Shielding 101

Good
Design?

Bad
Design?

What Shall We Talk About?

- Review basics of the plane electromagnetic shield as developed by Schelkunoff
- Highlights of magnetic field shielding to consider
- Additional aspects of shielding
- Alternative Approaches
- Conclusion and Questions

Shielding may be viewed from two different perspectives:

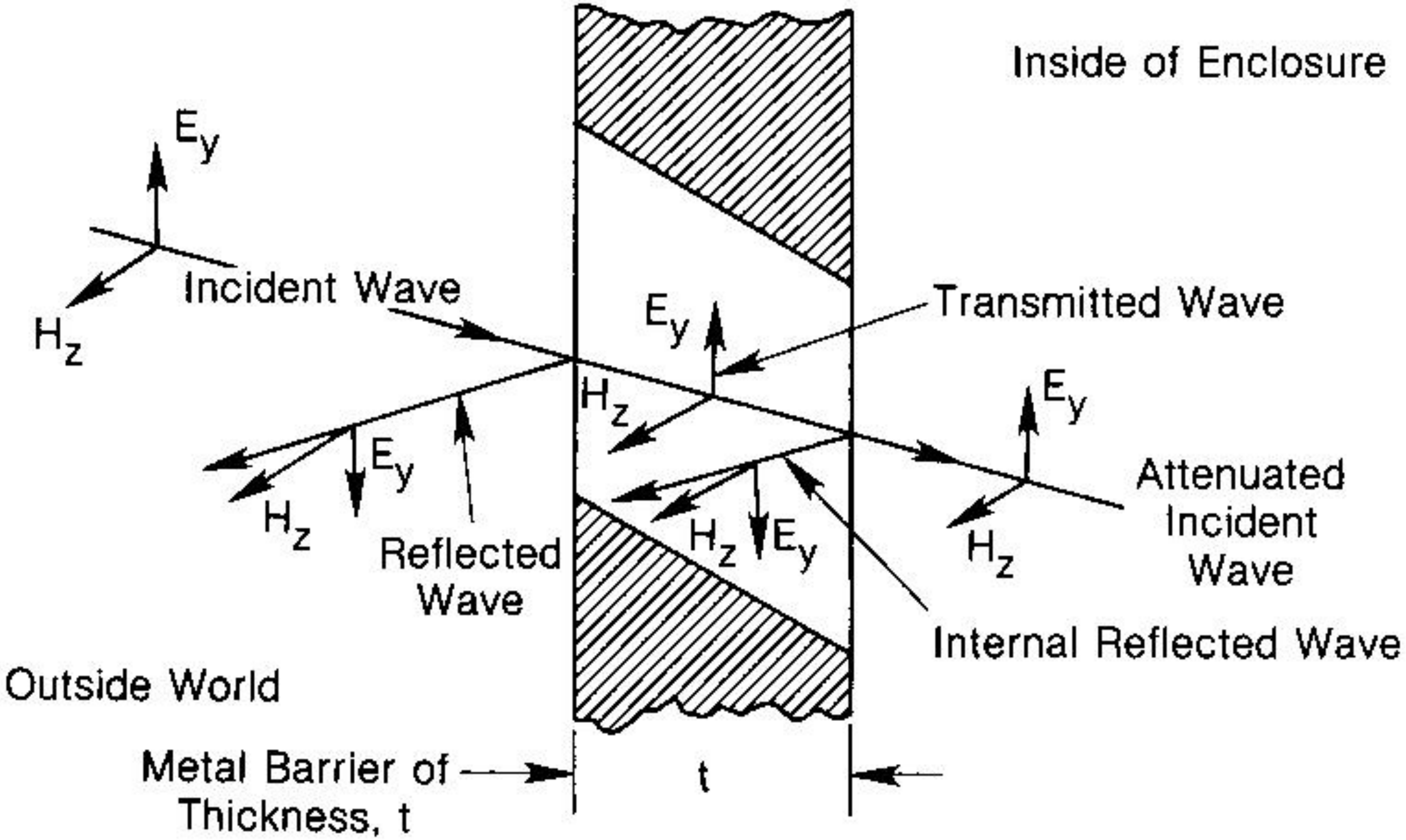
- Field Theory uses the principle that incident EM energy will be partially reflected and partially absorbed by the shield interface, with the absorbed energy attenuated/dissipated as it passes through the shield barrier.
- Circuit theory examines induced currents in the shield barrier that produce fields out of phase with that of the incident energy, thus cancelling it out.

Today we’ll be examining the first of these approaches, originally developed by Sergei Alexander Schelkunoff, and published by him in 1934, 1938, and a third time in 1943.

Fundamental EM theory you (maybe) got in university in general talks about orthogonal far field EM wave behavior at dielectric to dielectric boundaries and dielectric to perfect electrically conducting boundaries.

- Unfortunately, the shields we are interested in cannot be made of unobtain-ium PEC, and if we were to use poorly conductive or non-conductive dielectrics, little if any shielding action would be likely to take place.

So what *is* this shielding action we wish to accomplish, and what sorts of materials do we need to accomplish it?



By definition, a shield inhibits the passage of electromagnetic radiation from one side of the shield to the other.

The degree to which a shield performs this action is referred to as shielding effectiveness.

Image Credit: White, D. R. J. and M. Mardiguian, Electromagnetic Shielding, Vol 3 of A Handbook Series on Electromagnetic Interference and Compatibility, Interference Control technologies, Inc., Gainesville, VA, 1988, page 1.18

Shielding is a major tool in the arsenal of the EMC Engineer, aiding in the suppression of radiation of electromagnetic emissions generated inside electrical/electronic hardware, and the protection of susceptible electrical/electronic hardware from interference caused by the penetration of external electromagnetic radiated fields.

- Note that a shield may be designed specifically to control either electric fields or magnetic fields, or both.

Shielding may assume many different forms, including single barriers or multiple layer stack-ups to provide a custom-tailored electric and magnetic shielding capability.

Engineering considerations for shielding design include:

- Basic shield material characteristics
  - such as conductivity, permeability, and thickness
- All sources of EM radiation addressed
- Field characteristics of the threats
  - Near Field or Far Field?

- Enclosure size, shape, seams, fastener type and spacing, apertures, penetrations, connectors, thermal/humidity/vibration requirements, desired/required surface finish/treatments …
- Of course min mass, volume, cost, and schedule impacts mandatory

Schelkunoff first published his shielding theory in October of 1934 in his paper “The Electromagnetic Theory of Coaxial Transmission Lines and Cylindrical Shields”, Bell System Technical Journal, Vol 13, Issue 4, ppg 532–579. He published the theory again in his January 1938 paper “The Impedance Concept and its Application to Problems of Reflection, Refraction, Shielding and Power Absorption”, Bell System Technical Journal, Vol 17, Issue 1, ppg 17–48.

He published the theory a third time in his 1943 text “Electromagnetic Waves”, D. Van Nostrand, New York, NY, ppg 303 – 315. In this text, he included a section on laminated shields.

In the 1934 paper, Schelkunoff was focused on the behavior of coaxial cables and the effect of the presence of a cylindrical shield on the cylindrical waves emanating from wires contained within the shield.

He reasoned that shielding action could be described in the same fashion as the passage of an electromagnetic signal through a transmission line. Energy passing through a transmission line that encounters a mismatch between the impedance of the transmission line and the terminating load will be reflected and absorbed according to the ratio of the impedances.

Borrowing from Schelkunoff's representation from his 1938 paper, we have the transmission line representation of a shield. In this paper, Schelkunoff indicates that the theory is applicable to "boxes", and that the shielding effect is caused by a combination of reflection losses at the shield boundaries, and absorption within the shield itself.

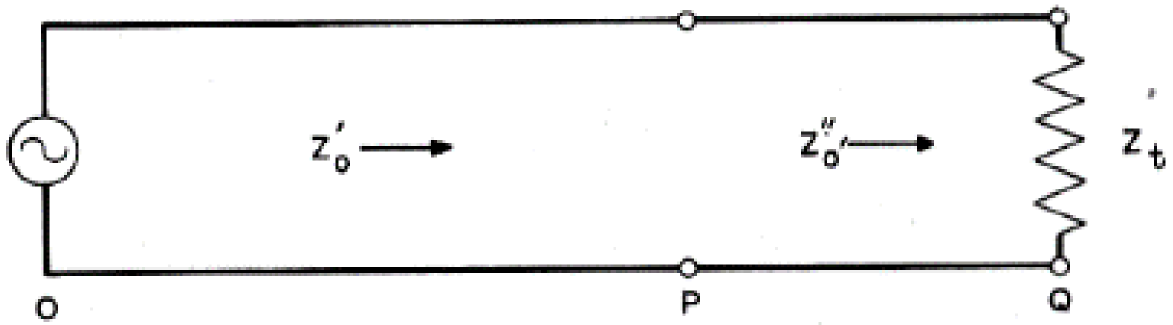
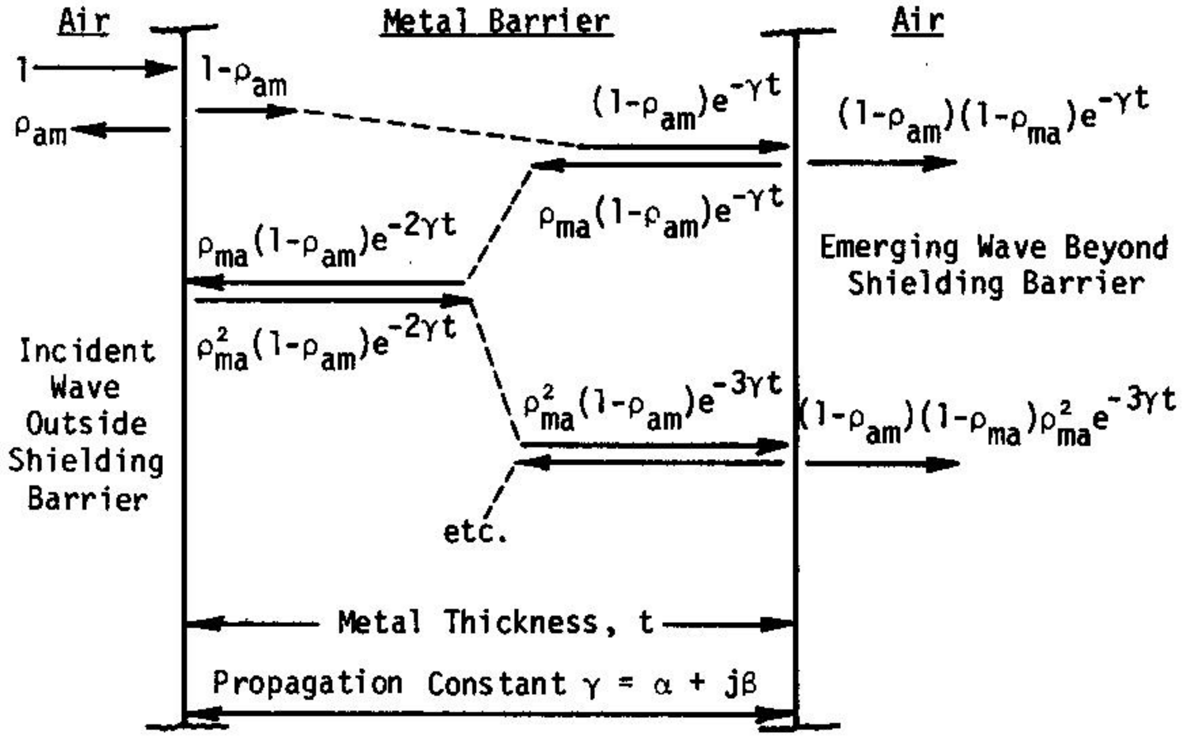


Fig. 3—Transmission line representation of a shield. The generator represents the source of the electromagnetic disturbance, the section OP the space surrounding the source, the section PQ the shield, and the impedance Z_t the space outside the shield.



From transmission line theory, the wave propagating from the source with normalized impedance enters the shield at the upper left-hand side.

The impedance mismatch at the air-metal boundary introduces a reflected loss.

The wave continues to pass through the shield and is attenuated according to the shield characteristics represented by the propagation constant.

As the wave encounters the metal-air boundary at the right-hand side of the shield, another reflection occurs.

Part of the wave passes through the shield, suffering additional loss from the metal-air boundary reflection. If the shield is “thick” enough, the wave reflected at the metal-air boundary will be sufficiently attenuated such that it has no impact on the wave entering the shield from the left-hand side.

Image Credit: White, D. R. J. and M. Mardiguian, Electromagnetic Shielding, Vol 3 of A Handbook Series on Electromagnetic Interference and Compatibility, Interference Control technologies, Inc., Gainesville, VA, 1988, page 1.19

The ratio of the incident wave to the transmitted wave, expressed logarithmically in dB, is known as shielding effectiveness.

Shielding effectiveness is defined for electric fields and magnetic fields as

$$SE_{dB} = 20\log\left(\frac{E_I}{E_T}\right) \;;SE_{dB} = 20\log\left(\frac{H_I}{H_T}\right)$$

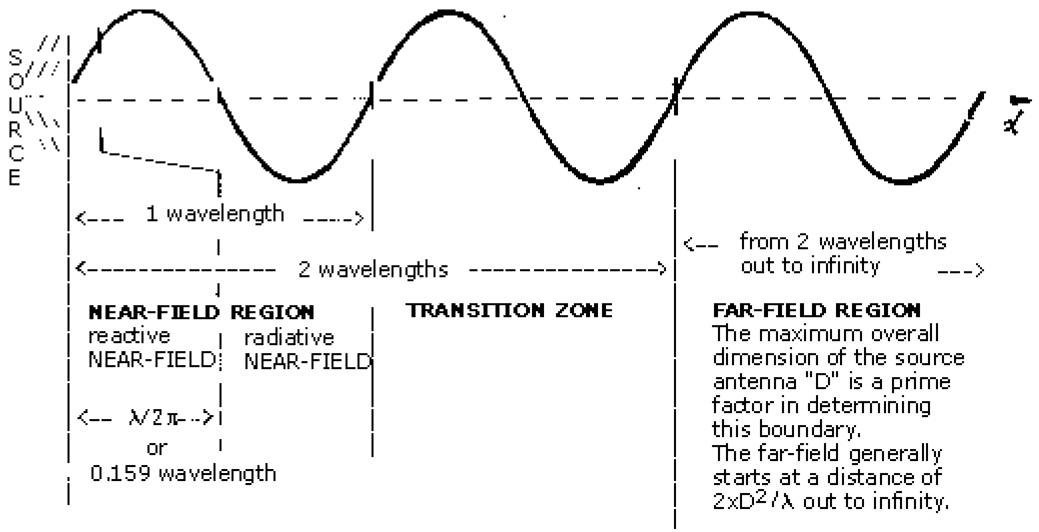
SE varies as a function of frequency, geometry of the shield, position with respect to the shield where the fields are measured, whether the field is electric or magnetic, the angle of incidence, and polarization. According to Schelkunoff, shielding effectiveness is the sum of attenuation (absorption) of the wave as it traverses the shield, reflections at shield boundaries, and the effects of multiple reflections inside the shield. This can be simply expressed as

$$S = A + R + B$$

All terms are normally expressed in dB. The correction factor B can normally be neglected for electric fields, or when the absorption term is greater than 9 dB (more on this shortly).

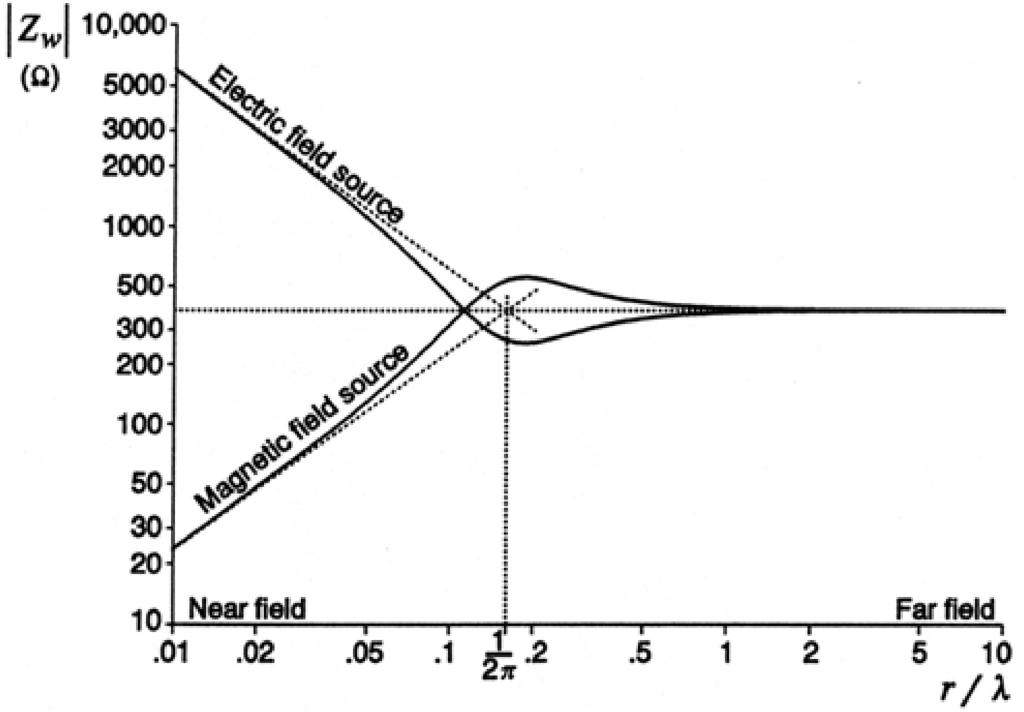
Before we go further, we need to talk about wave impedance, a VERY important shielding concept.

The ratio between the E and H fields in a given volume is known as wave impedance. Wave impedance varies as a function of distance from an electromagnetic source. This is because near to a source, the fields are characteristic of the source, whereas far from a source, the fields are largely dependent on the medium through which the fields are moving.



Three different regions can be identified with respect to a source. The region closest to the source is known as the near field. The near field itself may be broken further into to the reactive near field and the radiative near field. In the near field, the E and H fields are constantly varying with respect to each other in both magnitude and phase, and must be treated separately. The second region is known as the transition region. In this region, the magnitude and phase relationships between the E and H fields converge to become relatively constant and predictable. In the far field, the E and H fields are orthogonal to each other and the direction of their propagation, and their magnitude and phase relationships are for all practical purposes steady, constant, and predictable.

Image Credit: Electromagnetic Radiation: Field Memo, Occupational Safety & Health Administration.
url: https://www.osha.gov/SLTC/radiofrequencyradiation/electromagnetic_fieldmemo/electromagnetic.html



The E and H fields in each region will tend to dominate in some fashion.

If a given source exhibits high current and low voltage, the field close to that source is said to be predominantly magnetic. Loop antennas generally fall into this category, and they have a wave impedance exhibiting a low magnitude in (most of) the near field.

If a given source exhibits low current and high voltage, the field close to that source is said to be predominantly electric. Rod antennas are good example of this category, and they have a wave impedance exhibiting a high magnitude (most of) of the near field.

As distance increases away from the source, the E and H fields eventually reach a ratio equal in magnitude to 120π, approx 377 ohms. This value is sometimes referred to as the characteristic impedance of free space.

Image Credit: Mills, J. P., “Electromagnetic Interference Reduction in Electronic Systems”,
Prentice Hall, Englewood Cliffs, NJ, 1993, pg. 144

It is important to realize that wave impedance is a concept that applies to all media, be that free space, dielectric, or conductor. When talking about wave impedance in a dielectric or conductor, the term most often used is the characteristic, or intrinsic, impedance.

The characteristic impedance of any medium is generally expressed

$$Z_0 = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon_c}} \left\{ \begin{array}{l} \text{where } \omega = \text{ the frequency in radians of the wave} \\ \mu, \sigma, and \epsilon_c = \text{ the permeability, conductivity} \\ \qquad\qquad\qquad\qquad \text{and permittivity of the medium} \end{array} \right.$$

Materials may be classified as lossless, low-loss, lossy, or as conductors. This classification is governed in large part by the so-called loss tangent, defined as

$$\tan\vartheta_{eff} = \frac{\epsilon"}{\epsilon\prime} \cong \frac{\sigma}{\omega\epsilon_c}\text{; where } \epsilon_c = \epsilon' - j\epsilon"$$

For free space, considered to be lossless, we have a loss tangent equal to 0. Thus, the E and H fields are in phase, and the intrinsic impedance is given by

$$Z_0 = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon_c}} = \sqrt{\frac{\mu_0}{\epsilon_0}} = \sqrt{\frac{4\pi x 10^{-7}}{1/(36\pi x 10^{9})}} = 120\pi \cong 377\ \Omega$$

In low-loss or lossy dielectrics, we have a loss tangent that is non-zero, but may range from very small to quite large, depending on the magnitude of damping and ohmic losses in the material. For this case, we have a complex intrinsic impedance given by

$$Z_D = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon_c}} = \sqrt{\frac{\mu/\epsilon_c}{\sqrt{1 + \left(\frac{\sigma}{\omega\epsilon_c}\right)^2}}} \ ;\ \text{valid for } 0 < \tan\vartheta_{eff} < 1$$

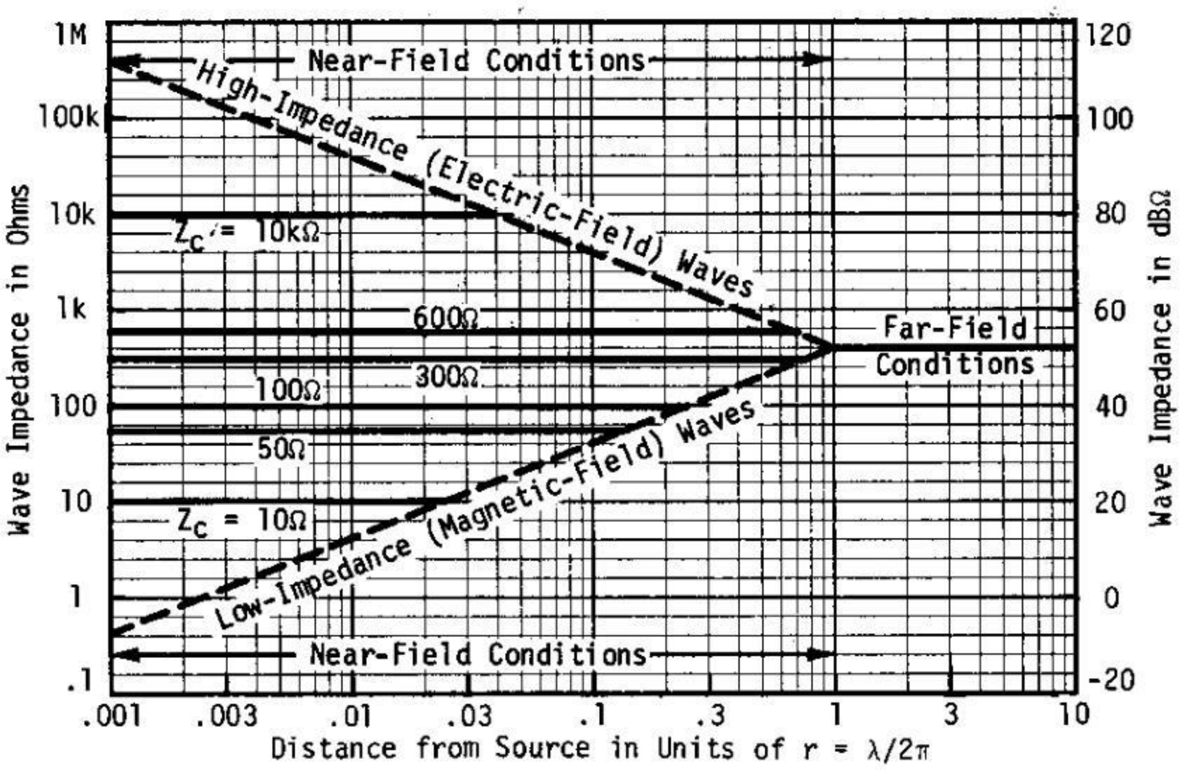
Note that the phase relationship between the E and H fields in a lossy dielectric is a function of the complex permittivity and the conductivity, embodied in the loss tangent expression. Note also that materials may exhibit a complex permeability. If that is the case, the math gets messier … we’ll leave that topic for another day.

In conductors, the characteristic impedance is also complex, and is given by

$$Z_s = \sqrt{\frac{j\omega\mu}{\sigma}} = \sqrt{\frac{\omega\mu}{2\sigma}}(1+j)\,;\ |Z_s| = \sqrt{\frac{\omega\mu}{\sigma}}$$

The phase relationship between E and H fields in a conductor is equal to 45°.

This is the intrinsic impedance of the shield itself we’ll be using going forward with our discussion of shielding today.



Getting the wave impedance correct in your calculations is imperative for accuracy. Choosing a wave impedance for the source that is too high can lead to optimistic results that lead you to under-designing your shield. Choosing a wave impedance that is too low could end up yielding an overdesigned shield that is heavier and costlier than necessary.

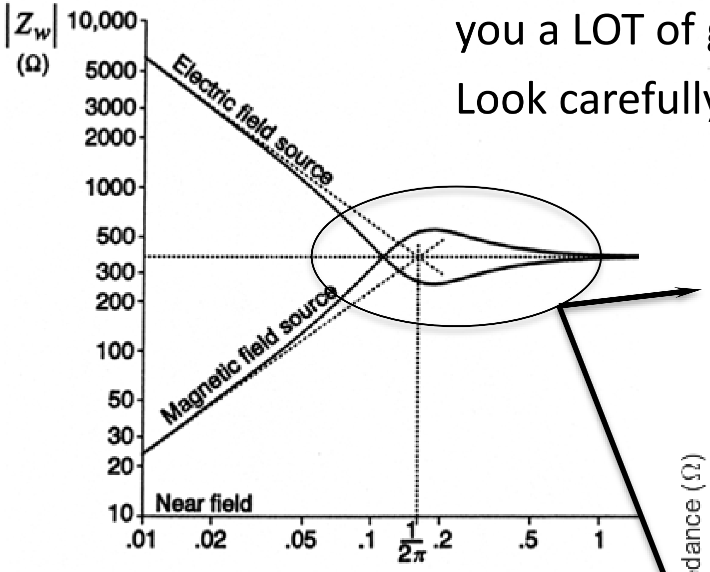
A useful "rule of thumb" that can be applied to get you "in the ballpark":

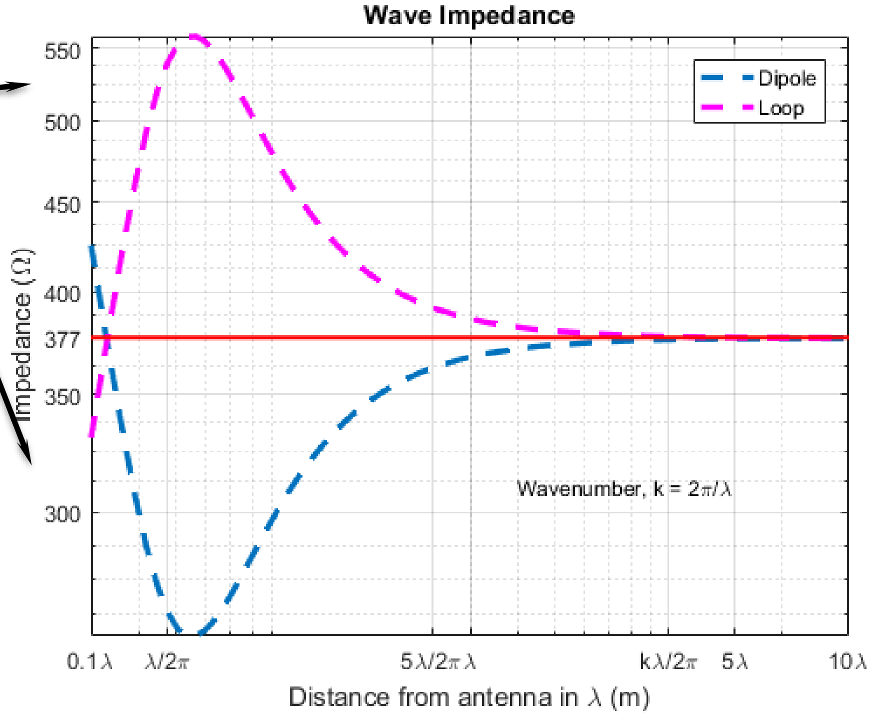
$$Z_W \cong \begin{cases} 18000/r_m f_{MHz} \ \ for \ \ Z_c \geq 18000/r_m f_{MHz} \\ Z_c \ \ for \ \ 18000/r_m f_{MHz} \geq Z_c > 7.9\, r_m f_{MHz} \\ 7.9\, r_m f_{MHz} \ \ for \ \ 7.9\, r_m f_{MHz} \geq Z_c \end{cases}$$

Image Credit: White, D. R. J. and M. Mardiguian, Electromagnetic Shielding, Vol 3 of A Handbook Series on Electromagnetic Interference and Compatibility, Interference Control technologies, Inc., Gainesville, VA, 1988, page 1.8

Before we leave this topic, we need to look at one last aspect that can cause you a LOT of grief if you don't pay close attention to it in your design efforts.

Look carefully at the wave impedance curves …





What you see is that the source impedances "flip" just before the distance reaches $\lambda/2\pi$, and grow quite large before finally settling down to the free space value.

Depending on operational frequencies, dimensions of your design, and how you have modeled your source(s), you *may* find yourself working in this region.

… caveat emptor …

Image Credit: Mathworks MATLAB Examples: Wave Impedance
url: https://www.mathworks.com/examples/aa/mw/antenna_product-atx_wave_impedance-wave-impedance

Starting with the absorption term, A, let's take a closer look at the shielding equation $S = A + R + B$.

Electromagnetic waves follow a relationship known as a propagation constant, defined as γ=α+$j\beta$.

The factors α and β are known respectively as the attenuation constant and the phase constant, and they appear in the solution to the Helmholtz equation for a uniform plane wave propagating in the z-direction

$$\bar{E} = \bar{a}_x E_x = \bar{a}_x E_0 e^{-\gamma z} = \bar{a}_x E_0 e^{-\alpha z} e^{-j\beta z}$$

Thus a wave is attenuated exponentially as it propagates through a medium. When a wave has propagated a distance through the medium equal to δ = 1/α, it has decreased in magnitude by a factor of 0.368. This distance is known as 1 skin depth.

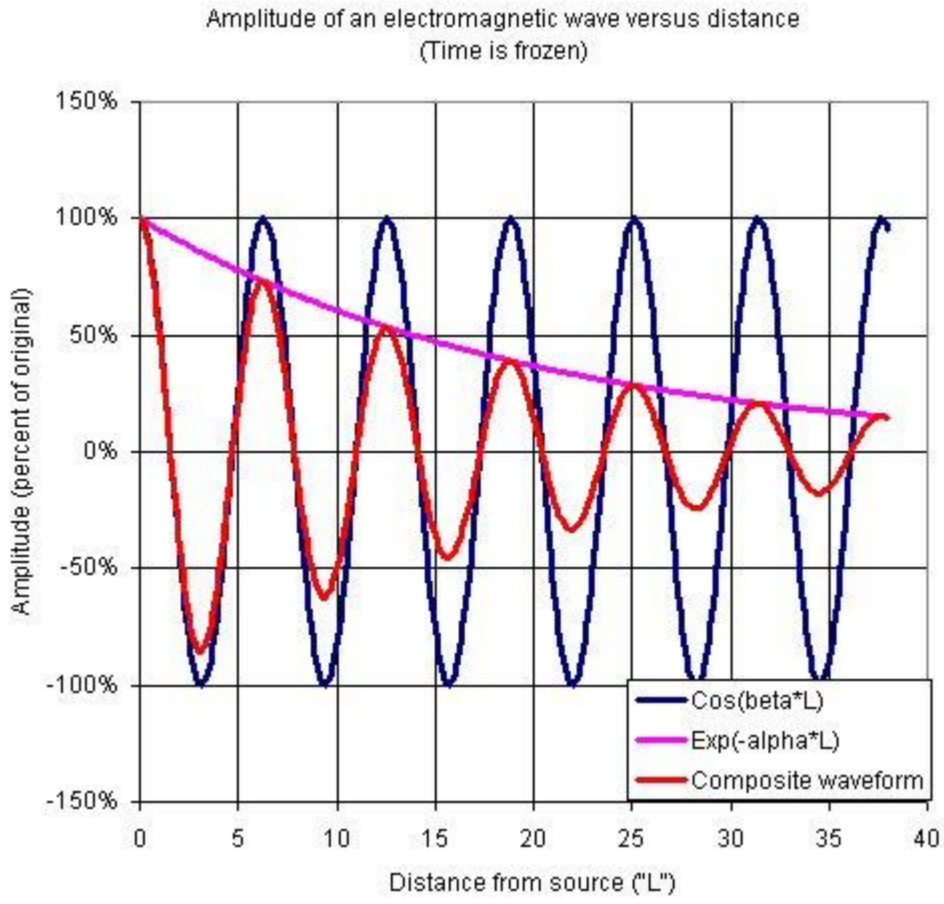


Image Credit: Microwaves 101: Propagation Constant
url: http://www.microwaves101.com/encyclopedias/propagation-constant

Using this attenuation relationship, we can define the absorption term in dB as

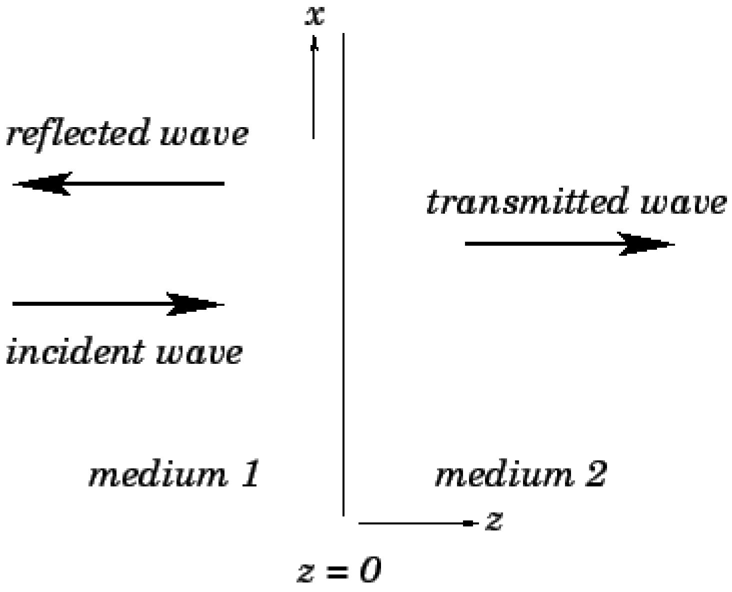
$$A = 20\log_{10}\frac{E_T}{E_I} = 20\log_{10}\frac{H_T}{H_I} = 20\log_{10} e^{-t/\delta}$$

Expressing as a positive value and rearranging yields

$$A = 20\log_{10}\frac{E_I}{E_T} = 20\log_{10}\frac{H_I}{H_T} = 20\log_{10} e^{t/\delta}$$

$$A = 20\left(\frac{t}{\delta}\right)\log_{10} e = 8.686\left(\frac{t}{\delta}\right)\ dB$$

This represents the attenuation of a wave as it passes once through a shield. For each successive pass caused by reflections, another 9 dB gets added. Recall I said that if A = 9 dB, we can neglect the B term. Here is where the 9 dB comes from … we'll talk about reflections next …



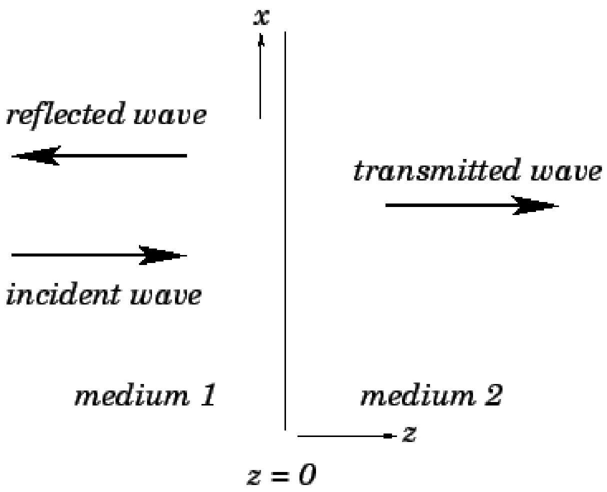
At the left-hand side, the incident wave enters the shield. Some part of the wave is reflected at the shield boundary, and some part of the wave is transmitted into the shield. From transmission line theory, the amount of the wave that is transmitted is given by

$$E_T = \frac{2Z_S}{Z_W + Z_S} E_I \ ; \ H_T = \frac{2Z_W}{Z_W + Z_S} H_I$$

The reflected components are given by

$$E_R = E_I - E_T = \frac{Z_W - Z_S}{Z_W + Z_S} E_I \ ; \ H_R = H_I - H_T = \frac{Z_S - Z_W}{Z_W + Z_S} H_I$$

For metal shields, $Z_S \ll Z_W$. That means that the initial reflection of an electric field will be much larger than that of a magnetic field. This strongly supports the concept that even thin shields that are highly conductive can provide very effective electric field shielding.



As the wave traverses the shield, it will encounter the opposite side of the shield, and again be partially reflected and partially transmitted. The amount of the wave that is transmitted is given by the same relationships as on the previous chart, with suitable change of variables.

$$E_{TT} = \frac{2Z_W}{Z_W + Z_S} E_T \;\; ; \;\; H_{TT} = \frac{2Z_S}{Z_W + Z_S} H_T$$

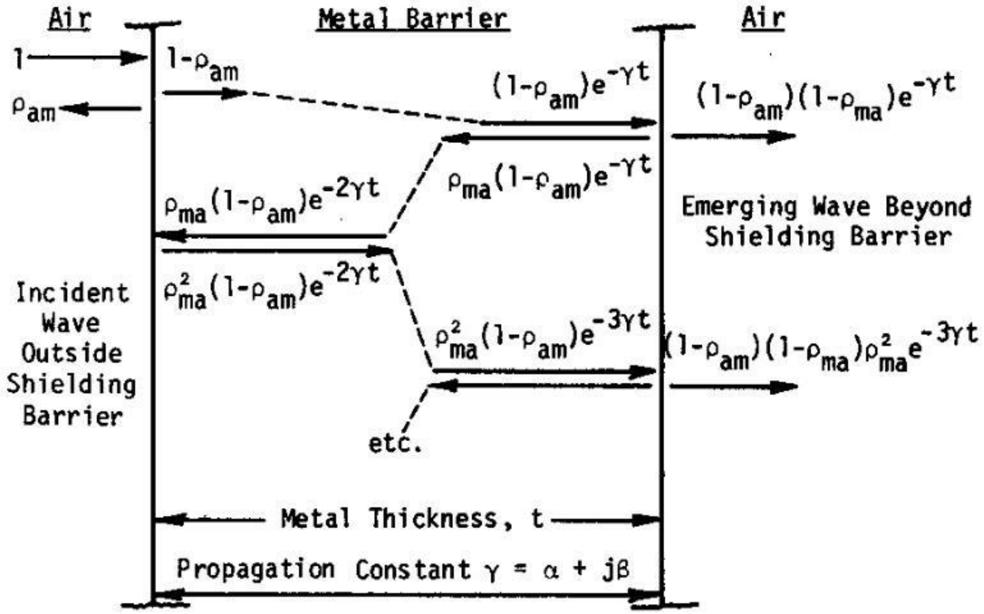
If the shield is at least 1 skin depth thick, the total transmitted wave components (ignoring the absorption loss) are then found by substitution of the previous relationships.

$$E_{TT} = \left(\frac{2Z_W}{Z_W + Z_S}\right)\left(\frac{2Z_S}{Z_W + Z_S} E_I\right) = \frac{4Z_S Z_W}{(Z_W + Z_S)^2} E_I$$

$$H_{TT} = \left(\frac{2Z_S}{Z_W + Z_S}\right)\left(\frac{2Z_W}{Z_W + Z_S} H_I\right) = \frac{4Z_S Z_W}{(Z_W + Z_S)^2} H_I$$

As was previously stated, for metal shields, $Z_S \ll Z_W$. These equations can be reduced and rewritten in the same fashion as for the A term, yielding

$$R = 20 \log_{10} \frac{E_{TT}}{E_I} = 20 \log_{10} \frac{H_{TT}}{H_I} = 20 \log_{10} \frac{|Z_W|}{4|Z_S|}$$



If we have either a thin or thick shield, and the incident wave is a magnetic field, multiple reflections are most likely to occur within the shield. From the previous it is clear that for a magnetic field, the initially transmitted wave may be twice the magnitude of the incident wave. This wave will be reflected at the right-hand side of the shield, and traverse back towards the left-hand side, where it will be reflected again.

This re-reflection process will continue until the internal wave has been attenuated to the point of insignificance.

The correction factor, B in the shielding equation, is given by

$$B = 20\log_{10}\left(1 - e^{-2t/\delta}\right)$$

B is expressed as a negative value, as it acts to reduce the total shielding effectiveness. Note that if the A term is equal to or greater than 9 dB ($t/\delta \geq 1$), the B term will be equal to or less than -1.26 dB, and may thus be neglected.

As we just saw, we need a shield that is at least 1 skin depth in thickness in order to be effective against magnetic fields. We talked about skin depth earlier. It is defined as

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

Just how “deep” is 1 skin depth?

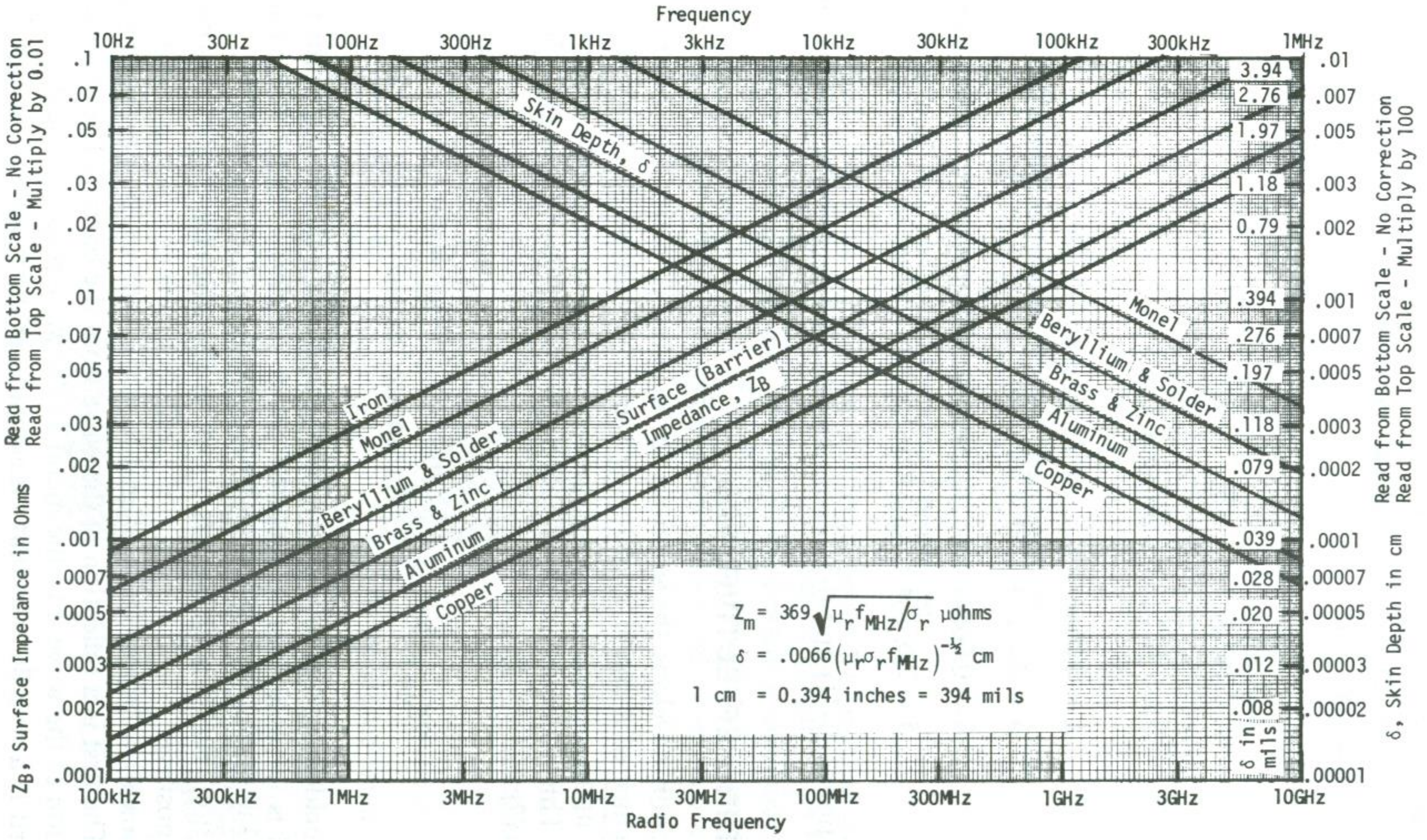


Image Credit: White, D. R. J. and M. Mardiguian, Electromagnetic Shielding, Vol 3 of A Handbook Series on Electromagnetic Interference and Compatibility, Interference Control technologies, Inc., Gainesville, VA, 1988, page 1.12

Metal	Relative Conductivity gr	Relative Permeability µr	Absorption Loss (dB) 1 mm thick	1 mil thick
Silver	1.05	1	51.96	1.32
Copper, annealed	1.00	1	50.91	1.29
Copper, hard-drawn	0.97	1	49.61	1.26
Gold	0.70	1	42.52	1.08
Aluminum	0.61	1	39.76	1.01
Magnesium	0.38	1	31.10	.79
Zinc	0.29	1	27.56	.70
Brass	0.26	1	25.98	.66
Cadmium	0.23	1	24.41	.62
Nickel	0.20	1	22.83	.58
Phosphor-bronze	0.18	1	21.65	.55
Iron	0.17	1,000	665.40	16.90
Tin	0.15	1	19.69	.50
Steel, SAE 1045	0.10	1,000	509.10	12.90
Beryllium	0.10	1	16.14	.41
Lead	0.08	1	14.17	.36
Hypernick	0.06	80,000	3484.00*	88.50*
Monel	0.04	1	10.24	.26
Mu-metal	0.03	80,000	2488.00*	63.20*
Permalloy	0.03	80,000	2488.00*	63.20*
Steel, stainless	0.02	1,000	224.40	5.70

* With no saturation by incident field.

Most metals with a relative permeability greater than 1 also exhibit a relatively low conductivity. Nickel, iron and mu-metal are all examples of such metals.

Examination of the graph on the previous page clearly shows that such materials can be very thin and still offer significant absorption capability at a low frequency, precisely what we want for magnetic shielding.

Data is taken from Table 8-3 in Mil-HDBK-419A, page 8-7

Other traits of effective magnetic shielding materials to keep in mind are:

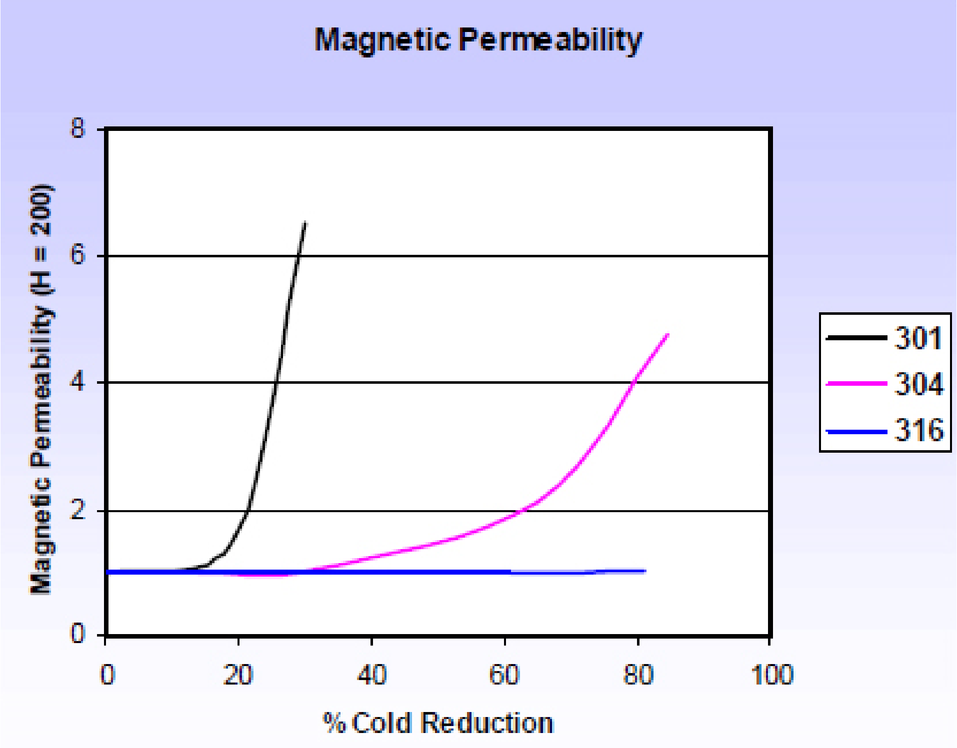
Permeability is dependent on applied field strength, and can reach a saturation point.

Permeability is generally inversely proportional to frequency.

-- Published permeability values are usually initial dc values.

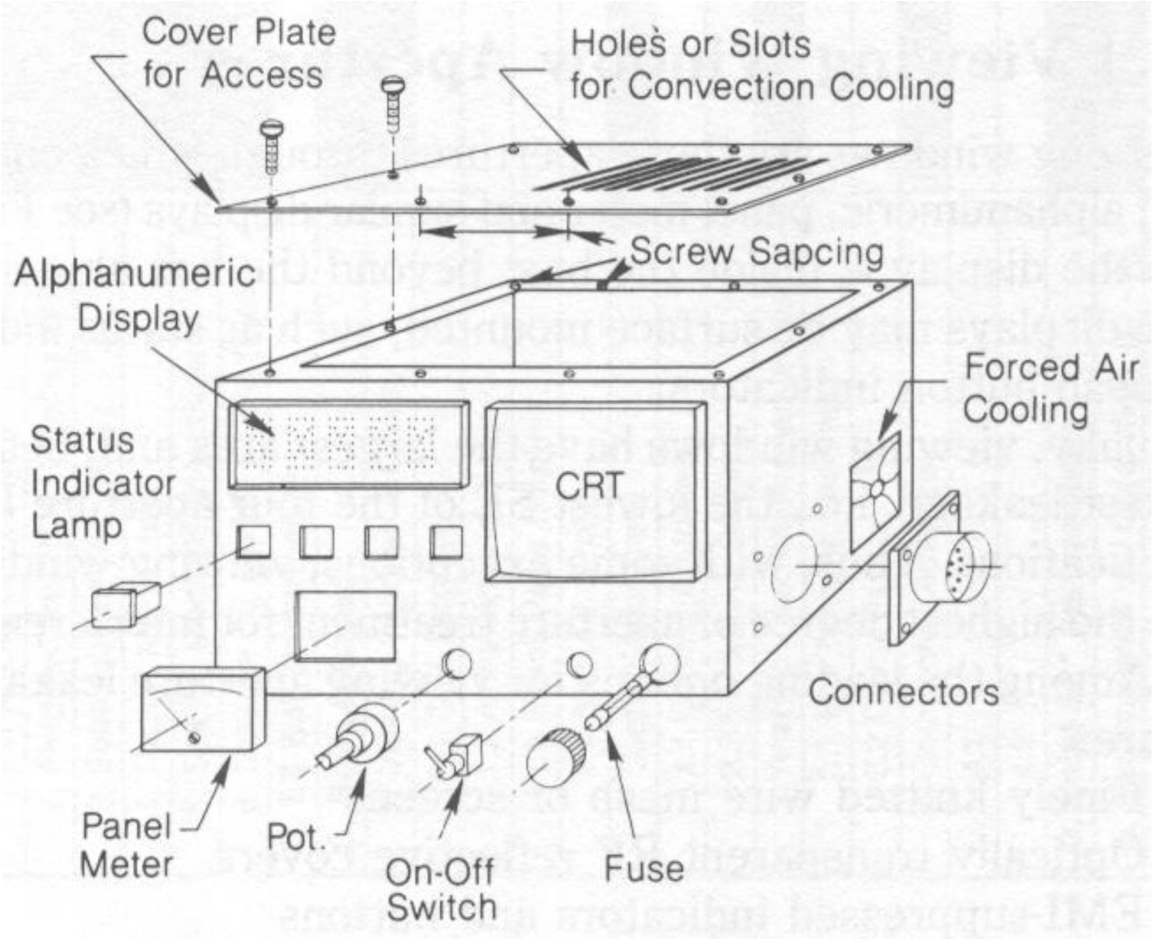
Permeability may be complex (as mentioned earlier).

Magnetic shielding materials can exhibit widely variant hysteresis curves and coercivity values.



The magnetic properties of some magnetic shielding materials can change as a result of machining or forming processes. That means that not all materials that you think have both high permeability and low conductivity fit that profile. For example, not all nickels are permeable, Pure iron has a relative conductivity equal to some aluminum alloys, but when alloyed 50% with pure nickel becomes almost 5 times less conductive. Electroless nickel exhibits a wide range of electrical conductivity and may or may not have any measurable permeability. Some austenitic stainless steels can become highly permeable as a result of cold-working.

Image Credit: Magnetic Response of Stainless Steels
https://www.kimballphysics.com/multicf-hardware/technical-information/magnetic-response-of-stainless-steels



Up to this point, we have been talking about simple plane wave incidence on solid shields. In real life, we rarely encounter solid shields. Instead we encounter equipment enclosures that have covers and connectors, access panels, penetrations of many different kinds, transparencies and displays, air passages for cooling, and so forth.

At the simplest level, any solid shield that has even a single aperture in it has a shielding effectiveness that is dominated by that of the aperture. Multiple apertures only serve to make it worse …

Fortunately we have a number of methods for dealing with these real life complications, including proper selection of fastener spacing, gasketing when necessary, coatings and screens on transparencies, the use of many small circular holes for air flow, rather than one large opening, proper electrical bonding of all penetrating metal objects, especially cables and connectors, and so forth.

The total design envelopes enclosure size, shape, seams, fastener type and spacing, apertures, penetrations, connectors, vibration and thermal requirements ("shake and bake"), salt, fog, fungus, humidity, atmospheric pressure, desired and/or required surface finishes and treatments … ??

If you want management to "buy off" on your work it has to exhibit minimum mass, volume, cost, and schedule impacts above all else.

But that's what you got into engineering for, right? The challenges …

Alas, I fear we are running out of time …

There are many different ways to approach solving the “shielding problem”:

1) One can use the Schelkunoff transmission line approach, as briefly discussed in this presentation.
2) One can rely on cook-book formulae developed by authors that may or may not be applicable to the situation at hand
   -- Be sure to study the basis for such formulae carefully before spending precious time and resources only to later determine that the design isn’t adequate or is “way” overkill …
3) One can take the more rigorous approach and write out Maxwell’s equations and the appropriate boundary conditions everywhere, and work out a set of solutions.
4) One can program the “problem” into a nice full wave solver, being certain to account for as much detail as possible, and hit the Enter key..
   -- This method can certainly generate excellent results, but only as good as the information you feed in …

No matter how you approach your “shielding problem”, one thing to keep in mind is that the literature is rich with studies and analyses that can inform you and provide food for thought. Be confident that the success or failure of your design is wholly within your ability and limited only by your imagination and creativity, and you will go far.

My purpose today has been to give you a glimpse into the engineering of shielding, and perhaps to whet your appetite to go seek out more detailed information as you confront your own design challenges. I hope I have in some way accomplished that goal.

We have talked about the basics of Schelkunoff's transmission line theory of shielding, including the very important concept of wave impedance. We touched on the differences between electric field and magnetic field shielding, and just a bit about the differences you might encounter with thick shields versus thin shields. We talked about the comparative complexity of magnetic shielding materials, and finally (very briefly!) talked about real-world enclosures and some of the aspects that will drive your final shielding package designs.

Thanks very much for your kind attention.

Questions?