Shielding Theory and Design

Presented by
Michael J. Oliver
Vice President
Electrical / EMC Engineering

MAJR Products Corporation
Manufacturer of EMI/RFI Gasketing and Shielding Products

EMC Fundamentals

- **Definitions**
  - **Electromagnetic Interference, (EMI)**
    - The undesirable effect due to an electrical signal other than the desired signal
  - **Electromagnetic Compatibility, (EMC)**
    - The ability to operate in an intended environment without being disturbed or disturbing other equipment
  - **Radio Frequency Interference, (RFI)**
    - Interference to communication/radio bands
  - **Emissions**
    - Energy generated by an electrical device's operation
      - Conducted - Transmitted by a conductive medium
      - Radiated - Transmitted by an electromagnetic field
  - **Immunity**
    - A measure of how resistant an electrical device is to external fields
  - **Susceptibility**
    - A measure of how susceptible a device is to external fields

EMC Fundamentals

- **To have an EMI problem, three elements are necessary**:
  - Source
  - Coupling path
  - Receptor
- **The amount of emission "leakage" from an aperture depends upon three main items:**
  - The maximum linear dimension (not area) of the aperture
  - The wave impedance
  - The frequency of the source
- **Multiple Apertures**
  - Reduction of shielding depends upon:
    - The spacing between the apertures
    - Operating frequency
    - The number of apertures within $\lambda/2$
  - When apertures of equal size are placed close together (within $\lambda/2$), the shielding loss is approximately proportional to 20 times the log of the number of apertures.

EMC Fundamentals

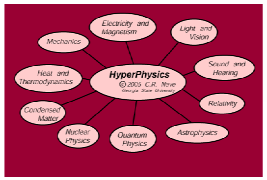
- **To have an EMI problem, three elements are necessary**:
  - Source
  - Coupling path
  - Receptor

Sources	Coupling Path	Receptor
Microprocessors	Radiated EM fields	Other logic circuits
Video drivers	Capacitance	Analog circuits
ESD	Inductance	Receivers
Power supplies	Conducted	Reset lines
Lightning	"Ground"	Equipment

EMC Fundamentals

MAXWELL EQUATIONS

- Forms the building blocks of understanding electromagnetic theory by defining the relationship among charges, currents, magnetic and electric fields.
  - Gauss's Law - There are + and - electric charges (flux) out of a surface proportional to the charge within the surface
  - Faraday's Law - Any change in the magnetic environment of a coil will cause a voltage (emf) to be "induced" in the coil.
  - Ampere's Law - A current flow creates a magnetic field.
- They are functions of three space variables (x,y,z) and time (t).
- They relate time-varying electric and magnetic fields to current and voltage.



HyperPhysics is hosted by the Department of Physics and Astronomy

Georgia State University

C. R. Nave

http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

EMC Fundamentals

MAXWELL EQUATIONS

- A time varying electric field between two conductors represented as a capacitor.
- A time varying magnetic field between two conductors represented by mutual inductance.
  - A potential difference causes a current to flow which generates a magnetic field which, in turn, creates an electric field.
  - For a time-varying field, we always have both an electric field and a magnetic field.

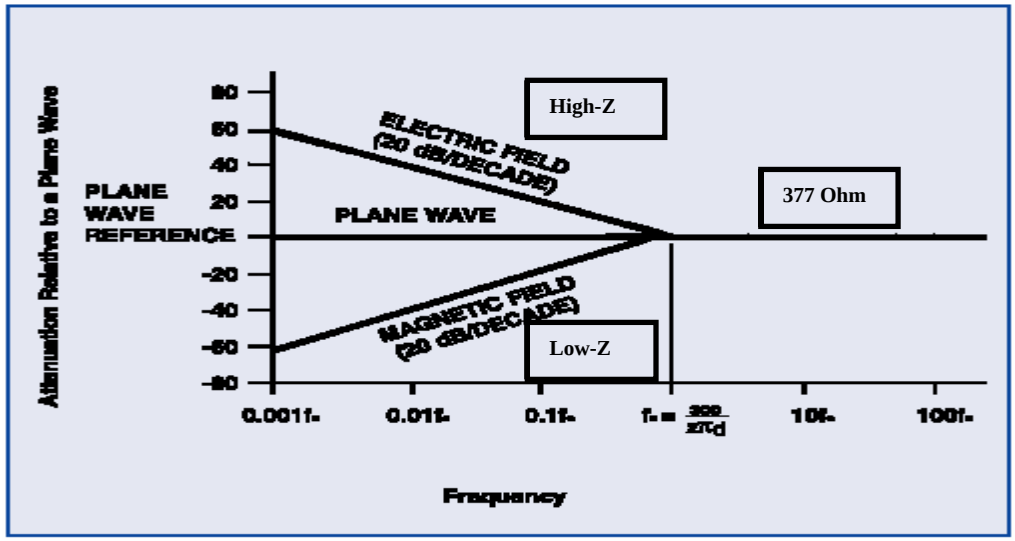
An RF voltage potential will cause a time varying current – generating magnetic field, developing a time varying transverse electric field, creating the electromagnetic field.

The Electromagnetic Wave

H-Field (magnetic)
E - Field (electric)
PW - Field (plane wave)

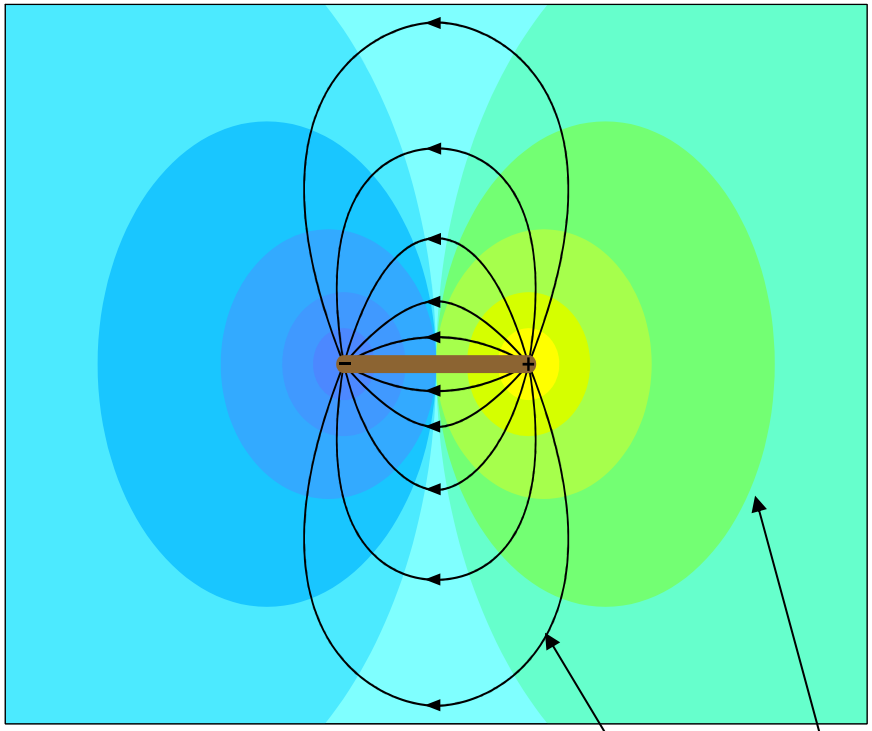
EF, HF, & Plane Wave

- The Electric Field (high impedance), Magnetic Field (low impedance), and Plane Wave (377 Ohm) are the three aspects of EMI/RFI wave propagation. Different shielding levels result from variations in wave impedance.
- Electric Field and Magnetic Field impedance change with separation distance.
- Plane Wave impedance is constant with separation distance.

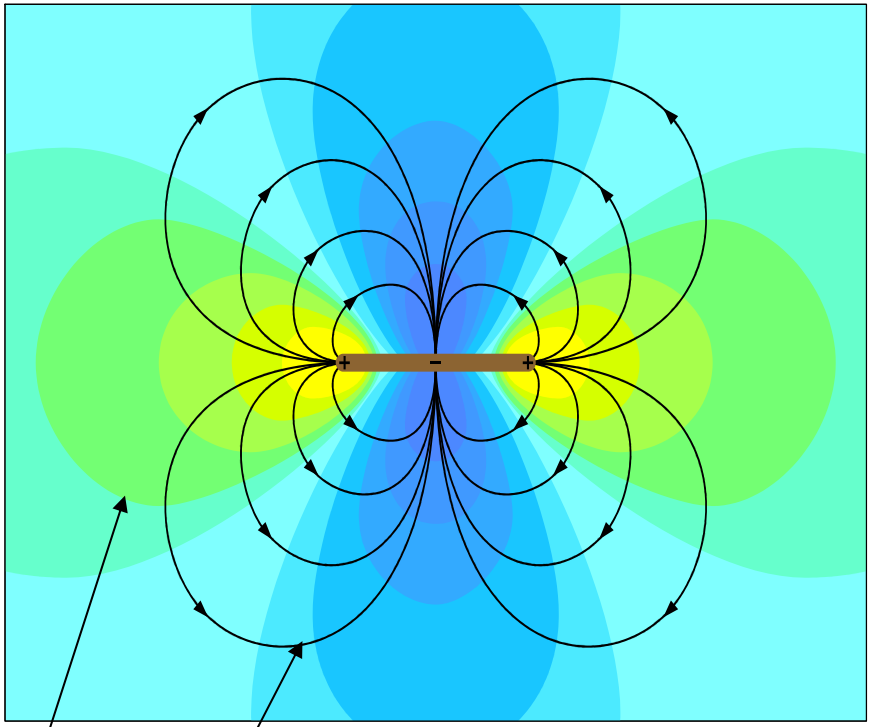


Radiated Field, No Shielding

Half-Wavelength Sized Emission



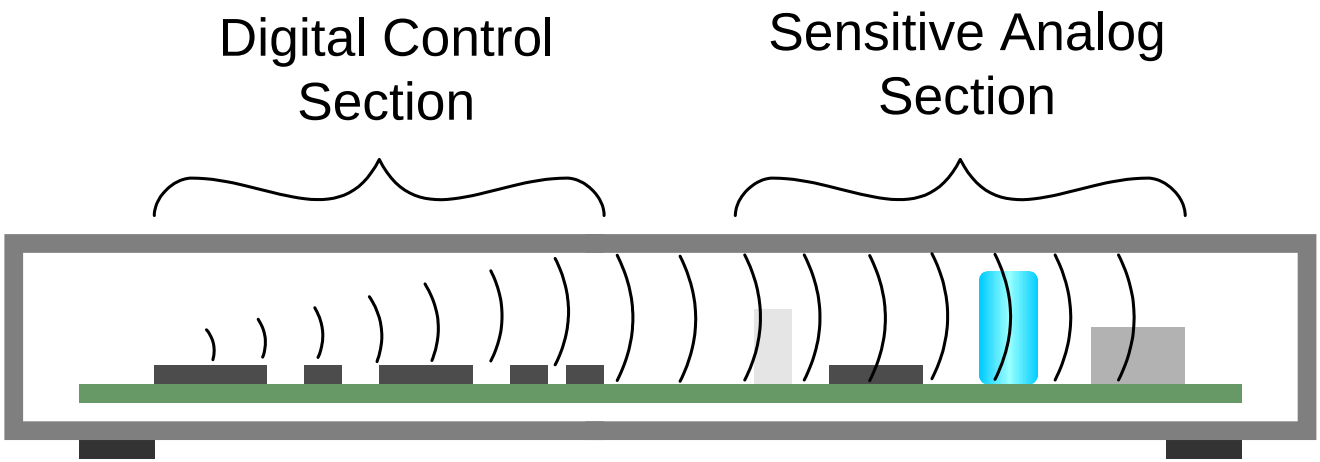
Full-Wavelength Sized emission



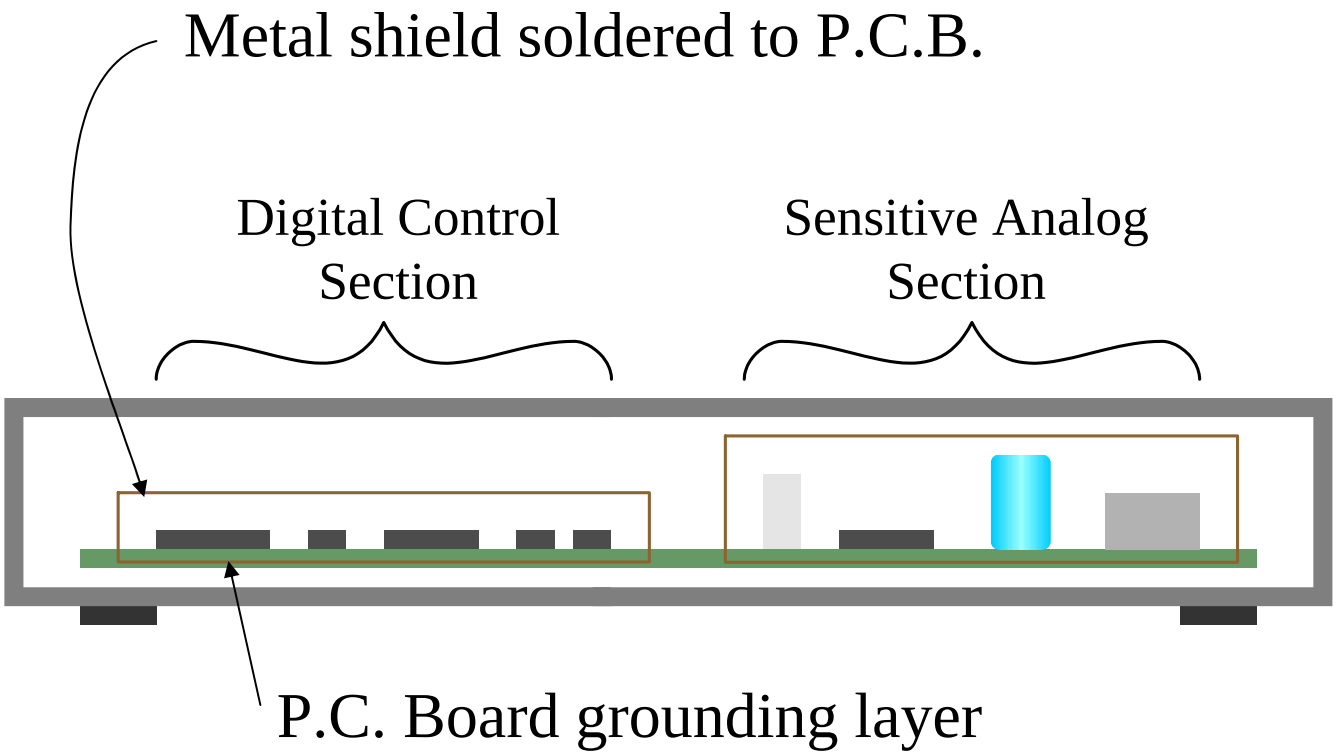
Equipotential Bands

Antenna Pattern Lobes

Typical Cross-Talk Problem



Board Level Shielding



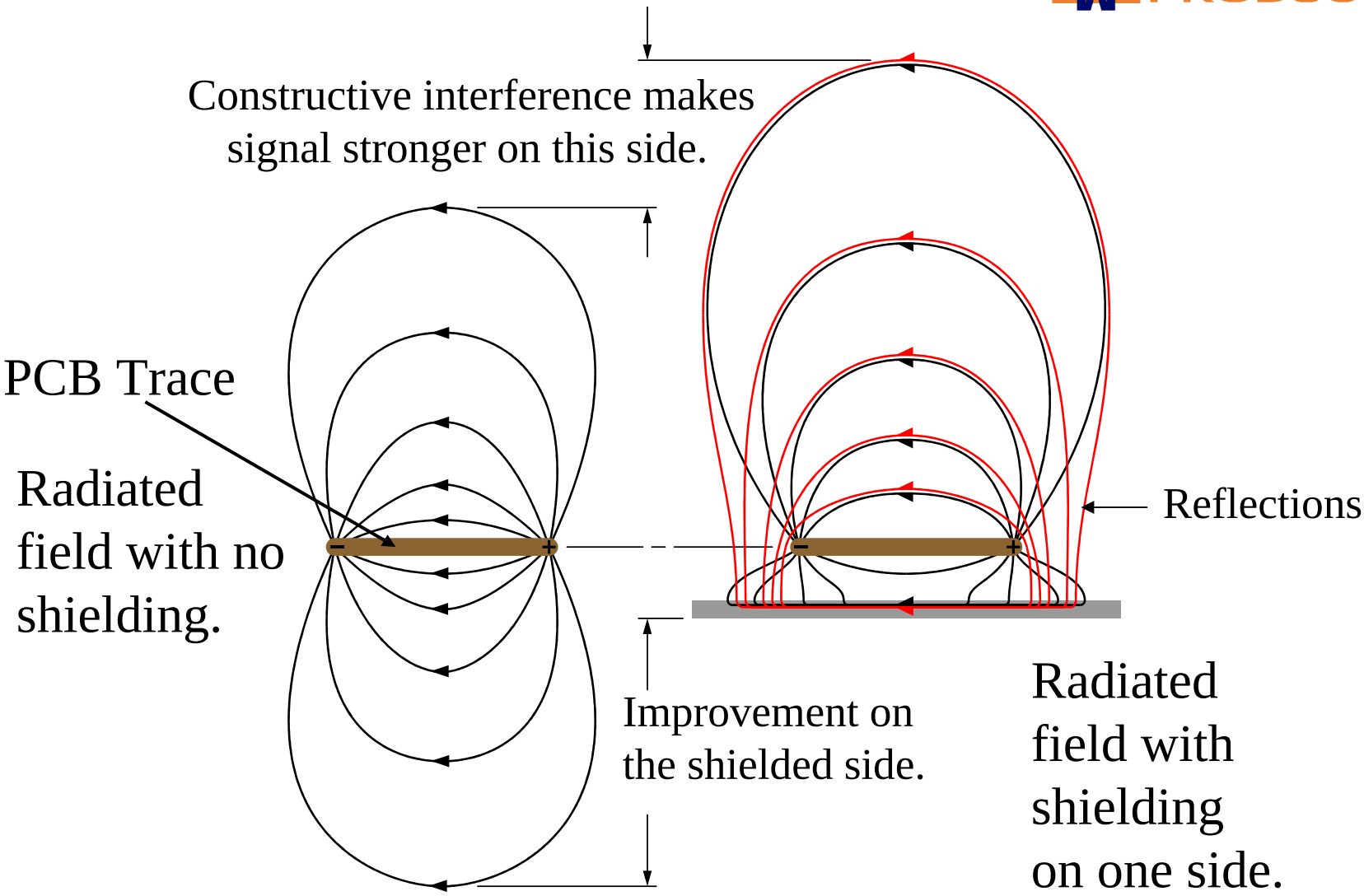
Rayleigh-Helmholtz & Carson reciprocity theorem:

- **Resolving radiated emission problems will also aid in resolving radiated immunity problems**

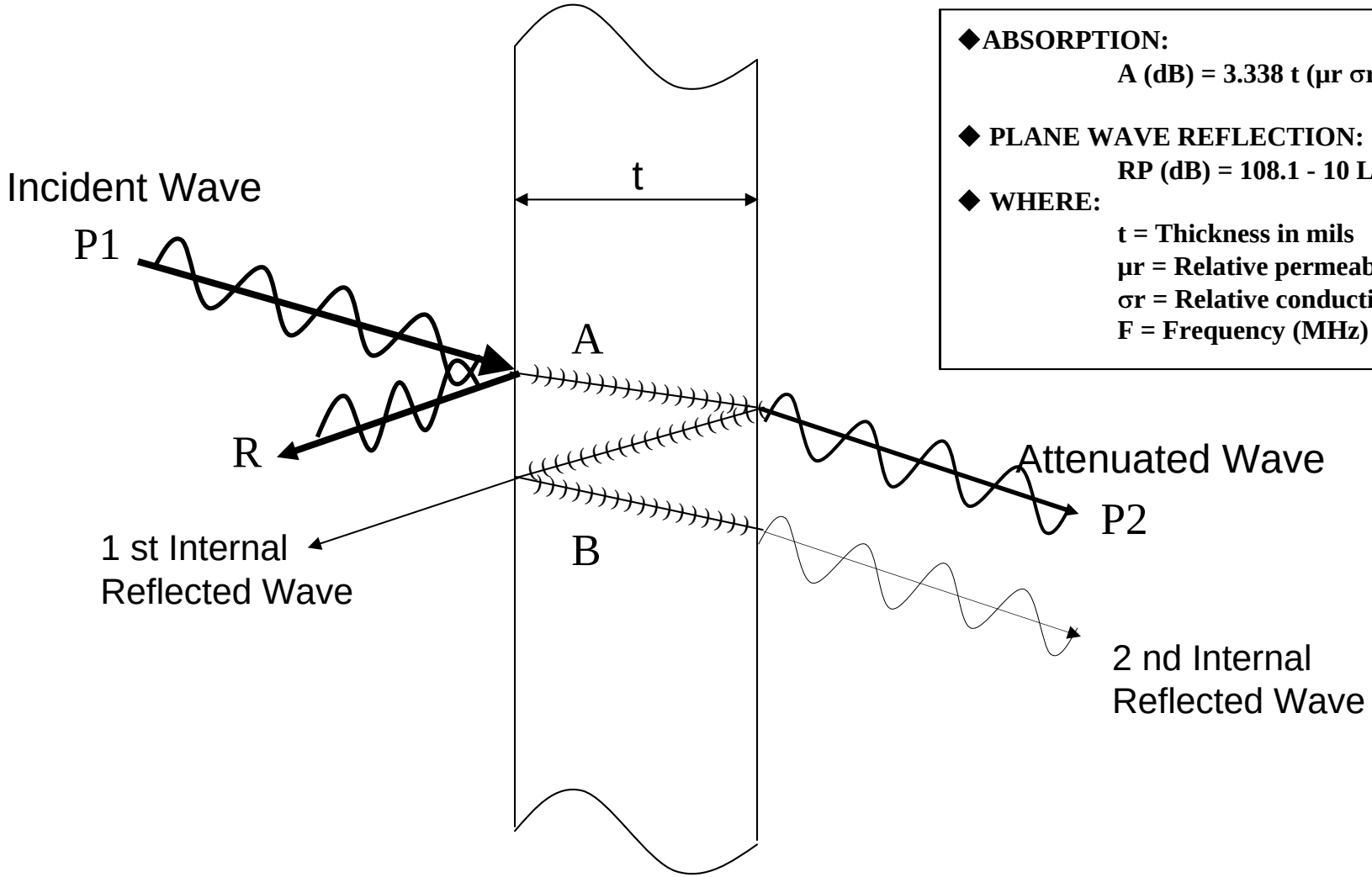
Reciprocity -Emission and Immunity

- **Reciprocity**
  - Rayleigh-Helmholtz & Carson reciprocity theorem
    - Same frequency
    - Medium is linear, passive, and isotropic
  - If a signal is applied and transmitted through antenna A and measured at another antenna B; an equal signal will be measured at antenna A if the same signal is transmitted through antenna B
  - **Basically means that resolving radiated emission problems will also aid in resolving radiated immunity problems**

The Problem with a Partial Shield



Shielding Material (Graphical Representation)



- **ABSORPTION:**
  A (dB) = 3.338 t (μr σr F)^1/2
- **PLANE WAVE REFLECTION:**
  RP (dB) = 108.1 - 10 Log (μr F/σr)
- **WHERE:**
  t = Thickness in mils
  μr = Relative permeability
  σr = Relative conductivity
  F = Frequency (MHz)

Note: If A≥ 6 dB then B=0

Surface Currents (Good Shield)

R.F. Current flowing through a conductor is non-uniform.

Current density is highest at the surface, and becomes exponentially smaller with depth into the conductor.

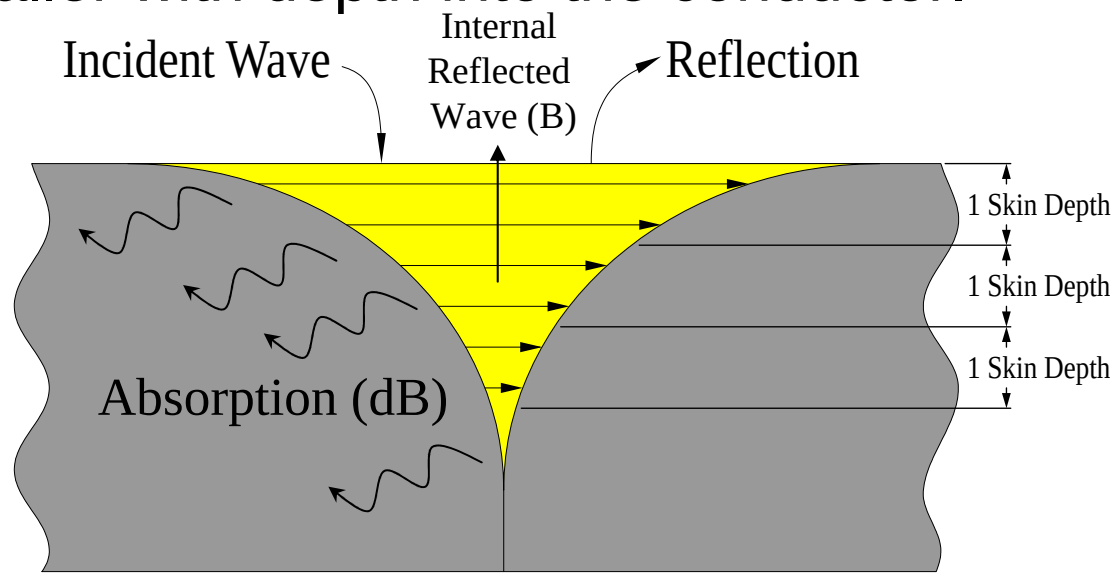
SE(dB) = 10 log P1 / P2

= SE(dB) + R(dB) + A (dB) + B(dB)

where : RdB = Reflection losses

AdB = Absorption losses

BdB = Re-reflection losses



The parameter quantifying this occurrence is called 'Skin Depth' (δ).

Definition of Skin Depth

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

where:

f = Frequency (Hz)

σ = Conductivity (Siemens)

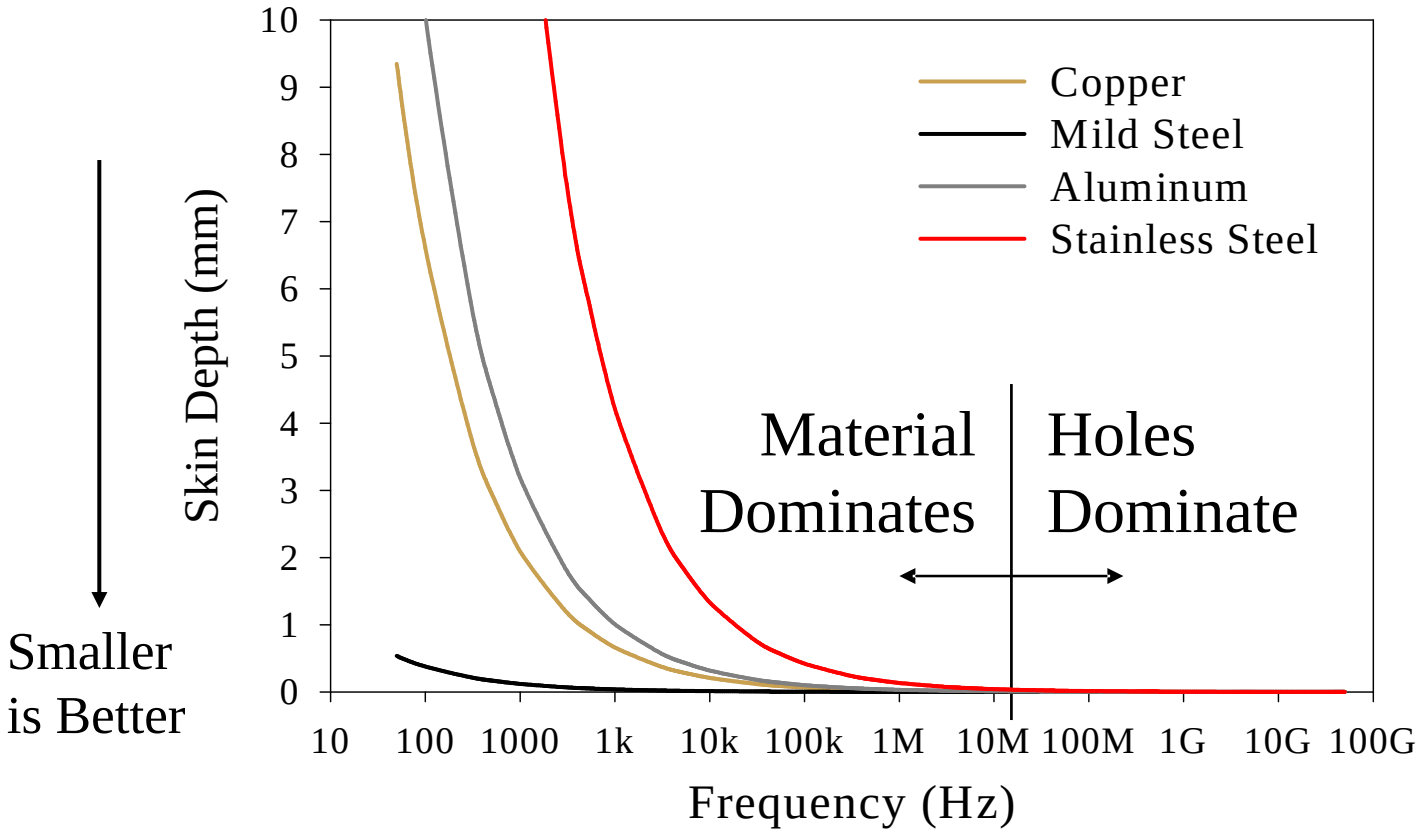
μ = Permeability (of material relative to air)

Each skin depth equals approx 37% of the amplitude of the propagating wave through the material.

Skin effect increases as frequency and amplitude of the losses increase therefore at higher harmonic frequencies there is a greater degree of heating in a conductor.

Skin Depth v.s. Frequency

For Common Shielding Materials

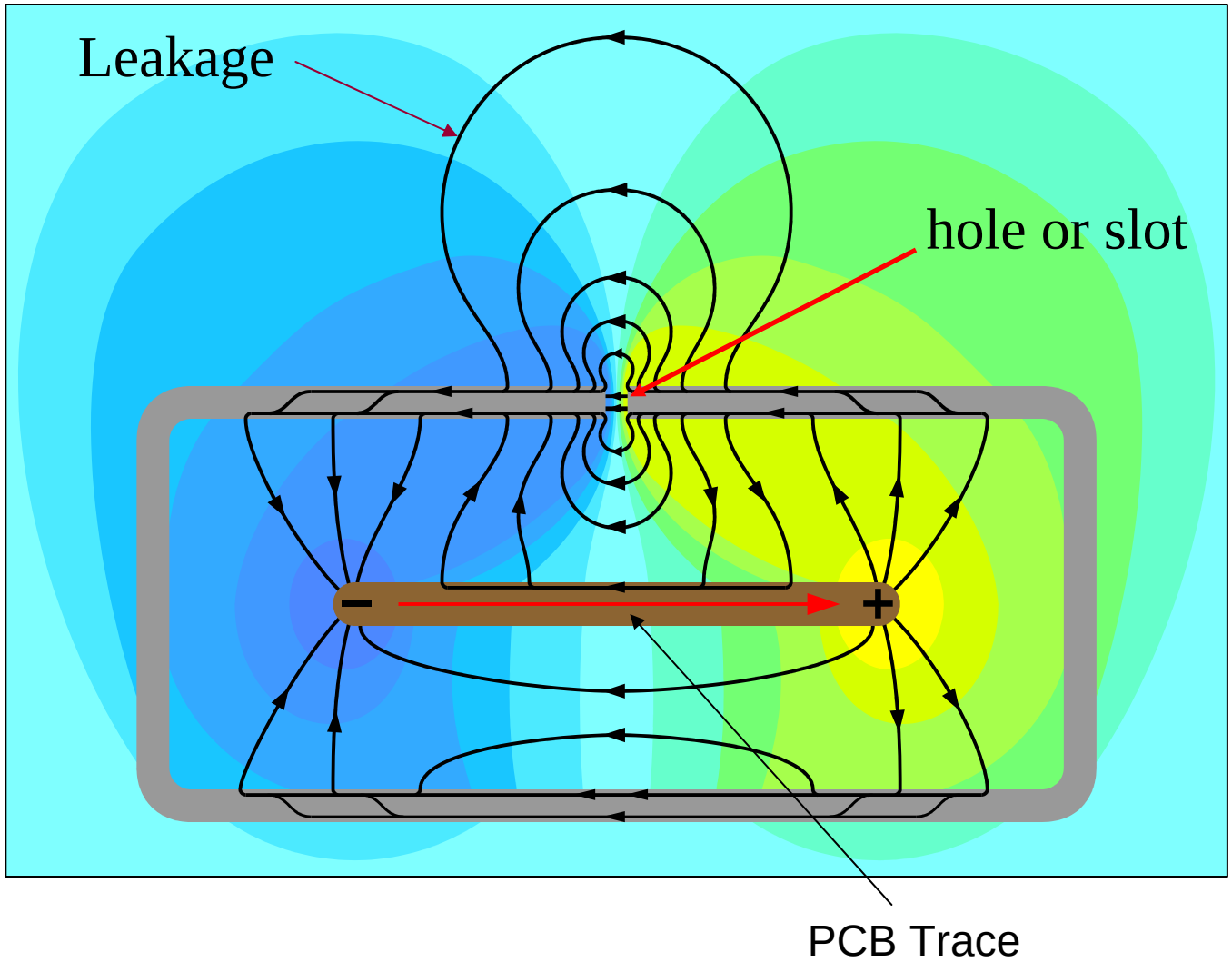


Common Shielding Materials

Material	Typical Uses
Magnetic Alloys	CRT's, Coils, Transformers
Mild Steel	Computers, Telecom Racks
Aluminum	Avionics, Portable Equipment
BeCu	Shielding gaskets
Stainless Steel	Snap-In Covers, Grounding Strips
Flame Spray Coatings	Plastic Housings
Metallic Plating	Small Plastic Housings
Filled Plastics	ESD Shielded Housings
Conductive Paint	Architectural, Plastic Housings

Holes (apertures) within a shielded enclosure

Radiated Field, Aperture in Shield

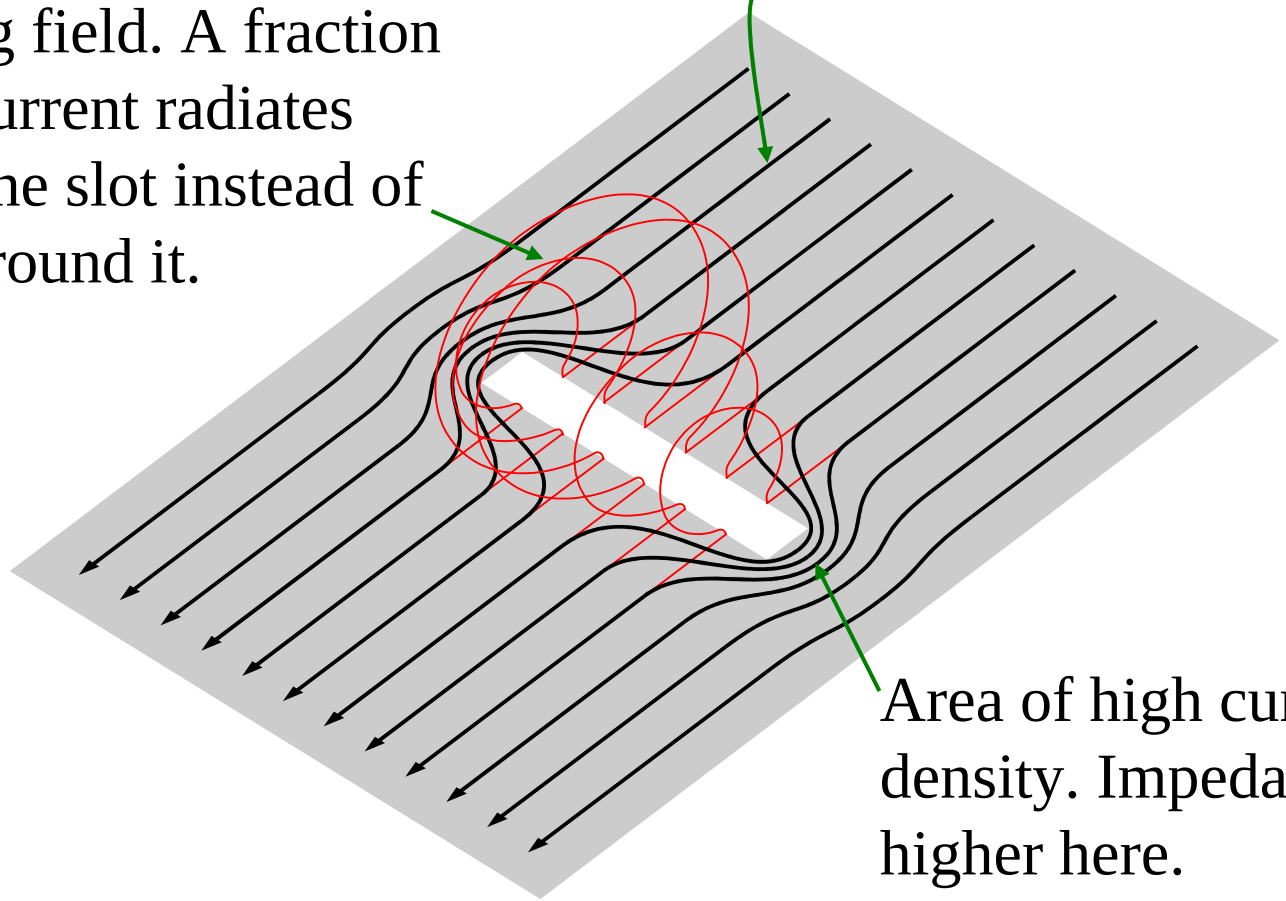


Shield Aperture Leakage

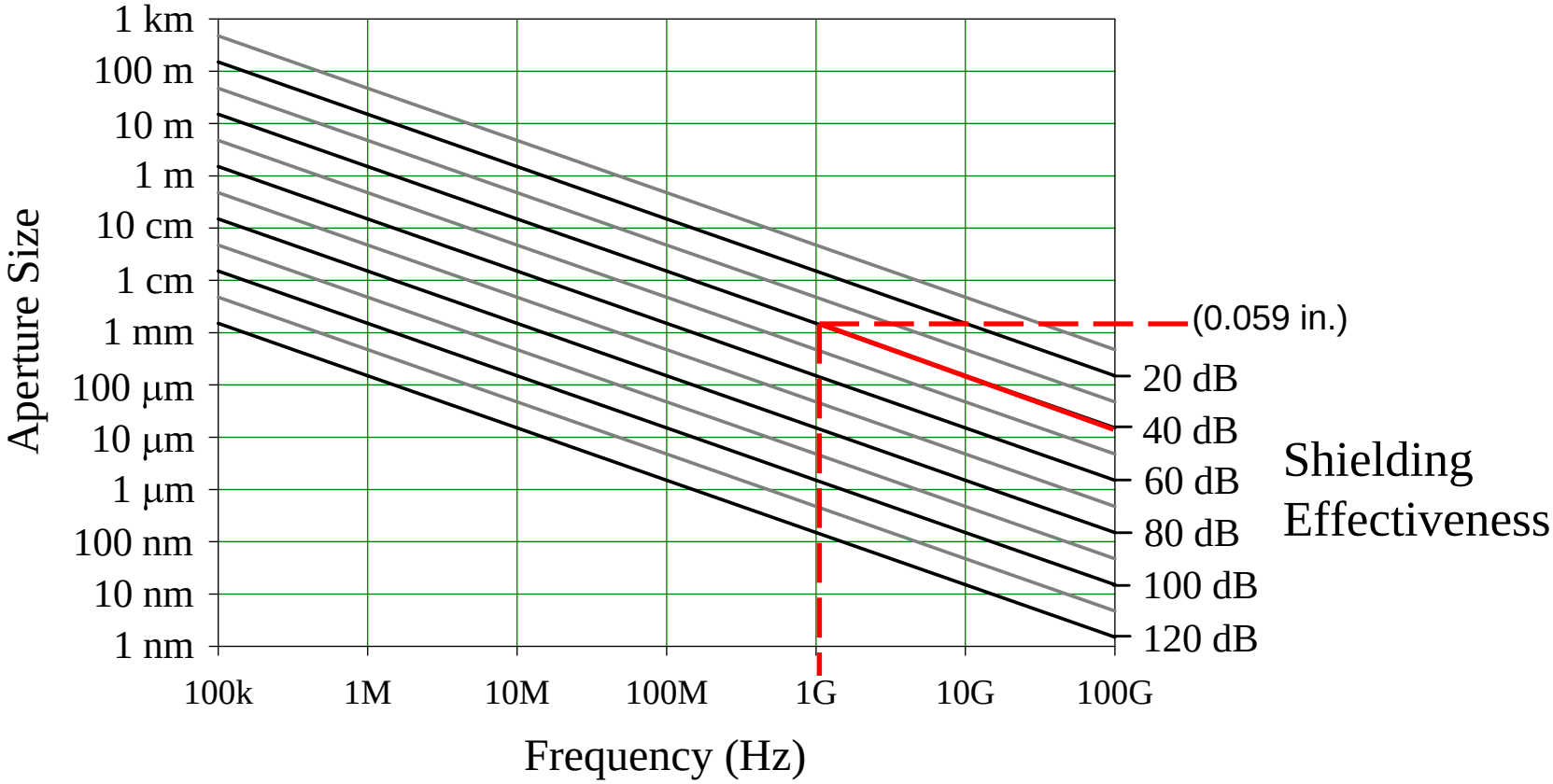
- The amount of leakage from an aperture depends upon three main items:
  - The maximum linear dimension (not area) of the aperture
  - The wave impedance
  - The frequency of the source

Current Flow Around a Slot

Fringing field. A fraction of the current radiates across the slot instead of going around it.



Shielding Level of an Aperture



$$\text{Shielding Effectiveness} = 20\log_{10}\left(\frac{\lambda}{2L}\right)$$

$\lambda = \text{Wavelength} = C / F$

$F = \text{Frequency}$

$C = \text{Speed of Light} = 3\times10^{8}\, m/\text{sec}$

$L = \text{Longest Dimension}$

Aperture calculations

- Multiple Apertures
  - Reduction of shielding depends upon:
    - the spacing between the apertures
    - the frequency
    - the number of apertures
  - When apertures of equal size are placed close together (within $\lambda/2$), the shielding loss is approximately proportional to 20 times the log of the number of apertures.

Aperture Attenuation Modeling Program

Aperture Attenuation Program

- We saw the need for a software design tool to assist engineers in the initial shielding design stage of their electronic product
- A modeling program that we can input the products' frequency of concern, aperture size, and quantity of apertures for connectors and/or heat management of the shield or enclosure
- An output indicating approximate but conservative shielding levels prior to expensive radiated emission and/or susceptibility testing
- A graph of aperture attenuation (dB) vs. frequency (MHz)

Test Fixture Factor		
Hole =	40	(40 is standard)
Slot =	20	(20 is standard)

APERATURE ATTENUATION MODELING PROGRAM

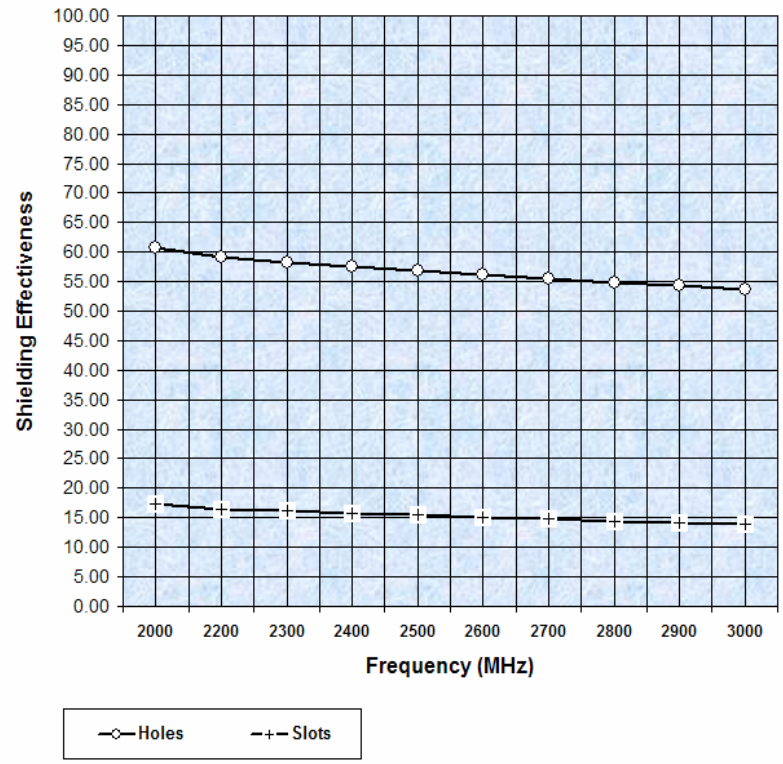
Shielding Effectiveness for apertures (holes) in a shield

COLUMN 1	COLUMN 2	COLUMN 3	COLUMN 4	COLUMN 5	COLUMN 6	COLUMN 7	COLUMN 8
Frequency	Wavelength	1/2 wavelength	Holes	Hole size	Hole Attenuation Calculation		Shielding Effectiveness
(MHz)	(λ in.)	(λ /2 in.)	within λ /2	(l in.)	40 log (λ/2l) -	20 log(n)	of holes (dB)
2000	5.9014	2.9507	5	0.040	74.7146	13.9794	60.7352
2200	5.3649	2.6825	5	0.040	73.0589	13.9794	59.0795
2300	5.1317	2.5658	5	0.040	72.2867	13.9794	58.3073
2400	4.9178	2.4589	5	0.040	71.5474	13.9794	57.5680
2500	4.7211	2.3606	5	0.040	70.8382	13.9794	56.8588
2600	4.5395	2.2698	5	0.040	70.1569	13.9794	56.1775
2700	4.3714	2.1857	5	0.040	69.5013	13.9794	55.5219
2800	4.2153	2.1076	5	0.040	68.8695	13.9794	54.8901
2900	4.0699	2.0350	5	0.040	68.2599	13.9794	54.2805
3000	3.9343	1.9671	5	0.040	67.6710	13.9794	53.6916

Shielding Effectiveness for apertures (slots) in a shield

COLUMN 1	COLUMN 2	COLUMN 3	COLUMN 4	COLUMN 5	COLUMN 6	COLUMN 7	COLUMN 8
Frequency	Wavelength	1/2 wavelength	Slots	Slot size	Slot Attenuation Calculation		Shielding Effectiveness
(MHz)	(λ in.)	(λ /2 in.)	within λ /2	(l in.)	20 log (λ/2l) -	20 log(n)	of slots (dB)
2000	5.9014	2.9507	4	0.100	29.3985	12.0412	17.3573
2200	5.3649	2.6825	4	0.100	28.5706	12.0412	16.5294
2300	5.1317	2.5658	4	0.100	28.1845	12.0412	16.1433
2400	4.9178	2.4589	4	0.100	27.8149	12.0412	15.7737
2500	4.7211	2.3606	4	0.100	27.4603	12.0412	15.4191
2600	4.5395	2.2698	4	0.100	27.1196	12.0412	15.0784
2700	4.3714	2.1857	4	0.100	26.7918	12.0412	14.7506
2800	4.2153	2.1076	4	0.100	26.4759	12.0412	14.4347
2900	4.0699	2.0350	4	0.100	26.1711	12.0412	14.1299
3000	3.9343	1.9671	4	0.100	25.8767	12.0412	13.8355

Shielding Effectiveness Graph of Holes and Slots for a Printed Circuit Board Shield



Follow the 3 steps below to calculate Shielding Effectiveness of holes and/or slots for printed circuit board shields. The shaded areas are variable, all other cells are protected. The holes usually represent air vent holes, slots usually represent folded metal corners or fence stand-off areas. If an aperture is an irregular shape use it's largest length for (l in.)

(1.) Enter from 1 (minimum), to 10 (maximum), the frequencies of interest in a MHz format for holes and/or slots in the spreadsheet below.

Note: Because of the calculation used for wavelength, always use MHz in the frequency column, i.e. 5 GHz is 5000 MHz etc....

(2.) Enter the number of holes and/or slots within the calculated l/2 (1/2 wavelength) circular area for each frequency entered.

(3.) Enter the hole and/or slot maximum diameter or length.

Recommendation: In general a slot or hole size should not exceed 0.02 x 1/4 of the highest frequency (λ in.) of concern.
As for all mathematical models, final radiated testing prior to new product release or final redesign is necessary for valid EMC compliance.

MAJR PRODUCTS

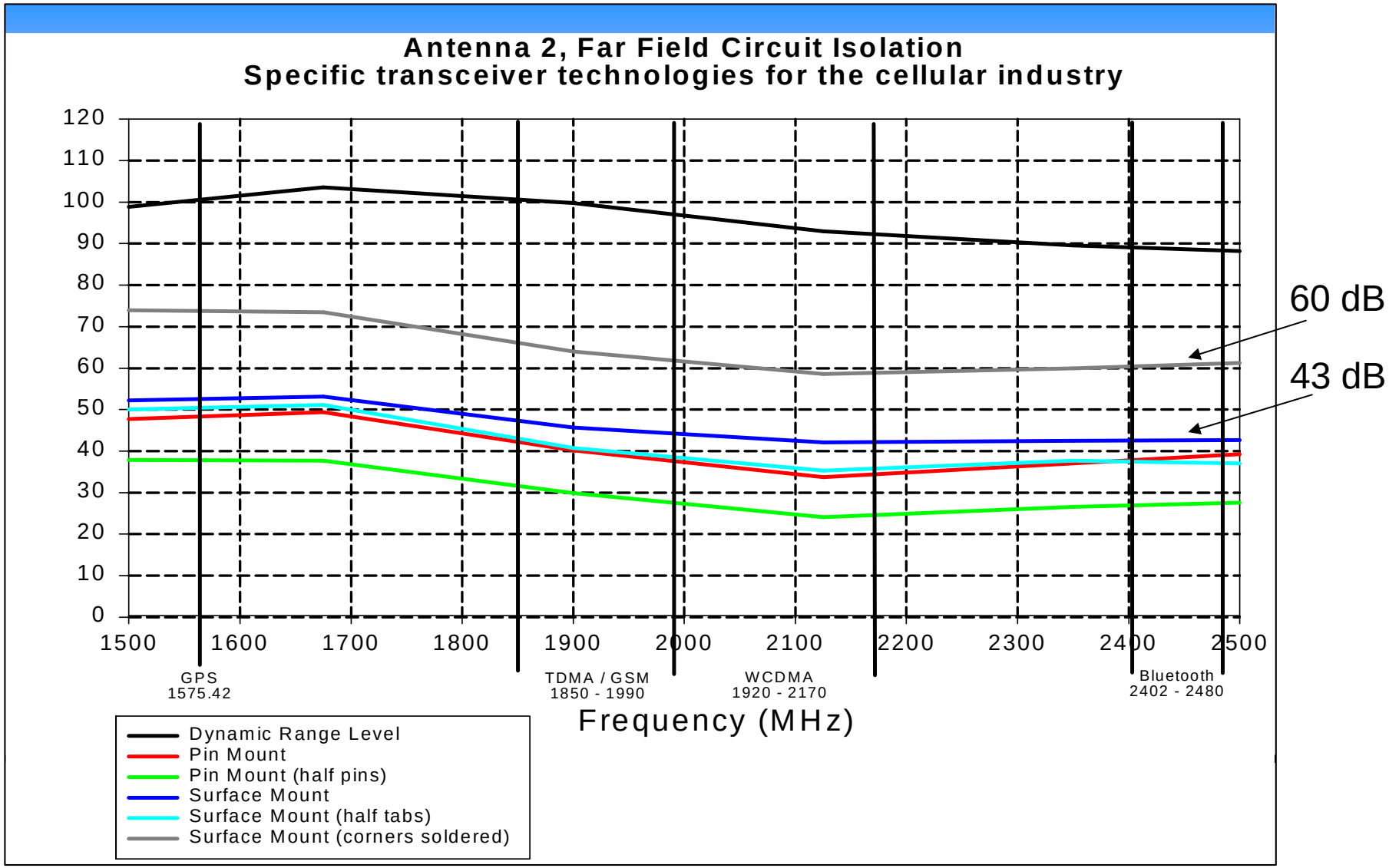
17540 State Highway 198
Saegertown, PA 16433
www.majr.com
e-mail: sales@majr.com

(814) 763-3211
(814) 763-2952 Fax
(877) MAJR PRO Toll Free

Modeling Fundamentals

- An important aspect of a shielding effectiveness modeling:
  - To verify theoretical shielding calculation error with a radiated emission of a shielded product under test
  - Analyze results
  - Adjust calculations to reduce shielding error based on analysis of the actual test
  - Keep in mind that even though important to reduce errors every radiated set-up is unique and incorporates its own anomalies such as reflections, resonances, coupling, VSWR losses, etc…

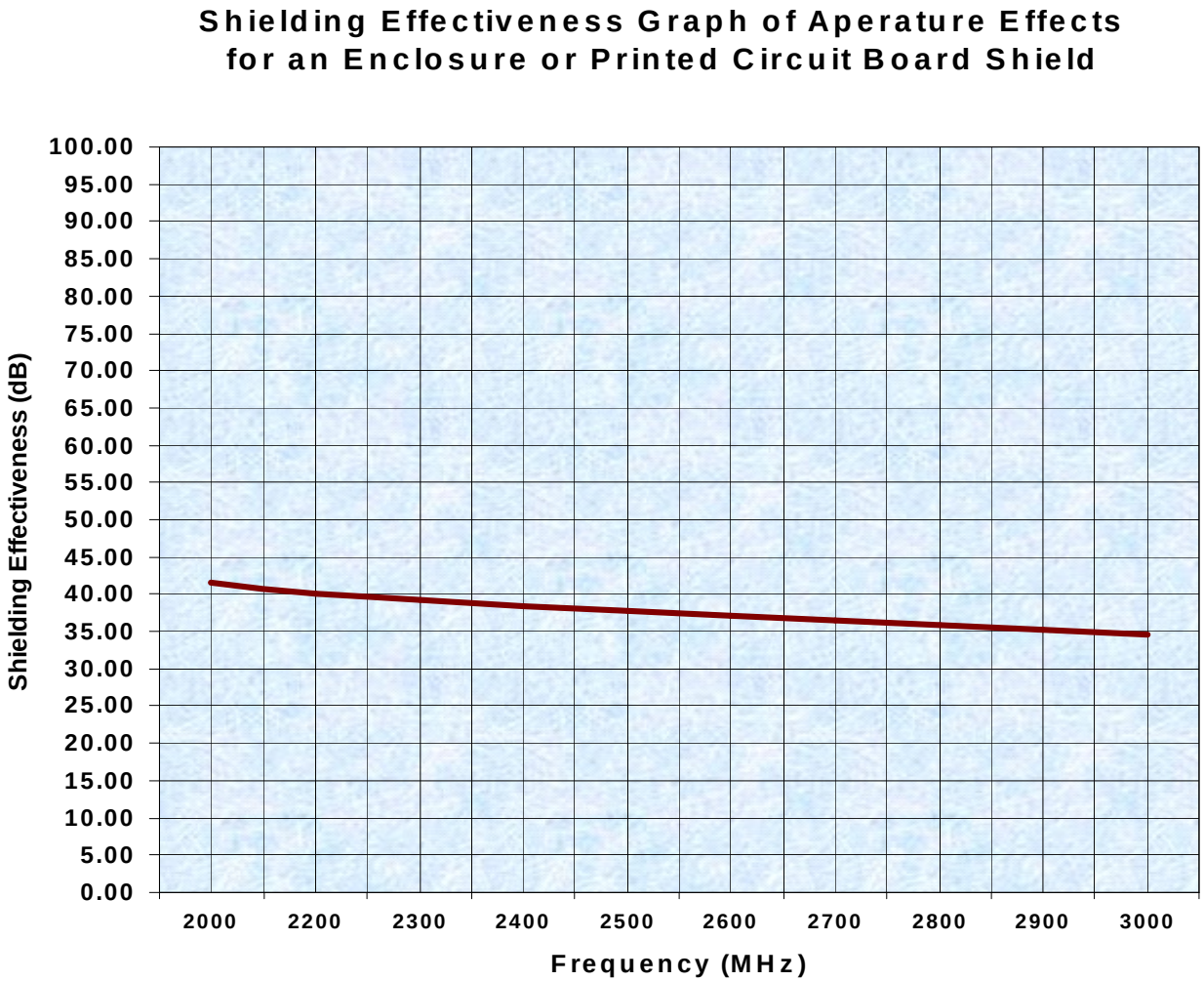
PCB Shield Measurement



Aperture Attenuation Program

Test Factor	
Aperature	40

- Factor of 1 =1.7 dB
- Factor of 5 = 8.46 dB
- Factor of 10 =15 dB



Test Fixture Factor		
Hole =	40	(40 is standard)
Slot =	20	(20 is standard)

APERATURE ATTENUATION MODELING PROGRAM

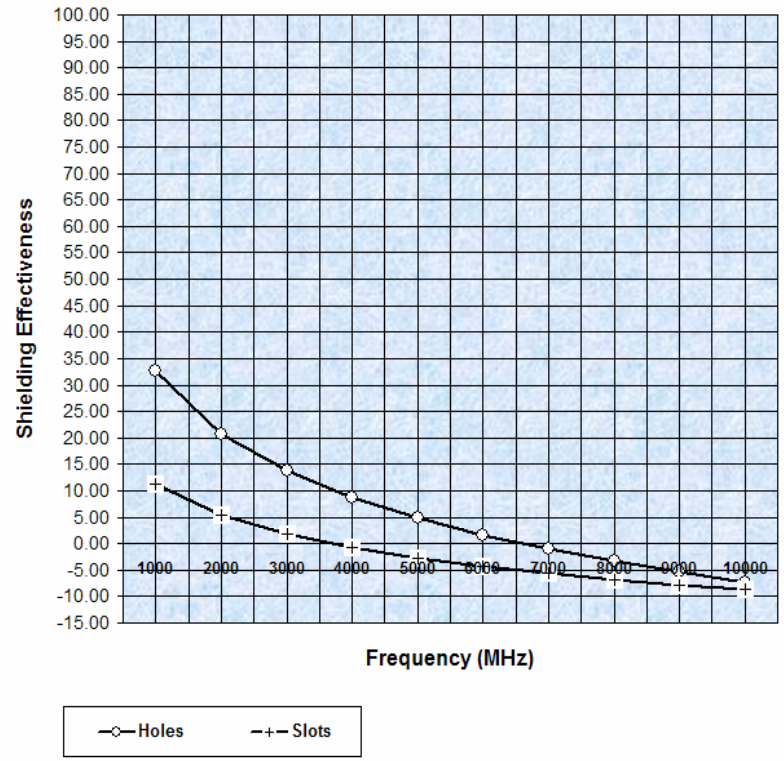
Shielding Effectiveness for apertures (holes) in a shield

COLUMN 1	COLUMN 2	COLUMN 3	COLUMN 4	COLUMN 5	COLUMN 6	COLUMN 7	COLUMN 8
Frequency	Wavelength	1/2 wavelength	Holes	Hole size	Hole Attenuation Calculation		Shielding Effectiveness
(MHz)	(λ in.)	(λ /2 in.)	within λ /2	(l in.)	40 log (λ/2l) -	20 log(n)	of holes (dB)
1000	11.8028	5.9014	20	0.200	58.7970	26.0206	32.7764
2000	5.9014	2.9507	20	0.200	46.7558	26.0206	20.7352
3000	3.9343	1.9671	20	0.200	39.7122	26.0206	13.6916
4000	2.9507	1.4754	20	0.200	34.7146	26.0206	8.6940
5000	2.3606	1.1803	20	0.200	30.8382	26.0206	4.8176
6000	1.9671	0.9836	20	0.200	27.6710	26.0206	1.6504
7000	1.6861	0.8431	20	0.200	24.9931	26.0206	-1.0275
8000	1.4754	0.7377	20	0.200	22.6734	26.0206	-3.3472
9000	1.3114	0.6557	20	0.200	20.6273	26.0206	-5.3933
10000	1.1803	0.5901	20	0.200	18.7970	26.0206	-7.2236

Shielding Effectiveness for apertures (slots) in a shield

COLUMN 1	COLUMN 2	COLUMN 3	COLUMN 4	COLUMN 5	COLUMN 6	COLUMN 7	COLUMN 8
Frequency	Wavelength	1/2 wavelength	Slots	Slot size	Slot Attenuation Calculation		Shielding Effectiveness
(MHz)	(λ in.)	(λ /2 in.)	within λ /2	(l in.)	20 log (λ/2l) -	20 log(n)	of slots (dB)
1000	11.8028	5.9014	4	0.400	23.3779	12.0412	11.3367
2000	5.9014	2.9507	4	0.400	17.3573	12.0412	5.3161
3000	3.9343	1.9671	4	0.400	13.8355	12.0412	1.7943
4000	2.9507	1.4754	4	0.400	11.3367	12.0412	-0.7045
5000	2.3606	1.1803	4	0.400	9.3985	12.0412	-2.6427
6000	1.9671	0.9836	4	0.400	7.8149	12.0412	-4.2263
7000	1.6861	0.8431	4	0.400	6.4759	12.0412	-5.5653
8000	1.4754	0.7377	4	0.400	5.3161	12.0412	-6.7251
9000	1.3114	0.6557	4	0.400	4.2931	12.0412	-7.7481
10000	1.1803	0.5901	4	0.400	3.3779	12.0412	-8.6633

Shielding Effectiveness Graph of Holes and Slots for a Printed Circuit Board Shield



Follow the 3 steps below to calculate Shielding Effectiveness of holes and/or slots for printed circuit board shields. The shaded areas are variable, all other cells are protected. The holes usually represent air vent holes, slots usually represent folded metal corners or fence stand-off areas. If an aperture is an irregular shape use it's largest length for (l in.)

(1.) Enter from 1 (minimum), to 10 (maximum), the frequencies of interest in a MHz format for holes and/or slots in the spreadsheet below.

Note: Because of the calculation used for wavelength, always use MHz in the frequency column, i.e. 5 GHz is 5000 MHz etc....

(2.) Enter the number of holes and/or slots within the calculated l/2 (1/2 wavelength) circular area for each frequency entered.

(3.) Enter the hole and/or slot maximum diameter or length.

Recommendation: In general a slot or hole size should not exceed 0.02 x 1/4 of the highest frequency (λ in.) of concern.
As for all mathematical models, final radiated testing prior to new product release or final redesign is necessary for valid EMC compliance.

MAJR PRODUCTS

17540 State Highway 198
Saegertown, PA 16433
www.majr.com
e-mail: sales@majr.com

(814) 763-3211
(814) 763-2952 Fax
(877) MAJR PRO Toll Free

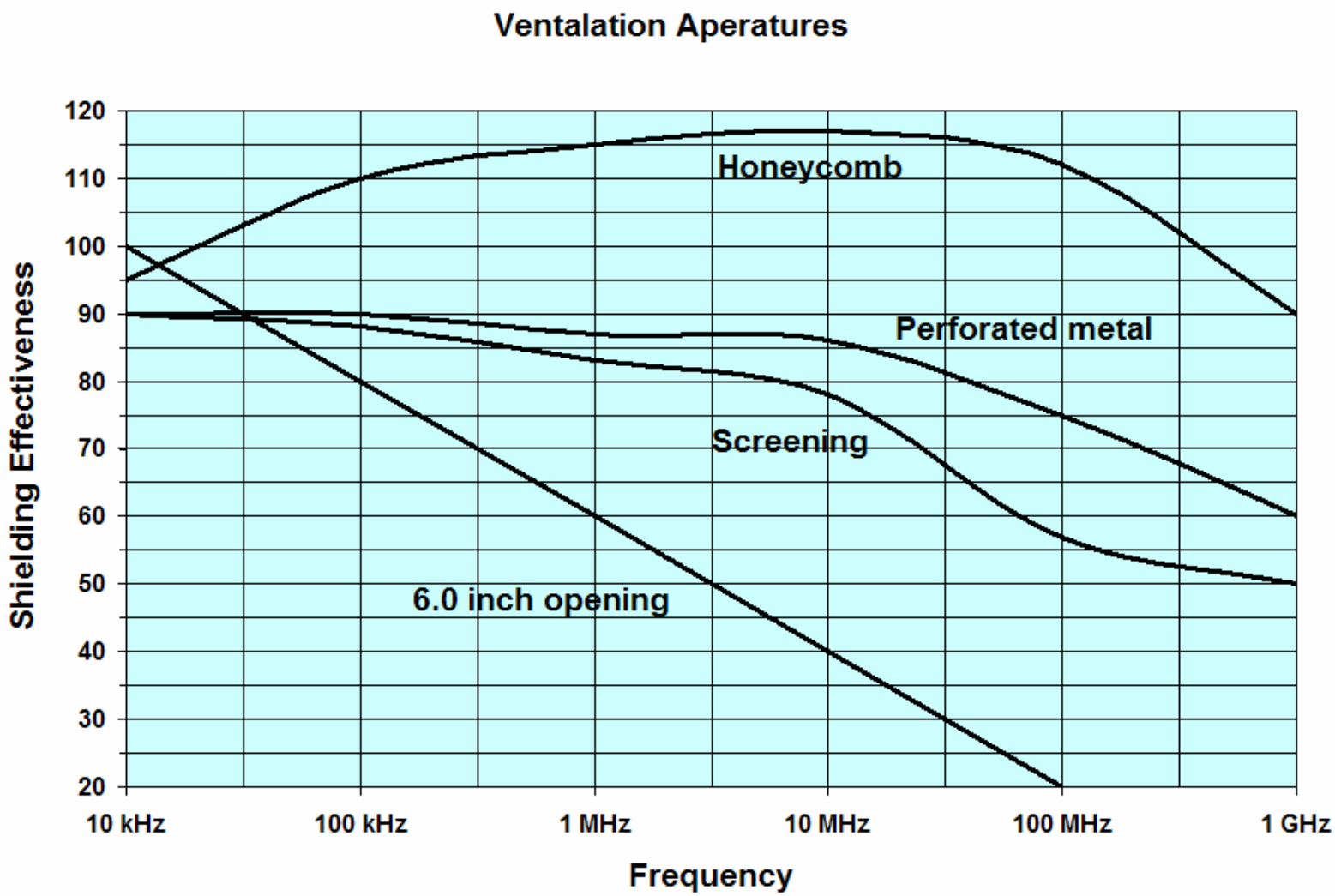
Honeycomb Ventilation Panels

Attenuation of Plated Honeycomb Shielding Panels

Shielding Effectiveness vs. plating and honeycomb materials

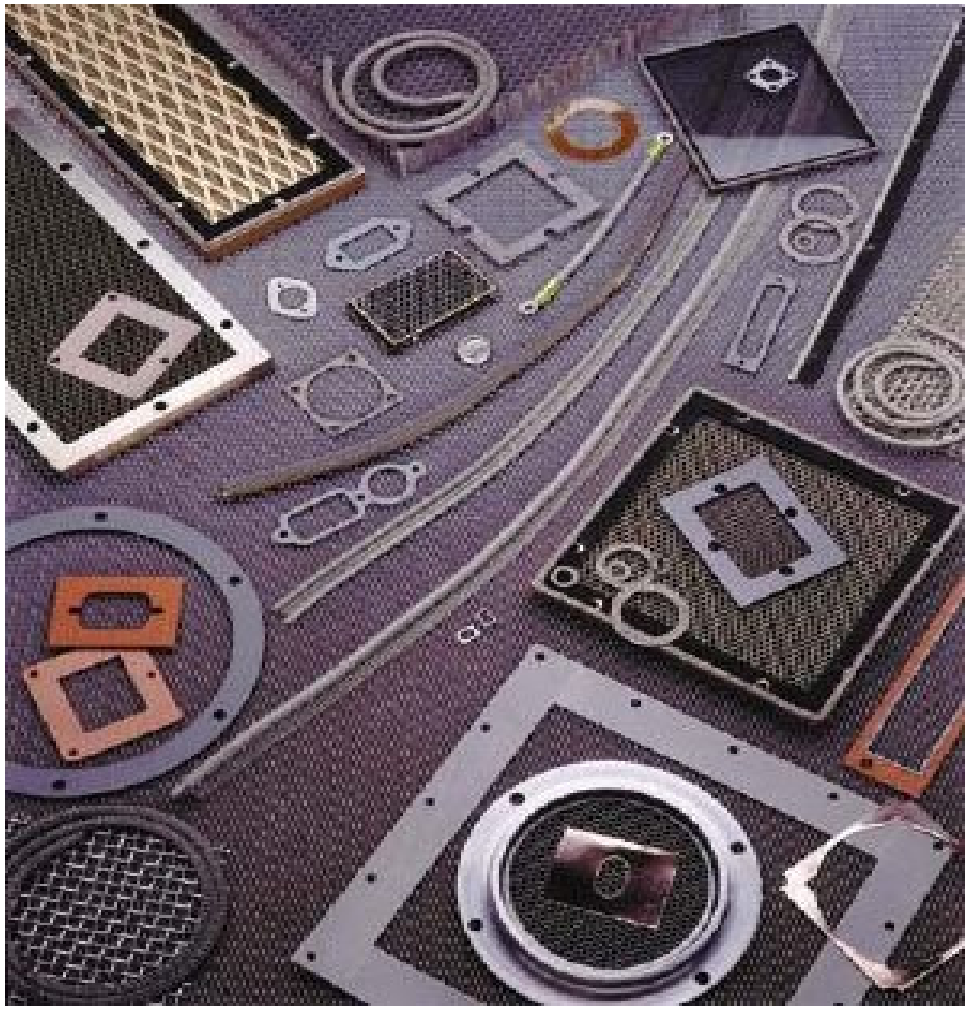
Frequency	Field	Alum H/C Chromate Plating (dB)	Alum H/C Nickel Plating (dB)	Alum H/C Tin Plating (dB)	Steel H/C Tin Plating (dB)
10 kHz	H	20	30	30	60
100 kHz	H	20	40	50	65
1 MHz	H	40	65	60	80
10 MHz	E	60	80	90	100+
100 MHz	PW	30	90	95	100+
400 MHz	PW	40	90	95	100+
1 GHz	PW	35	90	90	100+

Attenuation of Shielding Panels



Shielding Products and Materials

ISO-9001:2000 Registered



MAJR Products Corporation

An internationally recognized manufacturer of Shielding Products

Offering:
EMI/RFI Honeycomb Ventilation panels
Shielded windows
Knitted wire mesh gaskets
Multicon oriented wire gaskets
Conductive fabric gaskets
Board Level Shields
EMC Consulting
Fingerstock gaskets
Conductive Elastomer
Die-Cut gaskets
Grounding washers
Thermal materials
Ferrites and RF Absorber

www.majr.com

REFERENCES

Acknowledgment for partial assembly of this presentation: Ron Brewer, Gary Fenical, Ed Nakauchi, and Bill Stickney

ELECTRONIC SYSTEM DESIGN: INTERFERENCE AND NOISE CONTROL TECHNIQUES
John R. Barnes - Englewood Cliffs, NJ: Prentice-Hall, Inc. 1987

DIGITAL DESIGN FOR INTERFERENCE SPECIFICATIONS
R. Kenneth Keenan - Pinellas Park, FL: TKC, 1983

DECOUPLING AND LAYOUT OF DIGITAL PRINTED CIRCUITS
R. Kenneth Keenan- Pinellas Park, TKC, FL: 1985

INTERFERENCE CONTROL IN COMPUTERS AND MICROPROCESSOR BASED EQUIPMENT
Michel Mardiguian - Gainesville, VA: Interference Control Technologies, 1984

NOISE REDUCTION TECHNIQUES IN ELECTRONIC SYSTEMS
Henry W. Ott - New York: John Wiley & Sons, 1976

ELECTROMAGNETIC WAVES
S.A. Schelkunoff - Princeton, NJ: D. VanNostrand Co., Inc., 1943

EMC HANDBOOK VOL III EMI CONTROL METHODS AND TECHNIQUES
Donald R.J. White - Gainesville, VA: don White Consultants, Inc., 1973

EMI CONTROL IN THE DESIGN OF PRINTED CIRCUIT BOARDS AND BACKPLANES
Donald R.J. White - Gainesville, VA: Interference Control Technologies, 1981

ANSI/IPC-D-275: DESIGN STANDARD FOR RIGID PRINTED BOARDS AND RIGID PRINTED BOARD ASSEMBLIES, SEP 1991
Institute for Interconnecting and Packaging Electronic Circuits - Lincolnwood, IL

IPC-D-316: DESIGN GUIDE FOR MICROWAVE CIRCUIT BOARDS UTILIZING SOFT SUBSTRATES, NOV 1994
Institute for Interconnecting and Packaging Electronic Circuits - Lincolnwood, IL

IPC-D-317A (DRAFT); DESIGN GUIDELINES FOR ELECTRONIC PACKAGING UTILIZING HIGHSPEED TECHNIQUES, JAN 1995
Institute for Interconnecting and Packaging electronic Circuits - Lincolnwood, IL

Thank you:

Questions

or

Comments

MAJR Products Corporation
Manufacturer of EMI/RFI Gasketing and Shielding materials

www.majr.com