with multioutlets) or Bellmouth type inlets are preferred since they inherently provide very low discharge velocities at the bottom of the tank.

c. Install fuel flow balancing orifices as far upstream of the tank fuel inlet as possible to allow for maximum fuel charge relaxation. Never install the flow balancing orifice at the fuel inlet.

d. Ensure that the resistivity of the tank walls, including bladder cells, is less than the resistivity of the fuel. Ideal resistivity is 10^{10} Ω·cm or less.

e. When fuel electrical conductivity additive is used to dissipate static electricity, conductivity levels normally range from 100 to 700 conductivity units (CU). Aircraft fuel quantity gages should therefore be capable of operating within normal tolerance levels with fuel containing the electrical conductivity additive in the 100 to 700 CU range.

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f. Design the fuel system to accept nonadditive fuel without creating electrostatic problems.

g. Avoid air discharge through fuel or reticulated foam since it will generate static electricity. In cases such as external tank transfer systems where air is the primary fuel transfer mode, take care to ensure air shutoff at the end of each transfer, to prevent air from bubbling through fuel or foam.

h. Avoid two-phase flow, such as the flow of isolated slugs of fuel or fuel mist, in fuel and vent systems. This is especially true for fuel with antistatic additive. If treated-fuel flow becomes isolated from conductive structure, the increased charging characteristics of the treated fuel can result in rapid charge generation, then dissipation (sparking) when impingement of the slugs or mist occurs.

i. In the event two-phase flow conditions and charge dissipation cannot be avoided with polyurethane foam, consider inerting systems or explosion suppressant materials more conductive than polyurethane (if available).

j. In cases where fuel is used as a heat sink for cooling and is recirculated, return the fuel to the fuel tanks under quiescent conditions at the bottom of the tank to prevent static generation or discharge.

k. Design the vent system to operate satisfactorily and to provide protection from static electricity and lightning strikes without the use of explosion suppression devices or explosion suppressant foams. Flame arrestors are acceptable for use provided they have been tested for adequacy of fuel flow and anti-icing characteristics.

l. When using *MIL-B-83054* reticulated foams for explosion suppression in fuel tanks, particular care should be taken to provide adequate clearances (voiding) around all fuel inlets (single point and gravity filler openings) to minimize or eliminate direct fuel impingement onto the foam surface. The action of fuel on a polyurethane foam matrix tends to generate static electricity and can result in incendiary discharges which can ignite the flammable fuel vapors. This static generation is especially prevalent with the blue polyether foams (Types IV and V) due to their high electrical resistivity values (10^{15} Ω·cm). Whenever these foams are used in fuel tanks, an electrostatic certification test should be conducted to demonstrate its electrostatic compatibility with the fuel system and low conductivity fuel (1 to 10 CU). Laboratory testing has also shown that extreme fuel sloshing in a reticulated foam matrix can also be a potential problem from an eletrostatic standpoint.

5. SOURCES OF INFORMATION

For additional information, contact the following activities:

a. Aircraft fuel systems, components, and foam:

ASD/ENFEF
Wright-Patterson AFB OH 45433
(513) 255-3451
AUTOVON 785-3451

b. Turbine fuels:

AFWAL/POSF
Wright-Patterson AFB OH 45433
(513) 255-5106
AUTOVON 785-5106

c. Static electricity, bonding, grounding:

ASD/ENACE
Wright-Patterson AFB OH 45433
(513) 255-5078
AUTOVON 785-5078

d. Static electricity:

AFWAL/POSH
Wright-Patterson AFB OH 45433
(513) 255-4208
AUTOVON 785-4208

SECT 7C LIGHTNING TESTING

SECTION 7C LIGHTNING TESTING

DESIGN NOTE 7C1* SIMULATED LIGHTNING WAVEFORMS FOR LABORATORY TESTING

1. PURPOSE

Complete natural lightning cannot be duplicated in the laboratory. Most of the voltage and current characteristics of lightning, however, can be duplicated separately by simulated lightning generators. These characteristics are of two broad categories: (1) the high voltages produced by the lightning and (2) the currents which flow in the completed lightning channel. In general, it is usually not necessary to simulate high voltage and high current characteristics simultaneously. The high voltage characteristics determine attachment points, breakdown paths and streamer effects, whereas the current characteristics determine the physical and electromagnetic effects. In most cases, lightning voltages are produced by high impedance voltage generators operating into high impedance loads, while lightning currents are produced by low impedance current generators operating into low impedance loads.

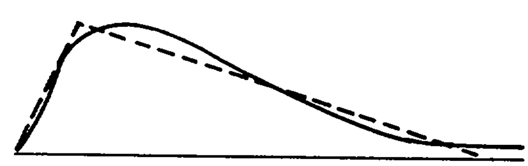
2. WAVEFORM DESCRIPTIONS

Lightning voltage and current waveforms, as described in the following paragraphs, have been developed for purposes of laboratory testing. The transient voltages and currents produced by simulated lightning generators are described by certain idealized waveforms which approximate the actual lightning characteristics. The most commonly encountered waveform is a double exponential waveform, as shown in *SN 2(1)*. Shown is both a physically realizable waveform (solid line) and a straight-line approximation (dotted line). The approximation is convenient for definition and analysis and is shown in subsequent waveform figures in this DN; it cannot, however, be generated by practical simulated lightning generators. The double exponential waveform can be generated and may have an undershoot as shown in *SN 2(1)*. An underdamped lightning generator can produce a damped oscillatory waveform, as shown in *SN 2(1)*. Waveforms for specific purposes are described in *DN 7A1*.

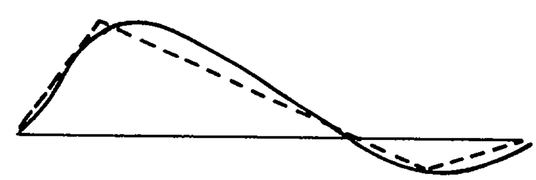
2.1 VOLTAGE WAVEFORMS

The basic voltage waveform to which vehicles are subjected is one that rises rapidly until the rise is interrupted either by puncture of solid insulation or flashover through the air or across an insulating surface. The path that the flashover takes, either puncture or surface flashover, depends on the rate of rise of the voltage as shown in *SN 2.1(1)*. During tests on model vehicles to determine possible attachment points, the length of gap used between the electrode simulating the approaching leader and the vehicle depends upon the model scale factor. During such tests it is desirable to allow the streamers from the model sufficient time to develop and this time should be the same for different model tests. Accordingly, for model tests it is necessary to standardize the time at which breakdown occurs, even though the rate of rise of voltage is different for different tests. During some types of testing it is necessary to determine the critical voltage amplitude at which breakdown occurs or does not occur. This critical voltage level depends upon both the rate of rise of voltage and the rate of voltage decay. Two examples are (1) determining the strength of the insulation used on electrical wiring and (2) determining the points from which electrical streamers occur on a vehicle as a lightning flash approaches. Voltage testing thus calls for three different standard voltage waveforms. These are shown in *SN 2.1(2)*.

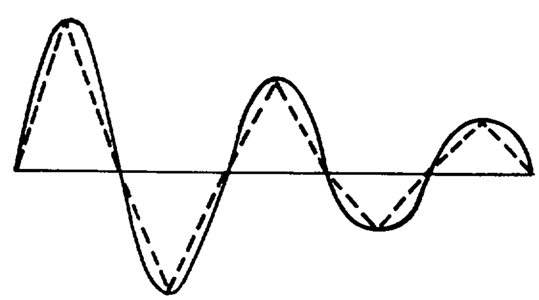
SUB-NOTE 2(1) Typical Simulated Lightning Current Waveforms



(a) Double Exponential Waveform



(b) Double Exponential Waveform With Undershoot



(c) Damped Oscillatory Waveform

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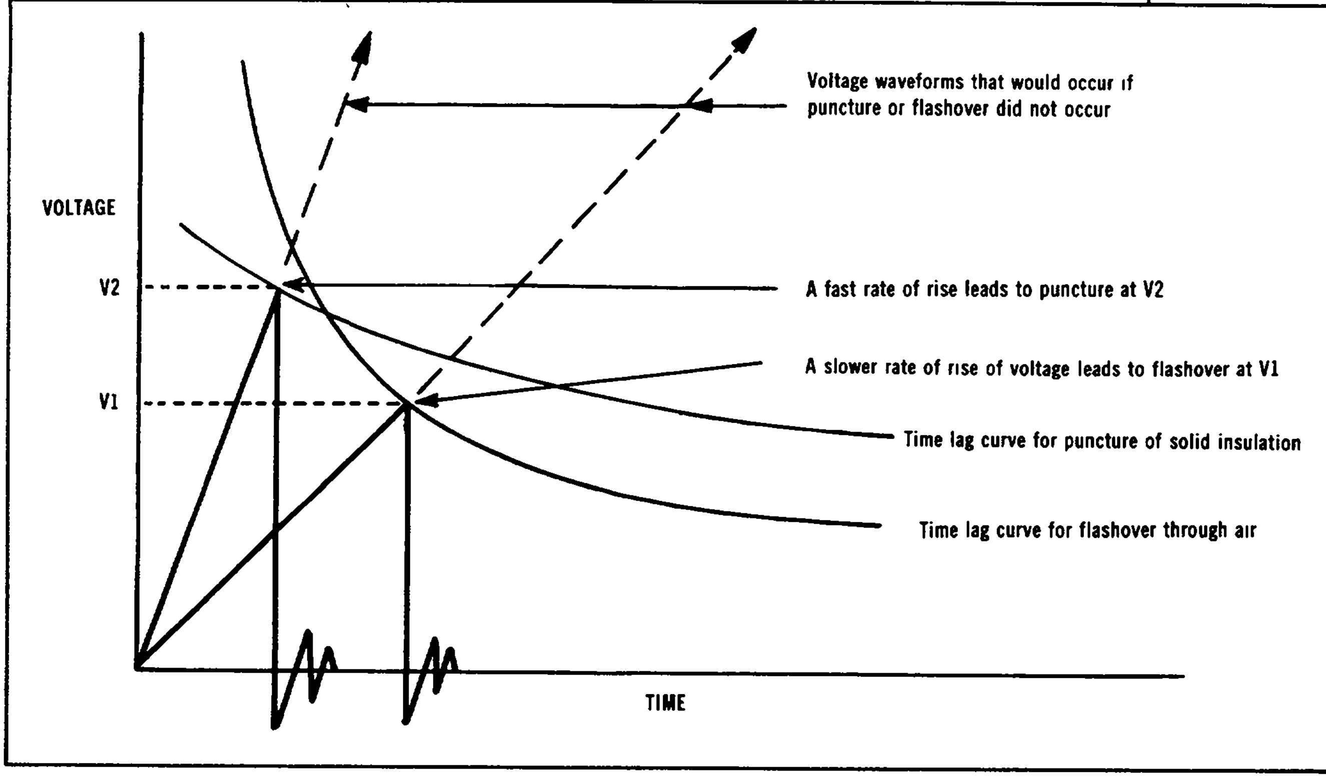
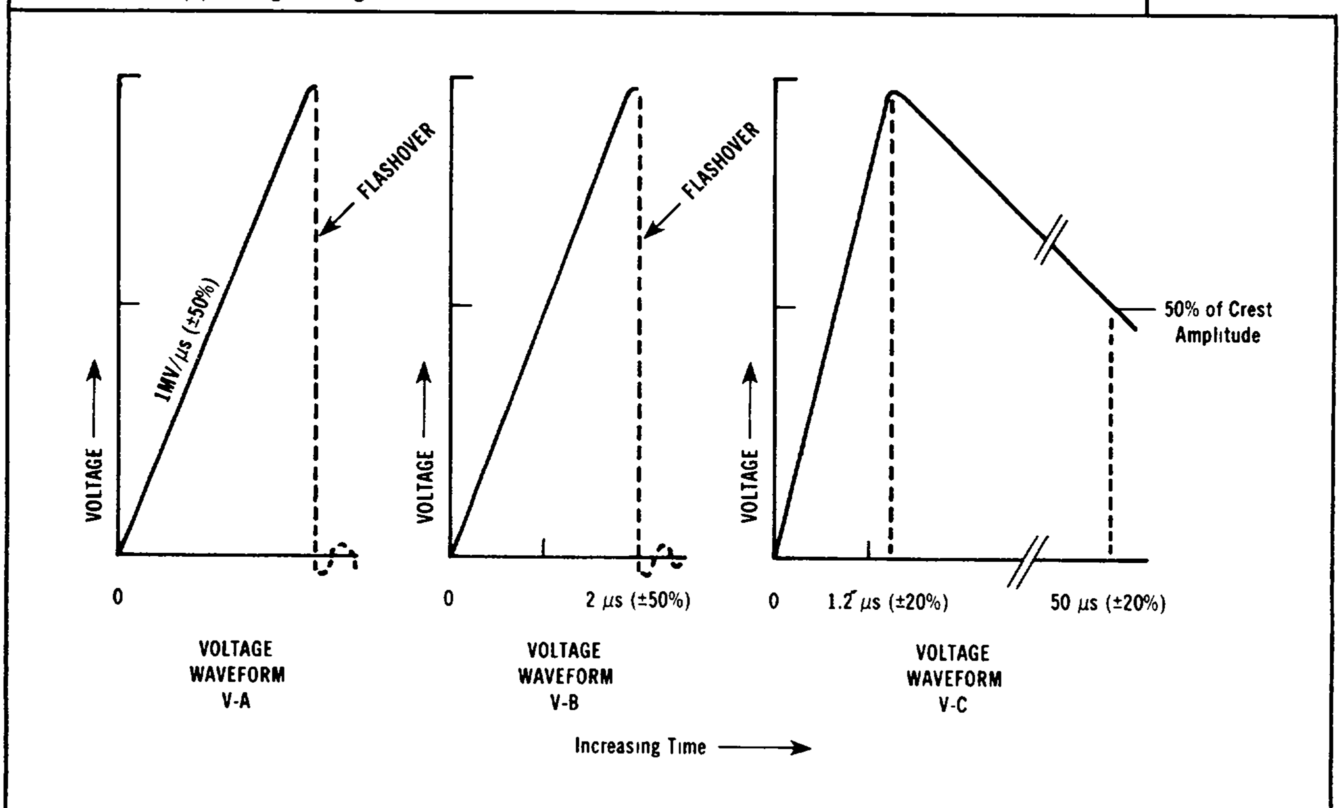
SUB-NOTE 2.1(1) Voltage Rate of Rise vs Flashover Path



SUB-NOTE 2.1(2) High Voltage Test Waveforms



2.1.1 VOLTAGE WAVEFORM V-A. This basic lightning waveform V-A rises at a rate of 1 MV/μs ($\pm$50%) until its increase is interrupted by puncture of or flashover across the object under test. At that time the voltage collapses to zero. The rate of voltage collapse or the decay time of the voltage if breakdown does not occur (open circuit voltage of the lightning voltage generator) is not specified. Voltage waveform V-A is shown on *SN 2.1(2).*

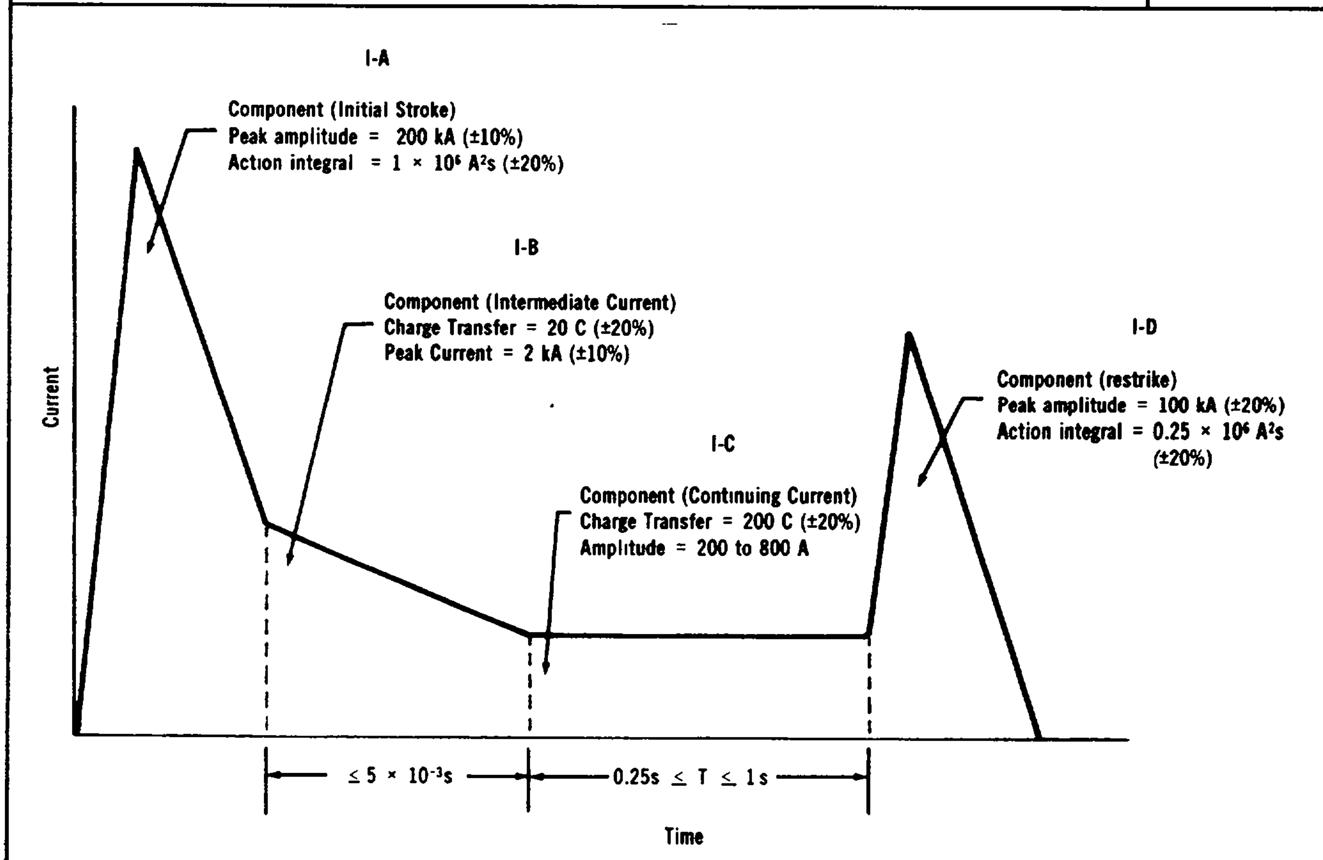
2.1.2 VOLTAGE WAVEFORM V-B. This model test waveform is a full voltage waveform V-B in which flashover of the gap between the model under test and the test electrodes occurs at 2 μs ($\pm$50%). The amplitude of the voltage at time of flashover and the rate of rise of voltage prior to breakdown are not specified. This waveform is shown in *SN 2.1(2).*

2.1.3 VOLTAGE WAVEFORM V-C. This (full wave) waveform V-C is a waveform which is the electrical industry standard for impulse dielectric tests. It raises to crest in 1.2 μs ($\pm$20%) and decays to half of crest amplitude in 50 μs ($\pm$20%). Time to crest and decay time refer to the open circuit voltage of the lightning voltage generator and assume that the waveform is not limited by puncture or flashover of the object under test. This waveform is shown in *SN 2.1(2).*

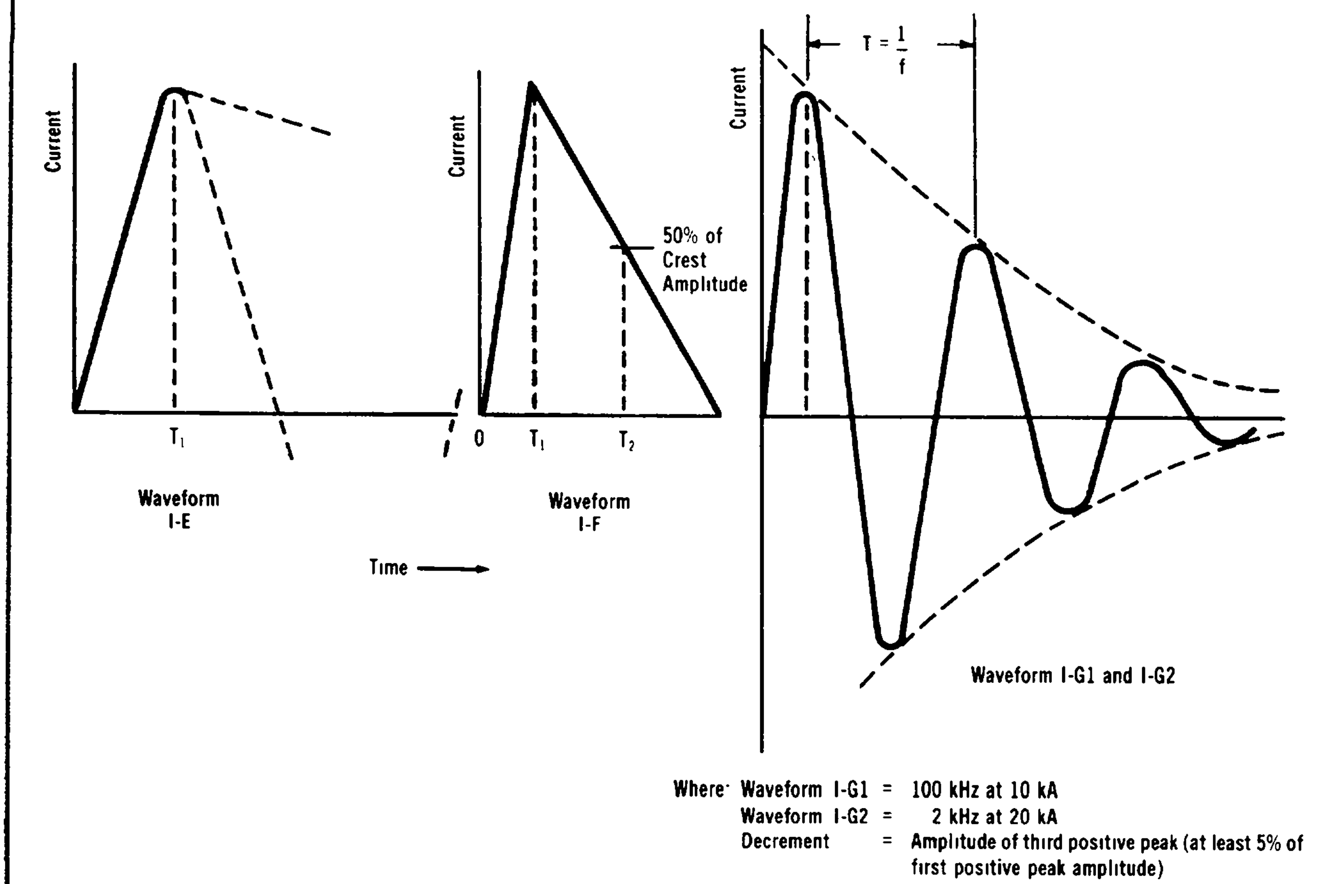
2.2 CURRENT WAVEFORMS

The current waveform components for qualification testing and evaluation of physical effects are shown in *SN 2.2(1)* and *SN 2.2(2).* There are four components, I-A, I-B, I-C, and I-D, used for determination of physical effects and three test waveforms, I-E, I-F, and I-G, used for determination of electromagnetic effects. Components I-A, I-B, I-C, and I-D each simulate a different characteristic of the current in natural lightning. They are applied individually or as a composite of two or more components together in one test. There are very few cases in which all four components must be applied in one test on the same test object. Rise time or rate of change of current has little effect on physical damage and, accordingly, has not been specified in these components. Components I-E, I-F, and I-G are each intended to determine the same type of electromagnetic effects though with different test techniques. When evaluating electromagnetic effects, rate of change of current is important and is specified.

SUB-NOTE 2.2(1) Current Test Waveform Components for Evaluation of Physical Effects



SUB-NOTE 2.2(2) Fast Rate of Change Current Waveforms for Evaluation of Electromagnetic Effects



2.2.1 COMPONENT I-A. This initial high peak current Component I-A simulates the first return stroke and is characterized by a peak amplitude of 200 kA (±20%) and an action integral ($\int I^2 dt$) of 1 x 10^6 A^2s (±20%). The actual waveshape of this component is purposely left undefined, since in laboratory simulation the waveshape is strongly influenced by the type of surge generator used and the characteristics of the device under test. Natural lightning currents are unidirectional, but for laboratory simulation this component may be either unidirectional or oscillatory.

2.2.2 COMPONENT I-B. This intermediate current Component I-B simulates the intermediate phase of a lightning flash in which currents of several thousand amperes flow for times on the order of several milliseconds. It is characterized by a current surge with a peak of 2 kA (±10%) flowing for a period of time to be determined from sweep-stroke tests.

2.2.3 COMPONENT I-C. This continuing current Component I-C simulates the continuing current that flows during the lightning flash and transfers most of the electrical charge. This component must transfer a charge of 200 C (±20%) in a time of between 0.25 and 1 second. This implies current amplitudes of between 200 and 800 A.

2.2.4 COMPONENT I-D. This restrike Component I-D simulates a subsequent high peak current. It is characterized by a peak amplitude of 100 kA (±20%) and an action integral of 0.25 x 10^6 A^2s (±20%).

2.2.5 WAVEFORM I-E. Component I-E simulates a full scale fast rate of rise stroke for testing vehicle hardware. It has a rate of rise of 50 kA/μs (±20%) and a minimum amplitude of 50 kA. An amplitude of 50 kA is used to enable testing of typical aircraft components with conventional laboratory lightning current generators. The action integral, fall time, and the rate of fall are not specified. If desired and feasible, components I-A or I-D may be applied with a 50–kA/μs rate of rise and the physical and electromagnetic effects evaluations conducted simultaneously. Electromagnetic effects measured as a result of this waveform must be extrapolated to the full lightning current amplitude of 200 kA.

2.2.6 WAVEFORM I-F. This reduced amplitude unidirectional Component I-F simulates, at a low current level, both the rise time and decay time of the initial high current peak of the lightning flash. It has a rise time of 2 μs ($\pm$20%), a decay time to half amplitude of 50 μs ($\pm$20%), and a minimum amplitude of 100 A. Electromagnetic effects measurements made with this component must be extrapolated to the full lightning current amplitude of 200 kA.

2.2.7 WAVEFORM I-G. Fast rate of rise current waveforms of higher amplitude than that possible with Component I-F can often be passed through complete vehicles if simulated lightning generators are operated without damping resistors. Damped oscillatory waveform Component I-G simulates with two different components (I-G1 and I-G2) an average amplitude lightning stroke. Two different components are necessary since aperture and diffusion coupling of electromagnetic fields into the interior of a vehicle is different at different frequencies. Component I-G1 has a minimum amplitude of 10 kA and a fundamental frequency of 100 kHz ($\pm$30%). Component I-G2 has a minimum amplitude of 20 kA and a fundamental frequency of 2 kHz ($\pm$30%). The decrement of the wave should be such that the amplitude of the fourth positive peak is at least 5% of the initial peak. Extrapolate measurements made with both of these waveforms to the 200 kA level.

3. REFERENCE

The ANSI and IEEE Standard Techniques for Dielectric Test, (*ANSI/IEEE Std 4-1969*) further defines basic waveform terminology and measurement techniques.

DESIGN NOTE 7C2* MODEL AIRCRAFT LIGHTNING ATTACHMENT POINT TEST

1. OBJECTIVE

This test is used to determine lightning attachment points on a model aircraft. These attachment points are primarily determined by the aircraft geometry and not by aircraft materials or surface finishes (see *DN 7A5*). Therefore, a practical test can be made on a scale model of the aircraft.

2. WAVEFORMS

Use voltage waveform V-B for testing model aircraft; see *DN 7C1, SN 2.1(2).*

3. TEST SETUP

Construct an accurate model of the vehicle exterior from 1/30 to 1/10 full scale. Also model possible vehicle configurations. Represent conducting surfaces on the circuit by conductive surfaces on the model, and vice versa. The model is then positioned on insulators between the electrodes of a rod-rod gap or the electrode and a ground plane of a rod-plane gap. Typically, the upper electrode and gap between that electrode and the vehicle is controlled in dimension and used to study the entry attachment point. The lower electrode and the gap between the lower electrode and the aircraft is typically left uncontrolled in dimensions and used to evaluate exit points. Ensure that the length of the upper gap is at least 1.5 times the longest dimension of the model. The direction of approach becomes less controllable at much higher ratios and the stroke may even miss the model. The lower gap may be the same length as the longest dimension of the model.

3.1 DIMENSION

Ideally, the model could be as large as the full-sized vehicle, but since the total length of the gap in which the model is tested may be about 2.5 times the longest dimension of the vehicle, a model of larger size may require such a long gap that the available voltage from the generator is not sufficient to cause flashover. While a smaller model requires less voltage from the generator, the results become more questionable since the processes of electrical breakdown cannot be linearly scaled. Results obtained from testing of a very small model would be questionable at best. In general a model 1/30 of full size is the smallest upon which a test should be made.

3.2 ROTATION

Commonly the electrodes are fixed and the model is rotated. Rotate the model through each of the three major axes (roll, pitch, and yaw) in steps not to exceed 30 degrees. Smaller steps may be used if greater resolution is desired. Typically 3 to 10 shots are taken with the aircraft in each orientation to simulate lightning areas approaching from different directions. Photographs, preferably with two cameras at right angles to each other, should be taken of each shot in order to determine the attachment points. Ensure that the upper electrode is positive with respect to ground and/or the lower electrode.

4. MEASUREMENTS AND DATA REQUIREMENTS

Measurements to be taken during this test include the following:

a. Test Voltage Amplitude and Waveform. The voltage applied to the gaps should be measured by a voltage divider and oscilloscope. Photograph the voltage waveform to verify that component V-B is in fact being applied. It is not necessary to take photographs of every test voltage waveform applied during the test sequence if the parameters of the lightning generator and length of the total air gap and model remain unchanged.

b. Attachment Points. Photograph each flashover from two viewpoints at right angles to each other to determine the actual attachment points.

c. Dimensions. Measure and record dimensions of the model and the length of the air gaps.

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DESIGN NOTE 7C3* FULL SIZE HARDWARE ATTACHMENT POINT TEST

1. OBJECTIVE

Conduct this attachment point test on full size hardware to determine the detailed attachment points on the external surface, and for nonmetallic surfaces the path taken by the lightning arc in reaching a metallic structure.

2. WAVEFORMS

Apply test voltage waveform V-A between the electrode and grounded test objects; see *DN 7C1, SN 2.2(2).*

3. TEST SETUP

See that the test object is a full scale production line hardware component or a representative prototype, since minor changes from design samples or prototypes may change the lightning test results. Ensure that all conducting objects within or on nonmetallic hardware which are normally connected to the vehicle when installed in the aircraft are electrically connected to ground (the return side of the lightning generator). Simulate surrounding external metallic vehicle structure and attach to the test object to make the entire test object look as much like the actual vehicle region under test as possible.

3.1 ORIENTATION

Position the test electrode to which test voltage is applied so that its tip is about 1 metre away from the nearest surface (either metallic or nonmetallic) of the test object. Dimensions of the test electrode are not critical. Since model tests and field experience have indicated that lightning can approach the object under test from several different directions, the test must be repeated with the high voltage electrode oriented to create strokes to the object from each of these different directions.

3.2 BREAKDOWN GAP

A 1–metre rod-plane gap will flash over at 1.3 MV after a 1 MV/μs rate of rise; however, exact voltage amplitude is left unspecified because it is dependent upon the other two parameters of gap length and rate of voltage rise. As long as rate of rise is specified, longer gaps will receive greater voltage and shorter gaps less, in accordance with the natural breakdown process. If the test object is so small that a 1–metre gap permits strokes to miss the test object or if a 1–metre gap is inappropriate for other reasons, shorter (or longer) gaps may be used. Apply multiple flashovers from each electrode position. Tests may be commenced with either positive or negative polarity. If test electrode positions are found from which the simulated lightning flashovers do not contact the test piece, or do not puncture it if it is nonmetallic, repeat the tests from these same electrode positions using the opposite polarity.

4. MEASUREMENTS AND DATA REQUIREMENTS

Measurements to be taken during these tests include the following:

a. Test Voltage Amplitude and Waveform. Measure the voltage applied to the gap by a voltage divider and oscilloscope. Photograph the voltage waveform to establish that waveform V-A is in fact being applied. If only attachment points on metallic surfaces are being evaluated, it is not necessary to take photographs of every test voltage waveform applied during a test sequence if the parameters of the lightning generator and the length of the gap to the test object remain unchanged.

b. When studying breakdown through nonmetallic test objects, however, voltage measurements should be made of each test voltage waveform applied since breakdown paths, and hence the test voltage, may change. Give particular attention to assuring that the gap flashes over on the wavefront (rise). If a flashover occurs on the wave tail, repeat the test with the generator set to provide a higher voltage or the test electrode positioned closer to the test object to produce flashover on the wavefront.

c. Attachment Points and/or Breakdown Paths. The voltage generators used for these tests are high impedance devices. The test current may be much less than natural lightning currents. Consequently, they will produce much less damage to the test object than natural lightning, even though the breakdown will follow the path a full scale lightning stroke current would follow. Occasionally a diligent search is required to find the attachment point on metals or the breakdown paths through nonmetallic materials. These attachment points or breakdown paths must be sought after each test and marked, when found, with masking tape or crayon markings to prevent confusion with further test results.

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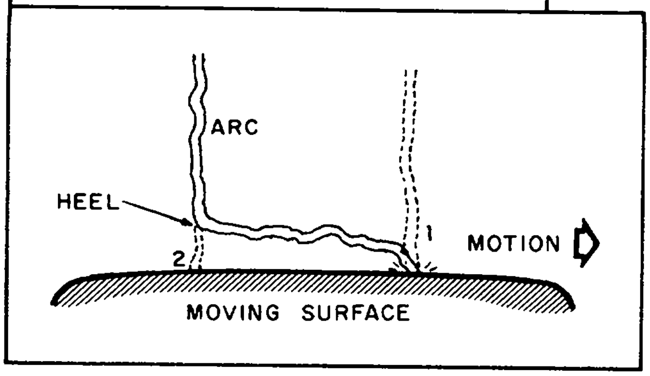
DESIGN NOTE 7C4* FULL SIZE HARDWARE SWEPT STROKE TEST

1. OBJECTIVE

In regions onto which a lightning arc may be swept by passage of the aircraft through the arc channel, the mechanisms of arc attachment are fundamentally different from those of direct strokes. The basic mechanism of attachment is shown in *SN 1(1)*. The arc first attaches to Point 1 and then, viewing the test object as stationary, is swept back along the surface to Point 2. When the heel of the arc is above Point 2 the voltage drop at the arc-metal interface is sufficiently high to cause flashover of the air gap and puncture of the surface finish at Point 2 causing it to reattach there. The arc will again be blown back along the surface until the voltage along the arc channel and arc-metal interface is sufficient to cause flashover and puncture at another point. The voltage at which each new attachment will occur depends strongly upon the surface finish of the object under test. The voltage available to cause puncture depends upon the current flowing in the arc and the degree of ionization in its channel. There is an inductive voltage rise along the arc as rapidly changing currents flow through it. There will also be a resistive voltage rise produced by the flow of current. The inductive voltage rise as well as the resistive rise can be quite significant when a lightning restrike occurs at some point in the flash.

SUB-NOTE 1(1) Basic Mechanism of Swept Stroke Attachment



1.1 DWELL TIME

In addition, if the flash is discontinuous for a brief period a very high voltage is available prior to flow of the next current component. Because the channel remains hot and may contain residual ionized particles, this voltage stress is greatest along it and subsequent current components are likely to flow along the same channel. Such a voltage may well be higher than voltages created by currents flowing in the channel and may cause reattachment to metallic surfaces or puncture of nonmetallic surfaces or dielectric coatings. Of interest besides the specific attachment points are the dwell times during which an arc may remain attached to any single point. The dwell time at one point is a function of the lightning arc and surface characteristics which govern reattachment to the next one. The dwell time is also a function of aircraft speed.

1.2 SWEPT STROKE ATTACHMENT POINT AND DWELL TIME

Swept stroke attachment point and dwell time phenomena are therefore of interest for two main reasons: First, if there is an intervening nonmetallic surface along the path over which the arc may be swept, the swept stroke phenomena will determine whether the nonmetallic surface might be punctured or whether the arc will pass harmlessly across it to the next metallic surface. Second, the dwell time of an arc on a metallic surface is a factor in determining if sufficient heating will occur at a dwell point to burn a hole or form a hot spot capable of igniting combustible mixtures or causing other damage. Thus, over a fuel tank it is particularly important that the arc move freely, in order that the metal skin of the tank not be heated or burned to a point that fuel vapors are ignited.

1.3 ATTACHMENT STUDIES

The objectives of attachment studies are then:

a. For metallic surfaces. To determine possible attachment points and associated dwell times.

b. For nonmetallic surfaces. To determine if punctures may occur.

2. WAVEFORMS AND TEST SETUPS

There are two basic methods of simulating swept stroke characteristics. One of these involves simulation of lightning currents and is most applicable for evaluation of dwell time phenomena on metallic surfaces. The other involves simulation of lightning voltages and is most applicable for evaluation of puncture of nonmetallic surfaces.

2.1 DWELL TIME TEST ON METALLIC SURFACES

In this technique usually the test object is stationary and the arc is moved across the surface by a laminar air

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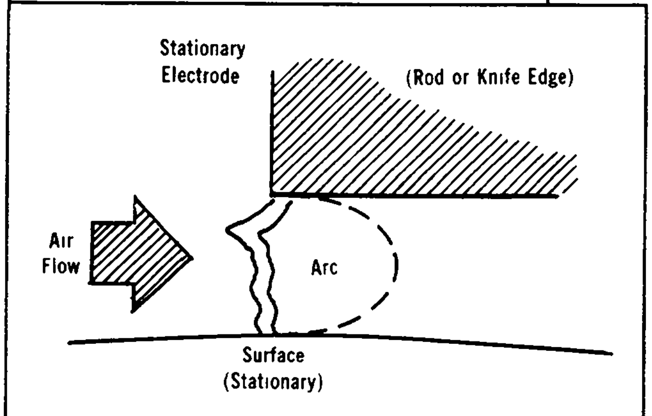
stream. The elements of this technique are shown in *SN 2.1(1)*. Important parameters for this type of test include the air flow velocity, test current amplitude and waveshape, and the length of time for which the current flows. Air flow velocity is typically on the order of 75 m/s. While this is lower than full velocity for some aircraft, it is in the range of vehicle take-off and landing velocities, when the dwell-time condition is most critical.

SUB-NOTE 2.1(1) Typical Setup for Dwell Time Tests on Metallic Surfaces



2.1.1 SIMULATED CONTINUING CURRENT. The simulated continuing current should have an amplitude averaging about 300 A over the time required for the ionized channel to sweep over the surface of the test object. The waveform may be either rectangular or exponential. The duration of current flow is:

$T_{duration}$ = surface length/velocity of airflow

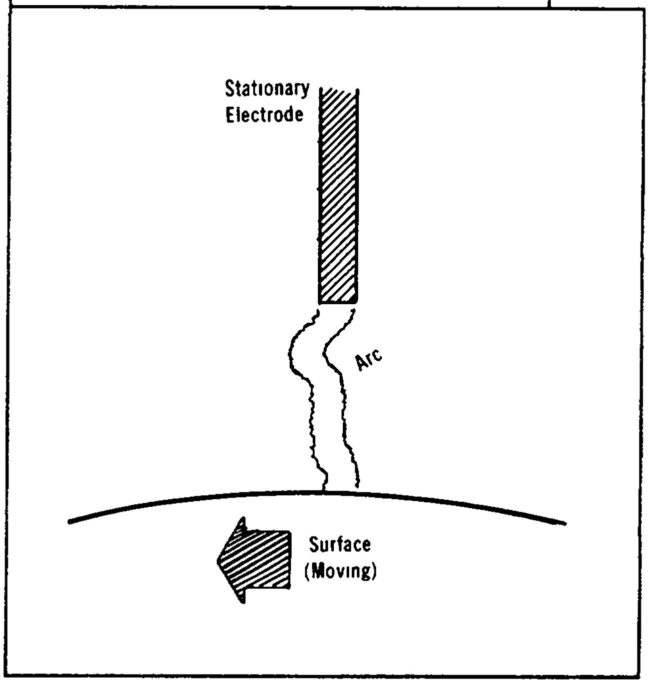
The current generator driving voltage must be sufficient to maintain an arc length that moves freely in the air flow. The test electrode should be a rod parallel to the air stream and approximately parallel to the test object.

2.1.2 RESTRIKE. A restrike may be added to the continuing current after initiation to determine whether a restrike with its associated high current amplitude would cause reattachment to points other than those to which the continuing current arc would reattach. If a restrike is used it is most appropriate that it be the fast rate of change of current waveform shown as component I-E. See *DN7C1, SN2.2(1)*.

2.2 PUNCTURE TESTS OF NONMETALLIC SURFACES

In this technique usually the test object is fastened to a moving vehicle and moved through stationary arcs. The elements of this technique are shown in *SN2.2(1)*. Higher voltages and longer arc lengths, typically 2 metres, are required for this technique. The test voltage is usually supplied by high voltage 60-Hz test transformers. The voltage is applied via a suspended electrode and its amplitude set so that no flashover occurs until the moving test object partially closes the gap beneath it, initiating nonsustained flashovers once or more for each positive polarity half cycle. Thus, multiple high voltage arcs are applied approximately once every 16 ms, approximately the separation of discontinuities in typical lightning. The current amplitudes are relatively low, a few amperes rms. The velocity (m/s) with which the test object is moved should be as close to flight conditions as possible.

SUB-NOTE 2.2(1) Typical Setup for Puncture Tests of Nonmetallic Surfaces



3. MEASUREMENTS AND DATA REQUIREMENTS

The most important measurements to make are those giving the attachment points, arc dwell times, breakdown paths followed, and the separation between attachment points. These are most easily determined from high speed motion picture photographs of the arc. Also make measurements of the air flow or test object velocity and the amplitude and waveform of the current passing through the test object.

DESIGN NOTE 7C5* PHYSICAL EFFECTS—STRUCTURAL

1. OBJECTIVE

These tests determine the direct effects which lightning currents may produce in structures.

2. WAVEFORMS

Tests of objects located in segments 1B, 2A, 2B and 3 require application of multiple waveform components in one discharge; see *DN 7A5, Para 3.1*. Apply one or more of the simulated lightning current waveform components of *DN 7C1, SN 2.2(1)*, depending on the vehicle zone of the test object, as follows:

2.1 SEGMENT 1A

Apply Waveform Component I-A.

2.2 SEGMENT 1B

Apply Waveform Components I-A and I-D in order.

2.3 SEGMENT 2A

Apply Waveform Components I-B and I-D in order. Determine the dwell time for Component I-B from a previously run attachment point test, as described in *DN 7C4* for metallic or nonmetallic surfaces. Set Component I-B generator timing mechanism to permit current to flow into the test object (at any single point) for the maximum dwell time at that point as determined from the attachment point test. Directly follow Component I-B by Component I-D.

2.4 SEGMENT 2B

Apply Waveform Components I-C and I-D in order.

2.5 SEGMENT 3

Apply Waveform Components I-A and I-C, in this order, to components in surface segment 3, where there is low probability of any arc attachment but through which lightning currents may flow from one attachment point on the aircraft to another. Thus, conduct these test currents into and out of the test object in a manner similar to the way lightning currents would flow through them in the aircraft.

3. TEST SETUP

The test currents are normally delivered to the test object from a test electrode positioned adjacent to it. The test object is usually grounded to the return side of the generator(s) so that test current can flow through the object in a realistic manner.

3.1 TEST ELECTRODES

The electrode material should be a good electrical conductor with ability to resist the erosion produced by the test currents involved. Yellow brass, steel, tungsten and carbon are suitable electrode materials. The shape of the electrode is usually a rounded rod firmly affixed to the generator output terminal and spaced a fixed distance above the surface of the test object.

3.2 TEST GAP

If a blunt electrode is used with a very small gap, the gas pressure and shock wave effects in the confined area may cause more physical damage than would otherwise be produced. Therefore, keep the gap spacing as great as the output voltage capabilities of the generator(s) will allow and round the electrode to allow relief of the pressure formed by the discharge. A gap spacing of 10 mm is recommended.

3.3 MULTIPLE COMPONENT TESTS

For multiple component tests, place the test electrode as far from the test object surface as the driving voltage of the intermediate Component I-B or continuing current Component I-C will allow. When these components are preceeded by the high peak current Component I-A, the high driving voltage of this generator initiates the arc and subsequent components (I-B and/or I-C) follow the established arc even though driven by a much lower voltage.

3.4 POLARITY

The polarity of the high peak Current I-A and restrike I-D components can be either positive or negative. Set the polarity of the I-B and I-C component generator(s) so that the electrode is negative with respect to the test object, because greater damage is generally produced when the test object is at positive polarity with respect to the test electrode.

4. MEASUREMENTS AND DATA REQUIREMENTS

Measurements to be made during these tests are TEST CURRENT AMPLITUDE(s) AND WAVEFORM(s). Initial stroke, restrike and intermediate current components may be measured with noninductive resistive

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shunts, current transformers or Rogowski coils. Continuing currents may be measured with resistive shunts. Measure the output of each of these devices on a suitable oscilloscope; record by photography of the oscilloscope trace. Since the condition of the test object or other parts of the test circuit may affect the test current(s) applied, make oscillographic measurements of these parameters during each test applied.

DESIGN NOTE 7C6*

PHYSICAL EFFECTS— COMBUSTIBLE VAPOR IGNITION

1. OBJECTIVE

The objective of these tests is to determine the possibility of combustible vapor ignition as a result of skin or component puncture, formation of hot spots or arcing in or near fuel systems or other regions where combustible vapors may exist. CAUTION: These are the possible physical effects which may cause ignition. Ignition of combustible vapors may also be caused by lightning electromagnetic effects such as induced voltages in fuel probe wiring, etc.

2. WAVEFORMS

Apply the same test current waveforms as are specified for structural damage tests in *DN 7C5*.

3. TEST SETUP

Test setup requirements are the same as those described in *DN 7C5* for structural damage tests with the following additional considerations:

a. To determine if ignition may occur, a maximum combustible mixture (e.g., for propane: Place a 1.2 stoichiometric mixture in the test chamber in contact with the test object (e.g., skin sample, access door or filler cap)). This can be a mixture of propane and air or vaporized samples of the appropriate fuel mixed with air.

b. If a complete fuel tank is not available or is impractical for testing, obtain a sample of the tank skin or other test object and fasten over an opening or chamber inside of which the combustible mixture can be inserted. Fasten the test object to the chamber securely and electrically bonded so that no sparking may occur across this bond when lightning current is delivered to the test object. If access doors and filler caps are tested on such a chamber, it is important that the door or cap and its customary adapter or receptacle also be installed in the test chamber in a production-like manner, since the resulting interface is a possible source of sparking in the aircraft. The test chamber must be connected to the return side of the lightning current generator.

c. Obtain verification of the combustibility of the mixture by ignition of it with a spark or corona ignition source introduced into the test chamber immediately after each lightning test in which no ignition occurred. If the combustible mixture was not ignitable by this artificial source, the lightning test must be considered invalid and repeated with a new mixture until either the lightning test or artificial ignition source ignites the fuel.

4. MEASUREMENTS AND DATA REQUIREMENTS

Make the same current measurements as are specified for structural damage tests in *DN 7C5*. Ignition of the combustible mixture will serve as the major diagnostic measurement to evaluate potential sources of ignition; however, more specialized instrumentation may also be added if additional information such as skin surface temperatures, pressure rises, or flame front propagation velocities are desired. If it is impossible or impractical to use a combustible mixture, the presence of an ignition source may be determined by photography of possible sparking. For this purpose a camera is mounted inside the test chamber. Seal off all light to the chamber interior and open the shutter to *f*/4.7 aperture. Any light indications on the film due to internal sparking after test should be taken as an indication of sparking sufficient to ignite a combustible mixture. CAUTION: Utilize this method of determining the possibility of sparking only if certainty exists that all locations where sparking might exist are visible to the camera.

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DESIGN NOTE 7C7* PHYSICAL EFFECTS—APERTURE STREAMERS

1. OBJECTIVE

The objective of this test is to determine the possibility of combustible vapor ignition as a result of high voltage streamering at apertures where combustible vapors may exist.

2. WAVEFORMS

Apply test voltage waveform V-C for this test; see *DN 7C1, SN 2.2(2)*. The crest voltage should be sufficient to produce streamering, but not sufficient to cause flashover in the high voltage gap.

3. TEST SETUP

If the electric field strength about an aperture exceeds the ionization potential of air, corona and streamering will occur at the edges. Such an opening may be a fuel vent where the possibility of igniting fuel vapor due to streamering exists. Therefore, the test object should be mounted in a suitable fixture representative of the surrounding region of the airframe and subjected to the high voltage waveform. The voltage may be applied either by (1) grounding the test object and arranging the high voltage test electrode sufficiently close to the test object to create the required field at the test voltage level applied or (2) connecting the test object to the high voltage output of the generator and arranging the test object in proximity to a ground plane or other ground electrode which is connected to the ground (low) side of the generator. Either arrangement can provide the necessary electric field at the test object aperture. The test object should be at positive polarity with respect to ground, since this polarity usually provides the most profuse streamering.

4. MEASUREMENTS AND DATA REQUIREMENTS

Measurements should include: TEST WAVEFORM and AMPLITUDE; DESCRIPTIONS OF TEST OBJECT and ELECTRODE PLACEMENT; and INTENSITY and LOCATION OF STREAMERING. The presence of streamering at locations where combustible vapors are known to exist may be considered as an ignition source. The presence of streamering can best be determined with photography of the test object while in a darkened area. If combustible vapor presence at an aperture is questionable, run the test with a combustible mixture actually present in the test object to determine if ignition occurs. Ensure that the test arrangement simulates relevant operational (i.e. in-flight) characteristics.

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DESIGN NOTE 7C8* PHYSICAL EFFECTS— EXTERNAL ELECTRICAL COMPONENTS

1. OBJECTIVE

The objective of this test is to determine the amount of physical damage which may be experienced by externally mounted electrical components, such as pitot tubes, antennas, navigation lights, etc., when directly struck by lightning.

2. WAVEFORMS, TEST SETUP, AND MEASUREMENTS AND DATA REQUIREMENTS

The waveforms, test setup, and measurements and data requirements are the same as for the structures tests described in *DN 7C5*.

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DESIGN NOTE 7C9*

ELECTROMAGNETIC EFFECTS—EXTERNAL ELECTRICAL HARDWARE

1. OBJECTIVE

The objective of this test is to determine the effects which occur when lightning strikes externally mounted electrical hardware, such as an antenna, electrically heated pitot tube or navigation light. For such hardware the possible effects include conducted currents and surge voltages and induced voltages. These currents and voltages may then be conducted via electrical circuits to other systems in the vehicle. Therefore, during the physical effects tests of electrical hardware mounted within surface segments 1 and 2, measurements should be made of the voltage appearing at all electrical circuit terminals of the component. In addition, make a high di/dt test to cause the most severe voltages to be induced in the component's electrical circuits.

2. WAVEFORMS

Apply current waveform components specified in *DN 7C5* for electromagnetic effects measurements. In addition, a test should be made in which the fast rate of rise current waveform Component I-E is applied (see *DN 7C1, SN 2.2(2)*). Waveform I-E amplitude is specified at 50 kA; however, if higher amplitudes can be generated, the test should be run at the highest amplitude possible (up to 200 kA). The measured induced voltages are then scaled upward by a factor determined by: 200/test kA.

3. TEST SETUP

Mount the test object on a shielded test chamber so that access to its electrical connector(s) can be obtained in an area relatively free from extraneous electromagnetic fields. This is necessary to prevent electromagnetic interference originating in the lightning test circuit from interfering with measurement of voltages induced in the test object itself. The test object should be fastened to the aircraft, since normal bonding impedances may contribute to the voltages induced in circuits within the test. If the shielded enclosure is large enough, the measurement oscilloscope may be contained within it. If not, a suitably shielded instrument cable may be used to transfer the induced voltage signal from the shielded enclosure to the oscilloscope. In this case, the oscilloscope itself is located so as not to experience interference.

3.1 ELECTRODE POSITION

Position the test electrode so as to inject simulated lightning current into the test object at the probable attachment point(s) expected from natural lightning. For tests run concurrently with physical effects tests on the same test object, this should be an arc-entry (flashover from test electrode to test object) but for tests made solely to determine the electromagnetic effects, hard-wired connections can be made between the generator output and test object. This is appropriate especially if it is desired to minimize physical damage to the test object. Ground the test object via the shielded enclosure so that simulated lightning current flows from the test object to the shielded enclosure in a manner representative of the actual installation.

4. MEASUREMENTS AND DATA REQUIREMENTS

Include measurements for test current amplitude(s) and waveform(s) as specified for the physical effects tests utilizing the same waveforms in *DN 7C5*. In addition, measure conducted and induced voltages at the electrical circuit terminals in the test object.

4.1 TEST OSCILLOSCOPE

Measure voltages appearing at the electrical terminals of the test object with a cathode ray oscillograph having a horizontal sweep rate of 10 mm/μs or faster and vertical deflection sensitivity adequate to measure all the induced voltage. Since most general purpose oscilloscope and preamplifier combinations permit maximum vertical deflections of only 100 V or so, a voltage attenuator network or voltage divider must be utilized to reduce the induced voltage to a level compatible with the oscilloscope vertical deflection sensitivity. If this is done, assure that the divider or attenuator has adequate response time and provides a faithful reproduction of the induced voltage at its low (oscilloscope) side. Also, this device must itself be free from electromagnetic interference originating in the test circuit. Special purpose, high voltage surge test oscilloscopes which can accept higher signal voltages are available, and their use is recommended.

REO· ASD/ENACE
*Contributed by SAE Committee AE-4 on Electromagnetic Compatibility

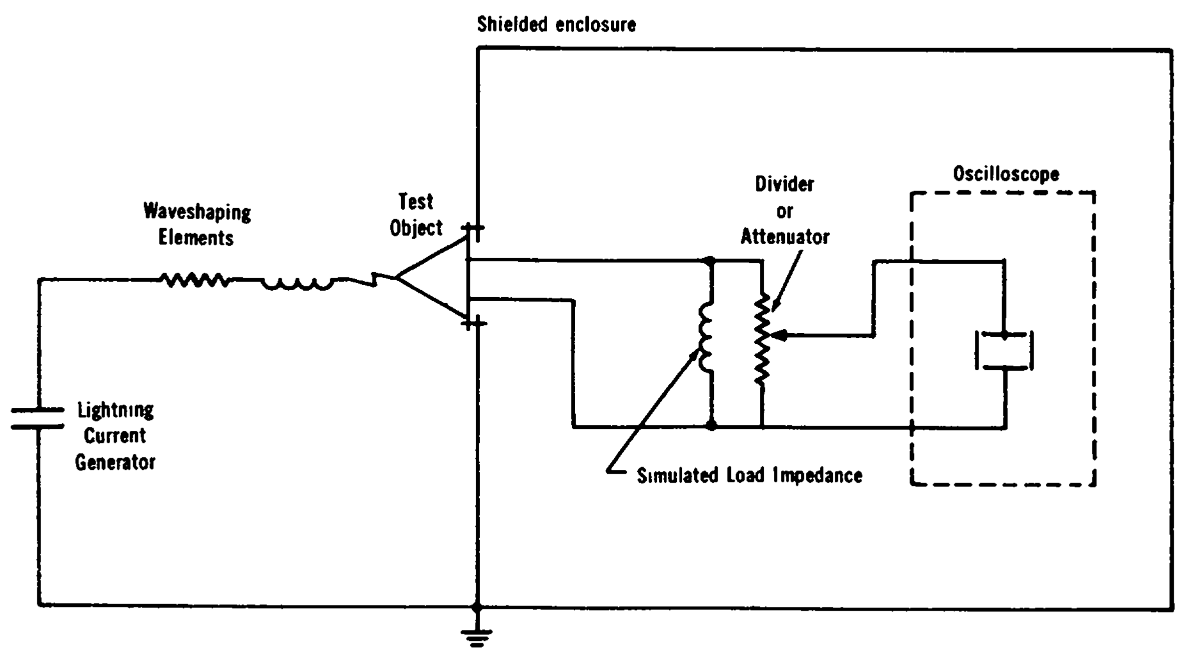
4.2 IMPEDANCE

Since the amount of induced voltage originating in the test object which can enter interconnected systems such as a power bus or an antenna coupler depends partly on the impedances of these items, these impedances should be simulated and connected across the electrical terminals of the test object where the induced voltage is being measured.

4.3 OPEN AND SHORT CIRCUITED TEST

Verify interference-free operation of the voltage measurement system by measurement of voltage with the test object disconnected and the measurement system terminals open circuited and then short circuited, at the vicinity of the test object. In neither case should the oscilloscope vertical deflection be more than 5% of any induced voltage subsequently measured with the test object connected. The resistance, inductance and capacitance of the load impedance should be included. A typical test and measurement circuit is shown in *SN 4.3(1)*.

SUB-NOTE 4.3(1) Typical Electrical Induced Voltage Test and Measurement Circuit



DESIGN NOTE 7C10* ELECTROMAGNETIC EFFECTS—AIRCRAFT

1. OBJECTIVE

The objective of this test is to determine the level of induced voltages and currents in electrical and avionics systems within a complete aircraft. When lightning currents flow through a vehicle, fields are created which couple transient voltages into internal electrical wiring. Even if the vehicle is metallic, its complex geometry and finite structural resistivity result in hazardous voltages being induced into vehicle wiring systems; as a result, upset and major damage has occurred to vehicle electrical and avionics components. Transient voltage protection devices are available which protect against such effects, but before they can be applied it is usually necessary to determine the level of voltage induced in particular circuits. This requires a test in which simulated lightning currents are passed through the complete aircraft.

2. WAVEFORMS

Two techniques, utilizing different waveforms, may be utilized to perform this test:

a. One involves application of a scaled down unidirectional waveform representative of a natural lightning stroke. No existing laboratory facilities are capable of passing full scale simulated lightning currents through an airframe using unidirectional waveshapes representative of natural lightning stroke currents. Also full scale test currents, even if possible, might damage on-board equipment. Accordingly, tests can be made with a unidirectional current representative of a natural lightning stroke waveform but with reduced amplitude. Measured induced voltages and currents resulting from such a waveform are then extrapolated to full scale (200 kA) levels.†

b. The second technique involves performance of the test with two or more damped oscillatory current waveforms, one of which (a high frequency waveform) provides the fast rate of rise characteristic of a natural lightning stroke wavefront, and the other (a low frequency waveform) provides a long duration period characteristic of natural lightning stroke duration. In the latter case, induced voltages should be measured in the aircraft circuits when exposed to both waveforms and the highest induced voltages taken as the test results. Use of damped oscillatory test current waveforms usually permits the generator(s) to provide higher test current amplitudes. These are possible with unidirectional waveforms but not usually as high as 200 kA. Therefore, the results must again be extrapolated to correspond with a 200-kA stroke amplitude.†

2.1 COMPLETE VEHICLE TESTING

Complete vehicle tests are intended primarily to identify systems incompatibility problems which may operate properly by themselves, but which may fail when the complete vehicle is subject to lightning currents. For example, redundant systems may provide no redundancy when simultaneously affected by the same induced voltages. Testing of complete vehicles with average lightning current amplitudes (20 kA) provides an overall systems check which gives greater confidence in the reliable operation in the thunderstorm environment of a vehicle with flight critical electronic systems. These tests are usually carried out after lightning protection development tests have been performed on the vehicle individual hardware located at direct or swept stroke points. Each test is carried out by applying test currents to the complete vehicle and measuring the induced voltages and currents. Checks are also made of systems and equipment operations where possible. Therefore, tests can be carried out with systems inoperative, but are preferably carried out with systems operating. Each of these test methods is discussed in the following paragraphs.

2.2 UNIDIRECTIONAL TEST WAVEFORM

Apply waveform I-F: see *DN 7C1, SN 2.2(1).*

2.3 OSCILLATORY WAVEFORMS

Apply waveforms I-G1 and I-G2; see *DN 7C1, SN 2.2(2).*

3. TEST SETUP

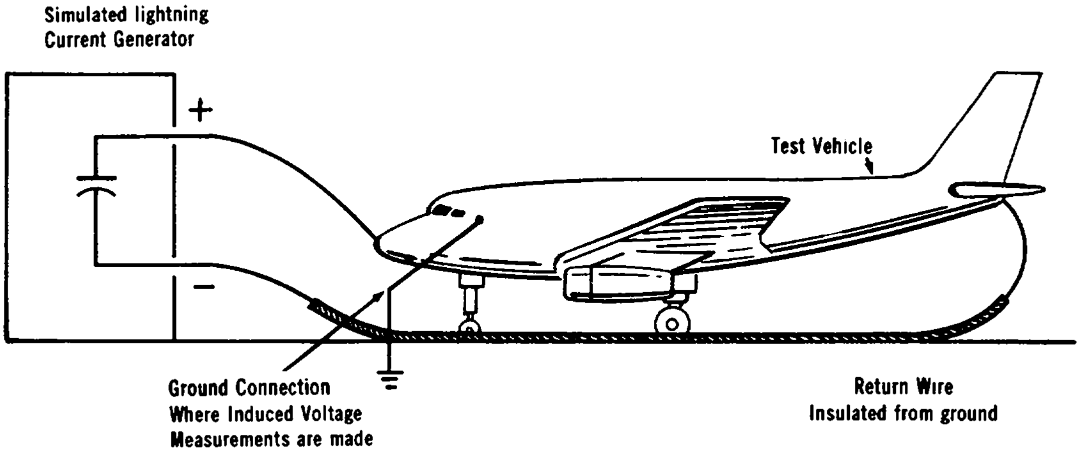
Generator connections to the vehicle are made at probable attachment points determined by previous attachment point tests or field experience. Since lightning strikes occur randomly at different attachment points, the test current should be applied between several representative pairs of attachment points such as nose-to-tail or wing tip-to-wing tip. Typical test setups are shown in *SN 3(1).*

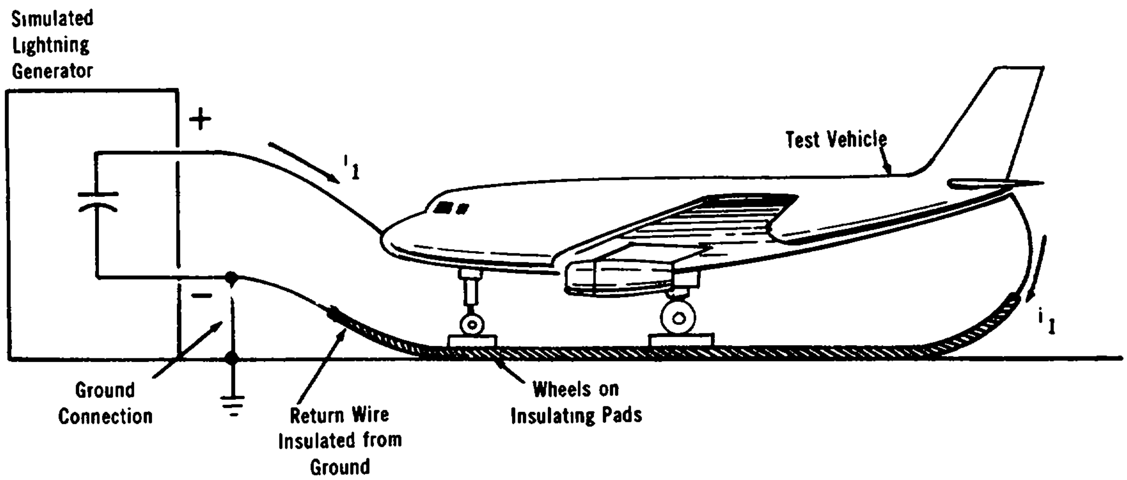
REQ._ ASD/ENACE

*Contributed by SAE Committee AE-4 on Electromagnetic Compatibility

†Test results using extrapolation techniques have been found to be generally invalid These tests are not recommended at this time

SUB-NOTE 3(1) Typical Test Setups for Complete Vehicle Tests





4. MEASUREMENTS AND DATA REQUIREMENTS

Measure the test current amplitude, waveform, and resulting induced voltages in the aircraft electrical and avionics systems. Verify by measurement of voltage with the instrument cable disconnected from the aircraft circuit and its terminals open-circuited and then short-circuited at the aircraft end, for interference free operation of the voltage measurement system. In most cases the induced voltages resulting from the low-amplitude test currents may be extrapolated linearly to correspond with lightning current amplitudes of 200 kA.† Situations exist, however, where full scale current may cause arcing paths, resulting in nonlinear relationships to induced voltages. Careful study of the vehicle under test, however, can usually identify such situations. When testing fueled vehicles, care should be taken to prevent sparks across filler caps, as even low amplitude currents can cause sparking across poor bonds or joints. In doubtful situations, fuel tanks should be rendered nonflammable by nitrogen inerting.

†Test results using extrapolation techniques have been found to be generally invalid These tests are not recommended at this time

APPENDIX A1 ABBREVIATIONS

A

A	ampere (unit symbol—current); absorption loss
ac	alternating current
af	audio frequency
AFB	Air Force base
AFC	automatic frequency control
AFCMO	Air Force Contract Management Office
AFEMCP	Air Force Electromagnetic Compatibility Program
afi	audio frequency interference
AFM	Air Force Manual
AFPRO	Air Force Plant Representative Office
AFR	Air Force Regulation
AFSC	Air Force Systems Command
AGC	automatic gain control
AM	amplitude modulation
ANSI	American National Standards Institute
ASCC	Air Standardization Coordinating Committee
ASD	Aeronautical Systems Division
ATACAP	Antenna-to-Antenna Compatibility Analysis Program
AVC	automatic volume control
AVGAS	aviation gasoline
AWG	American wire gauge

B

BC	broadcasting
BL	butt-line
BTBCAP	Box-to-Box Compatibility Analysis Program (a computer program)

C

C	quantity symbol-capacitance; unit symbol-coulomb
°C	degree Celsius
CDC	Control Data Corporation
CDRL	Control Data Requirements List
CR	capacitance—resistance
CU	conductivity units
CW	continuous wave

D

dB	decibel
dBmW	decibels above or below one milliwatt
dc	direct current
DH	Design Handbook
dia	diameter
DID	data item description
di/dt	derivative—change of current with respect to time
DN	design note
DOD	Department of Defense
DSARC	Defense Systems Acquisitions Review Council
DTIC	Defense Technical Information Center

E

E	electromotive force or voltage (symbol in formulas)
E field	electric field
E^3	electromagnetic environment effects
ECCM	electromagnetic counter countermeasures
ECM	electronic countermeasures
ECP	Engineering Change Proposal
EED	electroexplosive device
EEI	electroexplosive initiator
EHF	extremely high frequency
EIA	Electronic Industries Association
EM	electromagnetic
EMC	electromagnetic compatibility
EMCAB	Electromagnetic Compatibility Advisory Board
EMCP	Electromagnetic Compatibility Plan
EME	electromagnetic environment
emf	electromotive force
EMI	electromagnetic interference
EMI&S	Electromagnetic Interference and Susceptibility
EMP	electromagnetic pulse
EMR	electromagnetic radiation
EMV	electromagnetic vulnerability
Eq	equation

F

F	farad (unit symbol—capacitance); frequency (in formulas)
f	frequency
°F	degree Fahrenheit
FAR	Federal Aviation Administration Regulations
FCC	Federal Communications Commission
FET	field-effect transistor
FM	frequency modulation
FS	fuselage station
ft/s	feet per second
FTWCAP	Field-to-Wire Compatibility Analysis Program

G

GEN	generator
GHz	gigahertz
GPO	Government Printing Office
GS	glide slope

H

H	henry (unit symbol—inductance)
H field	magnetic field strength
HERF	hazards of electromagnetic radiation to fuels
HERO	hazards of electromagnetic radiation to ordnance
HERP	hazards of electromagnetic radiation to personnel
HF	high frequency
Hz	hertz (cycles per second)

I

I	current (in formulas)
IC	integrated circuit
ICBM	intercontinental ballistic missile
IDIPR	Input Decode and Initial Processing Routine (a computer program)
IDR	Input Decode Routine (a computer program)
IEEE	Institute of Electrical and Electronics Engineers
IEMCAP	Intrasystem Electromagnetic Compatibility Analysis Program (a computer program)
IF	intermediate frequency
IFB	Invitation for Bid
IFF	identification friend or foe
IL	insertion loss
IM	intermodulation
in.	inch
IPP-1	Interference Prediction Process (a computer program)
IPR	Initial Processing Routine (a computer program)
i/s	interruptions per second
IR	infrared; current times resistance
IRD	incidental radiation devices
ISF	Intrasystem File
ISM	industrial, scientific, and medical equipment
ITU	International Telecommunications Union

K

K	correction factor for thin material (a constant)
kA	kiloampere
kH_z	kilohertz
km	kilometer
kV	kilovolt
kW	kilowatt

L

lb	pounds
lbf/in.^{2}	pound force per square inch
LC	inductance-capacitance
LED	light-emitting diode
LF	low frequency
LISN	line impedance stabilization network
LO	local oscillator
LOC	localizer
LORAN	long range navigation
LR, L/R	inductance—resistance

M

MAS	Military Agency for Standardization
max	maximum
mC	millicoulomb
MF	medium frequency, microfiche
MHz	megahertz
mi/h	miles per hour
mil	thousandth of an inch
ms	millisecond
MV	megavolt
mW	milliwatt
MW	megawatt
mw	microwave
μ	mu, twelfth letter of Greek alphabet
μA	microampere
μF	microfarad
μs	microsecond
μV	microvolt

N

NAA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NFPA	National Fire Protection Agency
ns	nanosecond
NTIA	National Telecommunication and Information Administration

O

Ω	ohms (unit symbol—resistance)
OD	outside diameter

P

Para	paragraph
PCB	printed current board
pF	picofarad
PPI	plan position indicator
ppm	parts per million
pps	pulse per second
PRF	pulse repetition frequency
PSTAT	Precipitation Static Analysis Program (a computer program)
P-static	precipitation static

Q

Q	quality factor

R

R	resistance (symbols in formulas)
RADC	Rome Air Development Center
RADHAZ	radiation hazards to personnel
R&D	research and development
RC	resistance-capacitance
ref	reference
REO	Responsible Engineering Office
RF	radio frequency
RFI	radio frequency interference
RFP	Request for Proposal
r/min	revolution per minute
rms	root mean square
RRD	restricted radiation devices

S

SAE	Society of Automotive Engineers
SCR	silicon control rectifier
SE	shielding effectiveness
SHF	super high frequency
SI	International System of Units
SIG	signal
SN	sub-note
S/N	signal-to-noise ratio
SOW	statement of work
SSB	single sideband
STANAG	NATO Standardization Agreements

T

TART	Task Analysis Routine (a computer program)
TACAN	tactical air navigation
TEM	Transverse Electromagnetic Wave
TEMP	Test and Evaluation Master Plan
TEMPEST	short name referring to investigation and studies of compromising emanations
TEP	Test and Evaluation Plan
TF	transition frequency
TR	transmit-receive
TV	television

U

UHF	ultra high frequency
USAF	United States Air Force

V

V	volt
VHF	very high frequency
VLF	very low frequency
VOR	VHF omnirange
VSWR	voltage standing wave ratio
VTVM	vacuum tube volt meter

W

W	watts (unit symbol—power)
WL	waterline
WTWCAP	Wire-to-Wire Compatibility Analysis Program (a computer program)

X

X	reactance

Z

Z	impedance (in formulas)

APPENDIX A2 GLOSSARY

The various documents used as a basis for definition of common engineering terms throughout the AFSC Design Handbook series include:

a. Webster's Third New International Dictionary
G & C Merriam Co. Publishers
Springfield MA 01101

b. Aerospace Glossary
Research Studies Institute
Air University
Maxwell AFB AL 36112

c. The United States Air Force Dictionary
Research Studies Institute
Air University
Maxwell AFB AL 36112

d. Dictionary of Technical Terms for Aerospace Use
National Aeronautics and Space Administration (NASA)
Scientific & Technical Information Facility
P O Box 8757
Baltimore MD 21240

e. Dictionary of Military and Associated Terms
JCS Pub 1
Joint Chiefs of Staff Publication
The Joint Chiefs of Staff
Washington DC 20301

f. US Air Force Glossary of Standardized Terms
AFM 11-1, Vol I

g. Communications Electronics Terminology
AFM 11-1, Vol III

h. Glossary of Communications Security and Emanations Security Terms (*For Official Use Only*)
USCSB 2-17

i. Air Force Manual of Abbreviations
AFM 11-2

j. Standard for Metric Practice
ANSI/ASTM E380-79
American Society for Testing and Materials
1916 Race St.
Philadelphia PA 19103

k. Dictionary of Scientific and Technical Terms
McGraw-Hill Book Company, 1974

A

absorption—1. Loss of energy, due to conversion into heat or other forms, in the transmission of waves over radio or wire paths. 2. 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.

arc—Discharge of electricity through a gas, normally characterized by a voltage drop approximately equal to the ionization potential of the gas.

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. (*NAVAIR 5335*)

B

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. (*MIL-STD-188*)

bonding—In electrical engineering, the process of connecting together metal parts so that they make low resistance electrical contact for direct current and lower frequency alternating current. (*NATO*)

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

broadband interference—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 bandwidth 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. (*NAVAIR 5335*)

C

cable—Assembly of one or more conductors, usually within an enveloping protective sheath, in such structural arrangement of the individual conductors as will permit their use separately or in groups.

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

coaxial cable—A transmission line consisting of one conductor, usually a small copper tube or wire within and insulated from another conductor of larger diameter, usually tubing or copper braid. The outer conductor may or may not be grounded. Coaxial cable is sometimes called concentric line or coaxial line. (*NAVAIR 5335*)

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.

corona—Luminous discharge due to ionization of the air surrounding a conductor around which exists a voltage gradient exceeding a certain critical value.

cosmic noise—Radio static, the origin of which is due to sources outside the earth's atmosphere. The source may be similar to sunspots, or spots on other stars.

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

D

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.

direct current convertor—A device for converting direct current at one voltage to direct current at another voltage. (*NATO*)

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.

E

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. (*NATO*)

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. (*MIL-STD-1512*)

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. (*MIL-STD-1512*)

electroexplosive subsystem (EES)—The term EES is intended to include all components required to perform control, monitor, and initiation of an electrical initiated ordnance/pyrotechnic function. (*MIL-STD-1512*)

electromagnetic compatibility (EMC)—The condition which prevails when telecommunications, electrical or electromechanical equipment, or subsystems are performing their individually designed functions in a common electromagnetic environment without causing or suffering unacceptable degradation due to EMI or from other subsystems or equipment in the same environment.

electromagnetic interference (EMI)—Electromagnetic energy which interrupts, obstructs, or otherwise degrades or limits the effective performance of telecommunications equipment or subsystems.

electromagnetic pulse—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. (DOD)

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, equipment include, but are not limited to the following: receivers, transmitters, transceivers, transponders, power supplies, electrical office machines, hand tools, processors, test apparatus and instruments, and material handling equipment.

extraterrestrial noise—Cosmic and solar noise; radio disturbances from sources other than those related to the earth.

F

ferrite—Magnetic material made of a wide variety of ceramic ferromagnetic materials.

fiber optics—Thin fibers which transmit light by a process of total reflection, clustered together into bundles of flexible cables or bonded into rods. The ends are bonded, ground, and polished. Fiber optics will transmit light and light impulses efficiently around curves and into otherwise inaccessible places.

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

frequency changer—A device for converting alternating current at one frequency to alternating current at another frequency. (*NATO*)

G

galactic noise—All noise that originates in space due to radiation of all celestial bodies except the sun.

galvanic corrosion—Galvanic corrosion is 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. (*NATO*)

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

H

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. (*NAVAIR5335*)

harmonic distortion—Nonlinear distortion characterized by the appearance in the output of harmonics other than the fundamental component when the input is sinusoidal. (*NAVAIR 5335*)

hum—1. In audiofrequency systems, a low-pitched droning noise, usually composed of several harmonically related frequencies, resulting from an alternating-current power supply, from ripple from a direct-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. 2. In facsimile, a pattern produced on the record sheet due to powerline frequency or harmonics of the powerline frequency mixing with the facsimile signal or modulating the facsimile signal.

I

identification, friend or foe (IFF)—A system using radar transmissions to which equipment carried by friendly forces automatically responds; for example, by emitting pulses, thereby distinguishing themselves from enemy forces. It is the primary method of determining the friendly or unfriendly character of aircraft and ships by other aircraft or ships and by ground forces employing radar detection equipment and associated identification, friend or foe units.

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 characterized by nonoverlapping transient disturbance. The same source may produce impulse noise in one system and random noise in a different system.)

inductive coupling—1. 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.) 2. 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—1. At a given frequency, the insertion loss of a feedthrough 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:

$$\text{Insertion loss} = 20 \log \frac{E_1}{E_2}$$

Where:

E_1 = The output voltage on 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. (*MIL-STD-220*)

2. 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). 3. The ratio of received powers before and after the insertion of shielding between a source and a receiver of electromagnetic energy. (*NAVAIR 5335*)

interface—Common boundary between two components, systems, or phases.

interference—1. Electrical disturbance that causes undesirable responses in electronic equipment. 2. 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 degraded performance. Interference is sometimes spoken of as the current or power that causes noise in the telephone. 3. 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. (*MIL-STD-463*)

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. (*NAVAIR 5335*)

intersystem interference—Interference between systems. A lack of system-to-system electromagnetic compatibility. (*NAVAIR 5335*)

intrasystem interference—Interference and resultant performance degradation confined within the physical and EM bounds of a single system. (*NAVAIR 5335*)

inverter—In electrical engineering, a device for converting direct current into alternating current. (*NATO*)

L

lossy line—1. Cable used in test measurements which has a large attenuation per unit length. 2. Transmission line designed to have a high degree of attenuation.

M

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.

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

manmade noise—High-frequency noise signals, created by sparking in an electric circuit. When picked up by a radio receiver, it causes 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 Systeme International d'Unités (SI)" of the International Bureau of Weights and Measures. These units are described in *ANSI/ASTM E 380-79* or successor documents as listed in the DOD Index of Specifications and Standards.

N

noise—1. 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. 2. Unwanted energy (or the voltage produced), usually of random character, present in a transmission system due to any cause.

noise factor—1. Ratio of actual output signal-to-noise ratio to the output signal-to-noise ratio in the absence of internally generated noise. 2. Of a transducer, the ratio of actual output noise to that which would remain if the transducer itself were made noiseless. 3. Of a linear system at a selected input frequency, the ratio of: the total noise power per unit bandwidth at a corresponding output frequency available at the output terminals; and to the portion thereof engendered at the input frequency by the input termination, whose noise temperature is standard (290 K) at all frequencies. Also called noise figure.

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

O

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

P

photon noise—Noise caused by the fluctuation in the rate at which photons fall on an infrared detector. The spectrum of this energy is flat and follows the response curve of the detector.

plane wave—A wave in which the wave fronts are everywhere parallel planes normal to the direction of propagation. (*NAVAIR 5335*)

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. (*NAVAIR 5335*)

pulse—A variation of a quantity whose value is normally constant (not necessarily zero); this variation is characterized by a rise and decay and has a finite duration. (*NAVAIR 5335*)

Q

Q—The figure of merit of efficiency of a circuit or coil. Numerically it is the ratio of the inductive reactance to the resistance of the circuit or coil: $Q = X/R$. (*NAVAIR 5335*)

R

random (or fluctuation) noise—Noise characterized by a large number of overlapping transient disturbances occurring at random. It is characterized by a peak-to-average noise level ratio in the order of 4 : 3 to 5 : 4. This is a type of broadband noise. Thermal and shot noise are typical examples. (*NAVAIR 5335*)

rectifier—A device for converting alternating current into direct current. (*NATO*)

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. (*NAVAIR 5335*)

return wire—Ground wire, common wire, or the negative wire of a dc circuit.

S

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.

shield—A shield is a conducting enclosure surrounding a source of interference or a susceptible circuit, designed to reduce the radiation of interference or to prevent a susceptible circuit from being affected by interfering signals. (*NAVAIR 5335*)

shielding effectiveness—The ratio, usually expressed in decibels, of noise or induced current or voltage in a system element when a source of shielding is present, to the corresponding quantity when the shielding is absent. (*NAVAIR 5335*)

shot noise—Noise voltages developed in a thermionic tube by the random variations in the quantity and velocity of electrons emitted by the cathode. The effect is characterized by a steady hiss in audio reproduction, and by snow or grass in video reproduction.

signal-to-noise ratio—The ratio of the value of the signal to that of the noise. This 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. (See *DN 1A2.*)

spike—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. (*MIL-STD-463*)

spurious response—Any response of an electronic device to energy outside its designed reception bandwidth through its intended input terminal. (*MIL-STD-463*)

static—1. Interference caused by natural electrical disturbances in the atmosphere, or the electromagnetic phenomena capable of causing such interference. 2. Noise heard in a radio receiver caused by electrical disturbances in the atmosphere, such as lightning, northern lights, etc.

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. (*NAVAIR 5335*)

susceptibility—The characteristic of electronic equipment that permits undesirable responses when subjected to electromagnetic energy. (*MIL-STD-463*)

system—A composite of equipment, subsystems, 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. (EMC requirements for aerospace and weapon systems are included in *MIL-E-6051*; EMC requirements for space systems are included in *MIL-STD-1541* and *MIL-STD-1542*.)

T

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—1. Noise voltage generated in resistors due to minute currents caused by thermal motions of the conduction electrons. 2. Random noise in a circuit associated with the thermodynamic interchange of energy necessary to maintain thermal equilibrium between the circuit and its surroundings. Also called resistance noise.

transient—1. A physical disturbance, intermediate, to two steady-state conditions. 2. Pertaining to rapid change. 3. A buildup or breakdown in the intensity of a phenomenon until a steady-state condition is reached. The time rate of change of energy is finite and some form of energy storage is usually involved. 4. A momentary surge on a signal or power line. May produce fake signals or triggering impulses. (*NAVAIR 5335*)

V

VHF omnirange (VOR)—Standard 200-W omnirange operating within the radio-frequency band of 112 to 118 MHz.

W

white noise—A sound or electromagnetic wave whose spectrum is continuous and uniform as a function of frequency. (*NAVAIR 5335*)

APPENDIX A3 METRIC CONVERSION FACTORS

CONVERT FROM	MULTIPLY BY	TO OBTAIN UNITS IN
Circular mils	5.067 075 E-4	mm^2
°F	°C = 5/9 (°F-32)	°C
ft	0.3048	m
ft/s	0.3048	m/s
in.	25.4	mm
in.	0.0254	M
$in.^2$	645.16	mm^2
mil	0.0254	mm
lb	0.453 592 4	kg
$lbf/in.^2$	6894.757	Pa
mi/hr	1.609344	km/hr
$A/in.^2$	1550	A/m^2

APPENDIX B — REFERENCE SOURCES

1. DEPARTMENT OF DEFENSE SOURCES

1.1 DEPARTMENT OF DEFENSE INDEX OF SPECIFICATIONS AND STANDARDS

Many documents referenced in Design Handbooks are listed in the *Department of Defense Index of Specifications and Standards (DODISS)*. These include unclassified federal, military, and departmental specifications, standards, and related standardization documents including industry standardization documents officially adopted by the Department of Defense. Air Force-Navy Aeronautical Bulletins, Military Bulletins, USAF Specification Bulletins, and International Standardization Documents are also included. Procedures for obtaining listed publications are contained in the *DODISS*. Obtain information on interdepartmental distribution of the *DODISS* from:

a. Department of Defense:

Commanding Officer
Naval Publications and Forms Center (NPFC)
ATTN: Code 105
5801 Tabor Ave
Philadelphia PA 19120-5002

b. Government civil agencies and nongovernment activities (subscription basis only):

Superintendent of Documents
US Government Printing Office
Washington DC 20402-0001

Specifications and standards officially adopted by DOD and referenced in the Design Handbooks are available from the appropriate association listed in *SN 1.1(1)*.

1.2 DATA ITEM DESCRIPTIONS

Data Item Descriptions (DIDs) are indexed in *DOD 5000.19-L, Vol II* (supersedes *DOD ADL, TD-3)*, and may be obtained from the Naval Publications and Forms Center (NPFC), 5801 Tabor Ave, Philadelphia PA 19120-5002.

1.3 REGULATIONS, MANUALS, AND PAMPHLETS

Air Force regulations, manuals, and pamphlets are obtained by DOD organizations through their regular publication channels. These documents generally are not available for distribution to nongovernment organizations. However, if a specific regulation, manual, or pamphlet is needed to comply with Air Force requirements, obtain it through a US Government Procurement Contracting Officer; from the Superintendent of Documents, US Government Printing Office, Washington DC 20402-0001; Air Force Publications Distribution Center (AFPDC), 2800 Eastern Boulevard, Baltimore MD 21220-2898; or from the office of primary responsibility (OPR).

1.4 HANDBOOKS

Handbooks are distributed as follows:

a. Federal and Department of Defense handbooks are available to government organizations through their regular publication channels. Nongovernment organizations may obtain them from their US Government Procurement Contracting Officer or from the Superintendent of Documents, US Government Printing Office, Washington DC 20402-0001.

b. Military handbooks are procured from the Naval Publications and Forms Center (NPFC), 5801 Tabor Ave, Philadelphia PA 19120-5002.

c. AFSC Design Handbooks are available from ASD/ENES, Wright-Patterson AFB OH 45433-6503, (513) 255-6281 or AV 785-6281.

1.5 USAF STANDARD DRAWINGS

USAF Standard Drawings are available from 4950 TESTW/AMDD. Wright-Patterson AFB OH 45433-5000, (513) 257-7171 or AV 787-7171.

1.6 AF TECHNICAL ORDERS

Air Force organizations obtain Technical Orders (TO) through their Base TO Distribution Office. Other government agencies submit requests for TOs to Oklahoma City ALC/MMEDT, Tinker AFB OK 73145-5000. Industrial organizations with US Government contracts may obtain TOs to fulfill contract requirements through their US Government Procurement Contracting Officer.

SUB-NOTE 1.1(1) Sources of Specifications and Standards*

SPECIFICATION OR STANDARD	MAY BE OBTAINED FROM
Aerospace Materials Specifications† Society of Automotive Engineers Standards Publications	Society of Automotive Engineers, Inc 400 Commonwealth Dr Warrendale PA 15096-0001
American National Standards Institute Standards † International Electrotechnical Commission Recommendations	American National Standards Institute, Inc 1430 Broadway New York NY 10018-3363
American Society for Testing and Materials Standards †	American Society for Testing and Materials 1916 Race St Philadelphia PA 19103-1187
American Welding Society Standards†	American Welding Society, Inc 2501 NW 7th St Miami FL 33125-3136
National Aeronautics and Space Administration Specifications and Standards	NASA Scientific and Technical Information Facility PO Box 8757 Baltimore MD 21240-8757 (301) 859-5300 or the specific NASA Center
National Aerospace Standards †	Aerospace Industrial Association of America 1725 DeSales St NW Washington DC 20036-4406
Air Force-Navy Aeronautical Design Standards † Air Force-Navy Aeronautical Standards† Federal Specifications† Federal Standards † Military Specifications† Military Standards †	Naval Publications and Forms Center (NPFC) 5801 Tabor Ave Philadelphia PA 19120-5002 AUTOVON 442-3321 (215) 697-3321
National Fire Protection Association Standards	National Fire Protection Association Battery March Pk Quincy MA 02269-9101

* For reference abbreviations, see *DN 1A2, SN 7.2.1(1)*.
† Listed in *DODISS*. See *Para 1.1*.

2. OTHER GOVERNMENT SOURCES

2.1 NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA) PUBLICATIONS

NASA Procedures are obtained by qualified users from NASA Scientific and Technical Information Facility, PO Box 8757, Baltimore MD 21240-0600. Others may purchase copies from National Technical Information Service (NTIS), 5285 Port Royal Rd, Springfield VA 22151-2171.

2.2 FEDERAL AVIATION ADMINISTRATION (FAA) PUBLICATIONS

Federal Aviation Administration Regulations (FAR) are available from the Superintendent of Documents, US Government Printing Office (GPO), Washington DC 20402-0001, or Department of Transportation (DOT), Federal Aviation Administration (FAA), 800 Independence Ave SW, Washington DC 20591. FAA Advisory Circulars are obtained from the DOT, FAA.

2.3 NATIONAL BUREAU OF STANDARDS (NBS) INDEX

Standardization documents developed by industry are listed in *An Index of US Voluntary Engineering Standards* prepared by the National Bureau of Standards (NBS). This publication is available from the Superintendent of Documents, US Government Printing Office, Washington DC 20402-0001, or from local US Department of Commerce Field Offices. A microfiche copy may be ordered as *NBS Spec Publ 329* from the National Technical Information Service (NTIS), 5285 Port Royal Rd, Springfield VA 22151-2171.

2.4 NATIONAL TECHNICAL INFORMATION SERVICE (NTIS) DISTRIBUTION

NTIS acts as the billing agent for Defense Technical Information Center (DTIC). If you have an NTIS deposit account, you can place orders for technical reports directly with Defense Technical Information Center (DTIC), Cameron Station, Alexandria VA 22304-6145; charges are deducted from your deposit account automatically. Since NTIS operates on a cost-recovery basis, its prices are higher than DTIC's prices. For classified reports, DTIC's price is charged but these orders are accumulated at NTIS and forwarded to DTIC on computer tapes for determination of requester eligibility and eventual shipment. DTIC's determination is then sent back to NTIS. If the response is affirmative, DTIC supplies the report. These steps delay the user's receipt of needed reports. The exception to this policy is that a DTIC-registered user without a deposit account must order limited reports directly from DTIC using DTIC Form 55. If document release is approved, the requester will be billed, after shipment, for the cost of the report plus handling to the address specified.

2.4.1 HOW TO ESTABLISH A DEPOSIT ACCOUNT WITH NTIS. Send $25 (or enough to cover your first order if that amount is in excess of $25) to NTIS Deposit Account, 5285 Port Royal Rd, Springfield VA 22151-2171. You can obtain a deposit account application from the NTIS Customer Services Office at (703) 487-4770 or you may contact DTIC's Registration and Services Section at (202) 274-6871.

a. Once your account is established, call DTIC's Registration and Services Section.

(1) Give them your DTIC-assigned user code and the deposit account number which NTIS has assigned. DTIC can then begin to process your orders for technical reports.

(2) Keep at least $25 on deposit at NTIS or enough to cover 2 months' charges to ensure your orders are processed. After your deposit account is established, you may deposit any amount with NTIS prior to ordering.

(3) You will receive monthly statements both from NTIS and from DTIC. The NTIS statement will show charges, deposits, balances. DTIC's statement will show specific products which you have received.

NOTE: Do not send payment of any kind to DTIC. Send all money directly to NTIS.

b. NTIS ORDERING OPTIONS

(1) You may order by telephone, (703) 487-4650 or through TELEX 89-9405, if you have an NTIS Deposit Account, American Express, MasterCard, or VISA.

(2) If you're in a hurry, call NTIS Express or Rush Service (800) 336-4700. Orders will be processed within 24 hours. Express guarantees overnight courier delivery for a service charge of $20 per item. Rush guarantees First Class or equivalent delivery for a service charge of $10 per item. You may also arrange to pick up your order in Springfield VA or Washington DC for a service charge of $7.50 per item.

NOTE: Prices and cost of services tend to change and may be obtained by phoning (800) 336-4700.

2.5 DEFENSE TECHNICAL INFORMATION CENTER (DTIC) DISTRIBUTIONS

Technical reports at DTIC, Cameron Station, Alexandria VA 22304-6145, are distributed in accordance with the security level, need-to-know, and assigned distribution limitation of the reports.

a. Classified technical reports have their dissemination restricted because of security clearance and need-to-know controls. Classified reports which have no additional distribution limitation are available to registered DTIC users who are certified to receive classified information (for contractors this involves completion of DD Form 15141, Facility Clearance Register) and who have need-to-know in subject areas into which the reports fall.

b. Limited technical reports have been marked by their Department of Defense (DoD) controlling office with a distribution statement that confines release to certain categories of requesters (e.g., U.S. Government agencies only). Limited reports may be either classified or unclassified. Requesters who do not meet the limitation criteria may request the report through DTIC following the procedures outlined in *Para 2.5.1*.

c. Export-controlled technical reports are unclassified reports which contain technical data that disclose critical technology with military or space application in the possession of, or under the control of the Department of Defense. Such technical data may not be exported lawfully without an approval, authorization, or license under U.S. export control laws.

d. Unclassified/unlimited technical reports are reports which have been approved for public release.

2.5.1 HOW TO ORDER A TECHNICAL REPORT. DTIC technical reports are available either in hard copy or on microfiche. Registered DTIC users may participate in the Automatic Document Distribution (ADD) Program and receive biweekly shipments of selected documents on microfiche.

a. Technical Reports (TR) without distribution limitations:

(1) Users with National Technical Information Service (NTIS) deposit accounts can order technical reports directly from DTIC via telephone, letter, or DTIC Form 1, Document Request.

(2) Users without deposit accounts must order from NTIS. These users will be charged NTIS prices.

b. Technical Reports with distribution limitations. Use DTIC Form 55, Request for Limited Document, to request these documents. Send all DTIC Forms 55 directly to DTIC. DTIC will validate the request and forward it to the controlling office for release determination.

c. Export-controlled Technical Reports. These TRs are available to nongovernment users who have submitted to DTIC a copy of their DD Form 2345, Militarily Critical Technical Data Agreement, approved by the Defense Logistics Services Center (DLSC), Battle Creek MI. Contact the Registration and Services Section, DTIC-FDRB, (202) 274-6985, for more information.

2.5.2 DTIC PRICING SYSTEM. DTIC has a variable pricing system for hard copies of technical reports ordered from the DTIC collection. There is a charge of $5.00 for technical reports containing 100 pages or less and $.07 for each additional page over 100 pages. Microfiche rates are $.95 per demand document and $.35 per document supplied under the Automatic Document Distribution (ADD) program.

NOTE: Prices and cost of services tend to change. See *para 2.5.4* for telephone information.

2.5.3 DTIC BIBLIOGRAPHIES. As a related function within the technical report program, DTIC provides three bibliography services free to its registered user community.

a. CURRENT AWARENESS BIBLIOGRAPHIES: This service matches subject interest profile against newly accessioned documents in order to provide efficient, customized, automated bibliographies based on the recurring needs of DTIC users. These bibliographies are prepared and shipped every two weeks.

b. DEMAND (REPORT) BIBLIOGRAPHIES: These bibliographies are prepared in response to individual requests for references to technical reports which cover a particular subject. The requester describes the area of interest and specifies the time coverage of the search. The product is a computer printout containing descriptions and abstracts of documents in the collection which are most pertinent to his problem or project.

c. DIRECT RESPONSE BIBLIOGRAPHIES: This service provides a list of AD numbers which meet a specific information request received by telephone, telegram, mailgram, letter, or through the Telex Telecommunications System at Headquarters Defense Logistic Agency (DLA). DTIC's response is via telephone or Telex. The response time for this free service is 24 hours.

2.5.4 IMPORTANT TELEPHONE NUMBERS FOR DTIC USERS. Outside the Washington metropolitan area, dial Area Code 202. For an AUTOVON call, prefix the extension with 284.

Current Awareness Bibliography Service	274-7206
Demand (Report) Bibliography Service	274-6867
Direct Response Bibliography Service	274-6867
Document Identification	274-7633
Limited Document Requests	274-6985
Orders for Documents	274-7633
Problems with Orders (including missent documents/ unreadable copies)	274-7633
24-Hour Ordering Service (Recorder)	274-6811
Registration and Services Section	274-6985

2.6 HOW TO GET IT

HOW TO GET IT is a reference document developed by the Institute for Defense Analysis in cooperation with the Defense Technical Information Center (DTIC). This document is intended to assist all who need to identify or acquire government published or sponsored documents, maps, patents, specifications, standards, and other resources of interest to the defense community. The entries are arranged alphabetically, in a single list, by document type, source, acronym, series designation, or short title. Each entry identifies the item and provides detailed acquisition information such as source, order forms to use, cost, where indexed, and telephone numbers for additional information. Copies of *HOW TO GET IT* may be obtained by ordering accession number AD A110000 from Defense Technical Information Center, Cameron Station, Alexandria VA 22304-6145 or National Technical Information Service, 5285 Port Royal Rd, Springfield VA 22151-2171.

2.7 ADDITIONAL SOURCES OF INFORMATION

Often engineers need access to information normally not covered in the AFSC Design Handbook series. *Sub-Note 2.7(1)* indicates where to address queries that may fall into this category.

SUB-NOTE 2.7(1) Where to Address Requests for Air Force Technical, Supply, and Engineering Publications and Data

Type of Publication	Address Queries to
Air Force technical orders (TO): if the specific TO number is unknown, describe the desired TO, including the name of the equipment, manufacturer, model, serial and part number, and any other identifying information on the particular equipment.	Oklahoma City ALC/DAPD Tinker AFB OK 73145-5000 (or the prime ALC for the specific TO, if known)
Air Force technical reports (TR) when specific source is unknown.	NTIS 5285 Port Royal Rd Springfield VA 22151-2171 Exception: for DTIC Users, to: DTIC Cameron Station Alexandria VA 22304-6145
USAF and DOD Federal Supply Catalogs and related catalog publications indexed in USAF S-2A-1 (see exceptions below).	AFLC/IMPD Wright-Patterson AFB OH 45433-5001
Cataloging Handbooks (H2-1, H2-2, H2-3, etc), Federal Manuals for supply cataloging (M1-1, M1-2, M1-3, etc) and Master Cross Reference Indexes (CRL-1 and CRL-2).	Superintendent of Documents US Government Printing Office Washington DC 20402-0001
Engineering Drawing and Associated Lists.	AFLC/IMPD Wright-Patterson AFB OH 45433-5001
Armed Services Procurement Regulations (ASPR), Air Force supplements to ASPRs, and Defense Acquisition Regulations (DAR). These are now called Federal Acquisition Regulations (FAR).	Superintendent of Documents US Government Printing Office Washington DC 20402-0001
AF publications pertaining to Automated Data Systems (ADS).	AFDSDC/DAPD Gunter AFS AL 36114-5000
Specifications, standards, military handbooks, etc, indexed in the *DOD Index of Specifications and Standards (DODISS)* (see exception below).	Naval Publications and Forms Center 5801 Tabor Ave Philadelphia PA 19120-5002
The index to *DODISS* above (including part 1, alphabetical listing, and part 2, numerical listing).	Superintendent of Documents US Government Printing Office Washington DC 20402-0001

3. NONGOVERNMENT SOURCES

In addition to government or government adopted or sponsored industry documents, many valuable documents are published by nongovernment agencies. It is recommended those organizations be contacted directly to obtain listings of available publications and how they may be procured. Some representative sources are listed in *SN 3(1)*.

3.1 CODE NAME HANDBOOK

The Defense Marketing Service (DMS) publishes the *Code Name Handbook* which contains a short narrative of over 12 000 code names and acronyms used by the Department of Defense and the aerospace industry. This handbook may be purchased from DMS Inc., Dept 515, 100 Northfield St, Greenwich CT 06830-4698.

4. ELECTROMAGNETIC COMPATIBILITY REFERENCE SOURCES

Sources of electromagnetic compatibility (EMC) information are described in the following paragraphs.

4.1 USAF SOURCES

Several organizations and groups within the United States Air Force are involved in the Air Force Electromagnetic Compatibility Program (AFEMCP). Contact points and a brief description of the mission of each organization are provided in *SN 4.1(1)*.

4.2 GOVERNMENT SOURCES

The US Government contact points (other than Air Force) for organizations involved in EMC are contained in *SN 4.2(1)*. Canadian Government contact points are listed in *SN 4.2(2)*.

4.3 SOCIETIES

Various societies and engineering groups in the United States which are concerned with EMC are listed in *SN 4.3(1)*.

4.4 NATIONAL FIRE PROTECTION ASSOCIATION (NFPA) PUBLICATIONS

The importance of the NFPA documents and standards cannot be overemphasized and it is strongly recommended all EMC systems engineers become thoroughly familiar with the NFPA and its documents. A number of NFPA documents have been approved by the American National Standards Institute (ANSI), formerly United States of America Standards Institute. *Sub-Note 4.4(1)* contains a list of NFPA and ANSI standards that affect EMC.

4.5 SOCIETY OF AUTOMOTIVE ENGINEERS EMC RELATED DOCUMENTS

Sub-Note 4.5(1) gives the documents generated by the Society of Automotive Engineers AE-4 Committee on EMC.

SUB-NOTE 3(1) Other Sources of Design Information

Acoustical Society of America
335 East 45th St
New York NY 10017-3483

Aerospace Industries Association of America
1725 DeSales St NW
Washington DC 20036-4406

American Chemical Society (ACS)
1155 16th St NW
Washington DC 20036-4899

American Geophysical Union (AGU)
1707 L St NW
Washington DC 20036-4202

American Institute of Aeronautics and Astronautics (AIAA)
1290 Avenue of the Americas
New York NY 10019-0012

American Institute of Industrial Engineers (AIIE)
25 Technology Park/Atlanta
Norcross GA 30092-2988

American Institutes for Research in the Behavioral Sciences (AIR)
10605 Concord St
Kensington MD 20795-2504

American Meteorological Society (AMS)
45 Beacon St
Boston MA 02108-3693

American Nuclear Society (ANS)
244 East Ogden Ave
Hinsdale IL 60521-3608

American Psychological Association (APA)
1200 17th St NW
Washington DC 20036-3094

American Society of Mechanical Engineers (ASME)
345 East 47th St
New York NY 10017-2392

Anti-Friction Bearing Manufacturers Association, Inc (AFBMA)
60 East 42nd St
New York NY 10165-0079

Association of American Railroads (AAR)
1920 L St NW
Washington DC 20036-5099

Electronic Industries Association (EIA)
2001 I Street NW
Washington DC 20006-1899

Flight Safety Foundation (FSF)
1800 North Kent St
Arlington VA 22209-2104

Human Factors Society (HFS)
PO Box 1369
Santa Monica CA 90406-0136

Institute of Electrical and Electronics Engineers, Inc (IEEE)
345 East 47th St
New York NY 10017-2394

Interstate Commerce Commission (ICC)
12th St & Constitution Ave NW
Washington DC 20423-0001

NASA Scientific and Technical Information Facility
PO Box 8757
Baltimore MD 21240-8757

National Fire Protection Association
Battery March Park
Quincy MA 02269-9101

National Safety Council (NSC)
425 North Michigan Ave
Chicago IL 60611-4213

National Security Industrial Association (NSIA)
740 15th St NW
Washington DC 20005-1084

National Technical Information Service (NTIS)
5285 Port Royal Rd
Springfield VA 22151-2171

Nuclear Safety Information Center
Oak Ridge National Laboratory
PO Box Y
Oak Ridge TN 37831-2009

US Department of Commerce
National Bureau of Standards (NBS)
Washington DC 20230-0001

SUB-NOTE 4.1(1) USAF Sources (Sheet 1 of 2)

SOURCE AND ADDRESS	REMARKS
Headquarters United States Air Force HQ USAF/RDPDT* Washington DC 20330	
Air Force Systems Command AFSC/SDXE Andrews AFB DC 20334-0001	This is the focal point for engineering policy.
Aeronautical Systems Division ASD/ENACE* Wright-Patterson AFB OH 45433-6503	Maintains primary EMC engineering responsiblity for support of aerospace-oriented systems, including: a. Development and maintenance of EMC specifications and standards for the Air Force. b. Provisions for EMC technical support to AFLC, SD, AD, ESD, Operational Commands, and NATO, as required. c. Support of ASD systems throughout their life cycles.
Wright Research and Development Center WRDC/AAAI* Wright-Patterson AFB OH 45433-6523	Provides EMC research and development for aerospace systems and equipment. Programs have been established for interference reduction, static electricity, lightning, and microelectronics.
Electronics Systems Division ESD/TDET* Hanscom AFB MA 01731	Handles acquisition of ground-oriented systems and equipment and command and control systems.
Rome Air Development Center RADC/RBC* Griffiss AFB NY 13441-5700	Maintains EMC research and development for systems and equipment intended for ground-oriented missions.
Headquarters Space Division Hq SD/AQT* PO Box 92960 Wordway Postal Center Los Angeles CA 90009	Has primary responsibility for development and acquisition for ballistic missiles, satellites, and other space vehicles intended for Air Force missions.
Air Force Logistics Command AFLC/MMET* Wright-Patterson AFB OH 45433-5001	This is the Hq AFLC electronics/electro-optics focal point.
San Antonio Air Logistics Center SA-ALC/SFTH* Kelly AFB TX 78241-5000	This is the AFLC focal point for electrical grounding and fuel safety.
Aerospace Guidance and Metrology Center AGMC/MLPE* Newark AFS OH 43057-5990	This center is attached to AFLC, and is the Air Force "Bureau of Standards." The contact for EMC calibration.

*Abbreviated address where designated is sufficient for mailing purposes.

SUB-NOTE 4.1(1) USAF Sources (Sheet 2 of 2)

SOURCE AND ADDRESS	REMARKS
Air Force Communications Command 1842 EEG/EEIF* Scott AFB IL 62225-6348	Has primary EMC engineering responsibility for support of ground-oriented systems and equipment. Prevention, investigation, and resolution of ground EMC problems.
Air Force Weapons Laboratory AFWL/NT* Kirtland AFB NM 87117	Responsible for nuclear safety and EMP design criteria and testing.
United States Air Force School of Aerospace Medicine USAFSAM/TSMB* Brooks AFB TX 78235-5207	Responsible for medical equipment and medical research and development.
United States Air Force Radiology Health Laboratory USAFRHL/CC* Brooks AFB TX 78235-5001	Responsible for criteria and tests for electromagnetic hazards to personnel.

*Abbreviated address where designated is sufficient for mailing purposes.

5. USER CONTRIBUTIONS

Users of this handbook are invited to contribute information pertaining to new sources or documentation relating to EMC. Documentation may include new reports or older reports considered more authoritative than those currently referenced in *DH 1-4*. It is recommended the following information be provided: author(s), title, document number, date, ordering information, two-line abstract, sponsor, contract number, security classification, etc.

SUB-NOTE 4.2(1) US Government Sources (Sheet 1 of 2)

SOURCE AND ADDRESS	REMARKS
US Army Avionics R&D Activity ATTN: DAVAA-S Ft Monmouth NJ 07703	Army avionics EMC responsibility
US Army Armament Research & Development Command US Army ARRADCOM* ATTN: DRDAR-TSE-M Dover NJ 07801	EEDs and ordnance Conducted and radio frequency testing
US Army Tank-Automotive Readiness Command US Army TARADCOM* ATTN: DRSTA-GSES Warren MI 48090	Automotive equipment
US Army Missile Research & Development Command US Army MIRADCOM* ATTN: DRCPM-MBES Redstone Arsenal AL 35809	Missiles
Naval Air Systems Command Code: AIR-5161 Department of the Navy Washington DC 20361	Aircraft bonding, EMC, lightning, electrical power (*MIL-STD-704*), etc
Naval Air Development Center NADC/Code 2034 Warminster PA 18974	Navy lead laboratory for EMC
Naval Electronic Systems Command Code: ELEX 83221 Department of the Navy Washington DC 20360	Electronic systems and EMC standardization
Naval Facilities Engineering Command Code 041E1 200 Stovall St Alexandria VA 22332	Shore and base facilities
Naval Sea Systems Command Code 04H2 Washington DC 20362	EMC for ships
Naval Underwater Systems Center Code EA-41 New London CT 06320	EMC R&D for submarines
Naval Training Equipment Center Code N411 Orlando FL 32813	Training equipment and simulators

*Abbreviated address where designated is sufficient for mailing purposes.

SUB-NOTE 4.2(1) US Government Sources (Sheet 2 of 2)

SOURCE AND ADDRESS	REMARKS
Naval Electronics Systems Engineering Activity Code 026 Patuxent River MD 20684	EMC tests and evaluation
National Aeronautics and Space Administration NASA* Code ECD-4 Washington DC 20546	
Marshall Space Flight Center, NASA ATTN: R-QUAL-PIE Marshall Space Flight Center AL 35812	
Goddard Space Flight Center, NASA Code 324-1 Greenbelt MD 20771	
Lewis Research Center, NASA MS 500-109 21000 Brookpark Rd Cleveland OH 44135	
US Department of Commerce, National Telecommunications and Information Administration NTIA Washington DC 20005	NTIA standards and criteria become national policy and take precedence over documents published by individual Government agencies (i.e., DOD, FCC, etc.). See *DN 1B2, Para 2.2*, for NTIA publications that relate to EMC.
US Department of Commerce, Institute of Telecommunications Sciences USDC/ITS* Standards Working Group 3250 Broadway Boulder CO 80303	
Federal Aviation Administration ARD-350 2100 Second St NW Washington DC 20590	EMC requirements for all ground equipment
DOD Electromagnetic Compatibility Analysis Center Director, DOD/ECAC* ATTN: ALC North Severn Annapolis MD 21402-1187	Industry-contact DOD/ECAC through procuring activity

*Abbreviated address where designated is sufficient for mailing purposes.

SUB-NOTE 4.2(2) Canadian Government Sources

SOURCE AND ADDRESS	REMARKS
National Defence Headquarters DASP-6-4 Ottawa Ontario Canada K1A OK2	Focal point for Canadian National Defence

SUB-NOTE 4.3(1) Society Sources

SOURCE AND ADDRESS	REMARKS
Society of Automotive Engineers, Inc (SAE) SAE Committee AE-4* 400 Commonwealth Dr Warrendale PA 15096	The SAE has an extensive technical effort in support of aerospace systems and equipment. Committee AE-4, which deals with EMC, has about 25 various projects to develop EMC standards for industry.
Electronic Industries Association EIA Committee G-46* 2001 Eye Street NW Washington DC 20006	Committee G-46 of Electronics Industries Association has a number of EMC projects. This committee is organized with participants representing their own organizations in order to obtain an "industry" viewpoint.
Institute of Electrical and Electronics Engineers (IEEE) 345 East 47th St New York NY 10017	The IEEE Group on EMC has been sponsoring an annual symposium and also periodically publishes various EMC proceedings and transactions.
National Fire Protection Association (NFPA) 470 Atlantic Ave Boston MA 02210	The NFPA has developed a number of standards that directly involve EMC. However, the term EMC is not used by the NFPA.

*Abbreviated address where designated is sufficient for mailing purposes.

SUB-NOTE 4.4(1) ANSI/NFPA Standards

70-1983	National Electrical Code
77-1983	Static Electricity, Recommended Practice on
78-1980	Lightning Protection Code
325M-1977*	Fire Hazard Properties of Flammable Liquids, Gases, and Volatile Solids
407-1980	Aircraft Fuel Servicing
409-1979	Aircraft Hangars
495-1982	Code for the Manufacture, Transportation, Storage, and Use of Explosive Materials

*NFPA Standard only.

APPENDIX C NUMBERED REFERENCES

The numbered references in the AFSC DH-series handbooks are available as indicated below. Additional addresses for specific documents may be found in the list of other sources in *APP B*. Documents not covered by these categories must be ordered from the originating agencies, as identified in the individual listings.

a. Qualified users may obtain DTIC documents (AD, ATI, TIP NO.) from:

Defense Technical Information Center (DTIC)
Cameron Station
Alexandria VA 22304-5000

b. NTIS documents (DTIC Unclassified AD, ATI, and TIP Documents; NASA TNS; NASA TT; NASA MS; NASA TMS; NACA RMS; NACA TNS; NACA Reports; and NACA Wartime Reports) may be obtained from:

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield VA 22151-2103

c. Organizations and agencies qualified to receive NASA documents should address requests through their technical library or current recipient to:

NASA Scientific and Technical Information Facility
PO Box 8757
Baltimore MD 21240-0757

d. Selected NASA Special Publications, NASA abstract journal STAR, and selected NACA Reports may be obtained from:

Superintendent of Documents
US Government Printing Office (GPO)
Washington DC 20404-0001.

NOTE: Reference numbers are assigned from a master list covering all AFSC Design Handbooks.

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62 *Interference Reduction Guide for Design Engineers.* Filtron Co. Inc, Flushing NY, for the US Army Electronics Lab, Electromagnetic Environment Division, Ft Monmouth NJ 07703. 1 Aug 64. (Vol I, 326 pp, DTIC No. AD 619666; Vol II, 364 pp, DTIC No. AD 619667)

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108 *Electromagnetic Compatibility Principles and Practices.* NHB 5320.3. National Aeronautics and Space Administration, Office of Manned Space Flight, Apollo Program, Wash DC 20546. Oct 65. 670 pp.

114 R.E. Tweed, *Manufacturing Methods for Electroplating Silver, Gold, and Rhodium on Electrical Connector Contacts.* AFML-TR-65-321. Nu-Line Industries, Inc, 1015 S Sixth St, Minneapolis MN 55415. Oct 65. 337 pp. (DTIC No AD 473802)

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