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FIRST ANNUAL REPORT

(PERIOD: 3/30/95 - 3/30/96)

Includes Fourth Quarter
(Period: 1/1/96 - 3/30/96)

FOR

DEVELOPMENT OF DESIGN STANDARDS AND GUIDELINES FOR ELECTROMAGNETIC COMPATIBILITY AND LIGHTNING PROTECTION FOR SPACECRAFT UTILIZING COMPOSITE MATERIALS

Contract Number: NAS8-39983
Dated: March 30, 1996

Electromagnetics and Environments Branch
Systems Analysis and Integration Laboratory
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April 9, 1996

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Appendix

1. Introduction:

This Annual Report presents information on significant technical accomplishments (Section 2) for the first year of the contractual effort. These accomplishments are presented in the same basic format used for the first three Quarterly Reports. The main item to be presented in this report, however, is that of presenting a brief narrative report on three significant accomplishments of the first year's effort including the fourth quarter. All but one of these items has previously been covered in quarterly reports, thus they will not be covered in the same detail, except the one item, as they in the Quarterly Reports.

Information is presented, in Section 3, on the one problem that has occurred at this time relative to the contractual effort. This problem was and is concerned with obtaining composite material samples for use during the testing portion of the effort.

Section 4 will contain a few brief comments concerning the second year of effort for this contract. Basically, there are no changes anticipated for the contract. Thus, the second year of effort is expected to be as stated in the contract Statement-of-Work.

Financial information relative to the contract will be presented in Section 5.

2. Overall Progress:

This Annual Report presents information on significant technical accomplishments for the first year of contract effort. Three significant technical efforts and one non-technical were accomplished during this year. These efforts are described in the following Sub-Sections.

2.1. Perform and document a literature search:

A literature search was accomplished and the results were provided to the NASA Marshall Space Flight Center (MSFC) as a literature survey report (Appendix A to the Second Quarterly Report). The report, entitled "Electrical Properties of Non-Metallic Composites" and compiled by Mr. Hugh W. Denny was concerned with information related to electrical properties of non-metallic composite materials used on spacecraft, satellites, and aircraft. The particular properties of concern were conductivity and shielding characteristics which are useful in preparing guidelines for designers where electrical grounding, shielding, bonding, fault current returns, and lightning protection are important.

2.2. Define tests for low to moderate currents:

The type of tests defined so far are to some extent dependent on the type of composite to be used in the testing. At the present time MSFC is in the process of obtaining composite samples to be used. When the composite samples are made available, then the test plan will be complete. Test results will provide information relative to suitability of protective design methods where information is not currently available. This is the only area of the effort where a problem was experienced during the first year of effort as noted in Section 1 above and as will be described in Section 3 below.

2.3. Prepare and document "Preliminary Design Guidelines":

The preliminary design guidelines document entitled "Design Guidelines for Shielding Effectiveness, Current Carrying Capability, and The Enhancement of Conductivity of Composite Materials" is considered to be the most significant effort accomplished during the first year. As specified in the Statement-of-Work for this effort, the document covers preliminary design guidelines necessary to assure electromagnetic compatibility of spacecraft using composite materials, including enhancement techniques, and establish a database of electrical properties of composites. The Guidelines were finalized during the fourth quarter of the contractual effort and are being delivered as an appendix to this Annual Report. Some of the information contained in this guideline was provided to MSFC as an appendix to the Second and Third Quarterly Reports. The title used for those quarterly reports was, "Composite Materials - Conductivity, Shielding Effectiveness, and Current Carrying Capability."

2.4 An additional item of significance:

It is also considered to be significant that the first year of effort has been accomplished for less than was budgeted. This is primarily due to the fact that two months of testing and documentation of the testing, as called for in Tasks 2b and 2c of the Statement-of-Work, could not as yet be performed due to non-availability of composite materials for use in the testing. Additional information is presented on the non-availability of materials in Section 3 below.

3. Problems and Proposed Corrective Action:

The only problem of any significance at all during this first year's effort has been concerned with obtaining composite material samples for the testing portion. In actuality, this problem should be classified as a minor problem and one that will not impact the effort to any extent. As noted in Section 2.2 above this problem of obtaining composite samples is being worked by MSFC. If for some reason the samples are not obtained by MSFC, then the samples can and will be obtained as a part of the contract. A look at the Milestone Schedule (Page 6) will show that two months of the testing for low to moderate current has slipped two months and likewise for the documentation of this testing. The slip which occurred during the second and third quarters will be completed during the next quarter (fifth) of this contract effort. This low to moderate current testing can and will be accomplished during the planning (defining) period for the high current testing without impact to the total effort.

4. Effort(s) to be Performed During the Next Period (Fifth Quarter and Second Year):

Efforts to be performed, as shown on the Milestone Schedule (Page 6), during the second year period will be to finish the work on Task 2b "Perform Tests; (For Low to Moderate Current)," and 2c "Document Results of Tests," and commence work on Tasks 4a "Define High Current Tests," 4b "Perform Tests," and 4c "Document results of Tests." The high current testing which, is expected to be performed in a U. S. Army facility on the Redstone Arsenal, has been discussed and coordinated with army personnel. Additionally, test results from the incompleted effort on Tasks 2b and 2c will be added to the collection of data already obtained and will be provided to MSFC. The final parts of this contractual effort will be to commence and to accomplish Task 5a "Revise Design Guidelines," and to prepare and deliver a final report for the effort.

5. Additional Information Relative to the Contract:

5.1 Total Cumulative Costs:

The total cumulative cost of this contract through March 30, 1996, consisting of direct and consultant labor, and material costs as well as G&A, is $100,552. This value is approximately 82% of the total estimated cost of the first year of contractual effort and approximately 33% of the total two year effort.

5.2 Estimate Cost to Complete:

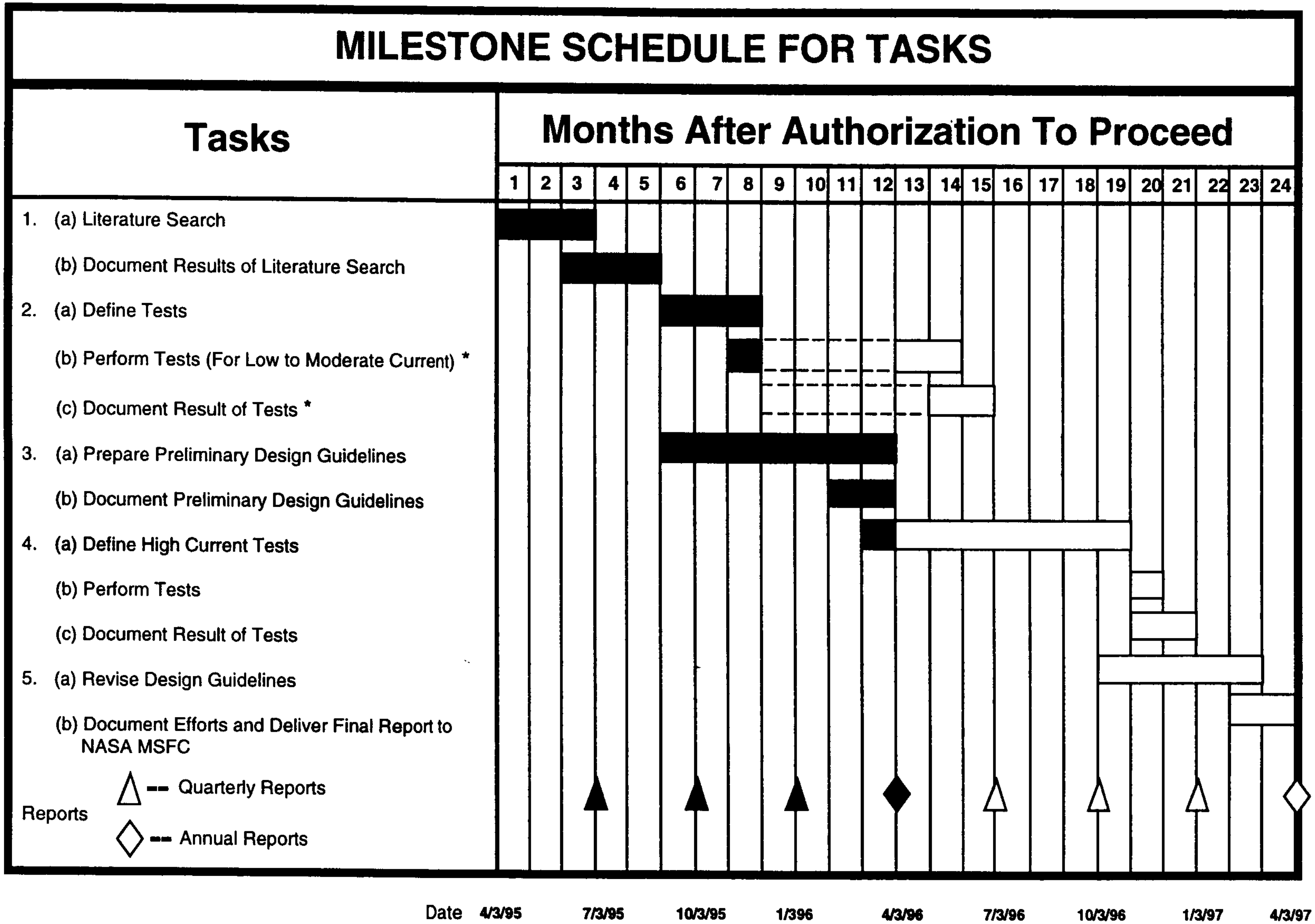
Remaining funds (approximately $22K of the first year's funding) are considered to be ample to finish the first year's effort, namely through Task 3 and two months of effort on Task 4a as well as funding the completion of Tasks 2b and 2c of the Statement of Work. The estimated cost to complete the total two year effort is approximately $206K.

5.3. Estimated Percentage Completion of Effort:

Based on costing information given above (Sections 5.1.1 and 5.1.2) and on work done to date as shown on the milestone schedule, the first year's effort is estimated to be about 95% completed. The total two year effort is estimated to be about 47% completed.

5.4. Relationship of Cumulative Costs to Percentage of Physical Completion and Comment on Any Significant Variance:

This effort, (at the end of the fourth quarter reporting period) is considered to be approximately on time and within allocated costs. No variance is anticipated at this time.



*Waiting on composite samples for testing.

3/31/96

APPENDIX

APPENDIX A

DESIGN GUIDELINES FOR SHIELDING EFFECTIVENESS, CURRENT CARRYING CAPABILITY, AND THE ENHANCEMENT OF CONDUCTIVITY OF COMPOSITE MATERIALS

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DESIGN GUIDELINES FOR SHIELDING EFFECTIVENESS, CURRENT CARRYING CAPABILITY, AND THE ENHANCEMENT OF CONDUCTIVITY OF COMPOSITE MATERIALS

April 3, 1996

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Contract No. NAS8-39983

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REFERENCES

ACRONYMS AND ABBREVIATIONS

ac	alternating current
A	current (amps); or cross sectional area (m^2)
A_{dB}	absorption loss (dB)
B_{dB}	rereflection coefficient (dB)
cm	centimeters
d	distance between points (m), or depth of slot
dB	decibels
dc	direct current
d_{mm}	depth of slot (mm)
D	box depth
e	2.718
E	electric field strength (V/m)
E_i	incident wave
EMC	electromagnetic compatibility
EMI	electromagnetic interference
E_r	reflected wave
ESD	electrostatic discharge
E_t	transmitted wave
f	frequency (Hz)
f_{MHz}	frequency (MHz)
F	Farads
g	air gap
g_{cm}	air gap (cm)
GFRP	graphite fiber reinforced plastic
H	magnetic field strength (A/m), Henries, or box height
Hz	Hertz
j	$\sqrt{-1}$
k	a constant depending upon distance and source impedance
K	a ratio of wave impedance to metal impedance
l	length (m or cm)
ln	natural logarithm
log	logarithm to the base 10

L	frame opening or slot length (m or mm)
L_A	slot length after subdivision
L_B	slot length before subdivision
L_{mm}	length or diameter of opening (mm)
m	meters
mm	millimeters
MEDIC	MSFC EMC Design and Interference Control (a handbook)
MHz	megahertz
MSFC	Marshall Space Flight Center
Ni	nickel
r	distance from source (m)
r_m	distance from source (m)
R_{dB}	reflection loss (dB)
R_{dc}	dc resistance (ohms)
RF	radio frequency
R_m	measured resistance
R_s	surface resistivity (ohms/square)
s	seconds
S	slot height or width (mm)
S_A	slot width after subdivision
S_B	slot width before subdivision
SE	shielding effectiveness
SE_{dB}	shielding effectiveness (dB)
SEE	Space Environments and Effects
SE_E	shielding effectiveness, electric field
SE_H	shielding effectiveness, magnetic field
SE_{shad}	shielding effectiveness due to shadow effect
SE_{total}	total shielding effectiveness
t	thickness (mils, m, or mm)
t_{cm}	thickness (cm)
t_m	thickness (m)
V	Volts
w	width (m or cm)
W	Watts or box width

Z	impedance or intrinsic impedance (ohms)
Z_{air}	intrinsic impedance of air
Z_B	intrinsic impedance of thin metal
Z_m	intrinsic impedance of metal
Z_{RF}	radio frequency reactance
Z_{source}	source impedance
Z_w	wave impedance
α	attenuation constant
δ	skin depth (cm or m)
ΔSE	change in SE due to subdividing slots
ε	permittivity (Farads/m)
ε_o	permittivity of air or space (8.84×10^{-12} Farads/m)
ε_r	permittivity relative to air
λ	wavelength (m)
μ	permeability (Henries/m)
μ_o	permeability of air ($4\pi\times10^{-7}$ Henries/m)
μ_r	permeability relative to air
π	3.1416
ρ	volume resistivity (ohm meter or ohm cm)
ρ_{cu}	resistivity of copper (1.724×10^{-8} ohm meter)
ρ_r	resistivity relative to copper
σ	conductivity (mhos/m)
σ_{cu}	conductivity of copper (mhos/m)
σ_r	conductivity relative to copper
Ω	ohms
ω	$2\pi f$ - angular frequency

DESIGN GUIDELINES

1. PREFACE

This guideline addresses the electrical properties of composite materials which may have an effect on electromagnetic compatibility (EMC). The main topics of the guideline include the electrical shielding, fault current return, and lightning protection capabilities of composite materials. This guideline concentrates on the composites that are somewhat conductive but may require enhancement to be adequate for EMC purposes. These composites are represented by graphite reinforced polymers.

This guideline includes an introduction to resistivity, conductivity, ground plane impedance, and intrinsic impedance of materials for informational purposes. This information is useful in determining characteristics of various types of composite materials and their shielding, current carrying, and lightning protection capabilities.

Information has been obtained from numerous sources that have been listed as references in the back. Items taken from specific documents have been designated with the number of the reference in brackets.

This guideline defines methods for determining adequate conductivity levels for various EMC purposes. This guideline also describes the methods of design which increase conductivity of composite materials and joints to adequate levels.

Funding for this study is provided by the Space Environments and Effects (SEE) Program administered by NASA MSFC's Electromagnetics and Aerospace Environments Branch through Contract NAS8-39983.

2. INTRODUCTION

Electromagnetic compatibility (EMC) occurs when all equipment in a system operates properly without electronic interference from equipment within or outside the system. Electromagnetic interference (EMI) occurs when there is a source of emission, a unit that is susceptible, and a method of transmission between the two. Thus, electromagnetic interference can be controlled by reducing unnecessary emissions, reducing susceptibility, and interrupting the transmission path.

Electromagnetic compatibility requires electrically conductive structure and joints that provide an antenna ground plane, an RF ground plane for filters, electrostatic discharge protection, electromagnetic shielding, fault current return, and lightning protection. Highly conductive material of adequate thickness and sound electrical bonding connections at joints are the primary components of a properly conductive structure. General guidelines for control of EMI can be found in the MSFC Electromagnetic Compatibility Design and Interference Control (MEDIC) Handbook.

Equipment cases and the basic structure of spacecraft and launch vehicles have traditionally been made of aluminum, steel, or other electrically conductive metal. When proper attention is given to electrical bonding between segments and from equipment cases to structure, these highly conductive materials provide a good fault current return path, an RF ground plane for filters, and some degree of shielding against radiated emissions. However, in recent years composite materials have been used for spacecraft structure and equipment cases because of their lighter weight, good strength, and ease of fabrication. Despite these benefits, composite materials are not as electrically conductive as traditional metal structures. Therefore, extra steps must be taken to alleviate this shortcoming. This document provides guidelines to help meet EMC requirements while using composite materials in spacecraft.

Composite materials usually consist of reinforcing fibers or woven mats embedded in thermoset plastic. When electrical conductivity is important, the embedded material may include flakes or fibers of conductive material. Composite materials may also consist of nonconductive reinforcing fibers in plastic with a conductive foil or screen bonded to the outside. Or, composite materials can be electroplated or painted with a thin layer of noncorrosive metal. Some materials, such as carbon filaments, may be used as reinforcement and will also provide some conductivity. However, the conductivity may vary with direction of the weave or layers of fiber.

3. MATERIALS

Plastics are synthetic materials made from raw materials called monomers. Long chains of repeating monomers are called polymers. Thermoplastic polymers consist of long, intertwined chains with no physical connections between them. They typically can be melted and recast maintaining the characteristics of the original material.

Thermoset polymers consist of chains that are crosslinked together. Rigid thermosets have short chains with many crosslinks. Flexible thermosets have longer chains with fewer crosslinks. Thermoset polymers typically are formed by mixing a resin with a hardener and allowing the mixture to set under pressure until hard. Heat is usually applied to speed hardening. Thermoset polymers can not be melted and reformed into the original polymer. Due to the tightly crosslinked structure, thermoset plastics resist higher temperatures and provide greater dimensional stability than thermoplastics.

Composite materials have been developed to rectify some of the shortcomings of plastic compounds. A composite is any combination of two or more materials designed to achieve some characteristic not offered by any of the materials alone. This combination usually provides reinforcement for strength, but it may increase stability or electrical conductivity. Reinforcing material consists of long fibers or mats that tend to strengthen and stabilize the plastic. They may be added to either thermoplastic or thermoset polymers to provide greater strength and stability.

To fulfill mechanical property requirements for aerospace applications, various high strength fibers are combined with appropriate binding resins such as epoxy, polyester, or phenolic. Among the high strength fibers most used are graphite, boron, Kevlar, and glass. Of these, only graphite offers some degree of electrical conductivity.

Fortunately, graphite mats and long fibers are the reinforcement of choice for aerospace work.

Other methods may be used to decrease resistivity, such as adding conductive fillers to the resin. Conductive fillers are usually small particles with low aspect ratios (small length to width) which are too small to provide reinforcement, and they could reduce the strength of the plastic alone. Typical conductive fillers include graphite flakes or fibers, metal coated graphite fibers, and metal flakes or fibers.

Conductivity may also be introduced by adding conductive screen, plating, or paint to the finished product. Increasing the conductivity of finished composite panels or cabinets by adding conductive coatings is a common occurrence in the commercial electronic cabinet industry. The technologies used to form conductive coatings include flame spray, arc spray, vacuum metallization, conductive paints, electroless plating, ion plating, conductive foil or tape, conductive filled plastic, and inherently conductive plastic. All of these methods provide some degree of shielding when used on enclosures. Compliance with FCC rules may only require 30 to 40 dB of electromagnetic shielding.

Flame spray or arc spray deposits metal, usually zinc, onto a prepared substrate. Flame spray uses superheated inert gas which melts metal powder and atomizes it onto the plastic part. Arc spray melts a metal wire as it passes through an electric arc and sprays it onto the plastic. Flame and arc spray techniques produce good conductivity and a hard finish. However, the finish could chip when subjected to temperature extremes.

Vacuum metallization uses pure metal to coat plastic parts. Metal is vaporized in a vacuum chamber, condensed, and deposited on the plastic surface. It has good adhesion and conductivity, but it is limited by the size and cost of the vacuum chamber. Vacuum metallization may be used more by the aerospace and medical industries where high performance and low production are involved.

Conductive paint is usually an organic paint heavily filled with conductive particles such as nickel, graphite, copper, or silver. Nickel in acrylic paint is the most common conductive paint. It may provide shielding of 30 to 60 dB. Graphite may be used to control electrostatic discharge only. Copper oxidizes and loses some conductivity. Silver provides the best conductivity, but it is expensive. These paints may require pretreatment of the plastic for good adhesion.

The electroless plating process involves chemically depositing copper and nickel on etched plastic. The copper layer provides good conductivity, and the nickel topcoat provides environmental protection. Although this process provides good conductivity, it requires pretreatment since the plastic must be etched to ensure adhesion.

This has been a short description of some of the many composites and coatings available at this time. New plastics and new methods of reinforcement are constantly being developed and introduced.

4. GRAPHITE FIBER REINFORCED PLASTIC

Shielding and current-carrying capabilities are directly related to conductivity. Where these capabilities are desired, resin with nonconductive reinforcement is clearly unacceptable for use as spacecraft structure or equipment enclosures. The conductivity of metal structure and equipment cases has proved to be fully adequate when proper thickness and good conductive joints are used. Graphite fiber reinforced plastic (GFRP) has much higher resistivity than metal sheets or fillers. However, the resistivity of graphite fibers is much lower than plastic alone or plastic with nonconductive reinforcement, such as fiberglass.

Some form of graphite embedded in plastic is the most common composite material presently in use by the aerospace industry. One type of graphite composite is made from loose fibers that are mixed with resin and a hardening agent to form a solid composite. Another type is made from unidirectional fibers prepackaged with resin as tape or woven fabric. The tape or fabric is placed in layers, and pressure and heat are applied. This hardens the layers to form the finished composite material. The graphite is oriented to take advantage of the high strength of the fibers in the linear direction. The electrical conductivity is also greater in the direction the fibers are oriented. However, electrical conductivity can be fairly uniform if several layers of graphite are laid in various orientations.

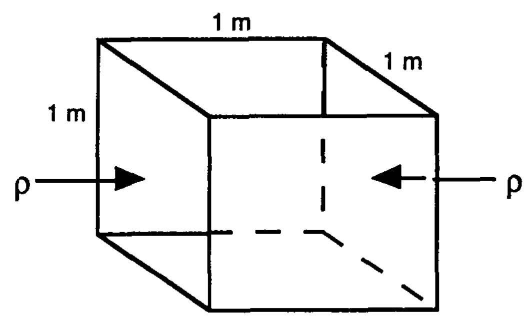
Graphite composites have resistivity about 1000 times greater than that of metals. Their suitability as conductive structure depends upon the extent of shielding or current carrying capability required and the amount and orientation of graphite fibers. If electrical bonding of the graphite composite mating surfaces can provide good conductivity across the joints, the total conductivity of a finished structure may be adequate for many applications. If additional conductivity is required for a specific application, conductive material may be added to the surface of the finished product or a layer of metallic material may be added as part of the laminate itself.

5. RESISTIVITY

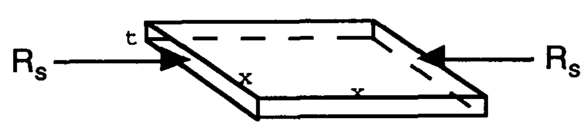
The following short review of resistivity of materials defines the applicable terminology and provides equations to facilitate calculation.

Volume resistivity (ρ) is the resistance from one face of a unit sized cube of material to the opposite face. When the cube is one cubic meter, volume resistivity is stated in ohm-meters. The volume resistivity in ohm-meters may be converted to ohm-cm by multiplying by 100.

Surface resistivity (R_s), in ohms/square, is the resistance from one edge of a square of the material to the opposite edge. Any size square has the same value for a given thickness.



Volume Resistivity



Surface Resistivity

If volume resistivity is known, surface resistivity can be found by dividing the volume resistivity by the thickness of the surface:

$$R_s = \frac{\rho}{t} \tag{1}$$

Where,

R_s = surface resistivity in ohms/square

ρ = volume resistivity in ohm-meters

t = thickness of the conductive surface in meters

If volume resistivity is in ohm-cm, use thickness in cm to determine surface resistivity in ohms/square.

Notice that volume resistivity remains constant for a given material. Surface resistivity varies inversely with thickness.

The relative resistivity of a material is the volume resistivity of the material divided by the resistivity of copper:

$$\rho_r = \frac{\rho}{\rho_{cu}} \tag{2}$$

Where,

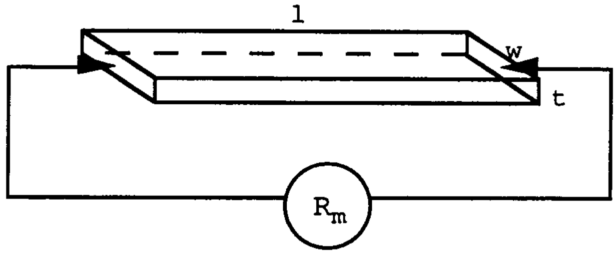
ρ_r = resistivity of a material relative to copper

ρ = volume resistivity of a material, ohm-meters

ρ_{cu} = volume resistivity of copper, ohm-meters

ρ_{cu} = 1.724×10^{-8} ohm-meters

Measurement of a composite material's resistivity can present a problem due to the difficulty of making a good connection with the conductive particles embedded in the resin. The nonconductive resin forms an insulating surface over the conductive filler. One method of measurement uses a small block sample. The ends of the block sample are lightly sanded to expose conductive fibers. The sanded ends are then coated with conductive paint to provide a consistent contact and a surface with much better conductivity than the composite material being measured. Resistance is then measured end to end between the conductive surfaces of the block sample. Surface resistivity is the measured resistance (R_m) times the width, divided by the length in meters to give ohms per square. Volume resistivity in ohm-meters is attained by multiplying the surface resistivity by the thickness in meters.



Resistivity From Measured Resistance (R_m)

$$R_s = R_m\left(\frac{w}{l}\right)$$

$$\rho = R_m\left(\frac{w}{l}\right)(t)$$

$$\rho = R_s(t)$$

Where:

R_s = surface resistivity (ohms per square)

R_m = measured resistance (ohms)

w = width (m)

l = length (m)

t = thickness (m)

ρ = volume resistivity (ohm meters)

The resistance is lower in the linear direction of the graphite fiber in single layer mats and tapes. However, several layers of material are usually oriented at different angles to provide strength for the finished graphite fiber reinforced plastic (GFRP). When four or more layers with different orientations are used, resistance calculations can be made on the finished composite as if it is a homogeneous material. The volume resistivity of the material may be determined as described above.

Tests have shown that the ac resistance of GFRP is close to the value for dc resistance at low frequencies. At higher frequencies the inductive reactance exceeds the dc resistance just as it does in a homogeneous conductor. [3-6]

Conductivity (σ) is the reciprocal of volume resistivity.

$$\sigma = \frac{1}{\rho} \quad \text{Siemens/meter or mhos/meter} \qquad (4)$$

The relative conductivity (σ_r) of a material is the conductivity of the material divided by the conductivity of copper:

$$\sigma_r = \frac{\sigma}{\sigma_{cu}}$$

Where,

σ_r = relative conductivity of a material

σ = conductivity of the material, mhos/meter

σ_{cu} = conductivity of copper, mhos/meter

σ_{cu} = 5.8×10^7 mhos/meter

Relative resistivity (ρ_r) and conductivity (σ_r) are used extensively in impedance and shielding effectiveness calculations.

Some typical resistivity values are given in Table 1 to show relationship between the resistivity of various materials and to provide values for rough calculations.

TABLE 1. - Typical Resistivity and Conductivity Values

MATERIAL	THICKNESS		RESISTIVITY			CONDUCTIVITY		
			volume		surface			
	mil t	cm t	Ω•m ρ	Ω•cm ρ	Ω/square Rs	mho/m	mho/cm	relative
Copper		0.10	1.72E-08	1.72E-06	1.72E-05	5.81E+07	5.81E+05	1.00E+00
Aluminum		0.10	2.87E-08	2.87E-06	2.87E-05	3.48E+07	3.48E+05	6.01E-01
Cold rolled steel		0.10	1.01E-07	1.01E-05	1.01E-04	9.90E+06	9.90E+04	1.71E-01
Stainless steel		0.10	8.62E-07	8.62E-05	8.62E-04	1.16E+06	1.16E+04	2.00E-02
Steel filaments in plastic		0.10	2.00E-03	2.00E-01	2.00E+00	5.00E+02	5.00E+00	8.62E-06
10% stainless filaments		0.32	8.20E-03	8.20E-01	2.56E+00	1.22E+02	1.22E+00	2.10E-06
Zinc plating	1	0.00	5.70E-08	5.70E-06	2.28E-03	1.75E+07	1.75E+05	3.02E-01
GFRP (typ.)		0.10	1.80E-05	1.80E-03	1.80E-02	5.56E+04	5.56E+02	9.58E-04
GFRP (meas.)		0.36	8.64E-05	8.64E-03	2.40E-02	1.16E+04	1.16E+02	2.00E-04
40% Carbon fiber	70	0.18	1.00E+00	1.00E+02	5.62E+02	1.00E+00	1.00E-02	1.72E-08
5% Ni coated graphite in polycarbonate	125	0.32	3.40E+02	3.40E+04	1.07E+05	2.94E-03	2.94E-05	5.07E-11
10% "	125	0.32	5.20E-01	5.20E+01	1.64E+02	1.92E+00	1.92E-02	3.32E-08
15% "	125	0.32	1.60E-03	1.60E-01	5.04E-01	6.25E+02	6.25E+00	1.08E-05
20% "	125	0.32	1.10E-03	1.10E-01	3.46E-01	9.09E+02	9.09E+00	1.57E-05

SUMMARY OF RESISTIVITY

To determine resistivity and conductivity of a rectangular sample of a composite material:

1. Expose conductive fibers by sanding opposite ends of the sample.
2. Make good electrical contact with the fibers by applying conductive paint to the sanded ends.
3. Measure resistance (R_m) from end to end.
4. Surface resistivity $(R_s) = R_m\left(\frac{w}{l}\right)$ ohms/square.
5. Volume resistivity $(\rho) = R_s(t)$ ohm-meters.
6. Conductivity $(\sigma) = \frac{1}{\rho}$ mhos/meter.
7. Relative conductivity $(\sigma_r) = \frac{\sigma}{\sigma_c}$

Where,

$\sigma_c = 5.8 \times 10^7$ mhos / meter

w = width of sample (meters)

l = length of sample (meters)

t = thickness of sample (meters)

or,

8. $\sigma_r = \dfrac{1.724 \times 10^{-6}}{R_s \times t_{cm}}$

GROUND PLANE IMPEDANCE

The impedance of large sheets of conductive material will be approximately the same as the surface impedance in ohms/square when the width of the sample is at least as much as the length between measuring points. The impedance (Z) is a combination of dc resistance (R_{dc}) and RF reactance (Z_{RF}): [5]

$$Z = (R_{dc} + jZ_{RF})\left[1 + \tan\left(\frac{2\pi d}{\lambda}\right)\right] \text{ ohms/square} \qquad (6)$$

$$Z = (R_{dc} + jZ_{RF}), \qquad \text{for } d << .005\lambda \qquad (6a)$$

Where,

d = distance between measuring points.

$j = \sqrt{-1}$

λ = wavelength

At low frequencies, the dc resistance will dominate until a frequency is reached where the RF reactance becomes greater. The impedance will then rise with frequency until the size of the material, or distance between ground points, approaches a quarter wave length where resonance causes the impedance to become very large.

The dc resistance (R_{dc}) of a large sheet, where the width is greater than the distance between measuring points, is approximately: [5]

$$R_{dc} \approx \frac{\rho l}{A} = \frac{\rho}{t_m} = \frac{100}{\sigma t_{cm}} = \frac{1.72\times10^{-6}}{\sigma_r t_{cm}} \text{ ohms/square} \qquad (7)$$

Where,

ρ = volume resistivity in ohm-meters

l = length in meters

A = cross sectional area in square meters (t x w)

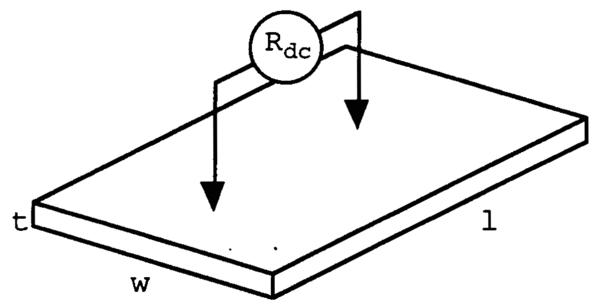
(Equation assumes width = length)

t_m = thickness in meters

t_{cm} = thickness in centimeters

$\sigma = \sigma_{cu}\sigma_r$

σ_{cu} = 5.80×10^7 mhos/meter for copper
σ_r = conductivity relative to copper



DC Resistance of Large Sheet

The RF reactance (Z_{RF}) of the same sheet is: [5]

$$Z_{RF} = \frac{369\sqrt{\frac{\mu_r f_{MHz}}{\sigma_r}} \times 10^{-6}}{1 - e^{-\left(\frac{t}{\delta}\right)}} \text{ ohms/square} \tag{8}$$

Where,

μ_r = permeability relative to air
σ_r = conductivity relative to copper
f_{MHz} = frequency in megahertz
δ = skin depth in cm = $\frac{.0066}{\sqrt{\mu_r \sigma_r f_{MHz}}}$ for any metal plane
t = thickness in cm

As long as the thickness of the metal is greater than three times the skin depth $(t \geq 3\delta)$, the following simplified equations may be used: [5]

$$Z_{RF} = 369\sqrt{f_{MHz}} \text{ micro-ohm/square for copper} \tag{8a}$$

$$Z_{RF} = 476\sqrt{f_{MHz}} \text{ micro-ohm/square for aluminum} \tag{8b}$$

$$Z_{RF} = 12.6\sqrt{f_{MHz}} \text{ milliohms/square for steel} \tag{8c}$$

INTRINSIC IMPEDANCE OF MATERIALS

All materials have an intrinsic impedance dependent upon the conductivity, permeability, and permittivity of the material. As an electromagnetic wave propagates through the material, the impedance of the wave approaches the intrinsic impedance of the material.

The general equation for intrinsic impedance is: [2]

$$Z = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}} \tag{9}$$

Where,

$j = \sqrt{-1}$

$\omega = 2\pi f$ radians

f = frequency in Hz

μ = permeability of the material = $(\mu_o \mu_r)$

μ_o = permeability of air or space = $4\pi x 10^{-7}$ H/m

μ_r = permeability of material relative to air

σ = conductivity of material = $(\sigma_{cu}\sigma_r)$

σ_{cu} = conductivity of copper = $5.8x10^{7}$ mhos/meter

σ_r = conductivity of material relative to copper

ε = permittivity of material = $(\varepsilon_o \varepsilon_r)$

ε_o = permittivity of air or space = $8.84x10^{-12}$ F/m

ε_r = permittivity of material relative to air

In determining the intrinsic impedance of air, even though $j\omega\varepsilon$ is small, the conductivity, σ, is much smaller--i.e. approaches zero. Thus, for the impedance of air, equation 9 becomes:

$$Z_{air} = \sqrt{\frac{\mu}{\varepsilon}} = 377 \text{ ohms} \tag{10}$$

An electromagnetic wave propagating through air at a distance (r) from the source, where $r \geq \frac{\lambda}{2\pi}$, the far field, has an impedance equal to Z_{air}.

In the near field, where $r \leq \frac{\lambda}{2\pi}$, the wave impedance depends upon the source impedance and the distance from the source. Assuming the source is small compared to a wavelength (λ), the wave impedance becomes:

$$Z_w = \frac{E}{H} = k377 \text{ ohms} \tag{11}$$

Where,

E = electric field strength (V/m)

H = magnetic field strength (A/m)

$k = 1$, if $r \geq \frac{\lambda}{2\pi}$

$k = \frac{\lambda}{2\pi r}$, if the source is high impedance and $r \leq \frac{\lambda}{2\pi}$

But Z_w cannot exceed the source impedance.

$k = \frac{2\pi r}{\lambda}$, if the source is low impedance and $r \leq \frac{\lambda}{2\pi}$

But Z_w cannot be less than the source impedance.

In determining the intrinsic impedance of a metal, the conductivity is high and $\sigma >> \omega\varepsilon$. Assuming the thickness of the metal is greater than three times the skin depth ($t >> 3\delta$), the intrinsic impedance (Z_m) of equation 9 becomes:

$$Z_m = \sqrt{\frac{j\omega\mu}{\sigma}} \text{ ohms/square} \tag{12}$$

or, in terms relative to copper:

$$Z_m = 369\sqrt{\frac{\mu_r f_{MHz}}{\sigma_r}} \text{ micro-ohms per square} \tag{12a}$$

Z_m can also be expressed in terms of skin depth (δ) for any metal:

$$Z_m = \frac{\sqrt{2}}{\sigma\delta} \text{ ohms/square} \tag{12b}$$

Where,

$$\delta = \frac{1}{\sqrt{\sigma \pi f \mu}} \text{ meters}$$

The skin depth is the depth within a metal where a current's amplitude at any frequency has decayed to 1/e (37%) of the current at the surface. At two skin depths, current has decayed to $1/e^2$ (14%), etc. So, 63% (1-1/e) of the current flows through metal between the surface and one skin depth; 86% ($1-1/e^2$) between the surface and two skin depths; etc., up to 99% at five skin depths. If the thickness of the metal is less than this, its apparent impedance must be higher than that calculated for Z_m. For thin metal the intrinsic impedance (Z_B) becomes: [1]

$$Z_B = \frac{Z_m}{1 - \frac{1}{e^{\left(\frac{t}{\delta}\right)}}} \text{ ohms/square for any value of } t/\delta \qquad (13)$$

For $t/\delta << 1$:

$$Z_B = \frac{\delta Z_m}{t} = \frac{\delta}{t} \times \frac{\sqrt{2}}{\sigma \delta} = \frac{\sqrt{2}}{t \sigma} \text{ ohms/square} \qquad (13a)$$

or:

$$Z_B = \frac{2.438 \times 10^{-6}}{\sigma_r t_{cm}} \text{ ohms/square} \qquad (13b)$$

The ratio (K) of wave impedance to metal impedance is used to determine reflection components in the shielding effectiveness equations in the next section.

$$K = \frac{Z_W}{Z_m} \quad \text{for } t > 3\delta \qquad (14)$$

$$K = \frac{Z_W}{Z_B} \quad \text{for } t < 3\delta \qquad (14a)$$

6. SHIELDING EFFECTIVENESS

The shielding effectiveness (SE) of equipment cases and spacecraft skin is determined by the type of material used and the holes in that material. Typical metals, thick enough to provide adequate mechanical strength when used for equipment cases and spacecraft skin, provide acceptable shielding effectiveness. Holes and slots in the metal are the most common detriment to SE. Therefore, most shielding design effort concentrates on reducing the number and size of openings.

With the increased use of composite materials and nonconductive plastics, designers are concerned with the SE of the material as well as SE degradation caused by the holes and slots. Designers must rely on embedded conductive filaments, conductive paints, metal deposits, etc., in the composite material to make it conductive enough to provide adequate shielding where required.

Data relating to types of materials, resistivity, conductivity, and shielding effectiveness, without regard to material thickness, was taken from references 2-5, 2-8, 2-11, 2-14, and 2-27. This data is compiled in Figure 1. It shows surface resistivity (R_s) versus shielding effectiveness (SE) against E fields at 1 MHz. Some of the data comes from tests and some comes from calculations made by the different authors using somewhat different techniques. Results are intermixed and plotted to show a direct relationship between shielding effectiveness and surface resistivity. The "Outline of Method for Calculating SE" is described later. It was used to calculate SE for materials with thicknesses of 1 cm and 1 mm. Plots of this data are also included in Figure 1. This data shows that the surface resistivity of a particular material can be used to determine the approximate shielding effectiveness across the limited resistivity and SE range of interest.

Figure 2 is a plot of SE versus frequency calculated by the same technique for two values of surface resistivity. The plot also includes three different thicknesses for each value of surface resistivity. The plot shows a small variation in SE between 1 mm and 1 cm thick materials with the same surface resistance. However, across the frequency range and SE of interest, SE decreases approximately 30 dB with a tenfold increase in surface resistivity.

Figure 3 shows the same SE versus frequency for several values of surface resistivity for 1 mm thick material. Figure 3 may be used for quick SE estimates for composite materials with a resistivity in the range of interest. For example, materials with resistivity greater than 10 ohms/square obviously cannot be relied upon for shielding. However, materials with surface resistivity less than 0.001 ohms/square can provide SE approaching that of metal when apertures are considered.

In some cases the amount of shielding required may be critical. In these specific cases determine the conductivity and calculate a more exact SE. First, determine the proper thickness or conductivity for the material to provide adequate shielding. Then minimize the size of apertures in the material and provide good conductivity across all joints and covers.

Shielding effectiveness calculations are made using various assumptions and, sometimes, different equations that produce variations in the answers. When tests are made on sample materials, the test results vary with the test set up, test technique, and the operators. These differences are not usually enough to invalidate the results, but they are enough to show that shielding calculations and tests are not an exact science. This fact, and the fact that apertures and joints will be the driving factor in most final results if the material is very conductive, makes the use of a quick estimate of the material SE very attractive.

More detailed calculations of material shielding effectiveness may be made using the equations in the next section. The "Outline of Method for Calculating SE of Conductive Material" provides an organized approach to these calculations and considers magnetic as well as electric fields.

The section on apertures must be used for SE calculation whether the equations for SE of materials or the quick estimate is used.

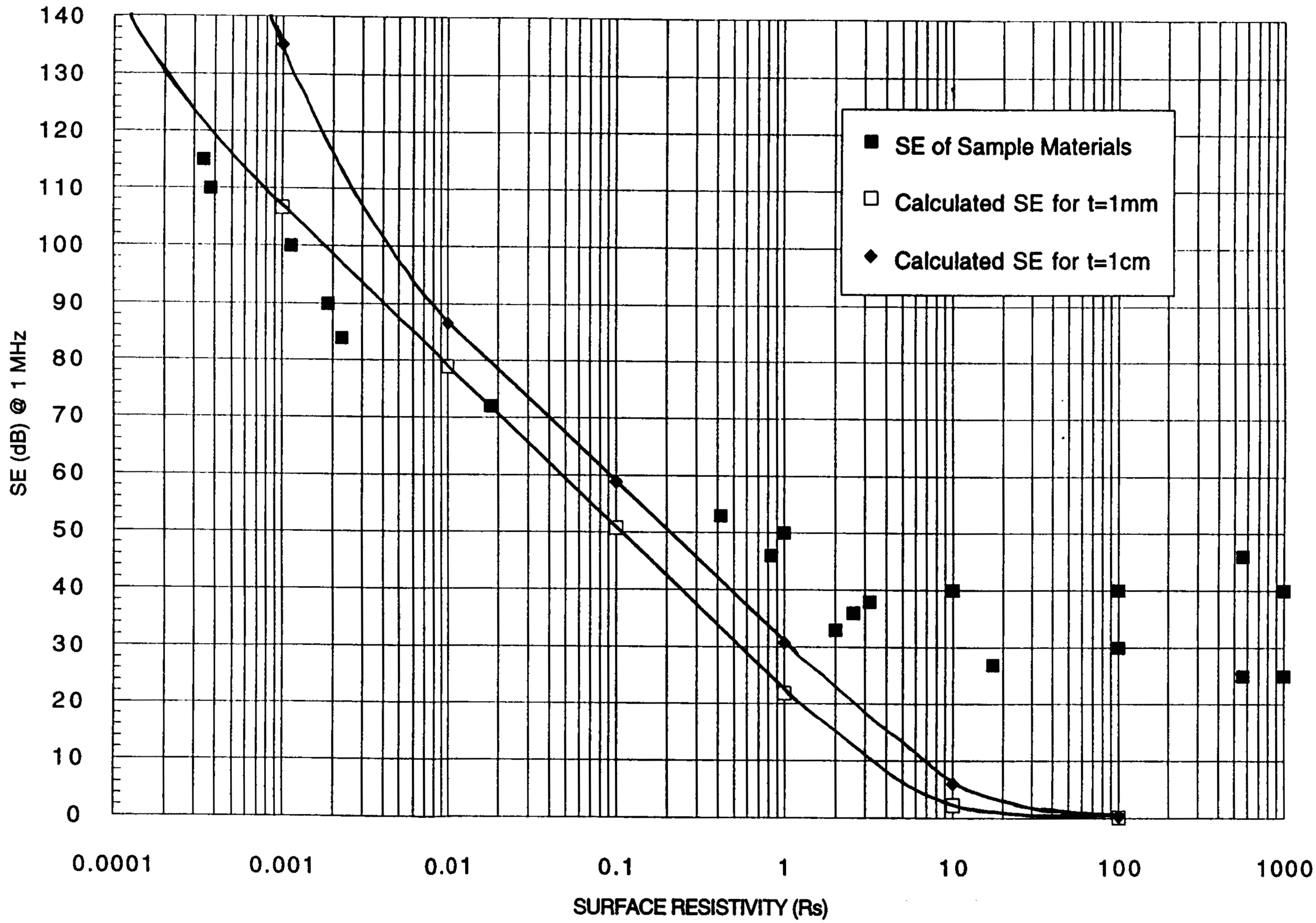


FIGURE 1. - Resistivity vs Shielding Effectiveness at 1 MHz.

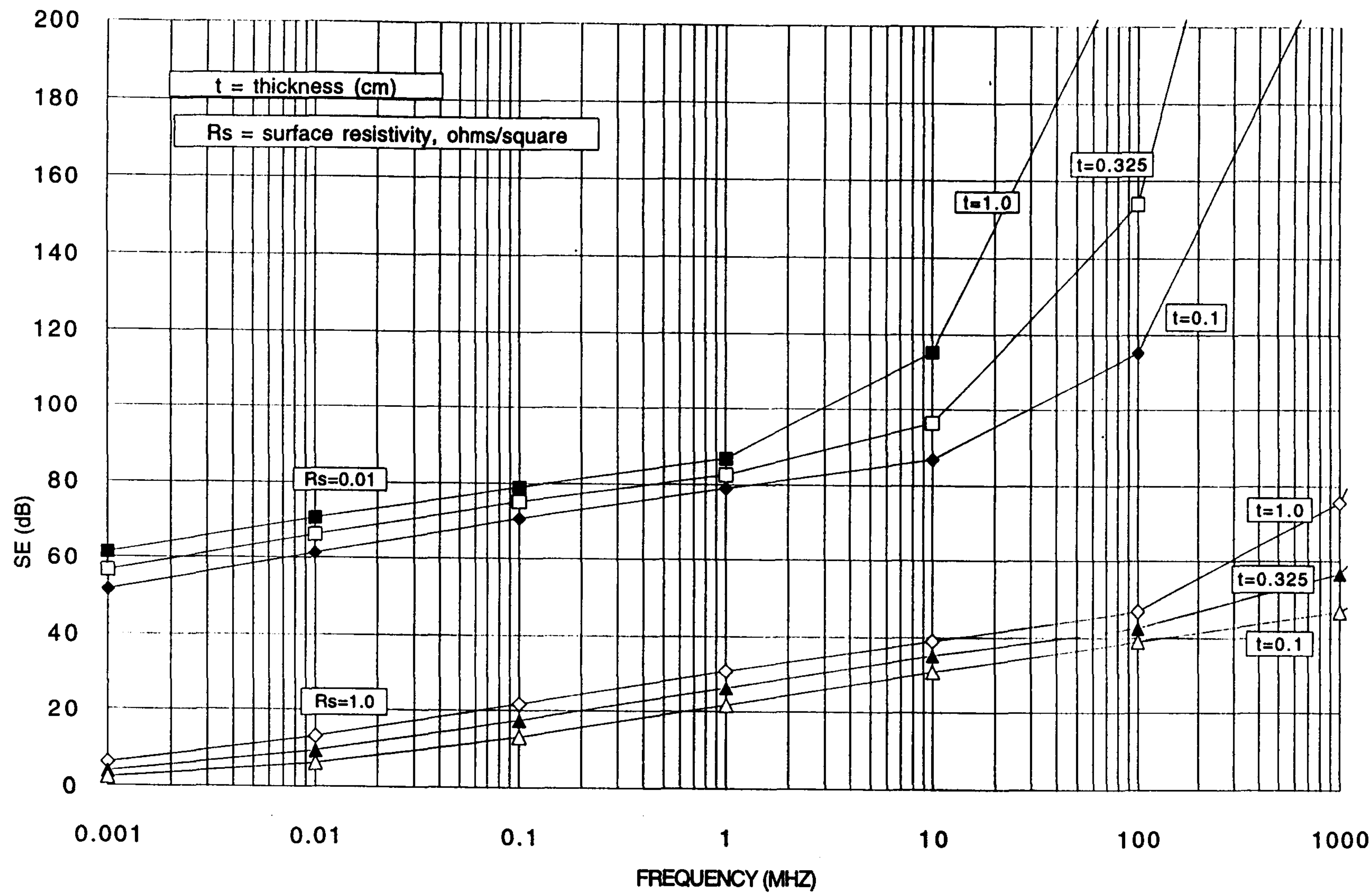


Figure 2. - Shielding Effectiveness Versus Frequency, Thickness, & Surface Resistivity

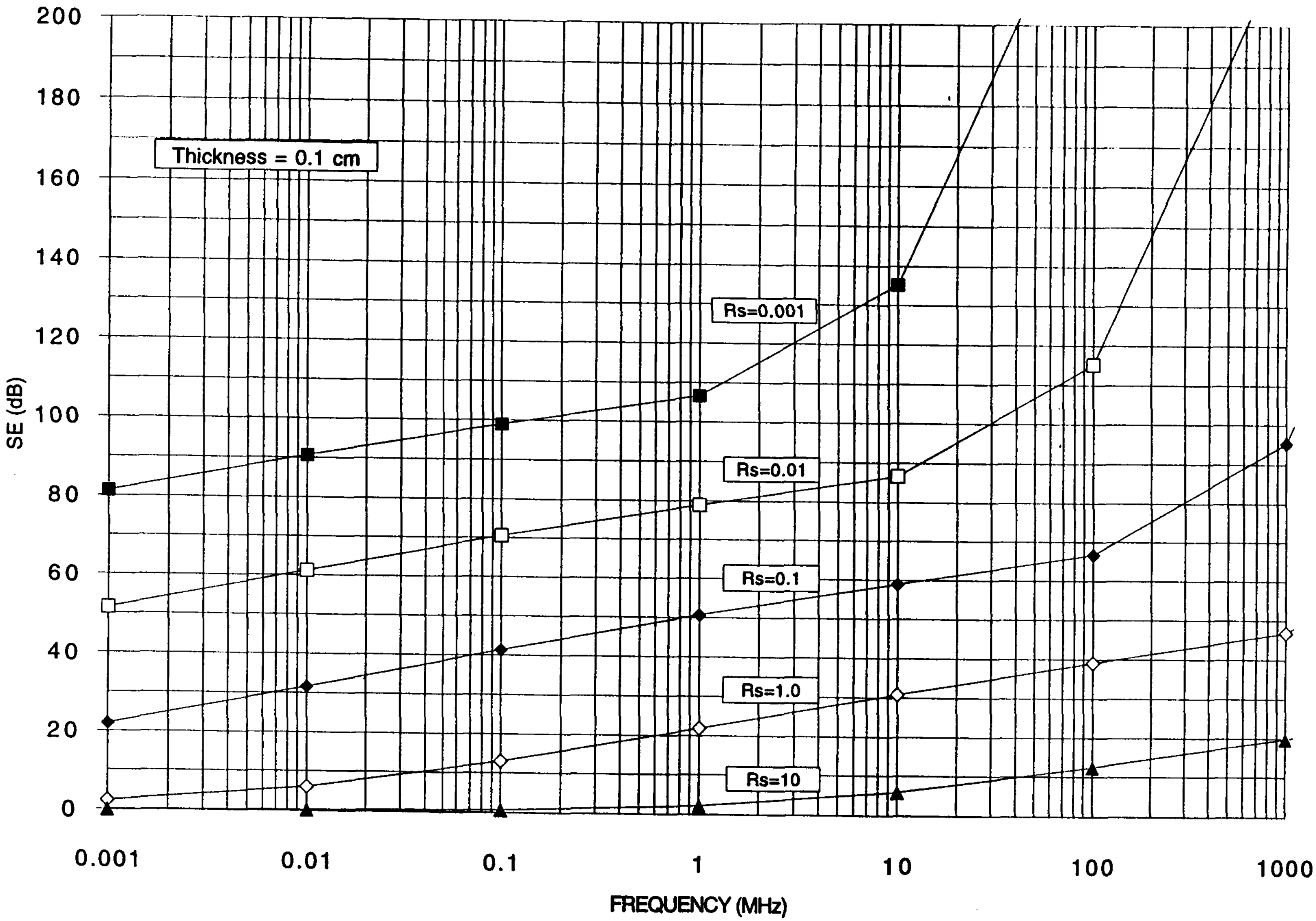


FIGURE 3. - Quick Estimate of Shielding Effectiveness.

GENERAL EQUATIONS FOR SHIELDING EFFECTIVENESS

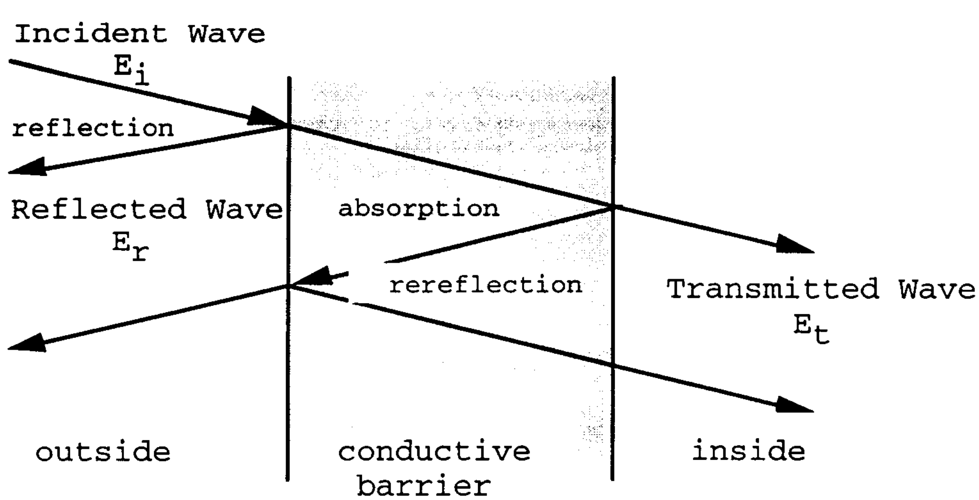
Shielding effectiveness of a barrier is defined as the ratio of radiated power received without the barrier in place to the power received with the barrier in place. It is usually stated in dB:

$$SE_{dB} = 10 \log \frac{\text{incident power density}}{\text{transmitted power density}}$$

Or, if the wave impedance is the same before and after insertion of the barrier, the equation in terms of electric field is:

$$SE_{dB} = 20 \log \frac{\text{incident electric field}(E_i)}{\text{transmitted electric field}(E_t)}$$

The shielding effectiveness of the barrier is caused by reflection from the surface due to the impedance mismatch between the two mediums and attenuation by absorption loss within the barrier. Rereflection of the wave occurs at the second barrier-to-air surface and again at the first surface as shown in the figure. Some absorption loss occurs each time the wave traverses the thickness of the barrier. The rereflected component usually reduces shielding effectiveness by adding power to the output. The reduction may be significant if the absorption losses are low.



Path of a Radiated Wave Through a Barrier

The equation for shielding effectiveness of a conductive sheet or panel takes the form:

$$SE = A_{dB} + R_{dB} + B_{dB} \tag{15}$$

Where:

A_{dB} = Attenuation due to absorption

R_{dB} = Loss due to reflection

B_{dB} = Rereflection correction

The separate terms can be found by the following: [1&2]

Absorption:

$$A_{dB} = 20 \log e^{\alpha t_m} = 8.686 \alpha t_m = 8.686 t_m \sqrt{\pi f \mu \sigma} \tag{16}$$

$$A_{dB} = 1314 t_{cm} \sqrt{f_{MHz} \mu_r \sigma_r} \tag{16a}$$

Where:

t = thickness of sheet or panel (m or cm)

Reflection:

$$R_{dB} = 20 \log \frac{(1 + K)^2}{4K} = 20 \log \frac{K}{4}\text{, for } K>>1 \tag{17}$$

Where K is found in equations 14 or 14a

In the far field, $\left(r \geq \frac{\lambda}{2\pi}\right)$,

for plane waves:

$$R_{dB} = 108.1 - 10 \log\left(\frac{\mu_r f_{MHz}}{\sigma_r}\right) \tag{17a}$$

In the near field, $\left(r \leq \frac{\lambda}{2\pi}\right)$,

for high impedance E fields:

$$R_{dB} = 141.7 - 10 \log\left(\frac{\mu_r f_{MHz}^3 r_m^2}{\sigma_r}\right) \tag{17b}$$

for low impedance H fields:

$$R_{dB} = 74.6 - 10 \log\left(\frac{\mu_r}{f_{MHz} \sigma_r r_m^2}\right)$$

Rereflection:

$$B_{dB} = 20 \log\left[1 - \left(\frac{K-1}{K+1}\right)^2 \times 10^{-.1A_{dB}}\left(\cos 0.23\,A_{dB} - j \sin 0.23\,A_{dB}\right)\right] \quad (18)$$

$$B_{dB} = 20 \log\left(1 - e^{-2t\sqrt{\pi f \mu \sigma}} e^{-j2t\sqrt{\pi f \mu \sigma}}\right) \quad (18a)$$

See Figure 4 for approximate values of B_{dB}, knowing A_{dB} and K.

B_{dB} is a negative number that reduces total shielding effectiveness.

B_{dB} can be ignored unless A_{dB} is small.

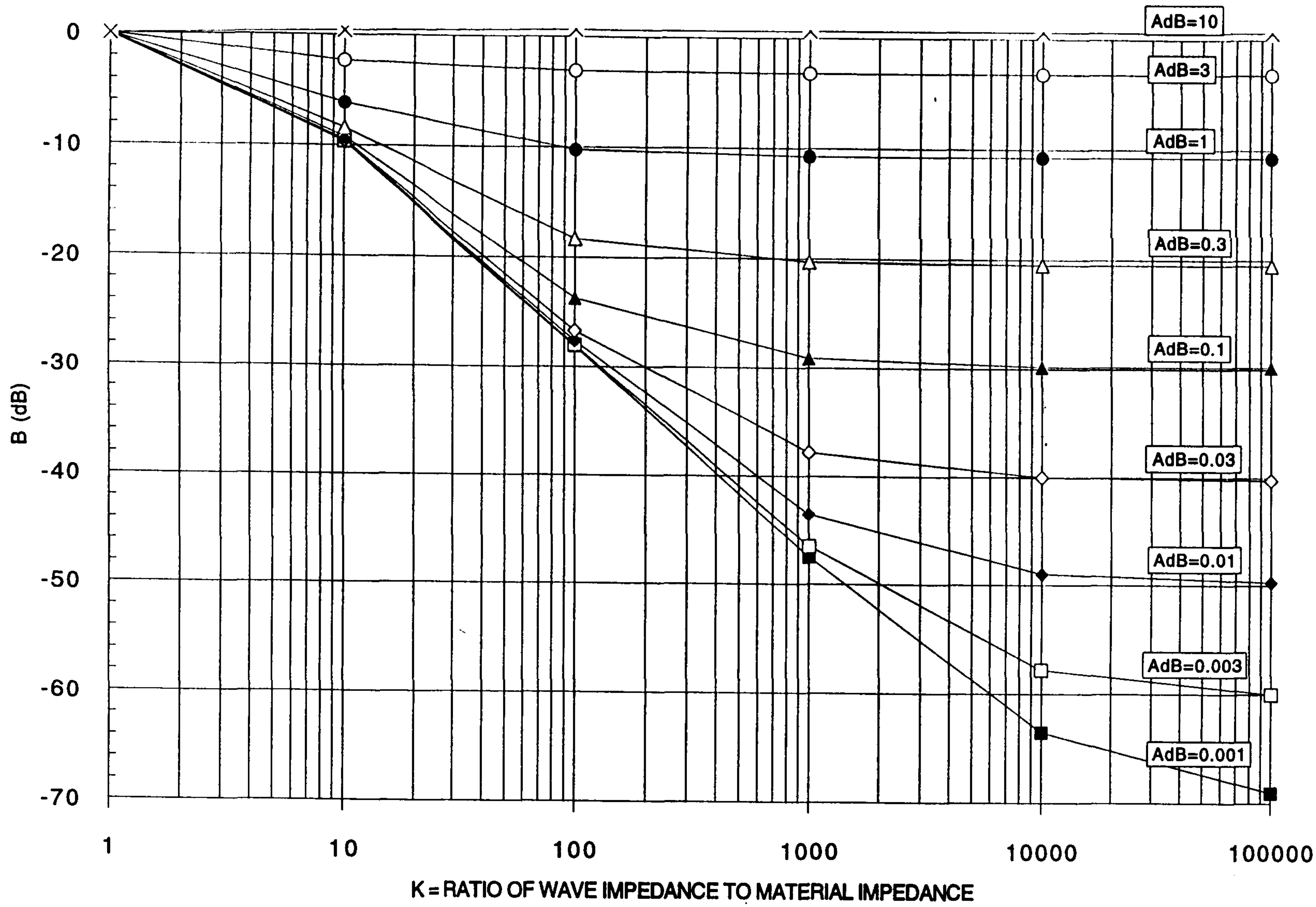


FIGURE 4. - Rereflection Coefficient B(dB).

Outline of Method for Calculating Shielding Effectiveness of Metal or Other Conductive Materials

General Equations for shielding effectiveness (SE) have been given in previous sections. Certain special equations which require fewer calculations, but have restrictions on their use, are available in references 1, 2, 3, and 4. The number of SE equations, and the many restrictions of the special equations, become somewhat confusing to the person trying to make a quick calculation of shielding effectiveness. However, the outline given here for calculating SE of a solid sheet or panel can be used for any metal or other conductive material with very few restrictions. The following steps for SE calculation are given in their proper order:

1. The constants required are: r, t, μ_r, σ_r, and (Z_{source}).

r = distance from radiating source (meters). If unknown, use a large default value for a plane wave calculation.

t = thickness of metal or conductive surface in meters and in centimeters.

$$\mu_r = \frac{\mu}{\mu_o} = \text{permeability of the conductive material}$$

relative to air.

μ = absolute permeability of material

$\mu_o = 4\pi \times 10^{-7}$ = permeability of air (Henries per meter)

$$\sigma_r = \frac{\sigma}{\sigma_c} = \text{conductivity of material relative to copper}$$

$$\sigma = \frac{1}{\rho} = \text{absolute conductivity of material}$$

$\sigma_c = 5.8 \times 10^7$ = conductivity of copper (mhos per meter)

$\rho = R_s \times t_m$ = volume resistivity (ohm-meters)

R_s = surface resistivity (ohms per square)

Z_{source} = estimated source impedance

Source impedance may be high or low with respect to 377 ohm impedance of space.

2. Choose specific frequencies (MHz) across the frequency range of interest.

Calculate the following at each frequency. A table including results of each calculation helps keep things organized:

3. $\lambda = \dfrac{300}{f_{Mhz}}$ = wavelength (meters)

4. $\delta = \dfrac{.0066}{\sqrt{\mu_r \sigma_r f_{MHz}}}$ = skin depth (centimeters)

5. $\dfrac{t}{\delta}$ = ratio (use same units for each)

6. $Z_m = 369\sqrt{\dfrac{\mu_r}{\sigma_r}\left(f_{MHz}\right)} \times 10^{-6}$ = impedance of material when $\dfrac{t}{\delta} \geq 3$ (ohms/square)

7. $\left(1 - \dfrac{1}{e^{\left(\frac{t}{\delta}\right)}}\right)$, $e = 2.718$

8. $Z_B = \dfrac{Z_m}{\left(1 - \dfrac{1}{e^{\left(\frac{t}{\delta}\right)}}\right)}$ = impedance of material for any value of $\dfrac{t}{\delta}$. (ohm/square)

when $\dfrac{t}{\delta} \geq 3, \left(Z_B \approx Z_m\right)$

9. $Z_w = k377$ = wave impedance (ohms)

Where,

$$k = 1 \quad \text{when } r \geq \frac{\lambda}{2\pi}, \quad \text{(for plane waves)}$$

$$k = \frac{\lambda}{2\pi r} \quad \text{when } r \leq \frac{\lambda}{2\pi},$$ and source impedance is high, but Z_W cannot exceed source impedance.

$$k = \frac{2\pi r}{\lambda} \quad \text{when } r \leq \frac{\lambda}{2\pi},$$ and source impedance is low, but Z_W cannot be lower than source impedance.

10. $K = \frac{Z_w}{Z_B}$, ratio (both in ohms)

11. $$R_{dB} = 20 \log \frac{(K+1)^2}{4K}$$

$$R_{dB} = 20 \log \frac{K}{4}, \quad \text{when } K>>1$$

12. $$A_{dB} = 1314\, t_{cm} \sqrt{f_{MHz} \mu_r \sigma_r}$$

or,

$$A_{dB} = 8.7\left(\frac{t}{\delta}\right)$$

13. $$B_{dB} = 20 \log\left[1 - \left(\frac{K-1}{K+1}\right)^2 x10^{-.1A_{dB}}\left(\cos .23A_{dB} - j \sin .23A_{dB}\right)\right]$$

or,

$$B_{dB} = 20 \log\left(1 - e^{-2t\sqrt{\pi f \mu \sigma}} e^{-j2t\sqrt{\pi f \mu \sigma}}\right)$$

Where:

f in Hz, μ and σ in absolute units

or, use figure 4, to determine B_{dB}, knowing A_{dB} and K

14. $SE_{total} = R_{dB} + A_{dB} + B_{dB}$, add algebraically, B_{dB} will usually be negative.

APERTURES

The methods of calculation presented so far have concentrated on the shielding effectiveness (SE) of a solid sheet or panel of conductive material. Typical equipment cases and spacecraft skins have apertures which degrade the SE of the conductive material. In such cases, a special method for calculating the SE of the structure is necessary. First, calculate the SE for a panel of the conductive material at each frequency of interest. Second, calculate the SE of the aperture at each of the same frequencies. Then use the lower SE value at each frequency.

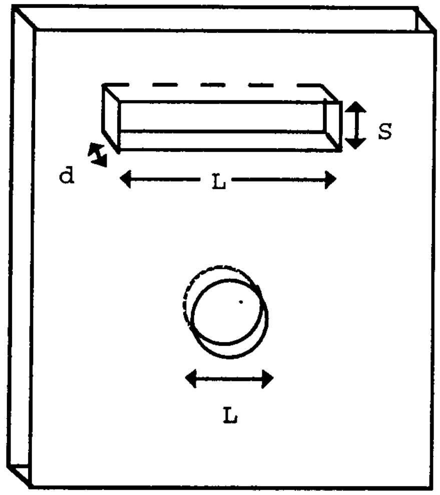
Usually, there are several types of apertures. The method of combining their effects is similar to the method of calculating total resistance produced by several parallel resistors:

$$\frac{1}{SE_{total}} = \frac{1}{SE_1} + \frac{1}{SE_2} + \frac{1}{SE_3} \ldots \qquad (19)$$

However, since the SE is stated in dB, each SE must be converted back to a ratio before adding. The total SE is then converted back to dB. The total SE of several apertures will be somewhat less than the lowest individual SE.

The following paragraphs demonstrate the methods for determining individual SE for various types of apertures.

Shielding Effectiveness of a Conductive Panel With Apertures



Aperture Dimensions

For a rectangular shaped slot: [1]

$$SE_{dB} = 97 - 20\log(Lf_{MHz}) + 20\log\left[1 + \ln\left(\frac{L}{S}\right)\right] + SE_{shad} + 30\left(\frac{d}{L}\right) \quad (20)$$

Where,

L_{mm} & S_{mm} = slot length and height (mm)

d_{mm} = depth of slot, usually thickness of material (mm)

SE_{shad} = shadow effect, see table 2, or default to 3_{dB}.

ln = natural log

For a circular hole: [1]

$$SE_{dB} = 99 - 20\log(Lf_{MHz}) + SE_{shad} + 30\left(\frac{d}{L}\right) \quad (21)$$

Where,

L_{mm} = diameter (mm)

In both cases, if the panel is thin (d<<L), the last term approaches zero. This is the absorption term.

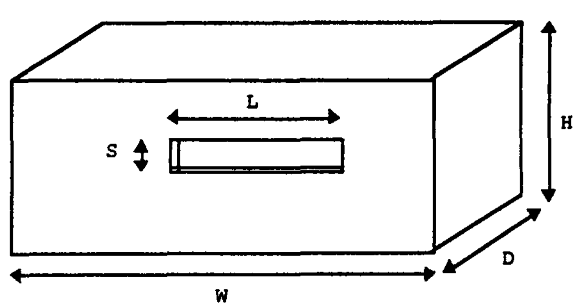
The shadow effect occurs when the slot is in one conductive wall of an otherwise enclosed box. The shadow effect depends upon the size of the slot, the dimensions of the box, and the frequency. In effect, the slot reradiates inside the box. This produces a pattern of lobes and nulls that scatter the incoming energy. The shadow effect is the integrated value of this pattern of lobes and nulls inside the box. It reduces the field intensity from the peak value received. Table 2, shows typical values of additional shielding due to shadow effect for various box and slot dimensions. Typical boxes will have less than 5 dB attributed to the shadow effect. Thus, 3 dB is a good default value for use in the equation.

At low frequencies the equation will produce values that appear to exceed the SE of a solid panel. At this point the solid sheet SE becomes the upper limit for shielding effectiveness.

It should be noted that any opening, such as the small gap created by a poor contact at a joint, can be considered a slot.

TABLE 2. Additional Shielding Effectiveness Due to Shadow Effect [1]

L/W	S/H	D/W 0.1	0.2	0.3	0.5	1.0	1.5	2.0
0.01	0.01	10	7	6	5	3	2	1
0.01	0.20	9	7	6	5	2	2	1
0.01	0.40	6	5	5	4	2	1	1
0.01	0.60	2	3	3	3	2	1	1
0.01	0.80	1	0	0	1	1	1	1
0.2	0.01	10	7	6	5	3	2	1
0.2	0.20	9	7	6	5	2	2	1
0.2	0.40	7	6	5	4	2	2	1
0.2	0.60	2	3	3	3	2	1	1
0.2	0.80	1	1	0	1	1	1	1
0.4	0.01	10	7	6	5	3	2	1
0.4	0.20	8	6	6	5	2	2	1
0.4	0.40	6	6	5	4	2	1	1
0.4	0.60	3	4	4	4	2	1	1
0.4	0.80	1	1	1	2	1	1	1
0.6	0.01	10	7	6	5	3	2	1
0.6	0.20	6	6	5	4	2	2	1
0.6	0.40	4	4	4	4	2	1	1
0.6	0.60	2	3	3	3	2	1	1
0.6	0.80	2	1	2	3	2	1	1
0.8	0.01	10	7	6	5	3	2	1
0.8	0.20	5	5	5	4	2	1	1
0.8	0.40	2	3	3	3	2	1	1
0.8	0.60	1	1	2	2	2	1	1
0.8	0.80	1	1	1	2	1	1	1
1	0.01	10	7	6	5	3	2	1
1	0.20	3	4	4	4	2	1	1
1	0.40	1	1	2	3	2	1	1
1	0.60	1	1	0	1	1	1	1
1	0.80	1	0	0	0	1	0	0

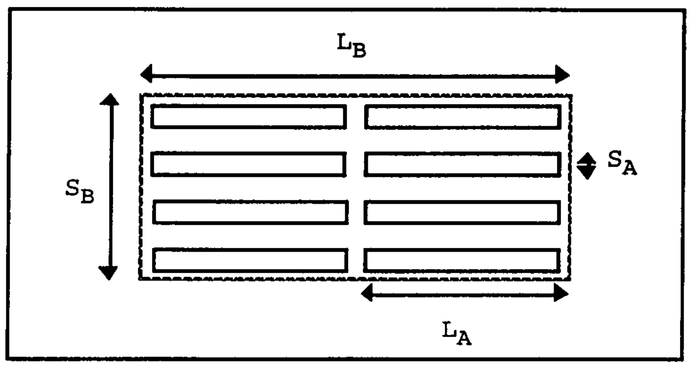


W = Box Width
H = Box Height
D = Box Depth

L = Slot Length
S = Slot Width

Shielding Effectiveness of Panel With Subdivided Aperture

To calculate the shielding effectiveness (SE) of a panel with a subdivided aperture, first, calculate the SE of a panel with one aperture as large as the outline of the outer edge of the smaller apertures. Then, using the equation below, calculate the improvement (ΔSE) caused by subdividing the large hole into smaller holes. Then add the improvement to the original calculation to get total SE. [1]



Subdivided Aperture

$$\Delta SE = 20\log\left(\frac{L_B}{L_A}\right) - 20\log\left[\frac{1+\ln\left(\frac{L_B}{S_B}\right)}{1+\ln\left(\frac{L_A}{S_A}\right)}\right] \tag{22}$$

Where,

L_B and S_B = slot length and width before subdividing

L_A and S_A = slot length and width after subdividing

Note: If the original hole is subdivided into smaller holes with the same L/S ratio as the original, the second term disappears.

Shielding Effectiveness of Wire Screens or Conductive Meshes

For plane waves, where $r \geq \frac{\lambda}{2\pi}$ [1]

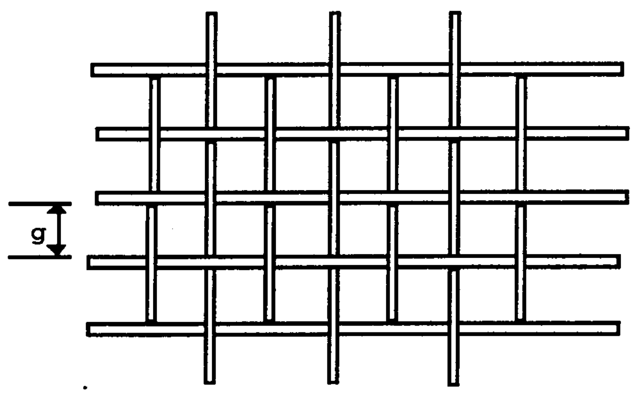
$$SE = 20 \log\left(\frac{\lambda/2}{g}\right) \text{ dB}, \quad \text{for } g \leq \frac{\lambda}{2} \tag{23}$$

$$SE = 0, \quad \text{for } g \geq \frac{\lambda}{2}$$

Where,

λ = wavelength

g = distance between wires in same units as λ



Wire Screen

For near fields, where $r \leq \frac{\lambda}{2\pi}$, [1]

Magnetic fields:

$$SE_H = 20 \log\left(\frac{\lambda}{2g} \times \frac{2\pi r}{\lambda}\right) = 20 \log\left(\frac{\pi r}{g}\right) \tag{24}$$

Electric fields:

$$SE_E = 20 \log\left(\frac{\lambda}{2g} \times \frac{\lambda}{2\pi r}\right) = 20 \log\left(\frac{\lambda^2}{4\pi r g}\right) \tag{25}$$

Where,

r = distance from source (m)

g and λ are in meters

Or SE can be calculated for plane waves using:

$$SE = 20\log\left(\frac{\lambda}{2g}\right) \tag{26}$$

then add:

$$20\log\left(\frac{2\pi r}{\lambda}\right) \quad \text{for near magnetic fields} \tag{26a}$$

or add:

$$20\log\left(\frac{\lambda}{2\pi r}\right) \quad \text{for near electric fields} \tag{26b}$$

Neither can be higher than the SE of an equivalent thin metal panel.

These equations are valid when $g \geq 10^{-6}\lambda$. When g is a tiny fraction of a wavelength, such as $g \leq 10^{-6}\lambda$, the screen looks like a solid piece of thin metal. Therefore, the conductive material equations should be used for both near field and far field calculations. Use material conductivity equal to that of the wire material times its percentage of optical coverage.

The previous sections provide methods for calculating shielding effectiveness (SE) of flat panels with and without holes assuming no leakage around the panel edges. The holes degrade the SE at higher frequencies for composites and metals. The limiting factor at the lower frequencies is the SE of the material itself. The SE of the material is generally dependent upon the conductivity of the material and the thickness of the panel.

The methods described in previous sections were used to calculate the SE of several typical materials and the SE due to slots in conductive materials. Figure 5 shows plots of the calculated SE values. As noted earlier, at low frequencies the SE of materials is the limiting factor, and at higher frequencies the slots cause increasing leakage and become the limiting factor. The plot shows that metals, such as copper and aluminum, make very good shields. When the metals have thicknesses that give good mechanical strength, there is no need to be concerned about the SE of the metal. Notice, however, that the composite materials in our examples--graphite filament reinforced plastic (GFRP) and steel filaments embedded in plastic--may not provide adequate SE with their assumed conductivity. Thus, increasing conductivity of composite materials should at least be an important design consideration. The zinc plated plastic, even though thin, is conductive enough to have fairly good shielding characteristics. The primary point of Figure 5 is that conductivity is the most important factor in the shielding effectiveness of materials.

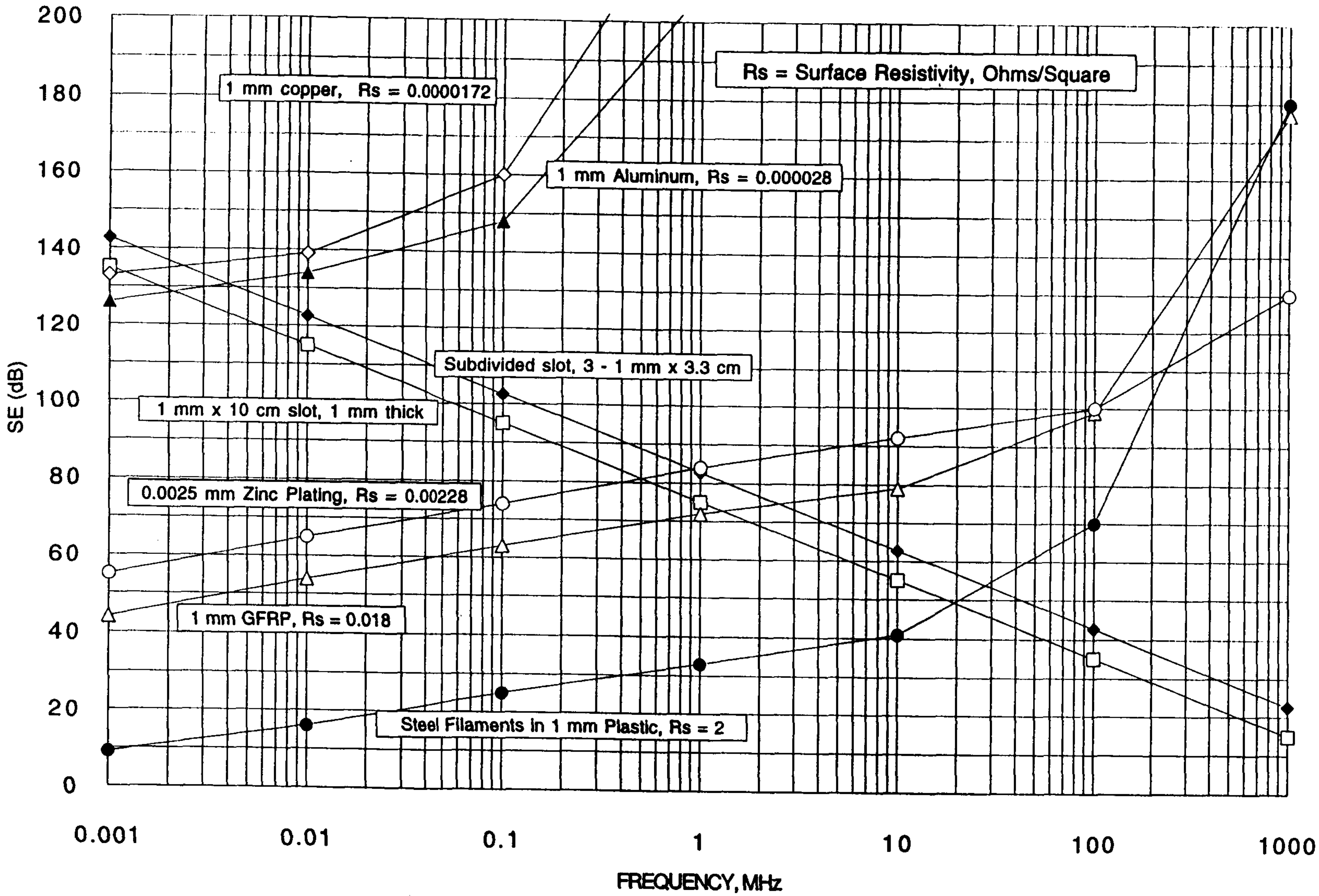


FIGURE 5. - Examples of Shielding Effectiveness of Materials and Slots

SUMMARY OF SHIELDING EFFECTIVENESS DETERMINATION

The following steps summarize the method for determining the shielding effectiveness (SE) of a panel or an enclosure:

1. To determine total SE, determine the SE of the material and the SE due to apertures across the frequency range. Then use the lower of the two at each frequency as the result.
2. To determine the SE of a material, use figure 3 for a quick estimate. If more exact values are required, use equations in the "Outline of Method for Calculating SE".
3. To determine SE due to apertures use equations 19, 20, 21, 22, and 23.

7. FAULT CURRENT

Results of this review indicate that composite materials used in aerospace work will probably be some form of graphite reinforcement in plastic. The most common form consists of layers of woven graphite fabric embedded in epoxy resin. The fabric may be in tape or mat form. Other graphite reinforcement includes graphite fibers and nickel coated graphite fibers in epoxy resin. Composites using other reinforcements will be more conductive if metals are used, or highly resistive if nonconductive fillers, such as fiberglass, are used.

When high current flows through graphite fiber reinforced plastic (GFRP), ohmic heating above 65°C can cause changes in the resistivity of GFRP. This probably occurs because heating the plastic relaxes contact between the graphite fibers. Since resistivity is 1000 times greater than aluminum, greater temperature rises will occur than would be expected with metal. Therefore, intentional returns for power or signal circuits should not be carried through GFRP.

Short circuits can cause high current density in GFRP. The small contact areas are conducive to temperature rises in the GFRP. Preliminary tests have shown that graphite epoxy composite material may not be able to carry enough current to blow circuit breakers in case of short circuits to the GFRP. Also, the current flowing through the small contact to the material causes pitted burns in the material surface.

Metallic electronic boxes should be electrically bonded to the basic metal structure to provide a fault current return path in case of a short to the box. If any part of the return path to structure is through GFRP, special mounting provisions must be followed. GFRP can carry a considerable amount of current if the entrance and exit points are distributed over an extended area.

To obtain good contact over a large area, sand the GFRP surface to expose the graphite layers. Apply conductive paint or conductive epoxy to the sanded surface and permanently mount a metal plate in good contact with the conductive surface. Mount the electronic boxes on the metal plate. Ensure that the exit points and any joints in the GFRP have similar treatment. This process will allow fault current return from short circuits within properly bonded metallic boxes. Ensure that resistance through each joint and metal to GFRP connection does not exceed 0.1 ohms for fault current bonds.

8. ANTENNA GROUND PLANE

The use of conductive composites for an antenna ground plane is not much different from the use of a metal plane except where a seam may cause a perturbation. Even then aluminum foil taped over the seam usually solves this problem. A good contact between the antenna base and the conductive composite is required. [3-15]

Antenna performance is not degraded by a uniform graphite epoxy ground plane, but the graphite epoxy cannot be used as a driven element. [2-5]

The conductivity of typical graphite fiber reinforced plastic is adequate for an antenna ground plane.

9. ELECTROSTATIC DISCHARGE

Electrostatic discharge (ESD) protection can be obtained by using conductive fillers, such as graphite, with connection between the conductive filaments and basic structure. Since the plastic surface may be nonconductive, a conductive layer may have to be added to the surface to prevent charge buildup in cases where charging conditions are favorable.

Resistivity of 10^2 to 10^7 ohms/square in any material is considered statically dissipative. This resistivity readily allows a charge to progress along the surface and dissipate in a short time. This resistivity can be obtained by using graphite fabric, by compounding carbon fiber or flakes, or by using any other filler as conductive as carbon. The conductivity of typical graphite epoxy composite material is adequate for electrostatic charge dissipation if provisions are made for electrical bonding between conductive filaments and basic structure. The nonconductive outer surface of some graphite fiber reinforced plastic presents a problem when it is exposed to a charging mechanism. Therefore, it may require an additional conductive coating to prevent charge buildup.

10. LIGHTNING

Lightning strikes produce high current that may reach peaks of 100 to 200 kiloamps for up to 100 microseconds, dropping to a continuous current of 400 to 7000 amps for up to 100 milliseconds, and sometimes followed by restrikes of somewhat lower amplitude. For test purposes, the strike is simulated in parts with an initial current of 200 kiloamps for less than 500 microseconds, with an action integral of $2 \times 10^6 A^2s$, and continuous current of 200 to 800 amps up to one second to deliver 200 Coulombs. The action integral is the integral of the current squared multiplied by the time. It is an indicator of the energy contained in the strike.

Direct effects from lightning strikes will cause damage to graphite fiber reinforced plastic (GFRP) due to the shock effect and high current. The shock effect may shatter a rigid composite. The high current produces enough heat to cause the resin and carbon fiber to disintegrate. The result, depending upon the amount of current in the strike, is usually a burned hole through several layers of laminate with charring for several inches around the contact point. This resultant direct effect to a launch vehicle is clearly unacceptable in most cases. Methods for protection against direct effects usually include an outer layer of metal screen, foil, or expanded foil cured into the laminate making contact with the graphite where possible. This metal layer helps disperse the current over a larger area while holding temperature at a lower level. However, the metal can be expected to be vaporized near the strike point. The metal used is usually 2 to 4 mils thick. By comparison, aluminum skins are sometimes punctured even though they are 1/8 to 1/4 inches thick.

Indirect effects on underlying electronic equipment and circuitry may not be completely negated by the single layer of metal. This protection becomes more of a shielding effectiveness problem and may require another layer of foil on the inside of the laminate.

The current-carrying capability of joints in the skin or structure is also a major concern, just as it has been in the previous topics. Further investigation and testing are planned for this topic.

11. JOINTS

Special attention must be given to joint preparation to maintain conductivity when using graphite fiber reinforced plastic (GFRP). Typical values of resistance across commonly used joints are 50 to 100 milliohms. The 2.5 milliohm requirement of MIL-B-5087B can only be met with specially designed joints. Graphite epoxy joints can deteriorate rapidly in salt spray conditions. [3-21]

Joints can be made almost as conductive as the GFRP material by inserting metal foil or screen at the edges to make contact with each layer of carbon filament during manufacture. This foil or screen can then be used as a conductive tab to make contact to other similarly prepared panels.

Tin plating on GFRP can aid conductivity through joints, especially if the surface of the GFRP is sanded lightly to expose the graphite. Using light sanding and conductive paint on mating surfaces can also prove useful for making acceptable joints. In both cases the conductive surface is spread over a larger area and more layers of graphite are in contact with the better conductor. The plated or painted surfaces are mated by overlapping at the joint or by butting the sections together and bridging the joint with metal foil or screen. The use of conductive paint on sanded surfaces seems to make the best joint for RF purposes. Joints using conductive paint can also be made conductive enough to carry fault currents if a large enough area of contact is used.

According to reference 3-15, tests showed that leakage of RF through simulated GFRP aircraft skin was dominated by joints. These joints act like slots if there is not a good conductive contact along the mating surfaces.

Making good contact across joints in composites is more difficult than in metals because their surfaces are typically poor conductors. Good contact must be made to the conductive particles or layers within the composite.

Differences in the electromotive series potentials of two different materials in contact may present a problem. Carbon is on the low potential end of the galvanic series, and aluminum, magnesium, and other common materials are on the high end. A potential difference over one volt can be expected between carbon and aluminum. This could cause corrosion in the joint resulting in a high resistance contact. Dielectric coating between materials stops corrosion but prevents electrical contact.

REFERENCES

During the first quarter of this task, Mr. Hugh Denny performed a literature search for items pertaining to composite materials. The result was a loose-leaf notebook containing three sections. Section 1 contains bibliography citations, section 2 contains copies of selected papers, and section 3 contains several papers from AGARD Conference Proceedings #283. This report uses some, but not all, of those papers as references.

References 1 through 5 for this report are books. The other references, 1-17 through 3-21, were taken from Mr. Denny's compiled data. The reference numbers are consistent with the numbers of the papers in the loose-leaf notebook. The notebook containing all the papers has been delivered along with this report.

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