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Final Report *July 1981*

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By: W. GRAF J. HAMM J. E. NANEVICZ D. E. TREMAIN

Prepared for:

U.S. ARMY AVIONICS R&D COMMAND, DAVAA-E
BLDG. 2525
FT. MONMOUTH, NEW JERSEY 07703
Attention: CODE W15P83 (F. CANSLER)

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SRI Project 2132

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This report discusses the effects of advanced composite materials on avionics equipment. Over 80 reports and articles on this subject have been collected; the bibliographic data resides in an on-line computer data base. A summary of previous and ongoing work is included.

The impact of composite materials on avionics systems and subsystems is discussed, and the major problem areas identified (viz., lightning, EMP protection, antenna performance, EMI/EMC, and radar cross section reduction).

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Possible solutions and approaches to these problems are presented and the importance of tradeoff studies at the system level is stressed. Problems peculiar to helicopters are reviewed separately.

The relation of this contract to the Advanced Composite Airframe Program (ACAP) is also discussed. Appendices present technical background on interference control and E^3 hardening concepts. An extensive bibliography is included.

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SUMMARY

SRI International has investigated and analyzed some of the effects that composite materials may have on avionics system integration, installation, and performance. The purpose of this program is to provide engineering assistance to AVRADA to determine how avionics systems and subsystems are affected when they are installed in a composite airframe. This report presents the results of this study. Concepts developed under this contract may be applied to the Advanced Composite Airframe Program (ACAP) and other Army composite programs.

The first section gives an introduction to advanced composite materials and their properties. A substantial amount of technical reports, engineering data, and related literature has been collected; a summary of previous and ongoing work is presented in Section II. In Section III, the impact of composite materials on avionics systems and subsystems is discussed. The major problem areas identified are lightning and EMP protection, EMI/EMC problems, antenna performance, and radar cross section (RCS) reduction. Section IV addresses these problems and discusses possible solutions. SRI has developed a unified approach to deal with electromagnetic interference problems; its applicability to the problem of an all-composite fuselage is discussed.

In addition to the problems affecting any aircraft with a composite fuselage, there are some problems specific to Army vehicles, viz., helicopters. Examples include the rotary wings, large openings, fixed landing gear, NOE (nap of the earth) navigation, and others. These subjects are discussed in Section V. The next section treats future work to be done in this area, in particular EMI/EMC problems, antenna performance over composite ground planes, RCS reduction, and lightning and EMP protection. The importance of tradeoff studies at the system level is stressed. Section VII briefly describes the relation of this contract to the Advanced Composite Airframe Program. Originally it was

envisioned that this program would give direct input to the manufacturers of the airframes; unfortunately, this was not possible due to delays in the award of ACAP contracts. SRI recommends that such inputs be provided in a follow-on contract to the present project.

Three appendices conclude the report. Appendix A contains a complete list of all the technical literature collected for this project. The data resides in an on-line computer data file which may be searched from any terminal that has access to the system. Appendix B describes the unified approach to electromagnetic interference control developed at SRI. The topological model discussed in this appendix can be used readily to solve the avionics integration problems which are expected to arise in an all-composite fuselage. The last appendix gives a discussion of the effects of lightning and EMP. Although already treated in Section V and VI, these topics are discussed in more detail and at a more technical level in Appendix C.

References are listed at the end of the report.

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I PROPERTIES OF ADVANCED COMPOSITE MATERIALS

Aluminum, titanium, and other metals traditionally have been the favored construction materials in the aircraft industry. Aluminum is light in weight, relatively strong, and therefore well suited for the fuselage of an aircraft. Where high temperatures are encountered, or where higher strength is necessary, titanium and other metals are used. These tougher materials are used in small quantities so that their much higher weight is not a serious drawback. Weight alone is not a determining factor; of greater interest in the aircraft industry is the strength-to-weight ratio of a material. For pure metals this ratio is to a large degree an inherent property of the chemical element; alloys may exhibit properties somewhat different from the elements making up the alloy. However, the degree of strength that ultimately can be achieved in even the best alloy is limited by the inherent strength of the metals used.

For about a decade man-made fibers have been available with a very large strength-to-weight ratio. For example, Kevlar fiber is five times as strong as steel on an equal weight basis. (Kevlar is DuPont's trademark for aramid fibers.) It is now possible to combine these fibers with a matrix material so that a composite material can be made which has mechanical properties superior to metals. With an almost infinite variety of fibers and matrix materials available, it may be possible in the future to specify all the material properties one desires for a particular application, and the materials scientist will be able to select the proper ingredients to achieve the desired properties.

Composite materials have been available for some time. Fiberglass is a familiar example. However, it is only in recent years that advanced composite materials have found more widespread use. In some cases the increase in use has been extraordinary. For instance, in 1970 only 6000 lb of Kevlar fiber were used, but in 1974 the amount jumped to

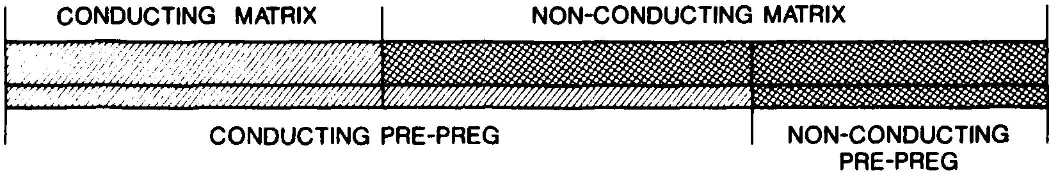
145,000 lb, and the projection is that, by 1985, about five million pounds of Kevlar will be used per year.

The price of metals is steadily increasing; aluminum production is particularly energy-intensive, and, as energy prices rise, so does the cost of aluminum. In 1978 the energy cost for the production of aluminum was \$1.23/kg, whereas for Kevlar composite it was only \$0.55/kg. Today the price of composites like graphite epoxy, Kevlar epoxy, and similar advanced composite materials is very competitive compared to aluminum and other metals. It is expected that in the future advanced composite materials will become substantially cheaper than metals.

Advanced composite materials appear to be ideal for many structural applications: they exhibit very high strength-to-weight ratio, and they are easy to fabricate, economical to buy, and highly weather resistant. However, one serious shortcoming of advanced composite materials is that their electrical properties vary widely, from poorly conducting (graphite epoxy) to not conducting at all (Boron epoxy). To the structural engineer this is perhaps unimportant, but if a fuselage is struck by lightning, the electrical properties of the material become very significant. If sensitive equipment inside an aircraft is to be immune to a radar transmitter outside, the shielding ability of the fuselage material is of obvious importance. As an example of the widely varying electrical properties of advanced composite materials, consider the skin depth of a material. This is the depth in the material at which the amplitude of an electromagnetic wave has been reduced to 37% of the amplitude at the surface of the material. At a frequency of 1 MHz the skin depth of aluminum is 0.1 mm, for graphite epoxy it is 3 mm to 6 mm, and for Boron epoxy it is about 10 m. These figures imply that for materials of practical thickness (1 mm to 2 mm) aluminum will shield electromagnetic waves at 1 MHz quite well, graphite epoxy only a little, and Boron epoxy not at all; that is, Boron epoxy is completely transparent to 1 MHz radiation.

In summary, when structural considerations alone are important, advanced composite materials are excellent candidates over metals, with few or no drawbacks to be expected. In fact, it is often possible to achieve cost savings in addition to the expected savings in weight of a structure made of advanced composite materials. The goal of the Advanced Composite Airframe Program (ACAP) is a 22% weight saving, and a 17% cost saving. However, when electrical considerations are important -- and they are for the avionics equipment inside a fuselage -- the advantages of advanced composite materials have to be weighed against the disadvantages (compared to an aluminum fuselage). Two principal courses of action are possible. One may build the structure in accordance with aerodynamic and structural requirements using advanced composite materials, as appropriate, and then attempt to buy back the properties given up when the advanced composite material was substituted for metal (for instance, by applying a metal surface layer to the advanced composite). Or, in the alternate course, the design takes electrical requirements into consideration from the start, incorporating metal structural members, as appropriate, redesigning and grouping the equipment layout, integrating lightning protection measures, etc. The second approach -- discussed in detail in Section IV -- has the advantages of a synthesized result; the first is a "band-aid approach" and does not favor innovative new designs.

It is convenient to divide advanced composite materials into three groups. There are conducting and nonconducting fibers as well as matrix materials. Combined they form composites which conduct electricity excellently, poorly, or not at all (see Figure 1). Metal matrix materials belong in the first group of excellent conductors, but because of their high manufacturing cost they have found only limited applications thus far. Graphite epoxy is an example of the second group of poor conductors. However, the conductivity is high enough so that the behavior of graphite epoxy at very high frequencies (above 100 MHz) cannot be distinguished from metals. The permittivity is indeterminable because the conduction current dominates the displacement current up to a frequency of 1 THz (1 THz = 1000 GHz). Boron epoxy is an example of the third group; materials in this group are insulators and, since the displacement current dominates the conduction current over most of the



$\sigma = 10^7$ S/m	$\sigma = 10^4$ S/m	$\sigma = 10^{-3}$ S/m
ϵ = (indet.)	ϵ = (indet.)	$\epsilon = 4$
Aluminum/Graphite	Graphite/Epoxy	Boron/Epoxy

FIGURE 1 GROUPS OF COMPOSITE MATERIALS

frequency range of practical interest, these materials can be described as dielectrics.

Of the three groups, the graphite epoxy group is the one which is most widely studied in aircraft applications, and it is also the material which has found the most widespread application. In the future, however, graphite epoxy may be replaced by Kevlar composites which belong to the group of nonconductors. Kevlar has a very high strength-to-weight ratio; this, combined with low cost, may make aramid fibers the fiber of the future. The lack of conductivity may be overcome by applying metal coatings of various kinds, or by other measures (e.g., embedded wire mesh). It is not clear at this time whether metal matrix materials will ever find widespread use. At the present time the cost of this kind of material is very high; since it also has a lower strength-to-weight ratio than Kevlar, it would not seem that the use of metal matrix material is essential. Table 1 gives a summary of the electrical properties of some advanced composite materials.

Table 1

ELECTROMAGNETIC PROPERTIES OF COMPOSITE MATERIALS

	G/E	B/E	Kevlar
μ_R	1	1	1
ε_R	-	5.6	3.6
σ_L (S/m)	2×10^4	30	6×10^{-9}
σ_T (S/m)	100	2×10^{-8}	6×10^{-9}
σ_L/σ_T	200	1.5×10^9	1

Conductivities for graphite epoxy (G/E) and boron epoxy (B/E) are given for unidirectional composites; subscript L refers to the direction along the fibers (longitudinal), subscript T refers to the direction perpendicular to the fibers (transverse). Siemens is the SI unit for conductance (formerly called mho). For comparison, the conductivity of aluminum is 37 MS/m.

II PREVIOUS WORK ON ADVANCED COMPOSITE MATERIALS

A survey of available literature was begun in the early part of this program. All references were entered into a computerized data file. The bibliography currently contains more than 80 reports and conference papers. The on-line data file is indexed by keywords; it can also be searched by year, author, and any other element if necessary. A complete listing of the data file is given in Appendix A; here, we summarize the most important findings from the survey.

A rather large amount of existing work centers around material properties of advanced composites. This is understandable since advanced composite materials are still relatively new, and before using them extensively one needs to know as much about them as possible. However, in almost every investigation only a single parameter was studied (for instance, conductivity, isotropy, stiffness, shielding effectiveness, permittivity, and so on). There are virtually no studies describing the effects of using advanced composite materials in lieu of metal on an integrated system, and it is also rare to find a discussion of system tradeoffs. One reason for this may be a desire for simplicity: it is relatively straightforward to investigate one parameter of a material, independent of all its other properties; a system study, on the other hand, may be so complex that it would be difficult, if not impossible, to investigate all effects of the advanced composite material on system performance and to deduce material properties from that investigation.

Another reason for the scarcity of system tests is cost: the difference between the cost of performing simulated lightning tests on a 30 cm by 30 cm test panel and performing the same tests on an actual aircraft may be several orders of magnitude. An interesting compromise is the F-16 forward fuselage lightning tests performed by Culham Laboratories for General Dynamics (Wallace et al., 1978). For these tests a complete forward fuselage was built with graphite epoxy and equipped with a set of avionics equipment. A coaxial test rig provided the same excitation which would be produced by a moderate lightning stroke under flight conditions. Each avionics unit was exercised during the simulated lightning strikes. The researchers found no effects on system performance which could be directly related to the graphite epoxy used in the fabrication of the fuselage. Apparently no other tests were performed. The positive results obtained in these particular tests are encouraging; however, it should be noted that the material used for the fuselage is just one of many available, and the tests did not involve sources of electromagnetic interference other than lightning. Furthermore, the safety margin of the equipment in these tests is unknown, because the only diagnostic used was the proper functioning of each unit during the simulated lightning strikes.

Antenna performance studies are quite numerous, although the frequency range considered is usually quite limited. Most of the reports we obtained describe performance studies of an antenna over a ground plane at frequencies of about 100 MHz and higher. Also, the ground plane almost always is assumed to be graphite epoxy which is still a good enough conductor to have little or no impact on antenna performance. (The skin depth for graphite epoxy is 0.3 mm to 0.6 mm at 100 MHz.) Only a limited amount of work has dealt with the problem of an HF antenna over an imperfect ground plane.

One of the models that has been developed to analyze the performance of HF antennas over imperfectly conducting ground planes is the WIRANT wire grid model developed by Boeing (Stapleton and Walen, 1978). This model approximates the aircraft structure as a wire grid. The charge and current distribution induced on each wire segment by an antenna on the aircraft are obtained using the method of moments. This model permits the calculation of antenna input impedance, radiation patterns, and gain.

Stapleton and Walen state that the wire segments must be of the order of $\lambda/6$ or less in length (λ is the free-space wavelength). Wire grid models, which in the past have been used to calculate scattering from aircraft, typically require electrically short wire segments. This constraint on wire segment length requires that a very large number of segments be used at the higher HF frequencies, with correspondingly large computer memory and time requirements. If too few segments are used at the higher HF frequencies, accuracy may be seriously compromised. Stapleton and Walen state that their model gives satisfactory agreement with experimental results for the performance of a tail-mounted shunt antenna on a Boeing 747SP aircraft, in the frequency range 2 MHz to 10 MHz. Less than satisfactory agreement was obtained in the frequency range 10 MHz to 30 MHz, because too few wire segments were used.

It should be noted that although Stapleton and Walen's calculations were made for an aluminum (i.e., finite, but not perfectly conducting) aircraft, this approach should be usable for ground planes having lower conductivity. However, when the conductivity is so low that the diameter of the wires in the grid is of the order of the skin depth, it is possible that this method will not yield useful results. It is clearly not useful for dielectric composite materials such as Kevlar composites.

Some analytical work has been done on the performance of HF loop antennas on the UH-1D and OH-58 helicopters (Medgyesi-Mitschang, 1976). In this work, the helicopter was modeled as a perfectly conducting body of revolution, with the rotor blade modeled as a dipole scatterer. Nap-of-the-earth (NOE) effects were included in the model; these effects were approximated by plane-wave scattering. Modeling NOE effects by plane-wave scattering should be a good approximation when the altitude of the helicopter is large compared to wavelength; for altitudes that are of the order of a wavelength or less it may be a poor approximation. Medgyesi-Mitschang's model does not appear to be readily adaptable to structures having finite conductivity, and it is not applicable to dielectric structures.

Much work has been done on the effect of lossy halfspace on antenna performance (e.g., Wait, 1961; Baños, 1966; King, 1979; King and Smith, 1981). However, this work does not appear to be relevant to the HF antenna problem, because a halfspace is clearly a poor approximation to an electrically thin ground plane (i.e., when the skin thickness is of the order of the skin depth or less).

Some of the work that has been done on performance of antennas over multi-layered lossy media (e.g. Wait, 1969) may, however, be applicable to the analysis of HF antenna behavior near an infinite, planar layer of conducting composite material.

III IMPACT OF ADVANCED COMPOSITE MATERIALS ON AVIONICS SYSTEMS

Substituting an advanced composite material where metal had been used in a fuselage is usually attractive from a structural (and perhaps economic) point of view. The impact this will have on avionics equipment performance depends on the kind of advanced composite selected and on the frequency range of the particular avionics unit considered. We will describe each area of interest in turn; possible solutions will be discussed in the next section. In some cases the impact may be quite small, as was the case in the F-16 forward fuselage test mentioned in the previous section, but in others the impact may be so substantial as to demand a complete redesign of the avionics system. The magnitude of the effects will depend in part on how well designed the system was from an electromagnetic interference point of view, and in part on what group of advanced composite materials is selected. If there are any effects which depend on the kind of composite material used they will be mentioned in the following paragraphs. We will limit our attention to materials which behave electrically like graphite epoxy and like Kevlar epoxy. However, the words "graphite epoxy" and "Kevlar epoxy" should be understood as group names, and any other advanced composite material with similar electrical properties may be substituted.

A. Power Ground Returns

It is common to use the fuselage as a current return in a traditional metal aircraft, although the practice is not recommended. Experiments have shown (Wallace et al., 1978) that graphite epoxy would be suitable for currents up to about 10 A, without heating up the material more than can be tolerated from a structural point of view. Because of its dielectric nature it is not possible to use Kevlar epoxy in this way. Alternate ways should be explored for power ground returns.

B. Bonding of Composites with Metal

In an all-composite fuselage this problem would not arise. However, there will always be some metal (for lightning protection, for example). It appears from the available literature that this problem has been solved, either by using tapered bolts fitting into tapered holes, or by first electroless plating the composite with nickel and then bonding the nickel in traditional ways.

C. Ground Planes for Antennas

Graphite epoxy provides a reasonable ground plane for VHF and higher frequency antennas with little or no difference observed when performance is compared to a metal ground plane. Kevlar epoxy provides no ground plane at any frequency of interest, and graphite epoxy provides none at low HF frequencies and below.

D. Conductivity

As discussed in Section I the conductivity of graphite epoxy, although poor compared to aluminum, is sufficient in many cases. This material can even conduct the full current due to a lightning stroke, except at the attachment point where the current density is too high. Kevlar epoxy is nonconducting, and if lightning protection is necessary some metal covering is essential.

E. Thermal Properties

Thermal conductivity of advanced composite materials is similar to the electrical conductivity, viz., graphite epoxy shows moderate conductivity, while Kevlar epoxy is an insulator. Thermal expansion coefficients are different than they are for metals and this may lead to problems in some applications.

F. Lightning and Precipitation Static

In the paragraph on conductivity above it was mentioned that graphite epoxy could conduct the full current due to a lightning strike, except at the attachment point. It is necessary to add a sacrificial layer of metal, at least at the most likely attachment points; otherwise, severe damage may result. Serious problems will arise with uncoated Kevlar epoxy. Because that material is electrically transparent the lightning stroke will attempt to attach to any suitable metal surface on the interior of the aircraft, thereby causing severe damage. As far as precipitation static is concerned, a fuselage made of graphite epoxy may be treated like a metal fuselage; that is, standard techniques using static dischargers may be applied. However, with Kevlar epoxy problems again are likely because the material is nonconductive, and therefore dielectric breakdowns may occur. (More details on the subject of lightning are given in Appendix C.)

G. Antenna Integration

With a graphite epoxy fuselage no problems are envisioned for antennas at frequencies of about 100 MHz and higher. Minor changes in the radiation pattern and in the VSWR may occur but they are not significant. However, an HF antenna which usually relies on the entire fuselage as a counterpoise will not work properly, because the surface resistance of graphite epoxy is too large at HF frequencies. Most traditional antennas will fail to give acceptable performance when Kevlar epoxy is used, and antenna redesign combined with a judicious use of metal seems to be indicated.

An additional problem will be the illumination of the interior of the aircraft by unwanted radiation from an HF antenna due to the insufficient size of the ground plane (especially when the fuselage is made of a dielectric). An example illustrates this concern: G. Dietrick of Florence, Kentucky, flew his Eagle I aircraft across the Atlantic Ocean. This aircraft is made almost entirely of fiberglass epoxy; only the floor is made of metal. This particular Eagle I was equipped with a

Sun-Air HF radio set (in addition to the customary avionics equipment in small aircraft). The pilot reported that serious problems occurred when the HF radio was in use (personal communication). These problems included an unusable autopilot and a non-functioning slave gyro. The level of interference produced by the HF transmitter was apparently quite high; in the pilot's own words: "the HF transmitter drove everything nuts." This problem will be of considerable concern for the ACAP since it is envisioned that HF communication will be part of the design.

H. EMI/EMC

There are several problems associated with electromagnetic interference, but there are no inherent problems as far as compatibility of the avionics units themselves is concerned. Graphite epoxy offers significantly less shielding (and Kevlar epoxy alone offers none) at lower frequencies; therefore, electromagnetic effects due to lightning or EMP may be significant in some cases (see Appendix C). Recall, however, that the F-16 forward fuselage tests by General Dynamics have not revealed any problem with graphite epoxy. It is clear, however, that serious problems may be expected in a Kevlar epoxy fuselage.

I. Corrosion

The advanced composite materials themselves show excellent resistance to many chemicals, including saltwater spray. However, they may be incompatible with some metals (e.g., when aluminum is bonded to graphite epoxy). Steps will have to be taken to ensure that such corrosive effects are not harmful and do not detract from the useful life expected of the airframe. The problem is being studied by material science laboratories, and some solutions are already available.

J. Shielding Effectiveness

In the paragraph on EMI/EMC it was mentioned that advanced composite materials generally offer less electromagnetic shielding than most metals do. This certainly is true for Kevlar epoxy which offers no measurable shielding up to very high frequencies. On the other hand, graphite epoxy of structural thickness (1 mm to 2 mm) may give a sufficient amount of shielding at frequencies of 100 MHz and higher so as to be indistinguishable from aluminum for practical purposes. At the lower frequencies the shielding effectiveness is poor compared to alumiunum. Note that the spectrum of both lightning and EMP contains a significant amount of energy at these lower frequencies.

K. Measurement Techniques

Unfortunately, no standards exist which give unambiguous results for measuring conductivity, shielding effectiveness, and other parameters. One problem is how to establish good contact with a material which is itself a poor conductor (or a dielectric). Another problem is the nonuniformity of most composite materials. In the case of graphite epoxy, for instance, the surface layer may consist of insulating epoxy, or it may consist of the outermost layer of graphite fibers. The electrical behavior for the two surface conditions is very different. Therefore, it is difficult to interpret test data; it is important to distinguish bulk and surface measurements. No rapid advances are expected in this field because of the intrinsic difficulty of the problem.

L. Power Distribution

When an avionics system is designed for incorporation into an advanced composite fuselage it is preferable to assume that the structure is unavailable for use as a return conductor; this has already been mentioned in the paragraph above on power ground returns. This may cause problems in that additional wiring and, therefore, weight will have to be added. Metal foil coverings or flame spray are too thin to serve the electrical function of a metal fuselage; alternate ways of solving the problem of power distribution must be explored. Personnel and equipment safety will also be a problem which must addressed.

M. Signal Wiring

As with power distribution the fuselage cannot be relied upon to provide a conductor for signal common. Furthermore, the advanced composite material does not offer the benefit of a good ground plane which may be especially significant for some RF circuits. Crosstalk in the signal circuits depends on the particular system and the signal wiring layout. The interconnections of the various avionics units warrant careful study.

N. Radar Cross Section

The importance of this area is scenario-dependent. The radar cross section (RCS) of an all-composite fuselage may be larger or smaller than that of an all-metal fuselage depending on the shape and many other factors. If RCS reduction is a concern for a particular application it is imperative to consider appropriate measures very early in the design phase of the fuselage. As with all the other problem areas discussed above, the solution to a particular RCS reduction problem can be beneficial or detrimental to another problem area; therefore, tradeoff studies again are important.

IV POSSIBLE APPROACHES AND TRADEOFFS

Substituting an advanced composite material for aluminum may reduce the weight of a fuselage by more than 20% and may at the same time lower the production cost by 15% or more. However, unless electrical considerations are taken into account early in the design, the weight and cost advantage may be lost because retrofit fixes will invariably add considerable weight and cost. In some cases no affordable retrofit may be possible.

A new approach to the general interference control problem has been developed by SRI International (Vance, 1980; Vance et. al., 1980); here we summarize the simple steps involved in the design of a system when the topological model described in Appendix B is used. First, the boundaries or barriers are identified; this also defines the zones. It is customary to number the zones starting at 0 for the outside (or any "noisy" environment); zone 1 comprises moderately noisy equipment, and zone 2 quiet equipment (circuit level). Second, the threshold for each zone is defined; this can be an upset level, a damage level, or any other desired noise level depending on the particular application. Each barrier must reduce the stress (produced by a source outside the barrier) to a level which is below the threshold. (For the containment of a noisy transmitter, or for TEMPEST considerations, the words "outside" and "inside" should be interchanged, and "threshold" takes on the meaning of "detectable signal level".)

To achieve the required attenuation the boundary should consist of a barrier which is substantially impervious to electromagnetic energy (either conducted or radiated). To this end the integrity of each barrier must be maintained. To be impervious the barrier must form a topologically closed surface. Such a barrier may consist of elements like filters, limiters, common-mode rejection devices, metal shields and wire meshes, and others. Usually none of these elements alone is sufficient to make the barrier impervious. However, if the main element of the barrier consists of metal plate (sheet metal), the barrier, and compromises in it, are readily identified. In this case the possible violations of boundary integrity are, in order of severity, (1) penetrations by insulated conductors, (2) apertures, and (3) diffusion through the wall itself (see Figure 2). The last item is usually negligible for metal walls other than thin foils, since reflection and absorption result in substantial attenuation of any unwanted signal. However, both penetrations and apertures may pose serious problems; an untreated insulated conductor may completely negate the attenuation offered by a metal equipment enclosure, while problems posed by apertures are somewhat less serious, but apertures are more difficult to characterize.

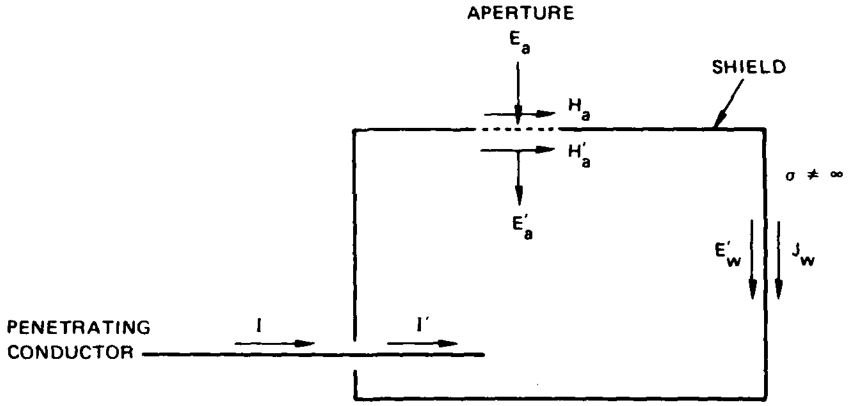


FIGURE 2 ELEMENTARY SHIELD WITH APERTURE AND PENETRATING CONDUCTOR

In a metal fuselage the first clearly defined boundary separating zone 0 and 1 is the fuselage itself, while cable shields and equipment boxes enclose the second zone (see Figure 3). However, in a fuselage of advanced composite material the first boundary is ill defined, depending on the kind of material used. In the case of Kevlar epoxy or similar materials, the fuselage cannot be considered to be an electromagnetic barrier. In such a case two alternate approaches can be used: metal foil coverings to establish the first boundary at the skin, or col-

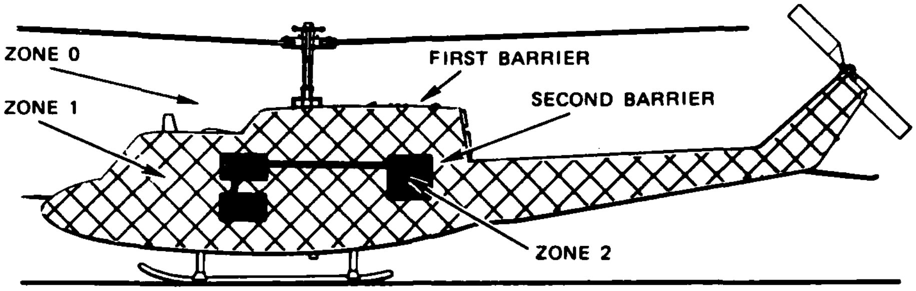


FIGURE 3 ZONES IN A METAL FUSELAGE

lapsing the first boundary to the cabinet level. Each of these approaches is discussed in turn.

Metal foil coverings (including flame spray and other techniques) have been developed in order to recover electromagnetic properties lost when the advanced composite material is substituted for the metal fuselage. These metal coverings offer a variety of advantages, but they also have some drawbacks. The main advantage is that configuration control in zone 1 is not necessary; any equipment which functions well in that zone can be moved about or relocated freely without jeopardizing its proper functioning. It could also be argued that if the advanced composite fuselage can emulate the electrical properties (or just the electromagnetic shielding) of an aluminum fuselage, then any set of avionics equipment which works properly in the metal aircraft will also work properly in the advanced composite fuselage. The drawbacks of metal coverings are added weight, added cost, corrosion control problems, and maintenance problems, to mention just a few.

In the second approach the first barrier consists of the equipment rack and the cable trays or conduits connecting the various avionics units (see Figure 4). The advantage of this method is that because of the smaller size of the enclosures, considerably less weight may be added than if a metal covering on the outside of the aircraft were used. Cost savings will be realized, especially when already existing cable trays or conduits can be used. Judicious use of fiber optical

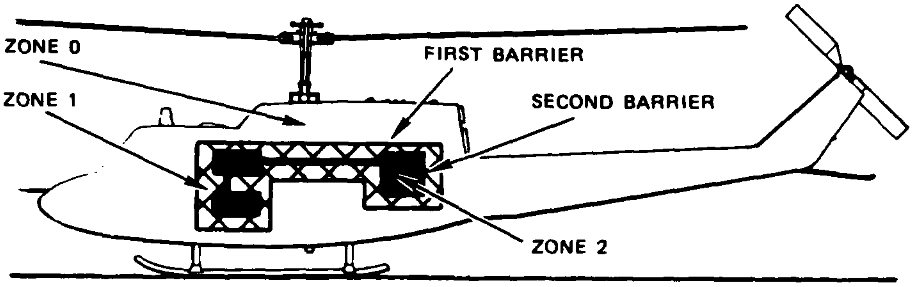


FIGURE 4 ZONES IN A COMPOSITE FUSELAGE

connections for digital circuits will give electromagnetic isolation without the need for long conduits, and this will probably result in weight and cost savings. The drawback of this method is that some configuration control is necessary; an avionics unit cannot be relocated as freely as when a metal covering is used, no lightning protection is offered by the untreated advanced composite, and a traditional avionics equipment system may have to be redesigned to take full advantage of existing boundaries.

To reach a decision on which of the two approaches to use in a particular application, tradeoff studies must be performed. It is important to consider all of the problem areas discussed in the previous section because a solution for one aspect may present a problem for another. For example, lightning protection of a graphite epoxy fuselage could be achieved by an aluminum foil covering. This aluminum skin may increase the shielding effectiveness of the fuselage to provide sufficient protection against the effects of an EMP, but at the same time this metal skin might increase the RCS. Thus, if both lightning protection and RCS reduction are desired, alternative solutions have to be considered. It is not possible to offer an optimal solution for all applications; however, some generic approaches to some of the problem areas outlined in the previous section are given below. A more technical discussion of the impact of lightning and EMP on electromagnetic interference control in metal and composite aircraft is given in Appendix C.

A. Power Distribution

Even in an advanced composite fuselage some structural members might be retained in metal; they could be used as power returns. A good example are the longerons; since they run along the fuselage they would be convenient as power return conductors. Other approaches would include the addition of a return wire for each power distribution. This would add some weight, but it would also simplify the separation of power and signal lines. The use of conduit as a power return is also a possibility, but for reasons of safety not a very attractive approach. At each barrier penetration the power lines must be filtered properly (see Appendix B). Furthermore, it is very important that the green wire (or any other ground conductor) does not penetrate the barrier.

B. EMI/EMC

If an outer metal covering for the advanced composite fuselage is chosen, most EMI/EMC problems will be the same as for a metal fuselage. However, if such a metal covering is not feasible, some interference problems will almost certainly arise unless specific steps are taken to prevent them.

A system designed with the topological zoning model in mind will be less likely to encounter interference problems. Full use should also be made of balanced circuits and twisted pair wiring whenever possible. For digital systems fiber optics is becoming an important alternative to shielded wiring. Because fiber optics are immune to electromagnetic radiation (but not to nuclear radiation) they can offer a degree of electromagnetic isolation which cannot readily be achieved by any other means. Fiber optics have been investigated by the NAVY in the ALOFT program with very favorable results (Harder et al., 1977). Compared to traditional metal wiring, fiber optics can save weight and cost, and can simplify maintenance. The reliability of optical fibers is quite high, even in the environment of a fighter aircraft. It remains to be demonstrated that they are equally reliable in the rough helicopter environment.

Because fiber optics can offer tremendous advantages as far as EMI/EMC is concerned they should be seriously considered for the Advanced Composite Airframe Program (ACAP). Fiber optical interconnections are particularly suited for digital data and control lines, while for analog signals traditional wiring would be more suitable. The greatest benefit will be realized if the avionics units to be interconnected are separated by a large distance, and many data lines are involved; this is because multiplexing will reduce the number of connections necessary, and eliminate an otherwise necessary long metal conduit.

C. Aircraft Antennas

The performance of HF antennas over composite airframes require careful evaluation. For example, the effectiveness of an infinite flat sheet of material as an antenna ground plane at HF depends in part on the ratio of thickness to skin depth and, more importantly, on the surface resistance. For aircraft skin constructed of conducting composite material such as graphite epoxy, the surface resistance can be large at the lower HF frequencies, and in this regime the material will behave differently from aluminum as a ground plane. It is likely that the antenna radiation pattern, as well as input impedance, will be affected. Some of the work on antennas over multilayered lossy media that has been reported in the literature (e.g., Wait, 1969) may be useful in estimating these effects. Furthermore, the effects of finite ground plane size will be different when the material is thin (compared to skin depth) compared to when it is thick. The antenna pattern and input impedance are affected by the shape of the airframe; this must also be taken into account in assessing the effects of finite skin conductivity. The multilayered lossy media studies, such as those of Wait, are not expected to be useful in estimating the effects of finite ground plane size or airframe shape. Evaluation of these effects will probably require the use of numerical techniques, such as the method of moments, or, in the case of finite ground plane size, the geometrical theory of diffraction.

A thin coating of aluminum over a dielectric composite material will exhibit effects at the lower HF frequencies similar to a conducting composite material, like graphite epoxy, because the coating becomes thin in terms of skin depth and the surface resistance becomes high in that regime. That is, metalizing a dielectric composite material may not guarantee good HF antenna performance. The effects due to metalizing would have to be considered carefully in the system design.

It is expected that the mutual coupling between multiple antennas on an aircract will depend on the conductivity of the skin; this effect should be considered in evaluating system performance. Whether coupling would be increased or decreased by a particular composite material is dependent on the aircraft geometry and antenna location.

If a dielectric material like Kevlar epoxy is used rather than a conducting material like graphite epoxy, it may be possible to design antenna structures which use the material properties to advantage. In other words, it may be advantageous to design antenna systems which operate in the presence of dielectrics, rather than to metalize the dielectric skin (with a resulting weight penalty) to allow the use of the same antennas that are used on metal aircraft. Of course, a conductive coating may be required for other reasons, such as lightning protection; this should be considered in the tradeoff analysis.

The performance of antennas in the presence of a dielectric or poorly conducting airframe of complex shape could be evaluated using method-of-moment techniques similar to those of Morgan and Mei (1979) for scattering by penetrable bodies of revolution. Body-of-revolution models are much more efficient computationally, and are easier to implement than general three-dimensional models, since many airframes can be approximated as bodies of revolution; use of such models should be considered in preference to more general models, whenever possible.

D. System Tradeoff Areas

A number of problem areas were discussed in Section III. Not all of those mentioned are of equal importance, nor is the list complete. Each application will emphasize different areas, depending on the priority of a particular problem. Thus, it is not possible to rank the problems listed in order of importance. However, we can comment on the ones which are likely to be important and should be considered at the system tradeoff level. In the following we discuss the questions which must be addressed for a system tradeoff study, for example in the ACAP.

Lightning. Commercial aircraft are struck by lightning once every 3000 h of flight time (about once a year). Should the aircraft be protected (added weight, cost) or can we accept the risk of (and subsequent damage due to) being struck? If we choose to protect the aircraft, how will other areas be affected (for example, RCS, laser hardness)?

Power Distribution. Can metal longerons or other structural members be used in power distribution, or would it be more economical to use (twisted) power leads connecting to each avionics unit?

Shielding. Is it necessary to have an outer metal covering (foil, flame spray) for shielding purposes, or do the equipment cabinets and racks, combined with the equipment enclosures, provide sufficient shielding?

RCS. How important is the RCS for the aircraft considered? If only NOE navigation is used, the RCS may be unimportant. If it is desired to lower the RCS, which methods interact most favorably with other requirements like shielding, lightning protection, weight saving, and cost?

Laser hardness. Must the fuselage be protected against laser weapons? If so, can this protection be combined with lightning protection? Will it be detrimental to RCS reduction efforts?

EMI/EMC. Are we constrained to use existing avionics equipment? If so, could interfaces be used for fiber optical interconnections, or are we forced to use conduit and cable trays for shielding purposes? Can the most sensitive circuits be designed with balanced front ends so that twisted pair wiring can be used?

Antennas. Most antennas need a ground plane; is it possible to group all antennas together so they can share a common ground plane? How would this arrangement affect mutual coupling between different antennas, and coupling to the interior? Will grouping affect RCS or lightning protection? If an HF antenna is desired, how can it be incorporated with the overall system design?

V SPECIFIC ARMY PROBLEMS

Considerations presented so far are applicable to both fixed and rotary wing aircraft. However, some additional or special considerations apply to helicopters (see Figure 5). The most obvious difference between fixed wing aircraft and helicopters is the rotary wing. Other differences include the presence of a metal rotor shaft, fixed landing gears, and large open doors. Tradeoff studies are again necessary to determine the impact of each special feature on the overall design goal.

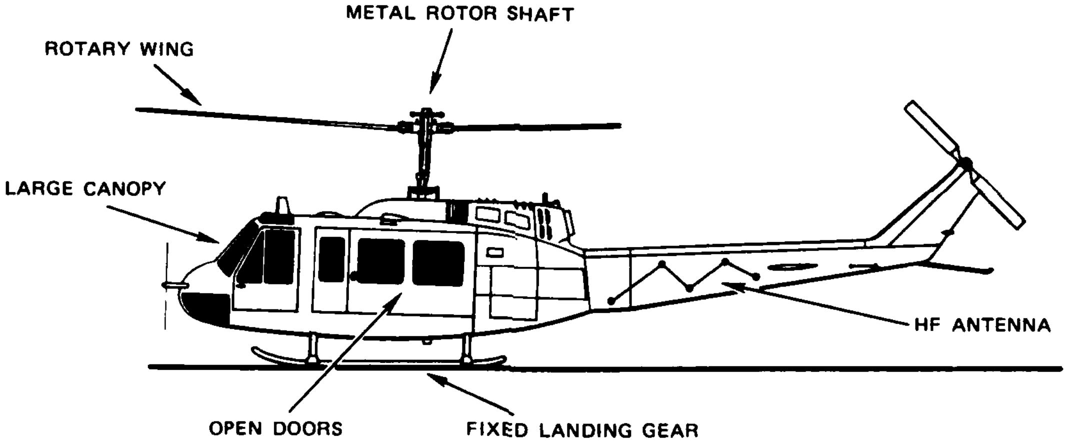


FIGURE 5 SPECIAL CONSIDERATIONS FOR HELICOPTERS

Rotary Wing. If minimum RCS is desired, special techniques must be used to obtain a blade with minimal reflection. The impact on lightning protection should also be considered.

Open Doors. Depending on the design and the particular mission, large open doors may present a problem for avionics equipment inside if the fuselage is relied upon for electromagnetic shielding (foil covering or flame spray). The system should be designed so that the doors need not be closed for proper operation.

Fixed Landing Gear. In some helicopters the landing gear is not retractable. Since it is likely to be composed of metal for some time, it would affect both RCS and lightning protection.

HF Communication. If NOE navigation is used, the HF band is currently the only means of communication available. The integration of an efficient HF antenna into an all-composite fuselage will be difficult to accomplish. Further study of this area is indicated.

Large Canopy. As with the large door openings mentioned above, the usually large canopy offers no electromagnetic shielding and equipment must be carefully located so that its proper functioning is not compromised. Some protection can be achieved by tinting the canopy with a conducting film; gold has been used successfully in other aircraft applications (e.g., the B-1). The large opening will also affect the RCS.

Metal Rotor Shaft. For both RCS and lightning protection, the presence of the rotor shaft must be considered.

Hovering Mode. Extended hovering in dry and dusty climates (desert) will lead to substantial charge accumulation on a helicopter. In the absence of a metal foil covering dielectric breakdowns are likely, and some means of discharging the static electricity is desirable.

VI FUTURE WORK

This section summarizes the major areas where more work is needed.

A. System Tradeoff Analysis

With the exception of the F-16 forward fuselage, built and tested by General Dynamics, there are no studies on the impact of advanced composite materials on a system level or tradeoff analysis. This is particularly true in the areas of lightning protection, RCS reduction, EMI/EMC, and antennas. Independent solutions to some problems in those areas exist, but the impact of the solutions on other than the considered area is not known. We have given some examples of how the different areas interact in the previous section.

B. EMI/EMC

One of the problems in this area is to develop a useful way of characterizing the coupling of internal and external interference to the critical circuits. The concepts of transfer impedance and shielding effectiveness presently in use are overly simplistic and not adequate. For instance, it is generally impossible to predict interference levels in a circuit if the shielding effectiveness of the circuit enclosure is known. The topological zoning approach would have a number of advantages and its applicability to the ACAP should be studied. One of the main advantages of the topological approach is that all interference sources — lightning, EMP, internal sources, TEMPEST, and others — are treated in a unified way. The chance that the solution of one particular problem interferes with another is therefore quite small. The correct treatment of power return, signal common, and safety and other grounds, follows directly from topological zoning considerations. The payoff from this analysis would be design guidelines for the ACAP avionics integration.

C. RCS

The RCS of an airframe depends upon the composite material selected, its surface treatment, and the shape of the airframe. Scale model measurements would give insights into the most effective approach to minimize the RCS, while analysis is indicated to tackle the problems of infrared signature and corona emissions. The importance of RCS is scenario-dependent. Therefore, work in this area may be unnecessary. If it is important, the impact of any measure to reduce the RCS on other electromagnetic problems and avionics integration must be considered.

D. Antennas

Studies have been conducted on antenna performance with composite materials at VHF and higher frequencies. Usually the ground plane is assumed to be graphite epoxy or a dielectric with a metal foil covering. To our knowledge no studies have been performed on the effect of grouping together several antennas over a composite ground plane, nor has there been any significant amount of research to determine HF antenna performance over a composite ground plane. Because of its importance to ACAP, this area needs particular emphasis. It is expected that the radiation pattern and the efficiency of an HF antenna strongly depend upon the size, shape, and material used for the composite; both the pattern and the efficiency may be altered significantly by the presence and distribution of internal metal (that is, avionics equipment and conduit, as well as metal structural parts). The HF antenna problems can be addressed by geometric theory of diffraction analysis techniques, modeling, actual measurements in anechoic chambers, some method of moments analysis, and scale measurements. The adequacy of scaling in this frequency range must be considered. The effects of metal coatings on antenna performance must also be analyzed.

VII THE ADVANCED COMPOSITE AIRFRAME PROGRAM

Originally it was anticipated that this program would provide inputs to the second phase of the ACAP. Unfortunately, due to delays in awarding contracts to the competing bidders, this was not possible. It is recommended that such inputs be provided in a follow-on to the present project. The successful bidders will probably not be familiar with all the electromagnetic problems associated with the use of composite materials. SRI International can provide assistance with these problems by reviewing the designs, suggesting alternate solutions to specific problems, and general consulting.

Appendix A

LIST OF TECHNICAL LITERATURE

The large amount of technical literature collected for this project made it necessary to enter essential bibliographic data into a computer data file for ready reference. We made use of the SPIRES (Stanford Public Information Retrieval System) data base management system on the Stanford University IBM-3033 computer facility. The main use of the data file was for our reference during the contract period; the file is searchable for all entries in a quick and efficient manner from any computer terminal which has access to the Stanford system.

The following pages list all current entries in the data file. The reports are listed in the order in which they were received and entered into the data base. The format is self-explanatory.

Two indices to the bibliography contained in this appendix are given at the end of the appendix. One index is arranged by keywords, the other by author's last name.

Abbreviations and Acronyms used in the Listing

ACAP	Advance Composite Airframe Program
AFAL	Air Force Avionics Laboratory
AFCRL	Air Force Cambridge Research Laboratories
AFFDL	Air Force Flight Dynamics Laboratory
AFML	Air Force Materials Laboratory
AGARD	Advisory Group for Aerospace Research and Development
AIAA	American Institute for Aeronautics and Astronautics
ASME	American Society of Mechanical Engineers
ATL	Advanced Technology Laboratory
AVRADA	Avionics Research and Development Activity
DNA	Defense Nuclear Agency
GD	General Dynamics
GE	General Electric
LTI	Lightning Technology, Incorporated
McDAC	McDonell Aircraft Company
NASC	Naval Air System Command
NELC	Naval Electronics Laboratory Center
NOSC	Naval Ocean Systems Center
ONR	Office of Naval Research
RADC	Rome Air Development Center
RIT	Rochester Institute of Technology
SAMPE	Society for the Advancement of Material and Process Engineering
SRC	Syracuse Research Corporation
USAEC	United States Army Electronics Command
WPAFB	Wright-Patterson Air Force Base

1. **Aviation Electronic Configuration Specification for Phase II/III ACAP Helicopter**

Keywords: ACAP, Avionics

Specification (1980)

Company: AVRADA

(Draft)

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2. **L-1011 Basic Materials and Design Features**

Keywords: L-1011, Structures, Avionics

Vugraph (1978)

Company: Lockheed

(Contains some informative vugraphs on the L-1011, including wiring and avionics. The year given above is an estimate only, there is no date given on any of the vugraphs.)

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3. **Materials and Structures, Science and Technology**

Keywords: ACAP

Apportionment Review (1979)

Company: Department of the Army

(Contains some vugraphs on ACAP)

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4. Simulated Lightning Tests on Graphite Laminates Protected with Thorstrand Aluminized Glass Cloth

Keywords: Lightning

Technical Report (1979)
Prepared by J. A. Plumer

Company: LTI for Hexcel Corp.

(Report No. LT-79-46, Lightning Technologies, Inc., Pittsfield, Massachusetts)

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5. Thorstrand

Keywords: Thorstrand, Lightning Protection

Catalog (1980)

Company: Hexcel Corp.

(Catalog contains two samples of Thorstrand fabric, and a paper presented by G. L. Patz, Hexcel Corp., 11711 Dublin Blvd., Dublin, California, at the Soc. Plastics Eng. Conference, Los Angeles, February 1980)

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6. RAM and Radome Materials Development Program

Keywords: RAM

Vugraph (1979)

Company: Boeing

(Lots of experimental absorption data. Difficult to interpret, there is almost no text. This may be an attachement to Reference #50.)

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7. Graphite/Epoxy Fabric Utilized on the C4 Trident Missile Program

Keywords: Structures

Abstract: Graphite/epoxy fabric was found to provide the optimum properties for the C4 Trident equipment section. The manufacturing development was initiated with the fabrication of test and subscale components and progress through full scale C4 assemblies.

Article (1975)
Prepared by D. R. Sidwell, F. B. Yarborough

Company: Lockheed

(Presented at the 20th National SAMPE Symposium, San Diego, California, April 1975)

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8. Design of Large Diameter Offset-fed Antennas

Keywords: Antennas, Structures

Abstract: A desire for maximum efficiency in space antennas is placing emphasis on the application of offset fed antennas. The basic wrap-rip design approach for large apertures as applied to both the symmetric and offset configurations is discussed and performance/growth capability presented.

Article (1979)
Prepared by A. A. Woods, W. D. Wade

Company: Lockheed

(Presented at the AIAA/NASA Conference on Advanced Technology for Future Space Systems, Hampton, Virginia, May 1979.)

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9. Advanced Antenna System Requirements and Implications on Material Characteristics

Keywords: Antennas, Structures

Article (1979)
Prepared by H. L. Staubs, G. G. Chadwick, A. A. Woods

Company: USAF/Lockheed

(Presented at the National SAMPE Symposium, San Francisco, California, May 1979.)

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10. Satellite Applications of Metal-matrix Composites

Keywords: Metal Matrix, Structures, Satellites

Abstract: Graphite, boron, silicon/carbide, and aluminum/oxide fibers in a matrix of aluminum or magnesium are compared to graphite/epoxy and conventional materials. The system effectiveness of graphite fibers in aluminum and magnesium is shown to be very good in satellite design applications in which thermal/structural distortion or high specific stiffness is a major considerations.

Article (1979)
Prepared by H. H. Armstrong

Company: Lockheed

(Presented at the National SAMPE Symposium, San Francisco, California, May 1979)

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11. Considerations on the Use of Graphite-reinforced Plastics for Space Erectable Antennas

Keywords: Antennas, Structures

Abstract: The results of an investigation of the relationships between time, humidity, vacuum, lay up geometry and initial strain, and viscoeleastic behavior are presented and compared to theoretical solutions.

Article (1978)
Prepared by A. A. Woods, M. Kural

Company: Lockheed

(Presented at the 7th AIAA Communications Satellite Conference, San Diego, California, April 1978.)

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12. Design of Self-deploying, Extremely Large Parabolic Antennas and Arrays

Keywords: Antennas, Structures

Abstract: A design solution for a large aperture space antenna is presented.

Article (1977)
Prepared by A. A. Woods, W. D. Wade

Company: Lockheed

(Presented at the IEE Mechanical Engineering in Radar Symposium, Arlington, Virginia, November 1977.)

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13. Application of Metal-matrix Composites to Spaceborne Parabolic antennas

Keywords: Antennas, Metal Matrix

Abstract: The application of graphite-reinforced metal composites is investigated for large deployable antennas. The performance of large parabolic reflectors is discussed, and the requirements for stiffness and precise surface accuracy are established.

Article (1979)
Prepared by W. D. Wade, A. M. Ellison

Company: Lockheed

(Presented at the National SAMPE Symposium, San Francisco, California, May 1979)

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14. Graphite/Epoxy Structures -- Design and the Manufacturing Interface

Keywords: Structures, Manufacturing

Article (1977)
Prepared by R. S. Petersen, F. B. Yarborough

Company: Lockheed

(Published by ASME, presented at the Design Engineering Conference, Chicago, Illinois, May 1977)

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15. AVRADA Support of ACAP

Keywords: ACAP Support

Memorandum (1979)

(This is an undated Memo discussing what AVRADA should be doing to support ACAP.)

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16. AVRADA and ACAP

Keywords: ACAP, Avionics

Memorandum (1980)

(This is a report on a meeting between ATL and AVRADA on the subject of ACAP and avionics integration.)

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17. Input Impedance Measurements of IFF/COMM and TACAN Antennas

Keywords: Antenna Impedance

Technical Memorandum (1976)
Prepared by G. N. Fruktow

(Supplement to Report No. MDC A3441, Ref. #33.)

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18. Electromagnetic Shielding by Advanced Composite Materials

Keywords: Shielding, Aircraft, Missiles

Abstract: The transmission of electromagnetic waves through planar sheets and cylindrical shells of advanced composite laminates is considered in both the frequency and time domains. Attention is concentrated on the frequency range characteristic of the nuclear electromagnetic pulse. The composite laminates are modeled for the purposes of this study by isotropic dielectric or conducting materials.

Final Report (1978)
Prepared by K. F. Casey

Company: Kansas State University for AFOSR

(Report No. AFWL-TR-77-201)

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19. Fundamental Study of the Electromagnetic Properties of Advanced Composite Materials

Keywords: **Permittivity, Permeability, Conductivity, Doping, Modeling**

Abstract: This report covers an effort to understand, model and modify the fundamental electrical properties of advanced composite materials, specifically graphite/epoxy and boron/epoxy. The electrical properties of graphite and boron fibers and of epoxy were measured. The anisotropic conductivity of boron fibers was studied. Models were developed which predicted the electrical properties of the composites-- with reasonable accuracy for some cases. The conductivity of graphite fibers was increased about a factor of 50 (to 10E6 mhos/meter) by doping with boron, the conductivity of boron fibers was increased about a factor of 10E3 by doping with carbon.

Phase Report (1978)
Prepared by W. J. Gajda

Company: Syracuse University for RADC

(Report No. RADC-TR-78-158)

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20. Measurement of Electrical Conductivity in Carbon/Epoxy Composite Material Over the Frequency Range 75 MHz to 2.0 GHz

Keywords: **Conductivity, Stripline Method, Electrical Measurements**

Abstract: A stripline technique for the measurement of longitudinal and transverse conductivity of graphite (carbon)/epoxy composite materials over the VHF/UHF (75 MHz to 2.0 GHz) range is described. The method is unusual in that it is essentially free of the uncertain effects of contact resistance between the sample and the measurement apparatus. The underlying theory of the method rests on the relationship between the conductivity of the sample and the lossy standing wave patterns established on the strip transmission line. The method accommodates a range of sample *conductivities from 10E2 mhos/m (e.g. transverse carbon/epoxy) to aluminum (approx. 10E7 mhos/m). Actual measurements were made fron 75 MHz to 2 GHz. The method itself should be usable from 50 MHz to 4 GHz.*

Phase Report (1979)
Prepared by W. F. Walker, R. E. Heintz

Company: RIT for RADC

(Report No. RADC-TR-79-255)

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21. Interaction of Advanced Composites with Electromagnetic Pulse (EMP) Environment

Keywords: EMP, Shielding Effectiveness, Diffusion

Abstract: This report presents the results of a program to investigate shielding effectiveness of advanced composite materials against an electromagnetic pulse (EMP). The primary objectives were to expand the existing data base by acquiring shielding test data on selected composite laminates, either coated with a variety of foil and screen materials, or uncoated, and develop design guidelines that can be used to support the development of composite structures having an EMP shielding requirement. A secondary objective was to obtain an improved understanding of the relationship between material shielding parameters and EMP coupled response.

Final Report (1975)
Prepared by D. Strawe, L. Piszker

Company: Boeing for WPAFB

(Report No. AFML-TR-75-141)

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22. Vulnerability/Survivability of Composite Structures -- Lightning Strike (Design Guidelines)

Keywords: Lightning Damage, Lightning Protection, NDI, Joint Design

Abstract: This design guidance manual is Volume II of the final report. It provides clear, easy to read, and easy to find guidance on how to establish lightning protection for graphite/epoxy structure. The basis for the guidance is the test work described in Volume I.

Final Report (1978)
Prepared by S. D. Schneider, C. L. Hendricks, G. O. Olson

Company: Boeing for WPAFB

(Report No. AFFDL-TR-77-127, Volume II)

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23. Vulnerability/Survivability of Composite Structures -- Lightning Strike (Program Results)

Keywords: Lightning Damage, Lightning Protection, NDI, Joint Design

Abstract: The objective of this program was to develop practical lightning protection systems for aircraft graphite/epoxy structure. The program was divided into five Tasks: Threat Definition, Damage Assessment--Unprotected Composites, Protection System Development, Full-Scale Hardware Demonstration, and Preparation of Design Manual. Three primary protection systems, aluminum wire screen, aluminum flame spray, and aluminum flame spray strips were selected and evaluated for extensive development and testing during Task III and Task IV.

Technical Report (1978)
Prepared by S. D. Schneider, C. L. Hendricks, G. O. Olson

Company: Boeing for WPAFB

(Report No. AFFDL-TR-77-127 Volume I)

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24. Electromagnetic Properties and Effects of Advanced Composite Materials: Measurement and Modeling

Keywords: Shielding Effectiveness, Antennas, Conductivity, Permittivity, Permeability, Method of Moments

Abstract: This report covers several areas: Electromagnetic properties of composite materials are given for the range DC to 30 MHz, Techniques of measurement are discussed in the range DC to 1 GHz, Electromagnetic shielding theory is discussed. Surface transfer impedance and the two-loop method are related to the conductivity. A matrix method for the calculation of shielding effectiveness for laminated anisotropic materials (perpendicular incidence) is presented, The modification required by the method of moments to allow calculation involving non-perfect conductors are discussed, A comparison of antenna patterns over a graphite/epoxy ground plane and an aluminum ground plane for dipole and monopole antennas at 370 MHZ and 837 MHz is given.

Phase Report (1978)

Company: Georgia Tech/Syracuse Univ./State Univ. of N. Y. or RADC

(Report No. RADC-TR-78-156)

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25. Effects of Electromagnetic Energy on Advanced Composite Aircraft Structures and their Associated Avionic & Electrical Equipment

Keywords: Electromagnetic Properties, Precipitation Static, Bonding, Grounding, Antennas, Lightning, EMP, EM Coupling, EMC, EMI

Abstract: This report presents the results of a program to investigate electromagnetic energy effects on advanced composite aircraft structures and their effects on aircraft electronic systems. The principal tasks were: determine intrinsic electromagnetic properties of graphite/epoxy composite material at DC and from 1 to 18 GHz, conduct an electromagnetic coupling analysis to quantitatively compare the effects into a hardened aluminum aircraft structure with *those of graphite/epoxy (G/E) and hybrid G/E aluminum aircraft structures, conduct antenna tests to compare the effects of an aluminum to a composite ground plane, obtain precipitation static....*

Final Report (1977)

Company: Boeing for NASC

(Report No. D180-20186-4, Volume I)

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26. Advanced Composite Technology Fuselage Program

Keywords: Shielding Effectiveness, Antenna Performance, Radar Cross Section

Abstract: The research and development activity reported in this volume covers the structure/system compatibility testing performed on an advanced composite F-5 mid-fuselage component composed primarily of graphite-epoxy. The three areas of investigation pursued were antenna performance, radar cross section, and electromagnetic characteristics.

Technical Report (1974)

Company: Convair for WPAFB

(Report No. AFML-TR-71-41, Vol.VII)

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27. Battle Damage Tolerant Wing Demonstration Test

Keywords: Structures, Damage Test

Summary Report (1978)

Company: Boeing for NASC

(This document provides an overview of the full-scale ballistic tests demonstrating the survivability of the Battle Damage Tolerant Wing design concepts.)

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28. Electromagnetic Effects of (Carbon) Composite Materials upon Avionics Systems

Keywords: Avionics Systems, Shielding Effectiveness, Lightning, EMX

Conference Proceedings (1980)

Company: AGARD for NATO

(Pub. No. AGARD-CPP-283. Contains several articles on Lightning and EMX. Preprint of the proceedings is Ref. 28A.)

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29. Metal Matrix Composites

Keywords: Metal Matrix

Catalog (1979)

Company: DWA

(Catolog gives mechanical properties only. Company address: DWA Composite Specialities, Inc., 21119 Superior Street, Chatsworth, California)

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30. Vertical Lift Technology Review

Keywords: Technology Review

Final Report (1980)

(This assessment of Army Vertical Lift Technology was conducted at the request of the Assistant Secretary of the Army for Research, Development and Acquisition.)

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31. Effects of Composites on Aviation Electronics

Keywords: EMX, Aviation Electronics

Abstract: This survey attempts to provide AVRADA with a comprehensive overview of the many areas of concern and of some proposed programs to address these areas.

Survey (1979)
Prepared by J. Rubin, F. Cansler

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32. Technology Plan for Electromagnetic Characteristics of Advanced Composites

Keywords: Shielding Effectiveness, Permittivity, Conductivity, Antenna Performance, EMC

Abstract: The report presents a program for the development of the fundamental technology for the assessment of the electromagnetic compatibility (EMC) effects of the use of advanced composite materials in aircraft. A survey of the electromagnetic impact of the use of advanced composite materials in aircraft is given. Electromagnetic hazards (lightning, nuclear blast EMP, precipitation static and radar) are described and related to the shielding performance of advanced composite materials. In addition the effects of composite materials on antenna performance is discussed.

Phase Report (1976)

Company: RIT for RADC

(Report No. RADC-TR-76-206)

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33. Electromagnetic Effects of Advanced Composites

Keywords: Shielding Effectiveness, Antenna Performance

Article (1975)
Prepared by C. D. Skouby

Company: McDAC for ONR

(Report No. MDC A3441)

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34. Advanced Composite Aircraft Electromagnetic Design and Synthesis

Keywords: Lightning, EMP, Shielding Effectiveness, Joint Coupling

Abstract: This report describes simple methods for determining the shielding provided by an aircraft's exterior surface and the coupling of the interior fields to cables and transmission lines within aircraft cavities. This data is used to determine whether devices commonly found on aircraft will be subject to upset or burnout. The results found in this volume can be used to perform trade-offs betweem EM shielding, weight, and cost.

Interim Report (1980)

Company: SRC for ONR/NASC

(SRC TR 79-490)

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35. Satellite Applications of Metal Matrix Composites

Keywords: Metal Matrix, Antennas, Stiffness

Abstract: The design study and data verification goal of this program was to determine the projected system payoff potential of metal matrix composites, as compared to conventional metals and non-metallic materials, for space system structural members. Twenty-one satellite components were surveyed for potential metal matrix advantages. Continuous filament fibers of graphite, silicon carbide, aluminum-oxide, and boron in aluminum and magnesium metal matrix systems were evaluated for selected components.

Final Report (1979)

Company: Lockheed for WPAFB

(Report No. AFML-TR-79-4007)

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36. Advanced Composites: Electromagnetic Properties, Vulnerabilities, and Protective Measures

Keywords: Conductivity, Shielding, Vulnerability

Abstract: This report outlines and discusses a measurement and analysis program for assessing the electromagnetic (EM) properties and vulnerability of and protective measures for, advanced composite materials that are being used, and being developed for use, in the design and construction of aerospace vehicles. The main purpose of the report is to suggest areas of investigation and the kinds of data required to compile a technical data base to accomplish this assessment.

Project Report (1977)
Prepared by A. L. Hiebert

Company: Rand for USAF

(Report No. R-1979-AF)

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37. Advanced Composites: Natural Space Environment Simulation, Testing, and Analysis

Keywords: Shielding, Mechanical Properties, Space Environment, Simulation

Abstract: The proposed program described in this report outlines the requirements for studying and developing a test facility capable of simulating the energy sources and temperatures encountered in the natural space environment and for measuring their effects on composite materials and structures used in aerospace vehicles for an effective 10-year lifetime.

Project Report (1978)
Prepared by A. L. Hiebert

Company: Rand for USAF

(Report No. R-1979/1-AF)

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38. Development of Graphite/Metal Advanced Composites for Spacecraft Applications

Keywords: Graphite Metal, Structures, Satellite

Abstract: The objective of this program is to develop reproducible precursor materials, fabrication techniques, preliminary design data, and design concepts on graphite reinforced metal composites for use in spacecraft components. This program shall provide sufficient data on processing, fabrication, mechanical properties, physical properties and structural element/subcomponent/component performance to permit a determination of utility of graphite reinforced metal composites applied to spacecraft and other space structures.

Interim Technical Report (1979)

Company: Lockheed for WPAFB

(Report No. LMSC-D671326)

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39. Composite Forward Fuselage Systems Integration

Keywords: Lightning, EMC, Avionics

Abstract: This program performed the necessary development to integrate avionic and electrical systems into a composite forward fuselage. This report documents the development and presents the findings in terms of design guidelines that should insure satisfactory electromagnetic compatibility.

Final Report (1978)

Company: GD for WPAFB

(Report No. AFFDL-TR-78-110, 2 Volumes)

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40. Joining of Advanced Composites

Keywords: Joints, Structures

Engineering Design Handbook (1979)

(Darcom Pamphlet No. 706-316)

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41. **Advanced Manufacturing Development of a Composite Empennage Component for L-1011 Aircraft**

Keywords: L-1011, Vertical Fin, Structures

Quarterly Technical Report (1979)

Company: Lockheed for NASA

(Report No. LR29127)

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42. **DOD/NASA Structural Composites Fabrication Guide**

Keywords: Materials, Structures, Fabrication, Costs

Final Report (1979)

(Second Edition, Two Volumes. Good introduction and overview of structural composites. No EM data, only structural and cost data.)

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43. **NARMCO Materials, Inc.**

Keywords: Materials, Adhesives, Structures

Catalog (1976)

Company: Celanese Corp.

(Contains structural data only, no information on EM properties. Narmco Materials, Inc., 600 Victoria Street, Costa Mesa, California)

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44. **Advanced Materials Technology**

Keywords: Materials

Catalog (1977)

Company: Ford Aerospace

(Contains pictures and brief descriptions about the capabilities of Ford Aerospace, no data.)

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45. S-3A Composite Spoiler In-Service Experiences

Keywords: Structures

Vugraph (1979)

Company: Vought Corp.

(Vugraphs showing how composite spoilers were repaired. Very little text.)

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46. Dielectric Materials

Keywords: Materials

Catalog (1977)

Company: Emerson & Cuming, Inc.

(Canton, Massachusetts)

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47. Protection Optimization for Advanced Composite Structures

Keywords: Lightning, EMC, Shielding Effectiveness, Structures, EMP

Abstract: The objective of this program is to develop practical optimized and integrated protection and shielding methodologies for the protection of composite aircraft structures against multiple threats. Threats addressed include lightning (direct and indirect), nuclear electromagnetic pulse (NEMP), electromagnetic interference (EMI) and high energy lasers (HEL).

Interim Technical Report (1979)

Company: Grumman for AFFDL/WPAFB

(Seventh Quarterly Progress Report, 15 March 1979)

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48. Protection Optimization for Advanced Composite Structures

Keywords: Shielding Effectiveness, Structures, EMP

Abstract: The objective of this program is to develop practical optimized and integrated protection and shielding methodologies for the protection of composite aircraft structures against multiple threats. Threats addressed include lightning (direct and indirect), nuclear electromagnetic pulse (NEMP), electromagnetic interference (EMI) and high energy lasers (HEL).

Interim Technical Report (1979)

Company: Grumman for AFFDL/WPAFB

(Tenth Quarterly Progress Report, 15 Deceember 1979)

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49. Development of a Low-Cost Field Fix for the RU-21H Aircraft Antenna

Keywords: Antennas, Structures

Abstract: A low-cost field fix for the RU-21H (Guardrail) aircraft antenna was developed, tested, and installed on a fleet of RU-21H aircraft to prevent catastrophic failure of the antennas, which was occuring in the field between 500 and 1000 hours of operation.

Technical Memorandum (1980)

(Report No. USAAVRADCOM TM 80-D-4)

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50. Structural Radar Absorbing Material Development Study

Keywords: RAM, Structure

Proposal (1979)

Company: Boeing for AAVRADA

(No date is given in the proposal, the year above is an estimate.)

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51. Antenna Analysis Using a Modified WIRANT Compiler Program

Keywords: Antenna Analysis, WIRANT

IR&D Report (1978)

Company: Boeing

(Document No. D6-44719)

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52. Effects of Graphite Composite Skins on HF Antennas

Keywords: Antenna

Letter (1980)
Prepared by D. F. Strawe

(This is a reply to F. Cansler, it gives an example for an HF antenna on a graphite composite ground plane.)

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53. Coatings for Lightning Protection of Structural Reinforced Plastics

Keywords: Lightning Protection, Coatings

Abstract: Coatings and coating systems developed for protecting boron-filament-and graphite-fiber-reinforced plastic composites from structural damage by lightning strikes were investigated and developed. These coatings are 6-mil-thick aluminum foil, 200 by 200 mesh aluminum wire fabric, 120 by 120 mesh aluminum wire fabric, and a coating containing aluminized glass filaments. Each of these was found capable of preventing mechanical damage to the composite at the 100-kA test level. None of the coatings could fully protect the composites from damage due to the high-coulomb component of the artificial lightning stroke.

Technical Report (1972)
Prepared by R. O. Brick, C. H. King, J. T. Quinlivan

Company: Boeing for AFML/WPAFB

(Report No. AFML-TR-70-303, Part II)

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54. Thermal and Electrical Conductivity of Metal-Powder/Resin Composites

Keywords: Metal Matrix, Thermal Properties, Conductivity

Abstract: The results of provisional measurements are given on the thermal and electrical properties in the temperature range from room temperature down to 2 K of the following composite materials: HERA-type polymer-moulded samarium-cobalt magnets and two kinds of carbon fibre reinforced plastic - the high tensile and the high strength types.

Annual Report (1977)
Prepared by H. M. Rosenberg

Company: Clarendon Laboratory, Oxford

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55. Summary of Required Input Parameters for Emitter Models in IEMCAP

Keywords: EMC, IEMCAP

Abstract: The Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP) requires the inputting of various parameters to describe the emitter ports' emission spectra. This information is contained in the IEMCAP User's Manual (RADC-TR-74-342) but is not presented in a very concise manner. This report has summarized the required parameters and their measurement units.

Final Technical Report (1978)
Prepared by C. R. Paul, D. D. Weiner

Company: University of Kentucky/Syracuse University for RADC

(Report No. RADC-TR-78-140)

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56. Intrasystem Electromagnetic Compatibility Analysis Program

Keywords: EMC, Intrasystem Analysis, IEMCAP

Abstract: This user's manual describes the operation and usage of the Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP). This volume, the Engineering Section, contains descriptions of the program, its organization, analytic basis, operating principles, and logic flow. A complete operation of all mathematical models used in IEMCAP is included. The emitter and the receptor spectrum model equations are described including their derivations. The transfer models, which compute emitter to receptor coupling, are similarly described.

Final Report (1974)
Prepared by J. L. Bogdanor, R. A. Pearlman, M. D. Siegel

Company: McDAC for RADC

(Report No. RADC-TR-74-342, Volume I)

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57. Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP) F-15 Validation

Keywords: EMC, Intrasystem Analysis, Avionics, IEMCAP

Abstract: The validity and usefulness of the Intr a-system Electro- magnetic Compatibility Analysis Program (IEMCAP) is assessed, based on its predictions for the F-15 air superiority fighter aircraft. The aircraft was simulated using a combination of known, measured and approximated data. A sensitivity study is also performed, indi cating the effects of approximating unknown IEMCAP input parameters. Finally, a physical interpretation of the integrated EMI margin is given, and an assessment is made of its validity as an EMC figure merit.

Final Technical Report (1977)
Prepared by R. A. Pearlman

Company: McDAC for RADC

(Report No. RADC-TR-77-290, Two parts)

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58. IEMCAP Implementation Study

Keywords: Intrasystem Analysis, EMC, IEMCAP

Abstract: This report addressed the need for an intrasystem analysis in the development of a new or modified weapon system. A survey was first performed to determine the current implementation of the EMC process in a weapon system's development. The results of this survey are presented. The economics of using a computerized intrasystem analysis was also examined. This report covers the costs associated with installing and using an analysis system and the cost reduction benefits derived from its utilization.

Final Technical Report (1977)
Prepared by E. Freeman

Company: Sachs/Freeman Associates for RADC

(Report No RADC-TR-77-376, 2 Volumes)

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59. Lightning Effects on and Electromagnetic Shielding Properties of Boron and Graphite Reinforced Composite Materials

Keywords: Lightning, Shielding Effectiveness

Abstract: An investigation employing both destructive and nondestructive testing techniques affirms that lightning-produced currents adversely affect boron- and graphite-reinforced composites for aircraft. While such composite materials offer significant structural advantages over conventional metals, they are much more easily damaged by the high currents associated with lightning. A majority of the coatings tested to determine their ability to protect composites in a lightning environment actually aggravated composite deterioration. To mitigate lightning damage, composite coatings must be either highly conductive or highly insulating. Limitations are identified that must be overcome before coatings of either type can be deemed acceptable. Studies were made of the electromagnetic shielding properties of composite materials. It is shown *that they have much poorer shielding properties than conventional metal structures. The implications as regards the electrical design of future aircraft are discussed.*

Technical Report (1972)
Prepared by F. A. Fisher, W. M. Fassell

Company: GE/HV Lab for AFAL/WPAFB

(Report No. AFAL-TR-72-5)

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60. Protection Optimization for Advanced Composite Structures

Keywords: Shielding Effectiveness, Structures, Optimization

Abstract: See Reference 47 & 48.

Interim Technical Report (1979)

Company: Grumman for AFFDL/WPAFB

(Eighth Quarterly Progress Report, 15 June 1979)

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61. Measurement of the Electrical Properties of Composite Materials in the Frequency Range of DC to 30 MHz

Keywords: Conductivity, Permittivity, Permeability, EMC

Abstract: Work reported here is an extension of work reported in RADC-TR-78-156 (see Reference No. 24). A much higher conductivity for boron/epoxy is reported using better contacting techniques. For graphite/epoxy coupled circuit theory is used to relate the conductivity to the measured resistance of a sample, the effect of absorbed moisture on the conductivity is reported, and the effective conductivity of a mutiply laminate is reexamined.

Phase Report (1979)
Prepared by W. J. Gajda

Company: Syracuse University for RADC

(Report No. RADC-TR-79-203)

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62. Assessment of the Electromagnetic Screening Characteristics of Carbon Fibre Composite Materials

Keywords: Shielding Effectiveness

Abstract: Investigation of the r.f. screening characteristics of carbon fibre samples was made in the magnetic mode at frequencies from 150 kHz to 30 MHz and in the electric mode in the range 50 to 1000 MHz.

Article (1980)
Prepared by D. A. Bull, G. A. Jackson

(Presented at the IERE EMC Conference in Southampton, September 1980)

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63. RF Resistivity of Carbon Fibre Composite Materials

Keywords: Resistivity, Conductivity

Abstract: This paper presents the investigations that have been made to determine the electrical resistance characteristics of carbon fibre composite samples at dc and frequencies up to 300 MHz.

Article (1980)
Prepared by B. W. Smithers

(Presented at the IERE EMC Conference in Southampton, September 1980)

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64. Modification and Modeling of the Electrical Conductivity of Fiber-reinforced Advanced Composites

Keywords: Conductivity, Modeling, Doping

Abstract: The basic mechanisms governing the electrical conductivities of composites are discussed. Models are developed which allow the prediction of these properties. Experimental measurements of composite and fiber conductivities are presented. The central importance of fiber conductivity in determining overall material properties is demonstrated. The initial results of experiments aimed at increasing the conductivities of graphite and boron fibers by adding selected impurities are discussed. Such doping techniques offer the promise of composite materials with near metallic conductivities and insignificant degradation in specific strengths.

Article (1978)
Prepared by W. J. Gajda

(Presented at the SAMPE Symposium in Anaheim, May 1978.)

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65. Electromagnetic Shielding Effectiveness of Advanced Composite Materials

Keywords: Shielding Effectiveness

Abstract: Several popular methods for measuring EM shielding effectiveness are reviewed and their interrelationships examined. The plane wave/flat plate configuration is used as a reference. Each measurement method is analytically related to the plane wave/flat plate case. Applicability of the methods of measurement of shielding properties to advanced composite materials is examined.

Article (1978)
Prepared by J. L. Allen

(Presented at the SAMPE Symposium in Anaheim, May 1978.)

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66. Relative Behavior of Graphite/Epoxy and Aluminum in a Lightning Environment

Keywords: Lightning

Abstract: The macroscopic electrical response of aluminum and Graphite/Epoxy (Gr/Ep) composite panels subject to a lightning environment was investigated to determine if metal and Gr/Ep would have different probabilities of lightning strike attachment. Results show that despite differences in electrical properties, metal and Gr/Ep do not exhibit any significant differences in lightning attach point characteristics.

Article (1978)
Prepared by C. D. Skouby

(Presented at the SAMPE Symposium in Anaheim, May 1978.)

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67. Effects of Lightning Current Waveform Components on Graphite/Epoxy Composite Material

Keywords: Lightning

Abstract: This paper deals principally with lightning current waveform related damage of unprotected multi-ply graphite/epoxy composite materials. The lightning test waveform was broken into component parts, which were applied individually and in various combinations to the test panels to observe differences in damage resulting from the different test conditions. Preliminary results indicate that testing of the material with the complete waveform may cause more damage than when the various waveform components were applied one at a time to one location. In a related experiment, a 9-ply unprotected Graphite/Epoxy panel was punctured by the high-peak current component of the lightning strike but not by the intermediate and continuing currents. In contrast, an aluminum panel will not be punctured by the high-peak current but the continuing current will cause burn through or rear surface melting.

Article (1978)
Prepared by E. H. Schulte

(Presented at the SAMPE Symposium in Anaheim, May 1978.)

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68. Lightning Conductive Characteristics of Graphite Composite Structures

Keywords: Lightning, Antennas

Abstract: The optimum lightning protection design approach for graphite composite aircraft structures is to fully utilize their electrical conductive properties. Douglas Aircraft Company has conducted a series of lightning tests to define various conductive properties of graphite composite panels and joints. A Thermovision mapping technique was used to successfully record the lightning current flow pattern on graphite composite panels. The conductive characteristics for different graphite fiber layups, panel dimensions, joint interface designs, and fastener effects are presented. The conductive characteristics for precipitation static charges and the antenna ground plane effects are also discussed.

Article (1978)
Prepared by J. T. Kung, M. P. Amason

(Presented at the SAMPE Symposium in Anaheim, May 1978.)

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69. Conductivity Measurements of Graphite/Epoxy Advanced Composites at Microwave Frequencies

Keywords: Conductivity

Abstract: Waveguide and freespace microwave transmission loss measurements of graphite/epoxy laminate were conducted at frequencies from 1 to 18 GHz. Radio frequency conductivity is derived from these measurements. A description of the measurements systems and a discussion relating advanced composite RF conductivity to effects on advanced composites aircraft and their associated systems are presented in this document.

Article (1978)
Prepared by R. D. Force

(Presented at the SAMPE Symposium in Anaheim, May 1978.)

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70. Electromagnetic Coupling to Advanced Composite Aircraft With Application to Trade-off and Specification Determination

Keywords: EMP, Lightning, Shielding Effectiveness, Circuits, Susceptibility

Abstract: This paper describes simple methods for determining the shielding provided by an aircraft's exterior surface and the coupling of the interior fields to cables and transmission lines within aircraft cavities. The results can be used to determine trade-offs between electromagnetic shielding, weight, and cost. The expected threat to a US Navy advanced composite aircraft is defined. The concept of transfer impedance is used to decouple the interior problem from the exterior. Penetration through joints in composites is discussed. Upper bounds are obtained on the open-circuit voltage, short-circuit current, power, and energy at the terminals of an unshielded transmission line. Comparisons are made to typical device upset and burnout levels.

Article (1980)
Prepared by R. Wallenberg, E. Burt, G. Dike

Company: SRC

(Review article, journal not known.)

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71. Generalized Network Formulation for Aperture Problems

Keywords: Method of Moments, Aperture Coupling, Theory

Abstract: A general formulation for aperture problems is given in terms of the method of moments. It applies to any two regions isolated except for coupling through the aperture. The aperture characteristics are expressed in terms of two aperture admittance matrices, one for each region. The admittance matrix for one region is independent of the other region, and hence can be used for any problem involving that region and aperture. The solution can be represented by two generalized n-port networks connected in parallel with current sources. The current sources are related to the tangential magnetic field which exists over the aperture region when the aperture is closed by an electric conductor. Explicit formulations are given for two problems, that of an aperture in a conducting plane with plane-wave excitation, and that of a waveguide feeding an aperture in a conducting plane.

Technical Report (1975)
Prepared by R. G. Harrington, J. R. Mautz

Company: Syracuse University for AFCRL

(Report No. TR-75-13.)

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72. Electromagnetic Transmission Through a Rectangular Aperture in a Perfectly Conducting Plane

Keywords: Aperture Coupling, Method of Moments, Theory

Abstract: A computer program is developed for calculating the transmission characteristics of a rectangular aperture in a perfectly conducting plane excited by an incident plane wave. The solution is obtained from the integral equation for the equivalent magnetic current using the method of moments.

Technical Report (1976)
Prepared by J. R. Mautz, R. F. Harrington

Company: Syracuse University for AFCRL

(Report No. TR-76-1.)

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73. Electromagnetic Transmission Through a Slit in a Perfectly Conducting Plane

Keywords: Method of Moments, Aperture Coupling, Theory

Abstract: Two computer programs are developed for calculating the transmission characterisitcs of a slit in a perfect electric conductor of infinite extent excited by an electric line source (TM case) or a magnetic line source (TE case) parallel to the axis of the slit. The computer programs are described in detail and sample input-output data given.

Technical Report (1976)
Prepared by D. T. Auckland

Company: Syracuse University for NSF

(Report No. TR-76-9, Master's Thesis.)

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74. Method of Moments Applications. Volume VII. Aperture Coupling Through Long Slots.

Keywords: Method of Moments, Aperture Coupling, Theory

Abstract: The problem of a plane wave incident upon one or more long, parallel slots in an infinite plane screen is treated by the method of moments. A Galerkin's solution with triangular expansion and weighting functions is used. The complete solution for aperture fields, transmission coefficients, near and far fields is formulated and programmed. Arbitrary polarization and arbitrary angles of incidence are treated. Where comparison is possible, there is good agreement with classical results. Wide slots, and multiple slots, which cannot be treated by classical methods, are readily handled by the method of moments. Two separate computer programs have been prepared for (a) single slots and (b) double slots. Program listings and descriptions are presented. Representative examples are given.

Phase Report (1975)
Prepared by J. Chou, A. T. Adams

Company: Syracuse University for RADC

(Report No. RADC-TR-73-217-Vol-7.)

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75. Analysis of Arbitrarily Oriented Thin Wire Antennas over a Plane Imperfect Ground

Keywords: Antenna, Ground Plane, Theory

Abstract: This work considers the analysis of thin wire antennas of arbitrary orientation above imperfectly conducting ground planes. Emphasis is placed on the development of fast and accurate techniques for computation of the characteristics of antenna systems. An important problem is the evaluation of certain semi-infinite integrals encountered in the exact Sommerfeld solution.

Article (1977)
Prepared by T. K. Sarkar

(Published in Archiv fuer Elektronik und Uebertragunstechnik, Vol. 31, pp. 449-457, 1977.)

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76. Lightning Protection of Aircraft

Keywords: Lightning, Avionics

Abstract: This handbook summarizes the current knowledge concerning the potential lightning effects on aircraft and the means that are available to designers and operators to protect against these effects. The impetus for writing this book comes from two sources -- the increased use of nonmetallic materials in the structure of aircraft and the constant trend toward using electronic equipment to handle flight-critical control and navigation functions. Nonmetallic structures are inherently more likely to be damaged by a lightning strike than are metallic structures. Nonmetallic structures also provide less shielding against the intense electromagnetic fields of lightning than do metallic structures. These fields have demonstrated an ability to damage or cause upset of electronic equipment. The purpose of this book is to present the most important parts of this body of knowledge in a manner most useful to the designer and the operator.

Reference Publication (1977)
Prepared by F. A. Fisher, J. A. Plumer

Company: General Electric Company for NASA

(Report No. NASA RP-1008. Chapter 7 includes a discussion of protection of advanced composite aircraft structures. Each chapter has an extensive bibliography.)

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77. Use of Electro-Optical Technology to Achieve EMP Hardness

Keywords: **Fiber Optics, EMP**

Abstract: (From the introduction) ... An approach to hardening which has not been effectively developed for EMP hardening (for that matter EMC or EMI applications) is the integration of electro-optical links into system designs. This paper will ... present the strengths and weaknesses of electro-oprical technology, and develop principles for its application in system EMP protection design.

Article (1981)
Prepared by G. H. Baker, W. H. Hardwick

Company: DNA and JAYCOR for DNA

(Paper presented at the 1980 DNA Symposium on EMP Simulation and System Hardening.)

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78. Thin-Wire Methods for Electromagnetic Problems Involving Advanced Composite Materials

Keywords: **Antennas, Thin Wire, Method of Moments, Conductivity, Antenna Efficiency**

Abstract: This report describes loaded thin-wire models for the representation of the electromagnetic properties of advanced composite materials. Techniques are described for the treatment of thin-wire antennas over advanced composite surfaces and for back-scattering from composites. Special techniques are required for the representation of attachment points. Skin effect is taken into account. Antenna efficiency and gain are computed. The results indicate that a small metal pad at attachment points may significantly improve efficiency. Far field beam patterns may remain essentially unchanged as efficiency or back-scatter varies over a wide range.

Phase Report (1979)
Prepared by A. T. Adams, C. Chang

Company: Syracuse University for RADC

(Report No. RADC-TR-79-18)

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79. Electromagnetic Coupling Analysis of a Learjet Aircraft

Keywords: EMP, Lightning, WIRANT, Learjet, Coupling

Abstract: This report presents the results of an electromagnetic modeling analysis of a Learjet aircraft. Coupling models were developed for the aircraft exterior and selected internal cabling. Calculations of pulse induced responses were made using the computer codes WIRANT and TRAFFIC. The calculated responses were compared to test data obtained by AFFDL. Lightning-induced responses were also calculated for a nearby 20 kiloampere stroke.

Final Report (1978)
Prepared by D. F. Strawe, M. O'Byrne, S. Sandberg

Company: Boeing for AFFDL

(Report No. AFFDL-TR-78-121)

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80. Prediction of HF Antenna Radiation Patterns

Keywords: HF Antennas, Method of Moments, Helicopter

Abstract: A numerical algorithm, derived from the method of moments theory is developed to predict the radiation patterns for HF antennas on helicopters. Results are presented for shorted loop antennas mounted on the UH-1D and OH-58 helicopters. Extension of this analysis to include the effects of helicopter rotor blades on the radiation pattern in the horizontal and vertical planes is discussed. Nap-of-the-Earth (NOE) effects on the radiation patterns, together with experimental validation of the predicted results are given.

Final Report (1976)
Prepared by L. N. Medgyesi-Mitschang

Company: McDonnell Douglas Research Laboratories for USAEC

(Report No. ECOM-75-0907-F)

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81. Electromagnetic/Weight Trade-offs for Advanced Composite Aircraft

Keywords: **Shielding, Trade-offs, Conducting Coatings, Weight, EM Coupling**

Abstract: This study is an extension of that performed by the Syracuse Research Corporation under ONR Contract N00014-78-C-0673.

Final Report (1981)
Prepared by R. F. Wallenberg, D. T. Auckland, R. F. Harrington, R. E. Rudolph

Company: SRC for NASC

(DRAFT of Report No. TR 80-1568)

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82. Electromagnetic System Trade-Offs and Data Base Management for Advanced Composite Aircraft Study

Keywords: **EM Coupling, EMP, Lightning, Theory**

Abstract: The problem of electromagnetic interference which couples to the interior of composite material shell enclosures is studied. Interference sources considered are a distant nuclear electromagnetic pulse, near-strike lightning, and direct-strike lightning. The electromagnetic properties of the composite material shell wall are simplified by assuming a constant bulk conductivity. Several models for the coupling mechanism are analyzed including integral equation formulations, exact series solutions, and a diffusion coupling model. Several computer programs are presented to determine the interior fields over a large range of frequencies when the shell is modeled as an infinitely long two-dimensional cylinder of arbitrary cross section. A user-oriented interactive computer program is also described which is used to determine the response of circuits situated inside the shell.

Final Report (1981)
Prepared by D. T. Auckland, R. F. Wallenberg

Company: SRC for ONR/NASC

(Report No. TR 81-1084)

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83. Flight Operational Wideband Fiber Optic Data Links

Keywords: Fiber Optics, Connectors, Optical Isolation

Abstract: Two point-to-point analog links were designed and constructed. One of the channels is 30.5m in length and transmits a 160 MHz IF signal. The other transfers 20 MHz baseband video information between points separated by 18.3m. An edge-emitting gallium arsenide light emitting diode, a pluggable strengthened cable containing plastic-clad fused silica, fibers, and a silicon PIN photodiode are utilized in each link, interface (transmitter and receiver) electronics and power supplies are included. Specified performance was demonstrated through laboratory evaluation and in actual use on an operational aircraft.

Final Technical Report (1977)
Prepared by L. L. Stewart

Company: Spectronics, Inc. for AFAL/WPAFB

(Report No. AFAL-TR-77-54)

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84. A-7 Airborne Light Optical Fiber Technology (ALOFT) Demonstration Project

Keywords: Fiber Optics, Multiplex Circuits

Abstract: The A-7 ALOFT project successfully demonstrated a fiber-optic signal transmission system can accurately transmit data in the demanding environment of a military aircraft. Included is a summary of the most significant test results, the conclusions reached from the economic analysis, and the compilation of reliability and maintainability data.

Final Technical Report (1977)
Prepared by R. D. Harder, R. A. Greenwell, G. H. Holma

Company: NELC for NASC

(Report No. NELC-TR-2024)

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85. YAV-8B Harrier Electromagnetic Immunity and Flight Test Program

Keywords: YAV-8B, Fiber Optics, EMI, Shielding

Abstract: Two YAV-8B aircraft accumulated 131.1 flight test hours through 30 June 1979. The fiber optic components in the test systems operated satisfactorily. Manufacturing procedures and installation processes were modified on YAV-8B No. 2 to alleviate buildup and installation problems. The EMI test of fiber optic and conventional wiring digital data link systems in the YAV-8B static wing showed that no interference existed on either digital data link from incident rf fields. This report summarizes the entire program and documents the results of the testing performed during Phase II. Phase II conclusions: Fiber optics cables having the proper jackets, connectors, and strain relief provisions will survive the fighter aircraft environment. Fiber optics is immune to the electromagnetic environment in and about Navy attack aircraft. The EM shielding effectiveness of graphite-epoxy is adequate for use on production aircraft. Improvement in fiber optic technology is needed before a commitment is made to an all-fiber-optics avionics suit for attack aircraft application, but current technology will allow the incoporation of elementary fiber optic data transfer links in the production AV-8B.

Final Rechnical Report (1979)
Prepared by R. A. Greenwell

Company: NOSC and McDAC for NASC

(Report No. NOSC TR-476)

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86. Use of Electro-Optic Techniques to Achieve Electromagnetic Pulse Hardness

Keywords: Fiber Optics, EMP

Abstract: Fiber optics will reduce the susceptibility of systems to a direct EMP threat. Cables shorter than 10 m present a tradeoff between the shielding effectiveness of standard cables and that of shielding around critical fiber optic receiver components. Long-haul ground systems require only electronics protection, the fiber optic cable is immune to em pickup and need not be buried for protection. Fiber optic susceptibility is less than that of hardwire to burnout and upset in systems that allow an outage time of 1 ms. In a steady-state or low-dose-rate environment, system vulnerability levels depend on fiber response and design margin. A fiber optic interface is feasible which will not fail under the dose rates and total dose levels equivalent to a natural space environment of 2 mrad(Si) per second for 7 years.

Final Technical Report (1980)
Prepared by R. A. Greenwell

Company: NOSC and JAYCOR for DNA

(Report No. NOSC TR-564)

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87. Aircraft Fiber-Optic Interconnect Systems Project

Keywords: Fiber Optics, Multiplex System, MIL-STD-1553

Abstract: This report summarizes the development and fabrication of a fiber-optic interconnect intended for use in a MIL-STD-1553 multiplex system.

Technical Report (1980)
Prepared by R. D. Harder

Company: IBM and NOSC for NASC

(Report No. NOSC TR-576)

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88. Airborne Fiber Optics Manufacturing Technology

Keywords: Fiber Optics, Installation, Aircraft, Manufacturing, Specifications

Abstract: Manufacturing processes were developed for installation of optical fiber harnesses and stand alone links on military aircraft. Fabrication and installation plans and procedures were developed and a routing analysis was performed to provide a basis for installation of fiber optics in military aircraft. A life cycle cost analysis of the optical fiber harness indicates economic advantages.

Final Technical Report (1980)
Prepared by G. Kosmos, R. A. Greenwell

Company: NOSC for NASC

(Report No. NOSC TR-591)

Author Index

The numbers following the author's names correspond to the reference numbers in the preceding complete list of documents.

Keyword Index

The numbers following the keywords correspond to the reference numbers in the preceding complete list of documents.

APPENDIX B

ELECTROMAGNETIC INTERFERENCE CONTROL

The following article has appeared in the IEEE Transactions on Electromagnetic Compatibility (Vol. EMC-22, No. 4, November 1980). It develops a unified approach to the general electromagnetic interference problem. Although the discussion centers around ground-based facilities the approach works equally well for aircraft and other facilities.

Electromagnetic-Interference Control

EDWARD F. VANCE, SENIOR MEMBER, IEEE

Abstract—**The use of shield topology concepts to design interference control is described. Starting with the postulate that electromagnetic environments can be separated by closed shield surfaces, the proper design of essential compromises such as insulated power and signal conductors, and openings for access and ventilation are deduced. The role of grounding is described and the relation of grounding conductors to shield surfaces is deduced. Some guidelines are given for determining how effective the shield needs to be. It is concluded that the effectiveness of a shield is usually limited most by interference propagating on insulated conductors passing through the shield, followed by leakage through apertures and diffusion through the shield walls.**

Key Words—**Shielding, EMP, topology.**

I. INTRODUCTION

SMALL-SIGNAL electronic circuits, whether they use discrete components or integrated circuits, are susceptible to malfunction or damage caused by transient interference. The problems are particularly common in data-processing circuits, because these circuits often cannot distinguish between a spurious transient and a legitimate signal, and because these circuits are designed for small switching levels to conserve power and reduce heat-dissipation problems. Logic levels are often a few volts or a few tens-of-milliamperes in these circuits.

On the other hand, transients associated with lightning and switching on power lines and buried communication cables commonly have peak currents of tens of kiloamperes and peak voltages of megavolts (EMP) [1]. Thus if small-signal electronic circuits are to be operated by commercial ac power, or used in systems that are interconnected by long buried or overhead cables, it is apparent that the structure between the outside cables or power conductors and the small-signal electronic circuits must be capable of reducing the transient peaks by over 100 dB.

In addition, grounding electrodes, such as ground rods, ring grounds, counterpoises, etc., typically have impedances of a few ohms, although grounding electrode impedances of tens or hundreds of ohms are not uncommon. In series with this soil impedance is the inductance of the grounding conductor, which is typically several microhenries (about 1 μH per meter of ground wire). Thus the $Ri + Ldi/dt$ voltages developed across the grounding impedance by the EMP or lightning may be of the order of 1 to 100 kV, even if a good grounding electrode is used. Therefore, as illustrated in Fig. 1, even the best electrical grounding practices cannot prevent wide fluctuations in the potential of a building ground point in a lightning or EMP environment.

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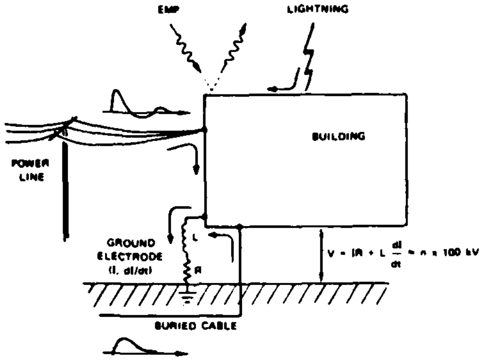


Fig. 1. Building potential produced by large transients.

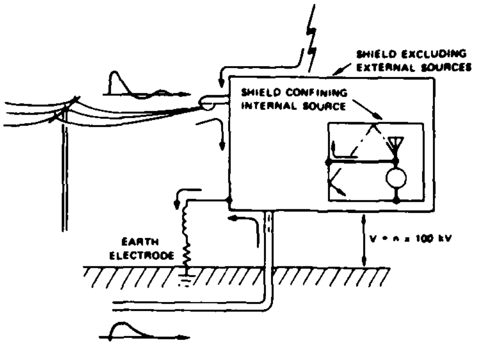


Fig. 2. Use of shields to exclude external sources and to confine internal sources.

For electronic systems to operate reliably in this environment, therefore, we must be able to accommodate these wide fluctuations in building-ground-point potential and reject the severe transients induced on external power lines and cables or impinging directly on the facility. In addition, however, we must be able to supply power to the electronic circuits and provide means of getting information into, and out of, these circuits. To achieve these goals, a systematic approach to interference control is required.

II. THE FUNCTION OF ELECTROMAGNETIC SHIELDS

If the walls of the building in Fig. 1 are perfectly conducting so that there is no penetration of either electric or magnetic field through the walls, the potential of the entire building and all of the space inside it will be the same, regardless of whether that potential is zero or 100 kV. Thus there are no *potential differences* within the building, even though the potential of the building with respect to the earth may fluctuate widely. The perfectly conducting shield is thus an electrodynamic Faraday shield that isolates the enclosed space from external influences, whether these be fields, currents, or voltages. All external fields are totally reflected by the walls and all current or charge injected on the outside surface remains on the outside surface (the skin depth in a perfect conductor is zero).

The perfect electrodynamic shield thus would provide a barrier between the external environment and the internal environment. The only gradients in the enclosed region would then be caused by sources or charge displacements within the shielded region. These internal sources fall into two categories: those associated with the normal operation of internal equipment such as rectifiers, transmitters, relays, solenoids, switches, and similar devices which may introduce interference into internal circuits; and those related to the buildup of static electricity and to power faults.

Those internal sources associated with the operation of internal equipment are part of the normal functioning of the system. Interference from very strong sources of this type may be confined by enclosing the sources in shields; the shield in this case separates the source inside the shield from the space outside, so that there are no gradients outside the shield produced by sources inside the shield. The use of shields to exclude and to confine interference waves is illustrated in Fig. 2.

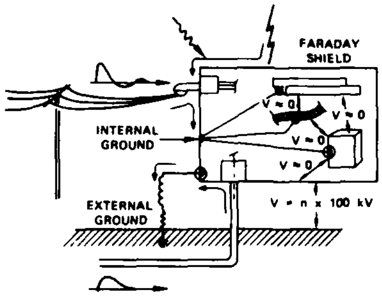


Fig. 3. Internal ground system for equipotential region.

Internal sources associated with static electricity and power faults constitute personnel, fire, and explosion hazards which are controlled by interconnecting all structural metal and electrical equipment frames and cabinets as illustrated in Fig. 3. Thus sparks and personnel shocks are avoided, and fault-current paths sufficient to ensure the operation of circuit breakers and fuses are provided. Since this interconnection of electrical and structural conductors traditionally includes a connection to earth, such interconnections are called "grounding." Grounding has little to do with interference control, although improper grounding may, indeed, introduce additional sources of interference. Also, some of the beneficial acts that are frequently called grounding are, in fact, acts of preserving shielding integrity.

III. SHIELD DESIGN CRITERIA

The shields discussed above were assumed to be perfectly conducting and completely closed. As was remarked in the introduction, however, we must supply power to, and communicate with, the equipment inside the shield. For shielded buildings, we also must provide openings for ventilation and for entrance and egress, as well as plumbing for water, sewage, heat or fuel, and other accoutrements. Each of these openings and penetrating conductors represents a compromise of the shield; as a result, a single shield is often inadequate to provide the 100 dB or more of interference reduction required by electronic circuits.

To achieve a greater degree of interference reduction, additional shields may be used. One can thus envision a set of nested shields which partition the space about the electronic equipment into environmental zones [2]-[4]. The interference environment becomes ever more benign as one progresses from the lowest level of shielding toward the highest. Shielded regions at any level may be irregular in shape or they may be interconnected as illustrated in Fig. 5. Topologically, the two shielded buildings in Fig. 5(a), interconnected with a shielded cable, form one continuous shielded region. Similarly, the equipment cabinets in Fig. 5(b), together with their shielded interconnecting cables or ducts, form a continuous Zone-2 region. Also illustrated in Fig. 5(b) is the use of doubly shielded cable to extend the Zone-2 region "outside" the building yet topologically inside two levels of shielding. As is suggested in Fig. 4. and 5, two levels of shielding can often be identified in facilities. The first level may be a welded-steel liner in a ground-based facility, the metal skin of an aircraft or rocket, or the steel hull of a ship. The second level of shielding is usually defined by the electrical and electronic equipment cabinets and their associated interconnecting cable shields, ducts, or conduits.

The first-level shield separates the harsh external environment of Zone 0 from the room or cabin environment, Zone 1. *The shield accomplishes this separation* by diverting or absorbing interference that would otherwise enter the system. However, there are practical bounds on the amount of interference reduction required of the first shield. This shield (including its penetrating conductor and aperture treatments) should provide at least enough interference reduction to prevent insulation breakdown or other damage to components inside the shield. Frequently, equipment inside the shield, such as low-voltage wiring and equipment operated directly from low-voltage power circuits, can tolerate peak voltages of 500 to 1000 V. *Thus the minimum interference reduction required of the first level of shielding is that necessary to prevent damage to components enclosed by the shield.*

On the other hand, there is little benefit to be gained from reducing externally generated interference to levels much smaller than those produced by internal sources. In many facilities, peak voltages of a few hundred volts are generated in Zone 1 by switches, relays, solenoids, rectifiers, and other devices essential to station operation [5], hence *reduction of the externally generated interference to levels more than a reasonable safety margin (say 20 dB) below these interference levels is not warranted.*

This criterion is based on the postulate that any internal equipment must tolerate the ambient internal environment without upset or failure. If it cannot, then either the equipment must be hardened or the internally generated interference must be reduced; in either case, the criterion is to reduce the externally generated interference below the level of the internally generated interference. The internally generated interference may be reduced by confining the strongest or most offensive sources inside shields as discussed earlier.

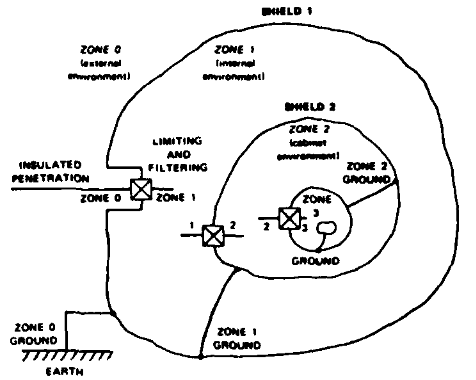


Fig. 4. Shileding and grounding zones in a complex facility.

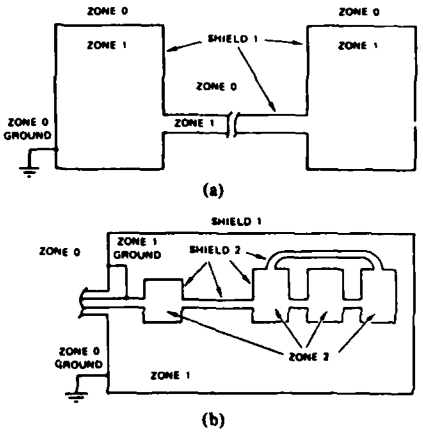


Fig. 5. Topology of interconnected regions. (a) Shielded buildings connected by shielded cable. (b) Interconnected cabinets.

The second-level shield separates the room or cabin environment from the sensitive small-signal circuits. Since these circuits may be upset or may develop an unacceptable error rate at peak interference levels of a few volts, the second-level shield must be capable of reducing the voltages induced on Zone-2 conductors by the room-level environment to less than a few volts. As before, however, little benefit accrues from reducing the cabinet interference produced by external sources (i.e., sources external to the cabinet) to levels more than a reasonable safety margin (again about 20 dB) below the internal interference level produced by the small-signal circuits. Internal interference of the order of 100 mV is often produced by fast switching devices in counters, clocks, etc., in the small-signal circuits.

Note that this approach to interference control requires the equipment, with its interconnecting cabling, to be capable of tolerating a normal room or cabin environment—a fairly modest requirement. The appraoch also requires that the facility or vehicle shield be sufficiently effective that the voltages induced on internal conductors by external sources (or whatever origin) be no larger than the switching transients and other interference generated by internal equipment—again, a fairly modest requirement.

To implement these criteria, it is necessary to estimate and control the interference induced on internal conductors as a result of (in order of importance):

1) Propagation along conductors passing through the shield (including grounding conductors and nonelectrical conductors).
2) Fields penetrating apertures and interacting with internal conductors (these apertures may include the openings in meshes and reinforcing steel and the imperfections at riveted or bolted joints in aircraft, missiles, and ships).
3) Fields diffusing through the metal walls of the shield and interacting with internal conductors.

It also is necessary to estimate the internally generated interference levels in the room or cabin, and in the small-signal electronic circuits.

IV. MAINTAINING SHIELDING INTEGRITY

A. Cable Entry Points

Inherent in the theory of electrodynamic shields is the fact that *current in conductors attached to the shield flows predominantly on the surface to which the conductor is attached.* This phenomenon, illustrated in Fig. 6, is a manifestation of the skin effect in conductors. It is very important in the application of the shielding topology because it permits interference currents on conductors outside the shield to be diverted to the outside surface of the shield. Notice the difference, for example, between the situation depicted in Fig. 6 and that shown in Fig. 7, where the conductor is brought through the shield and connected to the "inside" of the shield. In the latter example, the conductor current flows to the "inside" surface, where it may interact with internal components.

Several examples of the correct application of this principle to interference-excluding shields are given in Fig. 8, along with some common compromises and violations of the shield. Note that each of the compromises permits the harsh currents on the outside conductors to flow into the protected zone inside the shield. It should be observed that filters and surge arresters behave the same as any other connection of a penetrating conductor to the shield, that is, they divert harsh interference currents to the outside surface of the shield, thereby preventing these currents from entering the protected region. Because power and signal-carrying conductors cannot be continuously connected to the shield, they must be momentarily connected (when a certain threshold is exceeded) or connected only at frequencies not used for power or signals (i.e., through a filter). In any case, the diverted interference currents must flow to the outside surface of the shield, as illustrated at the left in Fig. 8(c), if the shield integrity is to be preserved. The importance of this current diversion is shown in Fig. 9 where the currents on the penetrating conductor inside the shield with and without diversion are compared.

Only "short-circuit" devices, those that divert the conductor current to the shield, have been illustrated here because, at the first level of shielding, the interference levels caused by the EMP and lightning are very large. "Open-circuit" devices, such as chokes and dielectric gaps, must be capable of withstanding voltages approaching 1 MV at the first shield. Devices

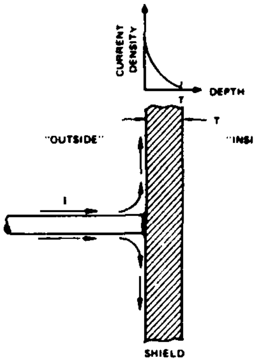


Fig. 6. Confinement of conductor current to "outside" surface by skin effect.

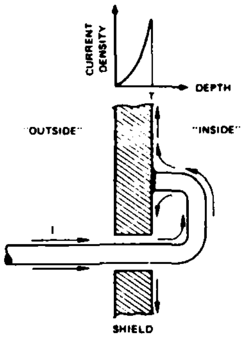


Fig. 7. Conductor current injected on the "inside" of a shield.

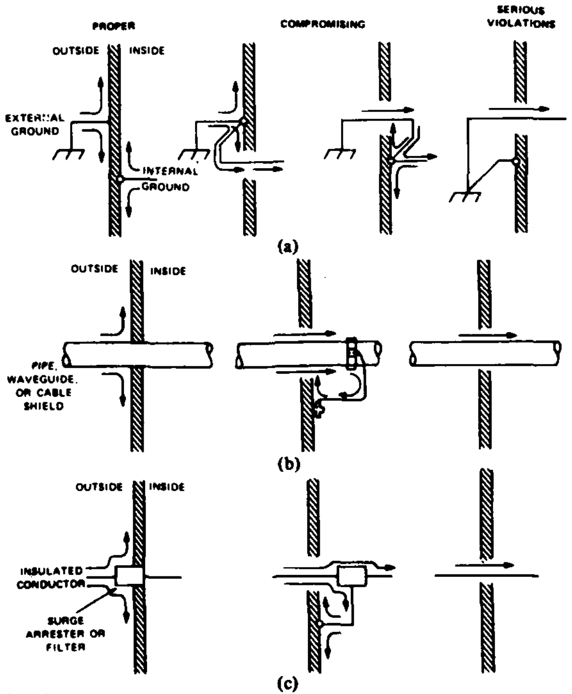


Fig. 8. Shielding integrity near interference-carrying external conductors. (a) Grounding conductors. (b) "Groundable" conductors. (c) Insulated conductors.

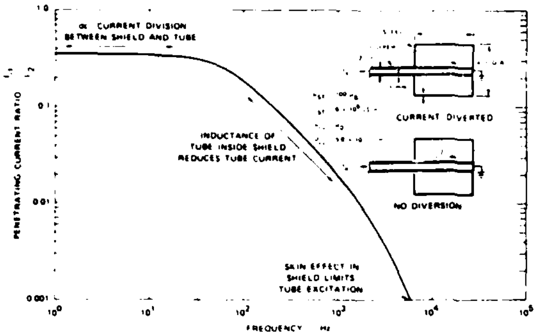


Fig. 9. Ratio of current penetrating shield wall (I_{l1}) to current conducted through wall (I_{l2}).

designed for these voltages are expensive and require considerable maintenance, whereas the "short-circuit" devices are cheap and require much less maintenance. (For water and sewage plumbing, however, plastic piping can be substituted for metal piping to eliminate the conductor.)

At secondary and tertiary shields where the open-circuit voltages are less severe (i.e., hundreds of volts instead of MV), current-interruption techniques can be applied quite satisfactorily. Several current-interruption techniques are illustrated in Fig. 10, where the open-circuit voltage impressed across the current-interrupting device also is indicated. Such techniques are usually applied only to insulated conductors, such as power and signal conductors; "groundable" conductors, such as cable shields, plumbing, and waveguides, are economically and reliably treated with the current-diversion approach of Fig. 8(b).

There are, of course, many other input/output circuits that can serve as buffers or isolators at the secondary and tertiary shields. Many of these are functional components of the system or electronic circuit that can be adapted to shielding purposes. Rectifier power supplies and dc-to-dc converters may serve to isolate the primary power conductors from the conditioned power supplied to the small-signal circuits. Tuned RF amplifiers and mixers serve as narrow-band filters to exclude interference on the input conductors. Well-designed electronic equipment often contains balanced transmitters and receivers, emitter followers, or other high-tolerance buffer stages to protect the small-signal circuits from interference propagating toward the input/output terminals. Indeed, one approach to interference control is to make the electronic equipment "inherently immune" by providing high-integrity shielding in the cabinets and using high-tolerance input/output circuits.

If the purpose of the shield is to confine an interference source, rather than to exclude the effects of an external source, the same principles hold, and the examples in Figs. 8 and 10 apply if "outside" and "inside" are interchanged in Fig. 8 and "Zone 1" and "Zone 2" are interchanged in Fig. 10. However, there are many system modules in which the module shield is required to perform both a confining and an excluding role. Some examples are encrypting and decrypting units and many avionics modules which require a limit on emanations as well as a tolerance to external interference.

For these dual-role shields, the treatment of ground and groundable conductors shown in Fig. 8 are appropriate since the "proper" techniques shown obviously perform equally well in either direction. A careful examination of the shield topology in the vicinity of the insulated conductor treatments in Fig. 8(c) and Fig. 10 will show that, as interference barriers, most of these devices also can be bilateral devices. A possible exception to this conclusion is the combination of a nonlinear surge arrester with linear, passive devices at the interfaces, but this combination is used for the case where the peak interference on one side of the barrier is expected to be much larger than that on the other side of the barrier. There appears to be no requirement in practice for such treatments to be bilateral, because if the peak interference fields were comparable on both sides of the shield, the shield is probably serving no useful function.

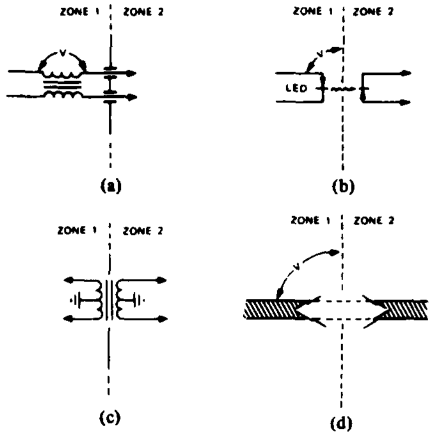


Fig. 10. Current interruption treatments for secondary shield penetrations. (a) Bifilar choke. (b) Photon coupler. (c) Isolation transformer. (d) Dielectric waveguide.

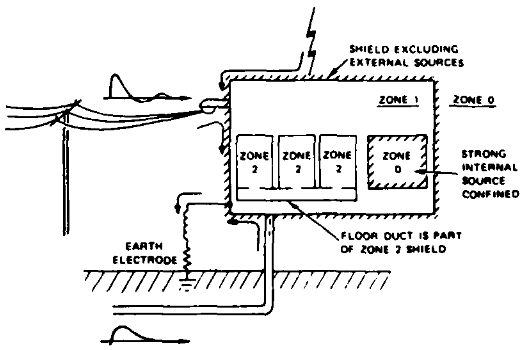


Fig. 11. Use of shields to exclude external sources and to confine internal sources.

A typical interference-control design for controlling both internal and external sources might look like Fig. 11. Here, a building or room shield provides primary protection against the external sources associated with the EMP, lightning, and switching and the induced effects of lightning and the EMP on external cables. A particularly offensive source inside the room is cordoned off by a shield that confines the offensive source or excludes it from the remainder of the interior space. The second-level shield then separates the small-signal circuits in the cabinets and their interconnecting cabling in the floor duct from the room environment. In addition, the Zone-1/Zone-2 interface treatments serve to confine any sources within the cabinet so that emanations from the circuits in the cabinet are controlled. It is reiterated that these emanations may propagate on grounding conductors and unintentional conductors as well as power and a signal lines. Thus the shielding integrity is preserved (and interference is controlled) only if all of these conductors are properly treated.

Another corollary of shielding theory is that *fields cannot diffuse through shields that carry no current*. The electric and magnetic fields parallel to the shield surface are both related to the current density in the shield through the intrinsic impedance of the shield material, and when the current density is zero, both of these fields also are zero. This corollary is useful for interference wavelengths that are large compared to the dimensions of the shield, where external conductors tend to be the dominant source of interference current on the shield. The performance of the shield can be enhanced if these large interference currents associated with long external conductors are prevented from flowing through large areas of the shield—particularly if the shield has many openings (e.g., a mesh or a metal building with many doors, windows, or poorly bonded joints).

Implementation of this principle has led to the concept of a single entry panel through which all penetrating conductors enter the shield at one small, controlled area. Fig. 12(a) illustrates the entry panel with all penetrating conductors and the external grounding conductor congregated at one face of the shield. Current flowing over the shield is small because there is no exit path on the opposite face—the shield is an open circuit to the combined conductor currents. The current entering on one conductor must either be reflected back on the same conductor or leave through another appendage or through the grounding conductor. By contrast, when the random entry illustrated in Fig. 12(b) is used, large current flowing toward the shield on one conductor may flow across the shield, exciting any leaks in its path, and exit on a conductor on the opposite face of the shield. Hence, the random-entry approach permits excitation of any flaws in the shield by the external interference currents, while the single-entry-panel approach concentrates these currents on the entry panel where almost flawless shielding can be maintained. Conversely, if the single entry panel is used, poorer quality shielding on the remainder of the shield often can be tolerated.

It will be enlightening at this point to examine some violations of the shield topology that have been encountered. One of these is a perversion of the single-point-ground concept that demands that signal common, a small-signal conductor, be connected by a single insulated conductor to the electrical ground electrode. The topology of this situation is depicted in Fig. 13, where it is apparent that the signal-common grounding conductor penetrates both levels of shielding. Therefore, the environment of the small-signal circuit has been degraded to that of Zone 0, the harsh external environment. Note that a closed shield is formed by Shields 1 and 2 in Fig. 13, but it *excludes* the interior of Shield 2. Proper treatment of grounding conductors at the shield is illustrated on the left in Fig. 8.

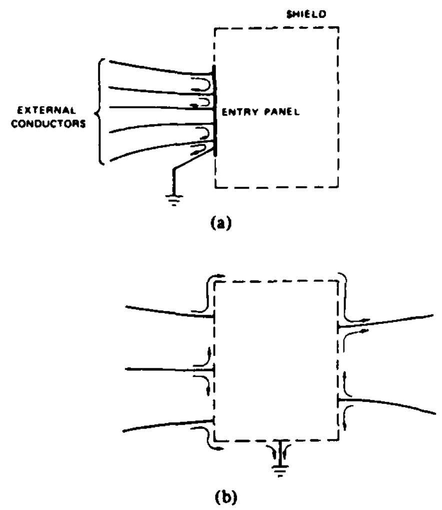


Fig. 12. *External-appendage current paths on shields. (a) Single entry panel. (b) Random entry.*

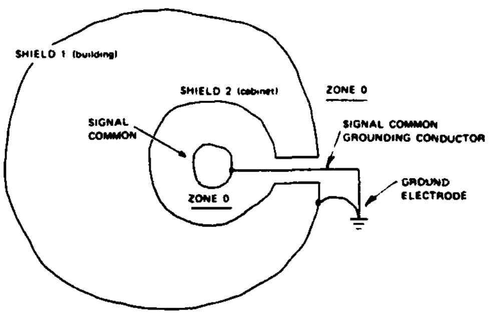


Fig. 13. Shield topologh when signal-common is connected to power ground electrode.

A second example is illustrated in Fig. 14 where the electric-power service entrance and ground are shown. In this case, the phase conductor is properly protected with a surge arrester and filter in the distribution panel. At the equipment cabinet, however, the filter on the phase conductor is installed so that the interference current diverted through the filter is delivered to the inside of the cabinet, (the small-signal zone) rather than to the outside. A much more severe violation of the shields is evident in the neutral and ground-conductor circuit, however. This conductor has been provided no surge protection or filtering at either shield penetration, although a long, inductive path to earth and to the equipment cabinet has been provided. Because there is little voltage limiting or current diversion on this conductor, it carries the external environment (Zone 0) through both the building shield and the cabinet shield into the small-signal area (Zone 2). It thus behaves in much the same undesirable manner as the "grounded" signal common in the previous example.

Another violation of the shield in Fig. 14 is the exposed grounding conductor between the distribution panel and the ground electrode. This is a particularly offensive Zone-0 conductor routed through the interior of the first shield zone by

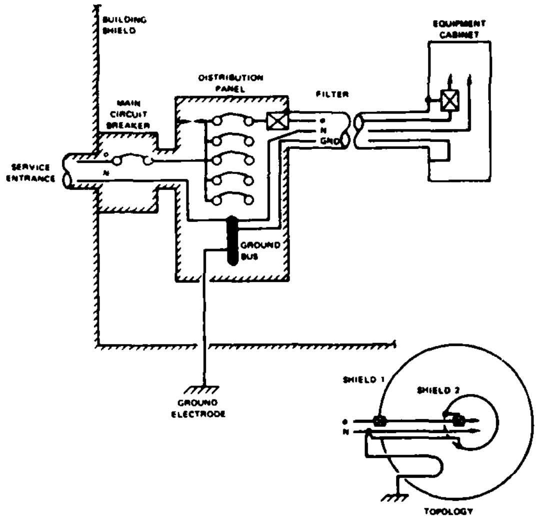


Fig. 14. Electric power service violating both levels of shielding.

means of two penetrations of the shield. This arrangement might have been used to avoid routing the grounding conductor through a steel conduit, thereby increasing its inductance; however, it could have been routed back through the conduit from the main circuit breaker without increasing its inductance or compromising the shield.

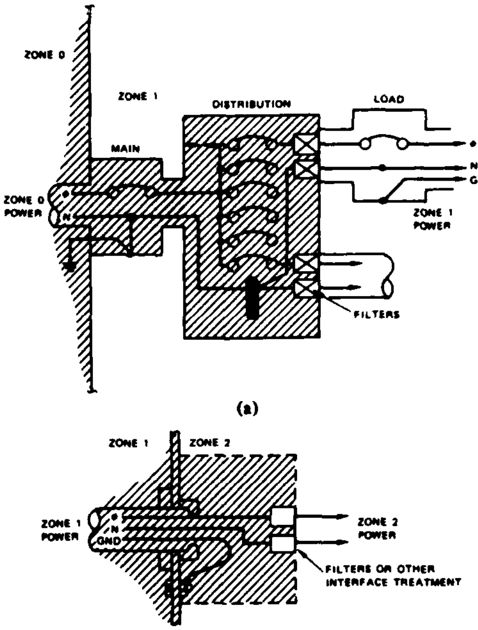
Fig. 15 illustrates proper preservation of shielding integrity at the power entry to the building and to the equipment. Shading is used to identify the topology of the shield. All of the shaded area in Fig. 15 is outside the shielded space, since the protected interface is at the load side of the distribution panels in Fig. 15(a) and the right side of the entry box in Fig. 15(b).

In both of these examples, the offending conductors are grounding conductors. Such conductors are often erroneously thought to be innocuous, when, in fact, they can be among the most offensive sources of interference. Therefore, an important rule of effective shielding and grounding practice is that, topologically, *grounding conductors should never penetrate shield surfaces.*

B. Aperture Control

Most facilities require windows, doors, ventilation openings, access hatches, etc., which also may compromise the integrity of the shield. The penetration of external fields through apertures that are small compared to a wavelength is illustrated in Fig. 16. As shown, part of the electric field that would otherwise terminate on the outside surface of the shield penetrates through the aperture, where it may induce charge on internal cables. Similarly, some of the magnetic field that would otherwise be bounded by the surface current in the shield is permitted to penetrate through the aperture, link an internal cable, and thereby induce a voltage in the cable; see Fig. 16(b).

If the aperture is large compared to a wavelength, the incident wave can propagate through the aperture as illustrated in Fig. 17. Because the shortest wavelengths of concern in EMP hardening typically are of the order of 1 meter, shine-through



(a)

(b)

Fig. 15. Proper electric power service without compromising shields. (a) Building entry. (b) Equipment entry.

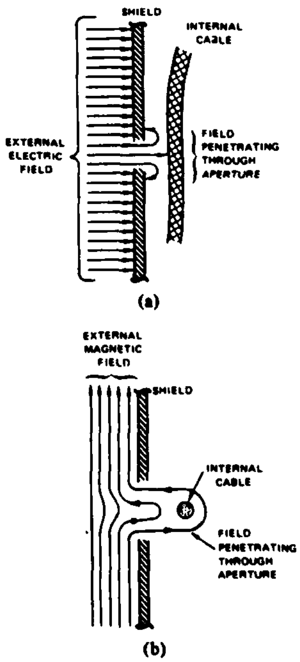


Fig. 16. Electromagnetic penetraion of small apertures. (a) Electric field. (b) Magnetic field.

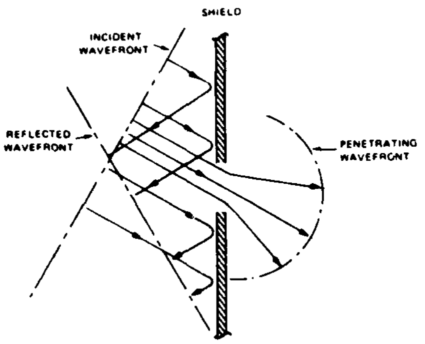


Fig. 17. Electromagnetic penetration of large apertures.

is usually significant only at large windows and doors. Because the shine-through wave is attenuated very little in the direction of propagation of the incident wave, however, almost the full incident field strength may be transmitted to the interior of the shield through large apertures.

The fields penetrating a small aperture depend on the aperture size. Therefore, if a given area of wall opening is subdivided into, say ten, small openings having the same total area, the penetrating fields at an interior point will be about $1/\sqrt{10}$ as large for the ten small openings as for the single large opening. Thus one common treatment for such openings is to cover them with a conducting screen or mesh, so that the large opening is converted into a multitude of small openings.

More reduction can be obtained with sacrifices in optical transparency and increased resistance to air flow by adding thickness to the screen. Then each small aperture becomes a tube through the wall and behaves as a waveguide beyond cutoff. Fields transmitted through a waveguide beyond cutoff are attenuated approximately exponentially with distance along the guide, so that very large attenuation may be achieved by using many small tubes welded or brazed together in a honeycomb structure. Sketches of the magnetic field in the vicinity of a single aperture, an array of small apertures, and an array of waveguides beyond cutoff are shown in Fig. 18.

Shield boundaries in the immediate vicinity of apertures are ill defined because the electromagnetic fields vary over a wide range in these regions and there is no physical barrier to make a distinct separation of the internal and external regions. However, a boundary often can be drawn to indicate the region inside which the aperture fields are smaller than those permissible inside the shield. Thus another treatment for penetration through apertures is to form an exclusion zone about the aperture. No internal coupling elements, such as cables or sensitive components, are permitted to occupy or pass through this exclusion zone. Therefore, the interaction of internal components with the fields of external origin in the vicinity of the aperture is limited by avoiding the regions where strong interaction can occur.

C. Diffusion Through Shield Walls

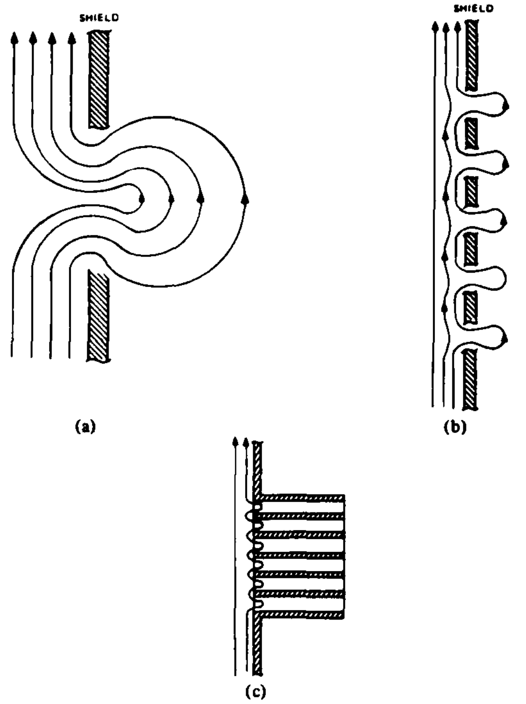


Fig. 18. Magnetic field penetration of apertures. (a) Single aperture. (b) Many small apertures. (c) Array of waveguides beyond cutoff.

Continuous, closed sheet-metal shields are, by far, the most effective electromagnetic shields because they severely limit the penetration of energy in the spectrum above $f_\delta = (\pi\mu\sigma d^2)^{-1}$ and they are good reflectors of propagating waves throughout the spectrum. However, these remarks and the discussion in this section apply only to continuous closed shields; the effects of apertures, penetrating conductors, and other imperfections discussed above are usually much more important than diffusion through the walls.

The ratio of the magnetic field inside the shield to the magnetic field incident on the outside of the shield is, when expressed in decibels, defined as the magnetic-field shielding effectiveness of the shield. This shielding effectiveness depends on the shape of the shield structure and the conductivity, permeability, and thickness of the shield wall. The shape of the body determines the concentrating effect the body has on the external fields. For example, an infinite plane sheet does not concentrate the fields at all, a long cylinder concentrates in two dimensions, and a sphere in three. The commonly used shielding-effectiveness formulas for these shapes are (in decibels)

$$\text{plane} \qquad R \approx 108 + 10 \log\left(\frac{\sigma_r}{\mu_r f_{\mathrm{MHz}}}\right)$$

$$\begin{array}{c}\text{circular cylinder}\\ \text{(infinite length)}\end{array} \qquad R \approx 75 + 10 \log\left(\frac{\sigma_r f_{\mathrm{MHz}} a^2}{\mu_r}\right)$$

$$\text{sphere} \qquad R \approx 70 + 10 \log\left(\frac{\sigma_r f_{\mathrm{MHz}} a^2}{\mu_r}\right)$$

which are valid for $10^{R/20} d/\delta \gg 1$ and $a/\mu_r\delta \gg 1$, where d is wall thickness, a is radius of the cylinder or sphere, σ_r and μ_r are the relative conductivity and permeability ($\sigma_r = 1$ for copper, $\mu_r = 1$ for vacuum), and f_{MHz} is the frequency in megahertz. These results are developed from more accurate formulas derived in [6]. The remainder of the shielding factor is related to the attenuation A of the fields within the wall and to multiple reflections F within the wall

$$A + F = 20 \log |\, 2 \sinh (1 + j)d/\delta \,|$$
$$= 8.69\, d/\delta + 10 \log (1 + e^{-4d/\delta} - 2e^{-2d/\delta}$$
$$\cdot \cos 2d/\delta)$$

where δ is the skin depth $[\delta = (\pi f \mu \sigma)^{-1/2}]$. The total shielding effectiveness is thus

$$S = R + A + F = 20 \log \left| \frac{H_{\text{incident}}}{H_{\text{inside}}} \right| .$$

Since the spherical shell more nearly represents the shape of a facility shield (in that it has no infinite dimension), we may use the shielding factors for the sphere to estimate the voltage induced on conductors inside a facility. This shielding effectiveness of spherical shells has been calculated and plotted in [7] as a function of a normalized frequency $2\pi\tau_s f$ for various values of a "size and material" factor $C = a/3\mu_r d$, where $\tau_s = \mu\sigma d^2$ is the shield diffusion time constant. These shielding-effectiveness data are shown in Fig. 19.

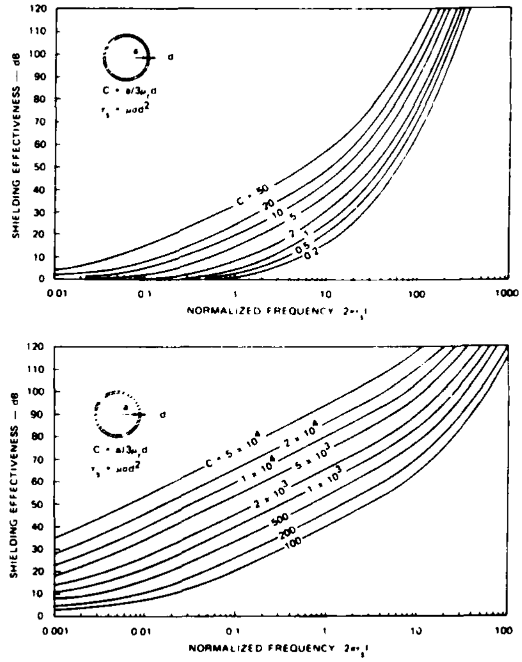


Fig. 19. Magnetic shielding effectiveness for spherical shell enclosure versus normalized frequency for various values of parameter C [7].

The inverse Fourier transform of the shielding-effectiveness data, giving the waveform of the magnetic field at the center of the sphere when a unit impulse of magnetic field is incident on the sphere, is shown in Fig. 20 from [7]; similar data also have been obtained by Lee and Bedrosian [8]. Because $\tau_s \gg 10\ \mu s$ for most shield materials and thicknesses, if the incident pulsewidth is less than 10 μs, the internal response will be the impulse response.

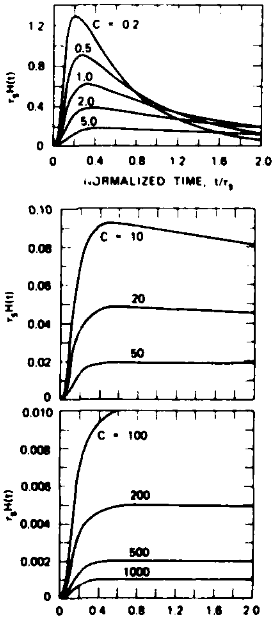


Fig. 20. Waveforms of magnetic field at the center of a spherical shield when a unit impulse of magnetic field is incident on the outer surface of the sphere [7].

For a closed metal shield, we can estimate the voltage induced on conductors inside the shield from the peak voltage induced in a loop of area πa^2 by this impulse. This voltage is

$$V_{pk}(t) \approx \mu_0 \pi a^2 H_0 \tau \frac{H_{pk}}{t_{pk}}$$

where H_{pk} is the peak internal magnetic field, t_{pk} is the time at which this peak occurs, and $H_0\tau$ is the value of the incident impulse. For the high-altitude EMP, the incident impulse is

$$H_0\tau = \int_0^\infty H(t)\, dt \approx 3.5 \times 10^5\ \mathrm{A \cdot s/m}.$$

The peak voltage induced in a loop inside a 10-m radius spherical shield by the high-altitude EMP is shown in Table I for 3 wall thicknesses (0.2, 1, and 5 mm) and 3 materials (copper, aluminum, and steel). As the table illustrates, a very thin shield will suffice to reduce the EMP-induced voltages to well below the levels of internally generated voltages if only diffu-

TABLE I
PEAK VOLTAGE INDUCED ON 10-M RADIUS LOOP INSIDE 10-M RADIUS SPHERICAL SHIELD BY THE HIGH ALTITUDE EMP (BY DIFFUSION THROUGH WALLS ONLY)

Shield Thickness (mm)	Internal Voltage Induced in Loop		
	Copper (5.8×10^7 mho/m)	Aluminum (3.7×10^7 mho/m)	Steel $\left(\begin{matrix} 6 \times 10^6 \text{ mho/m} \\ \mu_r = 200 \end{matrix}\right)$
0.2	0.34 V	0.85 V	0.076 V
1.0	2.6 mV	6.4 mV	1.1 mV
5.0	21 μV	51 μV	15 μV

sion through the walls is considered. For this reason, shield thickness may be determined more by structural considerations (or by other electromagnetic considerations such as lightning) than by electromagnetic-pulse considerations.

V. CONCLUSIONS

Since interference control is primarily a matter of providing adequate shielding barriers between the interference sources and potential victims, the techniques used tend to be relatively independent of the source or victim. That is, interfering signals of a given amplitude and spectral content will produce similar undesirable effects regardless of whether the source is the EMP, lightning, or an internal device such as a solenoid or rectifier. The goal of both EMP hardening and electromagnetic-compatibility work is to limit the amount of undesirable signal that reaches a victim circuit to levels that the circuit can tolerate without impaired performance. In the EMP environment, the source is outside the space to be protected, while in the EMC case the source may be either outside or inside this space. The shield in either case is used to separate the source from the protected space.

A systematic approach to interference control has as its foundation identification of the topology of the shielding surfaces. The integrith of these shield surfaces is to be preserved in spite of requirements for insulated power and signal conductors to pass through the shield, or of requirements for doors, access hatches, etc., to be cut in the shield wall. Much of interference-control technology is, therefore, devoted to accomodating these compromises of the shield without unnecessarily degrading the ability of the shield to separate the internal environment from the external environment.

Finally, a rationale has been developed for determining how much shielding is necessary for a given interference source based on the insulation strength inside the shield and the expected tolerance of the victim equipment. Thus, the shield must at least reduce the interference level to that which the insulation can withstand, but it need not reduce the interference to much below the ambient interference level generated in the protected region by internal equipment.

ACKNOWLEDGMENT

The author is indebted to Dr. J. E. Nanevicz of SRI International, Dr. W. R. Graham of R & D Associates, and Dr. C. E. Baum of the Air Force Weapons Laboratory for many enlightening discussions of this subject over the period during which the ideas in this paper were formulated.

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Appendix C

HARDENING AGAINST ELECTROMAGNETIC ENVIRONMENTAL EFFECTS (E^3) IN ADVANCED COMPOSITE AIRCRAFT

1. Background

The use of composite materials for aircraft fuselages and structural members influences almost every aspect of the aircraft design problem. This influence is particularly strong in the design of the electrical and avionics subsystems which, in the past, have relied on the presence of a metal fuselage for many important functions. One of the more important of these functions has been the use of the metal fuselage as a key element in electromagnetic interference (EMI) control. In this application, the fuselage has served as an electromagnetic barrier between externally generated signals and the internal equipment and wiring. The major sources of this external electromagnetic environment for Army aircraft are the aircraft's own transmitting antennas, RF radiation from other air- and ground-based antennas (e.g., intense beam weapons, radars, jammers, and countermeasure sources), natural atmospheric electricity (lightning and precipitation static), and the electromagnetic pulse (EMP) associated with a tactical nuclear environment.

A metal fuselage, while far from being a classical Faraday shield, can provide significant isolation between the external sources and the equipment inside the aircraft. Electromagnetic energy can enter the interior by means of three distinct coupling mechanisms:

(1) Diffusion through the imperfectly conducting skin

(2) Coupling through apertures on the fuselage (e.g., windows, vents, seams, and joints),

(3) Coupling via conducting wire penetrations of the fuselage (e.g., antenna feed cables, control cables, hydraulic lines, power wiring to exterior lights, and window de-icers).

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ENGINEERING EFFECTS OF ADVANCED COMPOSITE MATERIALS ON AVIONICS--ETC(U)
JUL 81 W GRAF, J HAMM, J E NANEVICZ DAAK80-80-C-0806
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The materials and thicknesses commonly used for metal fuselages provide excellent attenuation of the diffusion component. Aperture-coupled fields can be significant, but they can be greatly reduced by treatments (e.g., conducting wire mesh, RF gaskets, honeycomb panels) which rely on a low-impedance bond with the fuselage around the periphery of the aperture or seam. Wire penetrations can be treated in several ways (as indicated in Appendix B), many of which rely upon diversion of the interference to the conducting metal fuselage. Thus, the presence of a highly conducting fuselage has been crucial for the exclusion of external interference from the interior of the aircraft.

The use of composite fuselages results in a significantly increased internal interference environment. The internal voltage induced by the diffusion component will increase by many orders of magnitude, since the peak voltage induced by diffusion coupling to the internal volume is approximately proportional to the inverse square of the skin conductivity. In addition, the spectrum of the diffusion-coupled fields contains more high frequency energy as the skin conductivity is reduced. Since aircraft wiring couples most efficiently to high frequencies (typical ringing frequencies are from 1 MHz to 30 MHz for aircraft), the diffusion-coupled component can no longer be neglected in the design process.

Similarly, EMI treatments at apertures are less effective because their performance depends on a low impedance bond around the periphery. Treatments applied to wire penetrations are also compromised by a low conductivity fuselage. For example, the performance of filters and nonlinear voltage limiters is a very sensitive function of the conductivity of the fuselage, and the interference currents entering a composite aircraft on wire penetrations are increased significantly. Thus, the use of composite materials on the fuselage enhances each mode of coupling of external interference to the internal wiring.

Developments in aircraft technology and trends in tactical mission requirements are compounding the E^3 hardening problem even further. These developments imply that state-of-the-art avionics systems are now much more susceptible to upset and damage than were their counterparts in years past. In addition, the trends in mission requirements are such that modern aircraft are being operated in more severe weather environments, which implies an increased exposure to lightning and precipitation static. These trends alone have made EMI control much more difficult, even for metal aircraft; and it is obvious that new solutions to the E^3 hardening problem are needed. The following sections discuss this problem in greater detail and indicate the modern interference control strategies which are being developed to alleviate the problem so that the potential weight and cost benefits of composite materials can be fully realized.

2. The Magnitude of the Problem

A topological representation of the E^3 problem is shown in Figure C-1. The outer surface of the system has a finite conductivity σ, magnetic permeability μ, and dielectric permittivity ε. The surface is assumed to have a wire penetration and an aperture. The volume inside the first surface is assumed to contain electrical equipment and interconnecting wiring. Internal sources of interference are not shown in the figure but are assumed to be present. The basic E^3 problem is to ensure that the system can fulfill its mission requirements in the complex electromagnetic environment created by the system's own equipment and by natural and man-made sources external to the system.

Solution of this problem requires a knowledge of the source characteristics, a determination of the coupling of these sources to the system equipment, and a knowledge of the equipment response and susceptibility in the electromagnetic environment. The following sections discuss some elements of this problem.

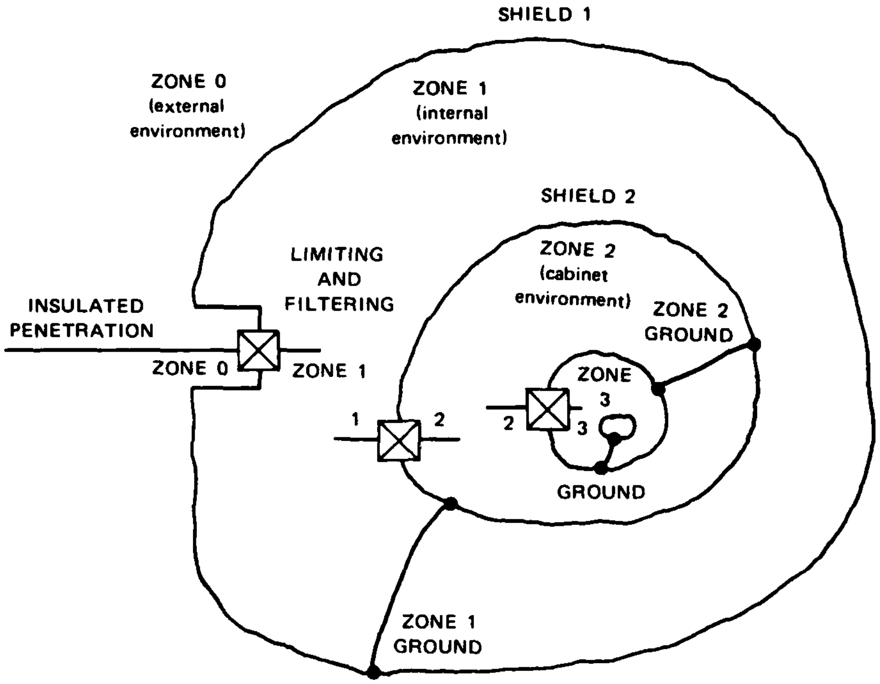

FIGURE C-1 SHIELDING AND GROUNDING ZONES IN A COMPLEX SYSTEM

a. Description of Interfering Sources

(1) System-Generated Interference: The EMC Problem

Any system containing electrical equipment creates its own electromagnetic environment. The exact nature of this environment varies from system to system and is a function of the ambient system signals and the configuration of the signal-carrying conductors. The chief sources of the environment for aircraft are power switching transients and fields radiating from the aircraft antennas. Transients having peak values comparable to the ac supply voltage occur routinely as a result of electric circuit switching and equipment regulation. Transients as large as ten times the peak supply voltage can occur if untreated relays are actuated, and peak currents as large as ten times the normal load current may occur from routine operation of on-board equipment. These transients are characterized by fast risetimes and, as a result, can couple efficiently to nearby signal and control wiring. Interference from aircraft antennas depends upon the antenna current and the radiation characteristics of the antenna, as well as upon the ability of the fuselage to provide some shielding of the internal equipment.

This problem of ensuring electromagnetic compatibility (EMC) for aircraft is routinely addressed for each system design and is governed by several military standards, specifications, and handbooks. The fact that aircraft have been able to perform and fulfill their missions while immersed in their own electromagnetic environments indicates that EMC design procedures have been successful. However, this does not necessarily indicate that the standard EMC practices are optimal. Recent research by SRI personnel has shown that routine EMC procedures relating to shielding and grounding are actually compromises of sound engineering principles, and that the advent of composite fuselages, more sensitive avionics, and more intense environmental requirements makes it imperative that these compromising practices be discouraged (Vance et. al., 1980).

(2) Natural Atmospheric Interference

Military aircraft are being required more frequently to fulfill their missions in severe weather environments. This implies a greater exposure to natural atmospheric electricity, namely lightning and precipitation static.

Research into the nature of lightning and into the electromagnetic fields produced by lightning strokes has been carried on for decades. A summary of the knowledge gathered prior to 1972 is presented by Cianos and Pierce, (1972). In recent years there has been an increased interest in the lightning environment as a result of the increasing requirements for all-weather operation and the use of more sensitive equipment. Lightning Technology (1980) gives much of the recently obtained data concerning the lightning stroke, and the AGARD Lecture Series (1980) presents a summary of state-of-the-art investigations into interactions between aircraft and static electricity. The work by Fisher and Plumer (1977) presents another study of the lightning/air vehicle interaction problem.

Knowledge of the lightning stroke parameters is statistical in nature. Table C-1 summarizes the statistics of observed cloud-to-ground lightning parameters, and Tables C-2 and C-3 summarize the properties of intracloud strokes. The data reported in these tables was observed prior to 1976. Recent measurements with wider bandwidth instruments

Table C-1

CLOUD-TO-GROUND LIGHTNING PARAMETERS

Parameter	Distribution*		
	2%	50%	98%
Peak return stroke current (kA)	140	20	3.1
Time to peak current (μs)	12	1.8	0.25
Rate of rise (kA/μs)	100	22	5.5
Decay time to half-amplitude (μs)	170	45	10.5
Time interval between return strokes (ms)	320	60	11.0
Number of return strokes per flash	10-11	2-3	--

*Percent which exceeds the listed values.
Channel length: 2 to 8 km, typically 4 km .
Stroke velocity: $2 \times 10^7 - 2.4 \times 10^8$ m/s, typically 10^8 m/s .

Table C-2

STATISTICAL DISTRIBUTION OF INTRACLOUD LIGHTNING PARAMETERS

Parameter	Distribution*		
	2%	50%	98%
Peak current (kA)	14	2	0.3
Interval between strokes (ms)	28	7	1.2

*Percent which exceeds the listed values.

Table C-3

DESCRIPTIVE PARAMETERS FOR INTRACLOUD LIGHTNING

Parameter	Typical Value	Range
Mean height (km)	5	1-12
Channel length (km)	1.5	0.75 - 15
Propagation velocity (m/s)	2×10^7	$10^6 - 1.3 \times 10^8$

have shown that the incidence of strikes with fast risetimes (less than 1 μs) is larger than indicated in the tables. These investigations report that risetimes of 40 ns to 200 ns have been recorded and that there is considerable high frequency energy prevalent in the environment just before the onset of a stroke. These recent studies suggest, therefore, that lightning interference is more broadband than had been thought previously.

The cloud-to-ground lightning stroke current is generally specified to have a double exponential waveshape, with a risetime of 1 μs to 2 μs and a peak amplitude of 100 kA to 200 kA. Intracloud lightning is often modelled by a four-exponential function. Recent theoretical research into the modelling of stroke currents and the resulting field environment has followed two paths: a physical approach which is based on the plasma-like nature of the stroke and its immediate neighborhood, and a mathematical approach which assumes the double exponential waveshape and a fixed channel velocity of the order of 10^8 m/s. The second type of model has been used to compute the fields as a function of position relative to the stroke using time-domain integration of Maxwell's equations. (Uman, et. al., 1977; Fowles, et, al., 1980). These analyses have shown that the peak vertical component of the electic field is approximately 50 kV/m at a distance of 500 m from a vertical stroke with a peak current of 200 kA. A lightning stroke with a peak current of 200 kA (less than 1% of all observed strokes), a risetime to peak of 1.5 μs, and a fall time to half-amplitude of 40 μs can be modelled by a double exponential with the following form:

$$I_{stroke}(t,z) = I_o\left[e^{-\alpha(t-z/v)} - e^{-\beta(t-z/v)}\right] \qquad (C-1)$$

where

$I_o = 206$ kA

$\alpha = 1.7 \times 10^4 s^{-1}$

$\beta = 3.5 \times 10^6 s^{-1}$

v = propagation velocity of the channel, usually equal to 10^8 m/s .

This form of the stroke waveshape is not strictly correct in that it has a non-zero derivative at $t = 0$. It produces errors at $t = 0$ in calculations involving the time derivative of the current (i.e., in external loop coupling problems and in aperture coupling problems). The derivative can be approximated with sufficient accuracy for engineering calculations by assuming $dI/dt = 0$ at $t = 0$, and that the slope increases linearly with time to a peak value of I_{peak}/t_{peak}, which occurs at $t = 0.5\ t_{peak}$. The derivative is zero at $t = t_{peak}$, and the double exponential expression above for I_{stroke} can be used to calculate the derivative for all times greater than t_{peak}.

The lightning protection problem has two aspects: direct stroke attachment to the vehicle and electromagnetic interaction with nearby and distant strokes. Direct stroke attachment usually occurs at sharp points on the vehicle structure, with the current flowing along the fuselage, exiting at the opposite end of the vehicle, and completing the earth-to-cloud channel. The incidence of direct stroke attachment to aircraft is approximately once per 3000 h of operation. (Fisher and Plumer, 1977). Electromagnetic interaction with nearby and distant strokes occurs much more frequently.

Static electricity is produced as a result of the frictional charging which occurs when two dissimilar materials rub or contact each other. For aircraft, this occurs during flights through airborne particulate material such as dust, ice crystals (cirrus clouds), or snow. The amount of charge deposited on an air vehicle undergoing triboelectric (frictional) charging depends upon the self-capacity of the vehicle. The rate at which the charge accumulates depends upon a large number of factors such as the type and density of the particulate material, the airspeed and projected frontal area of the vehicle, the humidity, and so on. During triboelectric charging, the aircraft will continue to accumulate charge until the increasing electric field stress on the airframe exceeds the corona threshold (this usually occurs in only a fraction of a second), at which time the aircraft will go into a corona discharge condition. Corona current will leave the vehicle from the high-field regions -- usually from the wing, elevator, and rudder trailing edge tips. Under steady-state conditions, the corona discharge current will just equal the triboelectric charging current, and the vehicle will remain at a high potential with respect to earth. Although the aircraft potential rarely affects any part of vehicle operation, the corona discharges can interfere with radio communication and navigation equipment. Figure C-2 shows a power spectral density of typical corona discharges from the trailing edge of an aircraft wing (Tanner and Nanevicz, 1961).

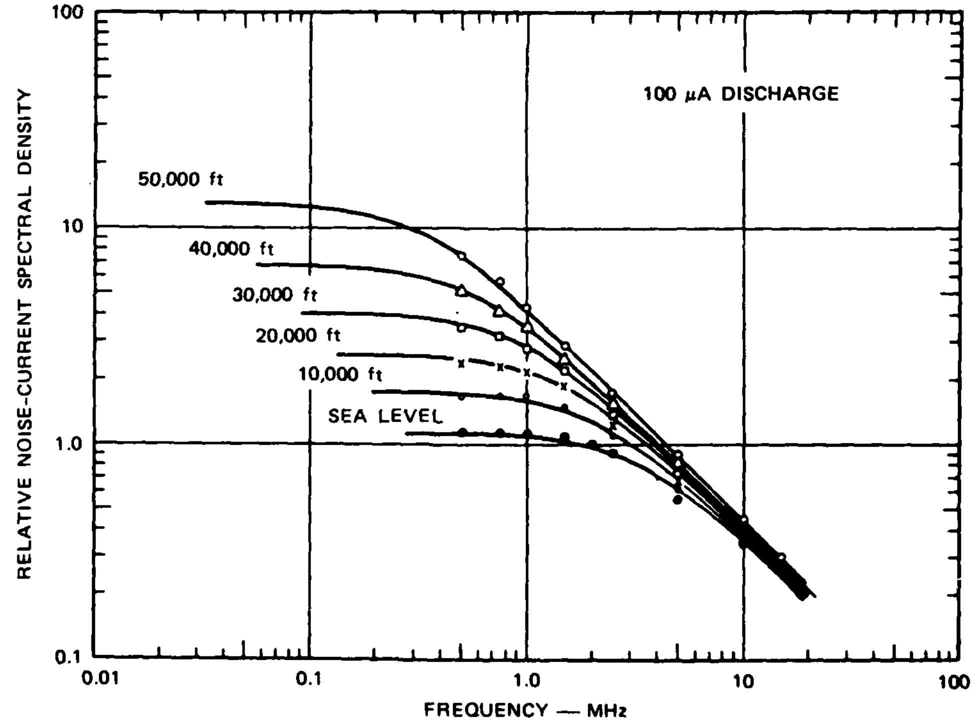

FIGURE C-2 NORMALIZED NOISE SPECTRUM FROM TRAILING EDGE

The electric potential that an aircraft can reach depends upon the electric fields produced by the airframe geometry; the "sharper" the edges of the wing-tips, for example, the greater the electric field will be at that point, and the sooner the corona discharge will occur as the aircraft charges up. The vehicle potential can thus be lowered by using corona "dischargers": needle-sharp devices located on the trailing edge of the airfoils. (These devices, properly oriented and attached to the airfoil through a high resistance, serve to "decouple" the discharge from the aircraft and reduce the interference that would be induced in avionics systems. They are commonly found in all U.S. commercial jet aircraft and many military jets.)

Experiments conducted by SRI on military fighter aircraft and on cruise missiles (Nanevicz, et. al., 1980; Graf, et. al., 1980) have shown that an unprotected (i.e., without dischargers) aircraft such as the F4 will go into corona at a potential of about 170 kV. The cruise missile, with its sharper edges on the rear control surfaces, goes into corona at a potential of about 42 kV. Helicopters, such as Boeing's CH-47 "Chinook," go into corona at potentials of about 100 kV (Douglas and Nanevicz, 1973). When attached, corona dischargers will reduce the corona thresholds of fixed-wing aircraft to about 20 kV to 25 kV. (Rotary-wing aircraft are more difficult to discharge due to the complex recirculation of air-flow patterns; a typical minimum potential for a discharger-equipped helicopter might be about 50 kV; therefore, helicopters are not equipped with dischargers due to the poor benefit/cost ratio.) Upon landing, an aircraft discharges the stored charge almost immediately into the soil through the tires. Thus, the post-landing residual charge on the aircraft poses minimum risk for stores, or for ordnance and refueling personnel.

Charging of a composite helicopter will occur much as it does on a conventional one. However, the consequences of the charge deposition may be quite different depending upon the electrical conductivity of the composite material used in fabricating the helicopter, and the degree to which adjacent sections are electrically bonded.

A helicopter made of Kevlar epoxy and left untreated would behave as a good insulator. Charge deposited on a particular section of the vehicle would remain there, so that substantial potential differences between adjacent sections of the skin would be possible. These potential differences lead to surface streamer discharges tending to equalize the potentials. Such noise-producing discharges are observed on dielectric sections of conventional aircraft.

Similarly, a Kevlar helicopter equipped with lightning-diverter strips on its surface would acquire static charge in the insulating regions between the strips. Surface streamers would occur from these regions to the adjacent strips.

Although the bulk conductivity reported for graphite epoxy panels is adequate to conduct frictional charging currents, it is not clear that the conductive properties of the material extend to the surface. In particular, certain panels are made up with a substantial thickness of epoxy as the outer layer. Static charge will accumulate on this surface until it is relieved by puncture through the epoxy layer to the graphite layers below.

Differential charge accumulation can be eliminated by applying a conducting coating to the helicopter surface. (Presently, on conventional aircraft, the leading surfaces made of fiberglass are coated with conducting material to prevent charge accumulations.) Whether such a coating should be used depends on the severity of the problems created by its omission. In the case of a Kevlar helicopter, substantial regions will accumulate charge so the streamers will be large and very noisy. The streamers on a Kevlar helicopter equipped with lightning-diverter strips will be shorter and less noisy. The streamers on a carbon composite helicopter (if they indeed occur) will be still shorter and even less noisy.

P-static noise can also be generated by sparking between unbonded adjacent sections of the aircraft. On aircraft made of metal, adequate bonding generally results naturally when the aircraft is riveted together. With graphite epoxy or coated Kevlar structures, on the other hand, careful attention must be paid to providing good electrical contact between adjacent sections.

(3) The Nuclear EMP Environment

The occurrence of a thermonuclear burst generates an electromagnetic transient whose properties depend upon details of the burst (size of the weapon, burst location in the atmosphere). The transient signal incident upon an aircraft depends upon the location of the burst with respect to the aircraft. For systems far from a high altitude burst (HAB), the incident excitation can be modelled by a plane wave with a waveshape and polarization dependent upon the burst location and yield. The excitation from a near-surface burst can be modelled by a wave propagating along the earth's surface (ground or water). Lee (1980) and Mindel (1978) describe simple physical models of the nuclear EMP and provide further references to numerical codes (many of them classified) which predict angle of incidence, polarization, and waveshape information.

For specification and modelling purposes, the incident EMP is considered to be a plane wave with arbitrary polarization and arbitrary angle of incidence, and with electric and magnetic field time histories given by

$$E_{inc}(t) = E_o\left(e^{-a_1 t} - e^{-a_2 t}\right) \qquad \text{(C-2)}$$

and

$$H_{inc}(t) = E_{inc}(t)/377 \qquad \text{(C-3)}$$

where $E_o = 52.5$ kV/m, $a_1 = 4 \times 10^6\ s^{-1}$, and $a_2 = 4.76 \times 10^8\ s^{-1}$.

Figures C-3 and C-4 describe the time- and frequency- domain behavior of this specification pulse. The time-domain waveform is plotted on a logarithmic scale to emphasize the fast early behavior of the pulse. The frequency plot includes a curve showing the normalized cumulative energy density and indicates that 99.9% of the incident energy is below 100 MHz. The time-domain curve indicates that the peak amplitude of the electric field is 50 kV/m, with a fall time (to 1/e of the peak value) of about 350 ns.

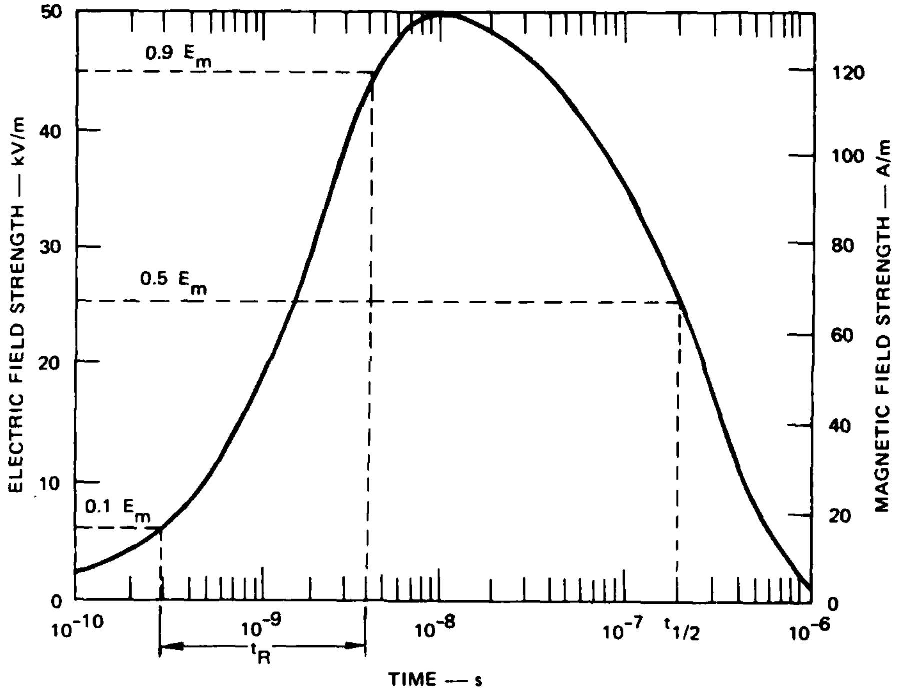

FIGURE C-3 GENERALIZED HIGH-ALTITUDE EMP ELECTRIC AND MAGNETIC FIELD TIME WAVEFORM

(4) Other External Sources of Interference

The other significant sources of EMI are associated with air- and ground-based transmitters. These may include countermeasure threats, high power radars, and intense beam weapons. The relevance of these threats to Army aircraft is partially dependent upon the mission of the

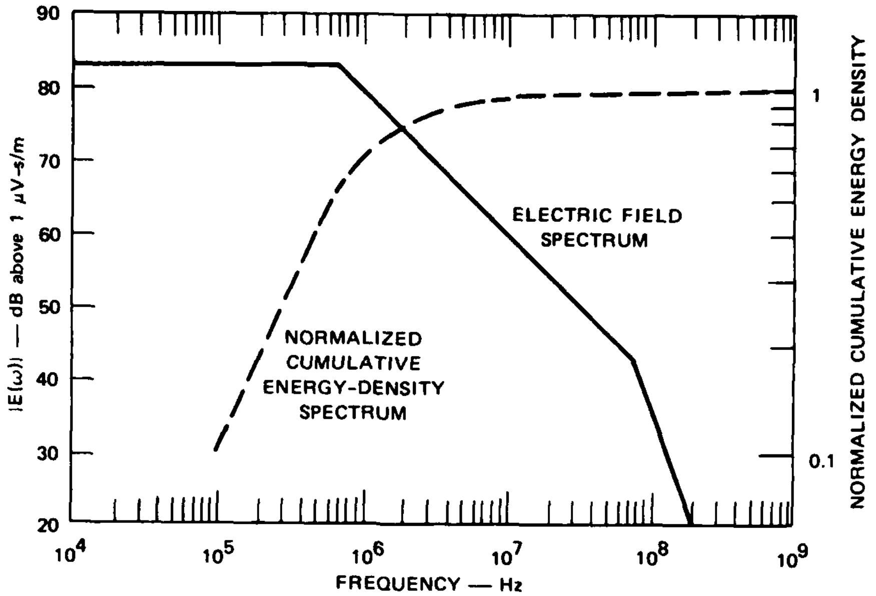

FIGURE C-4 HIGH-ALTITUDE EMP SPECTRUM (*electric field*) AND NORMALIZED ENERGY DENSITY SPECTRUM

aircraft. The nature of these sources is quite variable, as a broad range of intensities, bandwidths, and carrier frequencies can be expected. It is beyond the scope of this document to discuss these in greater detail, but the implications of these threats on coupling calculations and on mitigation of the interfering signals are similar to those for EMP and the radiated fields of a lightning stroke.

b. Coupling of External Interference to Aircraft

The interaction of external interference sources with aircraft results ultimately in the generation of undesired currents and voltages on equipment wiring. The coupling mechanisms involved in this are the processes discussed qualitatively in an earlier section. The incident fields interact with the external surfaces and appendages of the aircraft and produce currents flowing on the fuselage and on the external wire penetrations. The waveshape of the current induced on the fuselage is dependent upon the parameters of the source (waveshape, polarization and angle of incidence relative to the aircraft orientation) and upon the parameters of the aircraft (size, shape, and material properties). The fuselage currents can diffuse through the skin and can generate fields which leak through the apertures and seams.

Currents excited on wire penetrations are dependent upon the source parameters and upon the parameters of the penetration (size, shape, orientation wtih respect to the fuselage, and the wire termination impedances). The penetration current which ultimately enters the aircraft is dependent upon the impedance of the diversion treatment (filter, voltage limiter) at the point of entry and upon the impedances which terminate the wire inside the aircraft.

The following sections discuss the implications of advanced composite materials on each of these coupling modes. For the purposes of these discussions, a circular cylindrical shell is used to model an aircraft fuselage. While this example is not applicable to all aircraft, it provides a simple geometry for first-order coupling calculations which quantify the differences between metal and composite fuselages from an E^3 hardening viewpoint. It also leads to the discussion in Section 4 of additional hardening measures required for advanced composite aircraft. The cylindrical model is assumed to have a length of 15 m, an outer diameter of 2 m, and a wall thickness of 3.175 mm (0.125 in.). Fuselages constructed with aluminum, graphite epoxy, and Kevlar are considered in these calculations.

(1) Diffusion Coupling Calculations

The problem of diffusive coupling into cavities has a long history in the literature of electromagnetic theory. Lee (1980) (pages 555-566) provides an excellent summary of this topic. The problem is extremely difficult for cavities of arbitrary shape, but certain canonical shapes can be analyzed exactly (i.e., spherical shell, infinite cylindrical shell, infinite parallel plates). While many practical shapes cannot be analyzed exactly, excellent engineering approximations are available for cavities of arbitrary shape which are physically thin and for which the diffusion time across the wall is much greater than the pulsewidth.

For the sake of this discussion, the cavity is assumed to be the right circular cylinder described earlier: length $L = 15$ m, diameter $D = 2$ m, and wall thickness $\Delta = 3.175$ mm. The external electromagnetic field is assumed to be a plane wave incident in the broadside direction (i.e., the Poynting vector is perpendicular to the axis) with the electric field parallel to the axis (the worst-case coupling condition). The waveshape of the incident electric field is assumed to be that of the nuclear EMP resulting from a high-altitude burst; namely, a peak amplitude of 50 kV/m, risetime of 3.5 ns, and a fall time to (1/e of the peak) of about 350 ns. The choice of the nuclear EMP waveshape was made for ease of analysis, since the short pulsewidth relative to the time for the wave to diffuse through the skin allows certain simplifications in the analysis. The cavity parameters of importance are the volume V, surface area S, thickness Δ, conductivity σ, and relative permeability $\mu_r = \mu/\mu_o$. These parameters can be used to define the following quantities:

$R = 1/(\sigma\Delta)$ = dc wall resistance

$L = \mu_o V/S$ = cavity inductance

$\tau_f = L/R$ = fall time of interior field

$\tau_d = \mu\sigma\Delta^2$ = diffusion time across the wall

and

$$\xi = \frac{1}{\mu_r}\,\frac{V}{S\Delta} = \frac{L}{R\tau_d} = \frac{\tau_f}{\tau_d} = \text{a dimensionless parameter.}$$

With the above definitions, and for the following conditions, $\xi \gg 1$, $\epsilon\omega \ll \sigma$, and the dimension of the cavity in the direction of propagation $\ll$ wavelength — several important engineering formulas can be derived for the cavity. These expressions are:

$H^{int}(\text{peak}) = H_o/(\xi\tau_d)$ = peak time-domain value of the interior magnetic field

$\dot{H}^{int}(\text{peak}) = 6H_o/(\xi\tau_d^2)$ = peak time derivative of the interior magnetic field

Risetime $= \tau_d/4$ = risetime of the interior magnetic field (10%-90%)

Falltime $= \xi\tau_d$ = falltime (to 1/e) of the interior magnetic field

$V_{oc}(\text{peak,max}) = \mu_o A_{max} \dot{H}^{int}(\text{peak})$ = maximum open circuit voltage which can be induced in the largest loop (area $= A_{max}$) which can fit inside the cavity

In the above, H_o is given by

$$H_o = \int_{-\infty}^{\infty} H^{ex}(t)dt$$

where $H^{ex}(t)$ is the external (incident) plane wave magnetic field. For a 50 kV/m EMP pulse defined by the double exponential of Eq. (C-1), H_o is approximately equal to 3.45×10^{-5} As/m.

The expressions above can be used to find the largest voltage that can be induced by diffusion of the incident field through the skin. For an aluminum cylinder ($\sigma = 37$ MS/m), the peak open circuit voltage that can be induced in the largest loop which can fit inside the cavity (area approximately 30 m^2) is about 230 μV, and the risetime of this induced voltage pulse is approximately 117 μs. The results for a graphite epoxy cylinder ($\sigma = 10$ kS/m) are a peak voltage of about 3.1 kV and a risetime of about 32 ns. If the cylinder is constructed of Kevlar ($\sigma \approx 0$), the magnetic field is essentially unchanged by passage through the walls and the peak open circuit voltage is about 2.9 MV with a risetime of a few nanoseconds. This calculation for Kevlar assumed a peak time derivative of the interior magnetic field of about 0.8×10^{11} $Am^{-1}s^{-1}$.

Thus, the effects of fuselage material on the internal voltages excited by diffusion coupling alone are severe. For metal skins, the diffusion component is very small and the risetime is relatively large, implying minimal coupling to equipment wiring and minimal threat to avionics equipment. For graphite expoxy fuselages, the induced interior voltage pulse is significant in both peak amplitude and high frequency content. Kevlar fuselages provide very little attenuation of the incident field, unless accompanied by a metallic foil covering or flame sprayed covering. Additional investigations of diffusion coupling effects are contained in the AGARD Conference Proceedings No. 283 (1980) and the reported results are generally similar to those given here. The major implication for the viewpoint of the E^3 hardening problem is that the diffusion component cannot be neglected in hardening designs for advanced composite aircraft.

(2) Aperture Coupling Calculations

A summary of aperture coupling is given by Lee (1980), and a review of coupling through small apertures is presented by Butler (1978). The internal fields arising from aperture coupling are dependent upon the external excitation, upon the size and shape of the aperture, and upon the size and shape of the cavity behind the aperture (which includes the equipment in the cavity). In general, this problem is difficult to treat analytically for all but the simplest configurations. However, for the frequency range for which the aperture is electrically small (i.e., the largest aperture dimension is much smaller than a wavelength), the problem can be described by relatively simple formulas and equivalent circuits.

The field in the region behind the aperture can be computed by considering the sources of the cavity fields to be equivalent electric and magnetic dipoles located at the aperture, with the aperture shorted. This is an application of the equivalence principle, discussed in many graduate level electromagnetics texts. The steps involved in formulating the equivalent problem are shown in Figures C-5 and C-6. The equivalent dipole moments depend upon the external source fields and upon the aperture geometry. The geometry dependence is such that the

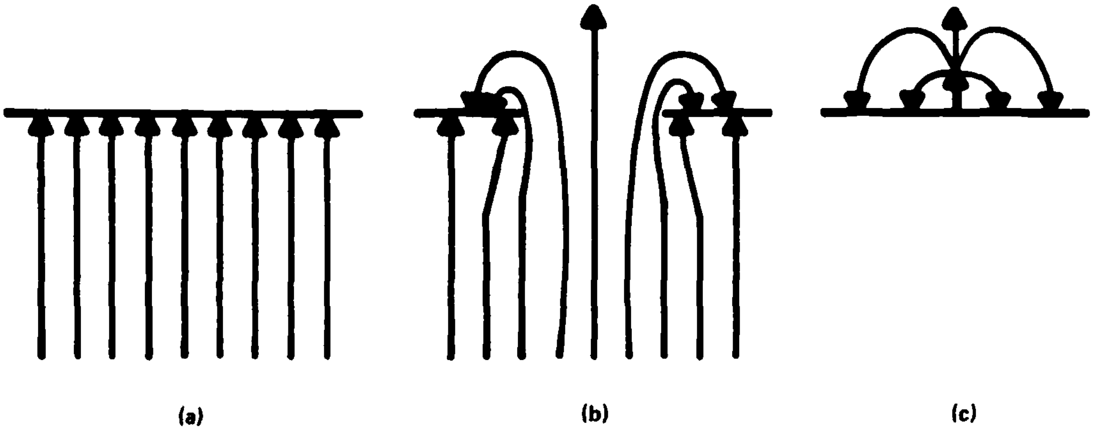

FIGURE C-5 ELECTRIC FIELD APERTURE-COUPLING GEOMETRY. (a) Impressed electric field perpendicular to screen with no aperture. (b) Electric field near aperture in screen. (c) Equivalent electric dipole (on screen with no aperture) and its electric field.

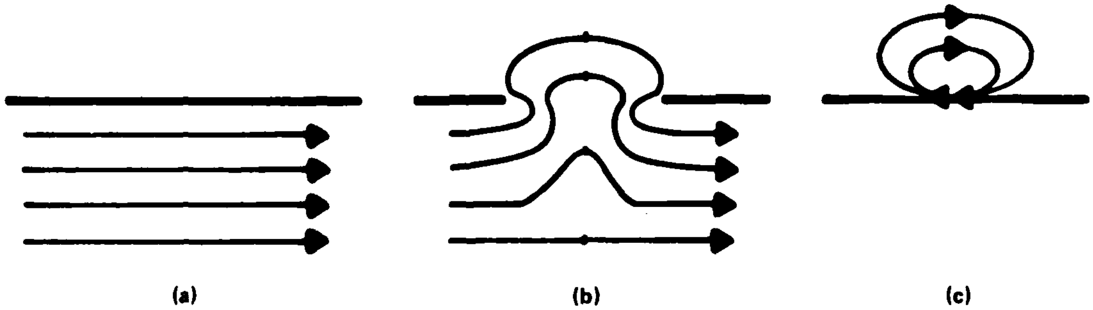

FIGURE C-6 MAGNETIC FIELD APERTURE-COUPLING GEOMETRY. (a) Impressed magnetic field parallel to screen with no aperture. (b) Magnetic field near aperture in screen. (c) Equivalent magnetic dipole (on screen with no aperture) and its magnetic field.

dipole moments are directly proportional to parameters (called the electric and magnetic polarizabilities) which are functions of the aperture size and shape alone. In general, these polarizabilities are tensors; however, for many cases commonly encountered, only a few components of the tensor are required. For apertures created by seams at metal joints, only the magnetic polarizability is required to solve the problem.

The apertures on aircraft are of two types: those corresponding to seams and joints and those corresponding to holes in the fuselage. For the case of holes in the fuselage a simple calculation can be made for the largest voltage able to be induced in a circuit in a cavity. The current flowing in the fuselage acts as a source for fields inside the cavity. Assume there is a square hole of dimension r on the skin; the magnetic flux linking the cavity interior is given by $\phi_m = \mu_o J_s r^2$, where J_s is the surface current density and is equal to $I_{skin}/(2\pi a)$, where a is the radius of the fuselage. The voltage induced by this changing flux is given by $d\phi_m/dt$, or

$$V = \mu_o r^2 \frac{d}{dt} J_s \quad . \tag{C-4}$$

The peak time derivative of the surface current density is

$$\left.\frac{dJ_s}{dt}\right|_{peak} = \frac{1}{2\pi a} \left.\frac{dI_{skin}}{dt}\right|_{peak} \quad .$$

The skin current is induced by interaction of the incident field with the cylinder. For a direct attachment of a lightning stroke to the fuselage, the skin current is the current in the stroke, as given in Eq. (C-1). Both cases can be treated here. An EMP incident from broadside with the electric field parallel to the axis induces a skin current which is a function of time and position on the cylinder. Figure C-7 (from Lee, 1980) indicates the normalized induced skin current at the center of the cylinder (z = 0 in the figure) and at a point halfway between the center and an end of the cylinder (z = L/4).

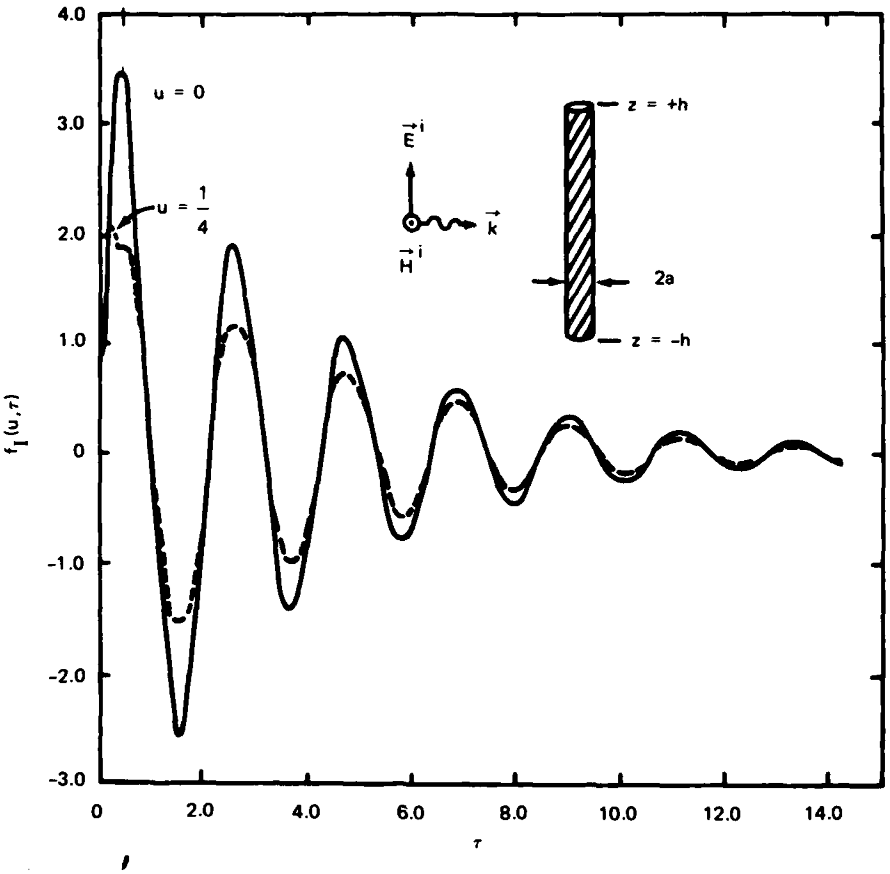

FIGURE C-7 NORMALIZED AXIAL CURRENT FOR A UNIT-STEP INCIDENT PULSE ($u = z/L$, $\tau = ct/L$, $L = 2h$)

The skin current as a function of position and time is given by

$$I(z, t) = \frac{LH^i}{\ln(L/4a)} f_I(z/L, ct/L)$$

where H^i is the peak amplitude of the incident magnetic field and c is the speed of light. The incident field is a plane wave with a step waveform. For a 50 kV/m incident electric field, the incident magnetic field amplitude H^i is approximately 133 A/m. The peak current induced at the center of the cylinder is about 5.3 kA, and the peak current at $z = L/4$ is about 3.2 kA. The induced current at the center reaches a peak at $t \approx 20$ ns, and the current at $z = L/4$ reaches a peak at $t \approx 10$ ns.

The peak time derivative of the current at the center of the cylinder can be estimated from these results to be about 2.6×10^{11} A/s, and the peak derivative of the skin current density is approximately 0.41×10^{11} $\mathrm{Am^{-1}s^{-1}}$. The peak in the derivative occurs at approximately 10 ns. These results are valid for cylinders with metal skins; the presence of a graphite skin ($\sigma = 10$ kS/m) would result in a smaller peak current and a slower risetime as a result of the lower conductivity.

For a metal skin, the peak voltage that can be induced on any circuit in the cavity is given by Eq. (C-4). If a hole of dimension 10 cm is assumed at the center of the cylinder, the peak internal voltage is approximately 515 V with a risetime of about 10 ns. This is orders of magnitude larger than the peak diffusion-coupled voltage for a metal cylinder. The voltage induced inside a graphite epoxy cylinder by aperture coupling would be smaller and would have a slower risetime.

The case of direct attachment of a lightning stroke to the cylinder with an aperture on the surface is now considered. The skin current is given by Eq. (C-1), and the peak time derivative of the skin current density is approximately 0.2×10^{11} $\mathrm{Am^{-1}s^{-1}}$, approximately one-half the value for the EMP-induced transient. Thus, the peak voltage induced on a circuit inside the cavity by coupling through a 10 cm aperture is about 250 V, with a risetime of about 750 ns.

The case of seams and joints on the fuselage, such as those found at doors and hatches, cannot be treated in the same fashion. Here the apertures are not clearly definable as "holes," but occur due to imperfect conducting paths between overlapping conducting pieces. Analytical expressions for the flux linkage (or, equivalently, the magnetic polarizability of the aperture) cannot be derived. These properties can be measured, however, and the report by Whitson and Vance (1977) discusses the results of an investigation into this problem. These analyses indicate that the largest voltage which could be induced on a circuit inside a cylindrical metal cavity with circumferential seams is of the order of 5 V peak with a 10 ns pulsewidth for seams having a magnetic polarizability of 10^{-5} m^3 per meter seam length. Polarizabilities of 10^{-6} m^3 per meter seam length are not difficult to achieve; this reduces the coupling by a factor of 10, since the coupling is directly proportional to the polarizability.

An analysis was reported by Lee (1980) to estimate the effect of long axial seams. For an assumed magnetic polorizability of 10^{-6} m^3 per meter seam length, the open circuit voltage induced on a wire inside the raceway, running the length of the raceway and connected to it at only one end, was found to be of the order of 40 V peak with a 10 ns pulsewidth.

The AGARD Conference Proceedings (1980) reports on several measurements of the properties of seams and joints on graphite epoxy fuselages. For frequencies below 100 MHz, the admittance of the seam appeared to be constant with frequency. No measurements of the magnetic polarizability for graphite seams have been reported, but the joint admittance can be related to the polarizability if details of the measurement system are known (Whitson and Vance, 1977). Analysis of graphite epoxy seams in the AGARD Conference Proceedings (1980) indicates that peak open circuit voltages inside the cavity are of the order of 10 kV for direct attachment of a lightning stroke, 500 V for nearby (20 m) lightning , and 30 V for EMP.

The results of these first-order, worst-case analyses of diffusion and aperture coupling are summarized below.

- For metal skins, the diffusion-coupling component can usually be neglected. The aperture-coupling component can be significant (hundreds of volts for holes and tens of volts for seams) and has risetimes of tens of nanoseconds.

- For graphite epoxy skins, the diffusion-coupling component can be of the order of several kilovolts, with risetimes of tens of nanoseconds. The aperture-coupling component can be of the order of 10 kV for seams (direct attachment of lightning) and several hundred volts for nearby lightning, with risetimes of less than 1 μs for a stroke with a 1 μs to 2 μs risetime.

- For Kevlar skins (assumed to be uncoated), there is no appreciable attenuation of the incident fields.

(3) Wire Penetration Coupling

Of all the modes of electromagnetic energy propagation into a volume containing sensitive equipment, currents entering on wire penetrations are often the most significant, especially for metal aircraft. These penetration currents may be on insulated power wiring, on deliberate antennas, on cable shields and conduits, on control cables and control surfaces, on hydraulic lines, etc. These penetrations are necessary for the desired operation and mission accomplishment of the vehicle and they occur at every topological level of the system. As indicated in Appendix B of this report, the proper treatment of penetrations for E^3 hardening is to divert the penetrating current to the exterior of the fuselage. This is achieved in several ways: peripheral bonds for "groundable" penetrations, and by filtering and voltage limiting for insulated penetrations. The effectiveness of these treatments is strongly dependent on the ability to make a low impedance bond to the fuselage. This is seldom a problem with metal fuselages, except in the case of corrosion at the bond. For graphite epoxy fuselages, the effects of the relatively low conductivity at the bond are not known in great detail at this time, but it is apparent that diversion techniques will not be as effective as they are on metal aircraft.

3. EMC Considerations for Composite Aircraft

The analysis of the previous sections has indicated the impact of a composite fuselage on some aspects of the E^3 hardening problem. The examples discussed — lightning, static discharges, and nuclear EMP — indicate the magnitude of the problem for interference sources external to the system. The EMC problem has not been addressed specifically; however, the calculations show that, for antennas mounted on the aircraft, the resulting interior electromagnetic environment is made more severe by the composite fuselage. This is particularly important in the frequency range of 1 MHz to 30 MHz, at which the aircraft equipment wiring tends to respond most strongly.

The environment produced by internal sources of interference (i.e., by the aircraft's own equipment in its normal mode of operation) has been described to a limited extent, and few specific conclusions can be stated concerning this topic without a more complete knowledge of the environment and the equipment susceptibilities. What can be said, however, is that the design of the signal and power reference systems (the so-called "ground systems") must carefully integrate both the operational requirements and the E^3 requirements. The viewpoint of topological zoning described in Appendix B of this report is a powerful tool for this aspect of the design. The topic of "ground system" design has been poorly understood in past years and has generated considerable confusion and controversy. Military standards and specifications have been particularly deficient in this area by permitting and, in some cases, recommending "grounding" practices which clearly compromise the electromagnetic immunity of the system (Vance et. al., 1980).

The traditional aerospace industry practices which most consistently violate topological design principles are those having to do with "ground" systems and their relationships to barrier (or "shield") surfaces. For example, the practice of abruptly cutting the cable shield a short distance from the connector and then soldering a wire to the shield and routing it through the connector to a "ground" lug inside the equipment container (the so-called "pigtailing" of a cable shield) is a serious compromise of the design. For frequencies above 10 MHz, pigtails as short as a few millimeters can negate a large part of the potential effectiveness of the shield (Paul, 1980). While compatible aircraft have been successfully designed and manufactured with these standard practices, the compatibility has been achieved in spite of these practices rather than because of them. The advent of composite structures and the subsequent enhancement of the high frequency interference environment imply that these practices can no longer be permitted, especially in conjunction with equipment which is less tolerant of interfering signals.

4. E^3 Hardening Strategies for Composite Aircraft

Composite aircraft will contain a combination of hard-wired electrical and electronic equipment, with increasing use of multiplex and fiber optic systems in the near future. Multiplex systems will require a smaller number of wires, and their increased use will reduce the electromagnetic complexity of the aircraft. Fiber optic systems will carry this trend one step further by eliminating the input/output pair, leaving only the power conductors and mechanical elements. These trends promise to reduce the electromagnetic complexity of aircraft, simplify the shield topology, and ease the hardening constraints.

The hardening techniques used for composite aircraft will be essentially the same as those used for metal aircraft, but they will be used in different combinations and with different shield configurations. Although it is apparent that one can recover the loss in shielding by covering the composite structure with metal coatings, such acts add weight and cost. Since two of the strongest motivations for using composites in the first place were to reduce weight and cost, these factors must be minimized in the recovery of the desired electromagnetic properties. Therefore, it may be more economical, for example, to shrink the shielded volume to the avionics equipment bays or racks and use conduits for interconnecting cables (if any) and power, rather than maintain the first shield at the skin or outer surface. Often bays and racks are designed with sufficient metal to accommodate electromagnetic shielding so that only a slight modification in construction can provide the shielding required with little or no added weight.

Other low-weight techniques involve the use of twisted-pair, balanced load wiring, which can provide significant isolation for frequencies below a few megahertz. Filter pin connectors and voltage-limiting devices are also low in weight, but have undesirable features which must be investigated before their use can be justified. For example, filter performance depends on the source and load impedances, and certain combinations of filters and terminating impedances can produce gain over significant frequency ranges. Likewise, the operation of voltage-limiting devices can generate spurious high frequency interference which may adversely affect other parts of the system.

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