# Modeling the Shielding Effectiveness of Metallized Fabrics

***A simple model for predicting the shielding effectiveness of metallized fabrics has been developed.***

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## INTRODUCTION

The recent and prominent emergence of metallized fabrics in the marketplace for electromagnetic radiation (EMR) shielding materials has brought about the need for a way to predict the shielding effectiveness (SE) of such products. As far as the authors are aware, there is no published theory or model for directly predicting shielding effectiveness or attenuation of metallized fabrics.[1,2] Equations describing the shielding effectiveness of thin foils, wire meshes, and perforated plates are well known,[2] but metallized fabrics do not appear to have been theoretically treated in the literature. It is the intent of this paper to describe a straightforward, semi-empirical method for calculating the shielding effectiveness of metallized fabrics, both woven and nonwoven, based on the geometry of the fabric (e.g., pore size and thickness), and the amount of metal present on the fabric. More rigorous theories involving Maxwell's equations can be devised, but they would still have to take into account the geometry of the fabric and the amount of metal on the fabric.

## THE MODEL

A reasonable starting assumption is that if the wavelength of electromagnetic radiation incident on a fabric is significantly larger than the openings in the fabric, the metallized fabric would appear to that radiation as a thin metal foil and attenuate the signal accordingly.[3] When the wavelength becomes small enough, the fabric will begin to act increasingly as a mesh or a thick foil with small holes in it and shield correspondingly. Based on our empirical observations, this appears to be the case. Figure 1 shows roughly how this is true for metallized fabric. Actual data for a copper-coated fabric are given along with the appropriate lines fitted to the two roughly straight portions of the curves. The flat portion of the curve is the attenuation an equivalently thick foil would give, while the sloped portion drops off at about a rate of 20 dB/decade of MHz, which is the predicted behavior of an aperture or mesh.[4] Thus, it is proposed that, to a first approximation, the shielding effectiveness of a metallized fabric can be modelled as a combination of the attenuation due to a thin metal foil having an effective thickness based on the amount of metal deposited on the fabric plus the attenuation of an irregular mesh or a panel possessing various aperture shapes and sizes.

While any fabric will have a distribution of pore sizes and shapes, it is the maximum pore size that concerns us. According to White and Mardiguian,[5] when there are dissimilar apertures in a panel,

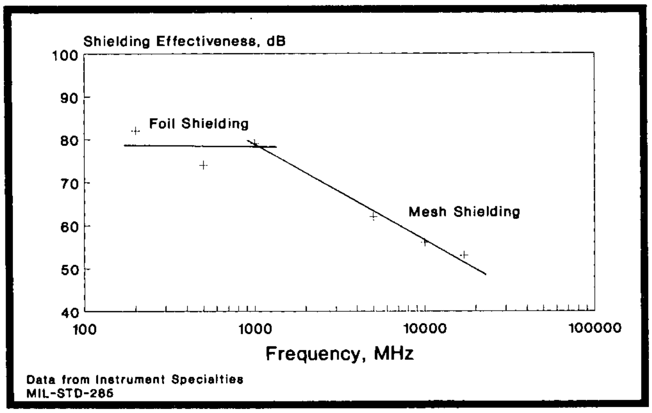


***FIGURE 1.*** *Foil and Mesh Contributions to the Far-field Shielding Effectiveness of a Metallized Fabric (Cu/nylon nonwoven).*

which is the situation for fabrics, the largest aperture will limit (determine) the SE of the panel. This is because the shielding effectiveness of any system is only as good as its weakest part. This phenomenon is continually seen in enclosures such as protective tents and rooms where doors are notorious for limiting the shielding effectiveness of the enclosures. A hole or the largest pore in the fabric will be responsible for the major signal leakage through the material. Therefore, the ratio of the maximum pore size in the fabric to the radiation wavelength will largely determine the shielding effectiveness of that metallized fabric. As discussed later, there are certainly other important parameters, but their contributions are controlled by this important ratio.

Based on the aforementioned considerations, a function is sought that depends on the wavelength-to-aperture-size ratio, and which combines the SE of a homogeneous foil and a plate with apertures in a smooth and continuous fashion. A reasonably straightforward function to use is an exponential decay function of the form

$$SE = \exp[-W(L/\tau)]SE_{foil} + \{1-\exp[-W(L/\tau)]\}SE_{aperture} \quad (1)$$

where $\tau$ is the wavelength of radiation, L is a maximum aperture dimension in the fabric, and $W(L,\tau)$ is a weighting or scaling function to be determined later.

Such an expression gives us the desired behavior at the two ends of the wavelength spectrum. At low frequencies, the shielding is due predominantly to the foil; but as the ratio of the $L/\tau$ gets larger with increasing frequency (wavelength decreases), the metallized fabric behaves less like a thin foil and shields more like a foil with an aperture of major dimension L.

Since the frequency of radiation is more commonly utilized than wavelength for most practical purposes (and is inversely related to the wavelength), we find it more convenient to rewrite Equation 1 as

$$SE = \exp[-W(L,f)]SE_{foil} + \{1-\exp[-W(L,f)]\}SE_{aperture} \quad (2)$$

where f is the frequency of radiation, and W now depends on L and f in some fashion.

The shielding effectiveness of a foil consists of reflection and absorption contributions. The reflection term is determined by the mismatch that occurs between the impedance and the wave incident on the shielding material and the impedance of the shield. It is represented as[6]

$$SE_{refl.} = 20\log\left\{\frac{(1+K)^2}{4K}\left[1-\left(\frac{K-1}{K+1}\right)^2 e^{-2\sqrt{2}t/\delta}\right]\right\} \quad (3)$$

where
$K = Z_{wave}/Z_{shield}$ = ratio of wave impedance to shield impedance
$t$ = foil thickness
$\delta$ = skin depth
All but t depend on frequency.

Equation (3) determines the reflective component of shielding for both thick and thin metal layers as it contains a re-reflection contribution.

Since a metallized fabric is not a homogeneous foil, a means of defining an equivalent, or effective, thickness for the deposited metal is required. To calculate such an effective, equivalent foil thickness, $t_{eqv}$, for use in Equation (3), the total amount of metal on the fabric, given in weight/unit area, is converted to a thickness assuming a homogeneous, uniform foil. For example, 0.265 oz/yd$^2$ (8.97 g/m$^2$) of copper deposited on a fabric is equivalent to a 1-micron-thick copper foil layer.

For many metallized fabrics, the equivalent foil thickness of the metal calculated above is on the order of a micron or less, which is smaller than the skin depth of copper throughout much of the frequency range of interest. Electron microscopy reveals that the average annular metal layer around individual filaments in a typical metallized fabric is less than one micron thick.

To take into account the thinness of the metal layers when computing $Z_{shield}$ in Equation (3), one requires the following relation.[7]

$$Z_{shield} = 369(\mu_r f/\sigma_r)^{1/2}[1-\exp(-t_{eqv}/\delta)] \qquad (4)$$

where $\mu_r$ and $\sigma_r$ are the permeability and conductivity, respectively of the shield material relative to copper, and $t_{eqv}$, $\delta$, and f have their usual meanings.

The absorption term of the foil shielding equation is given as[6]

$$SE_{absorption} = 20 \log \exp[t_{eqv}/\delta] \qquad (5)$$

The contribution of the absorption term to the overall foil shielding effectiveness is minimal in the low frequency region, but at high frequencies it can become significant even for very thin layers of metal.

The total shielding effectiveness of a foil is the sum of Equations (3) and (5).[7]

$$SE_{foil} = 20\log \left\{e^{t/\delta} \frac{(1+K)^2}{4K}\left[1-\left(\frac{K-1}{K+1}\right)^2 e^{-2\sqrt{2}\, t/\delta}\right]\right\} \qquad (6)$$

The remainder of this discussion addresses only copper-coated fabrics in far-field, plane-wave conditions. Near-field conditions are more complicated to describe and are of less interest for high frequency applications and architectural shielding.

The far-field SE of an aperture of dimension L x s x D is given by[8,9]

$$SE_{ap}=100-20\log Lf + 20\log[1+1n(L/s)]+30/L \qquad (7)$$

where
L = maximum pore dimension of the aperture
s = minimum pore dimension
D = thickness, or depth, of the aperture

All three dimensions are in mm, and f is in MHz (1n is the natural logarithm).

Note that since the holes in a nonwoven material are totally irregular, L is assumed to be the largest dimension of the largest opening, which most frequently is equivalent to the aperture diagonal, not its longest side. Henceforth, the ratio of the longest dimension to the smallest dimension in any pore, L/s, is referred to as the aperture aspect ratio, $\beta$. Thus,

$$SE_{ap} = 100-20\log Lf + 20\log(1+1n\beta) + 30D/L \qquad (8)$$

The first two terms in this equation are due to reflection.[4] The third term is a kind of polarization factor (White and Mardiguian[4] call it a "fatness factor"), and the last term describes the attenuation arising from the wave-guide-beyond-cutoff effect,[10] which manifests itself as an absorption term. D must be greater than 1/6 of the radiation wavelength for the expression to hold,[10] but this does not pose a problem for typical metallized fabrics until one is well into the high GHz range. Obviously, the last term can have a significant contribution to the overall shielding effectiveness of an aperture if D/L is close to one or greater.

In the present model, the equation for shielding by an aperture rather than a mesh was chosen because the pores in a fabric are dissimilar in size and shape, which means the largest structure, as mentioned before,[5] should be the predominant factor. A second, and just as important consideration, is the fact that fabrics, particularly nonwovens, are very much three-dimensional objects. That is, they can have a thickness dimension that critically determines much of their overall behavior. Whereas a mesh is considered a two-dimensional material, the aperture equation takes into account the thickness and non-uniform pore shape of the fabric.

To find a reasonable weighting function, W(L,f), based on the original assumptions, a condition was employed that required that the reflection contribution of the aperture be a small fraction of the plane-wave reflection term of copper foil at some low frequency. Equating the far-field reflective terms, one finds $Lf^{1/4} = 0.398$ for copper foil, and the frequency at which the two reflectance components are equal then is $f_0 = 0.158/L^2$ MHz. Typical maximum pore sizes in the fabrics studied here are on the order of tenths of millimeters. For instance, if L = 0.15 mm, a $f_0$ of 6-7 MHz results, which corresponds to a wavelength of around 50 m. At a L-to-wavelength ratio of 3 x $10^{-5}$, it is highly likely, as White and Mardiguian state,[3] that the fabric approaches a homogeneous medium from a macroscopic point of view and for the most part, interacts with the radiation as a foil.

Next, akin to accepting three skin depths, $3\delta$, as the point beyond which current flow is negligible in a foil, i.e., 95% of the current flows with $3\delta$ (vide supra),[11] at $f_0$, the foil likeness, or character, of a fabric is assumed to provide 95% of the reflective shielding. Taking $W = CLF^{1/4}$ as the scaling function requires $C = 0.129$ to make the exponential function in Equation (2) equal to 0.95 at $f_0$. Thus, the expression for W(L,f) is

$$W(L,f) = 0.129Lf^{1/4} \quad (9)$$

and the selected, final functional form for Equation (2) becomes

$$SE_{foil} = \exp[-.129Lf^{1/4}]SE_{foil} + \{1-\exp[-.129Lf^{1/4}]\}SE_{aperture} \quad (10)$$

where $SE_{foil}$ and $SE_{aperture}$ are defined as before.

Using Equations (4), (6), (8), and (10), the far-field shielding effectiveness of Cu-plated fabrics can be calculated if the following variables are known: the largest pore dimension; the pore aspect ratio, the thickness of the fabric; and the amount of Cu, in terms of weight per unit area, deposited on the fabric. The thickness (or caliper) of the fabric is taken to be equivalent to the depth, D, of the aperture. This is probably only roughly true, but it seems a reasonable approximation. Fabric thickness is measured by standard techniques for determining the caliper of fabrics or paper. A typical gauge with 9 psi was used to measure the calipers reported here according to ASTM D1777. Pore dimensions are determined from photomicrographs of the fabrics. A Lotus 123® spreadsheet program was prepared to calculate the shielding effectiveness of various copper-plated fabrics using the listed input variables.

The effect of the amount of metal, as given by $g/m^2$ or $oz/yd^2$ of Cu, on a fabric is exhibited in Figure 2. It is assumed that the metal is uniformly distributed over the individual filaments. As one can see, by increasing the amount of Cu by a factor of 8 from 0.1 to 0.8 $oz/yd^2$ Cu, there is a difference in far-field shielding of about 27 dB at 50 MHz. By the time the radiation is in the GHz range, the difference is down to around 10 dB, and by 10 GHz, there is almost no effect of metal content on shielding. This is because the mesh, or hole, character of the substrate dominates the shielding at high frequencies.

Figure 3 shows the major influence the maximum pore size has on the shielding effectiveness of the same fabric sample. In this figure, the pore size ($L_{max}$) ranges from 50 μm to 300 μm. At low frequencies, there is little effect because the fabric behaves as a foil, but the SE curves clearly start to diverge at only a few hundred MHz. This behavior also depends on the fabric thickness, as seen below.

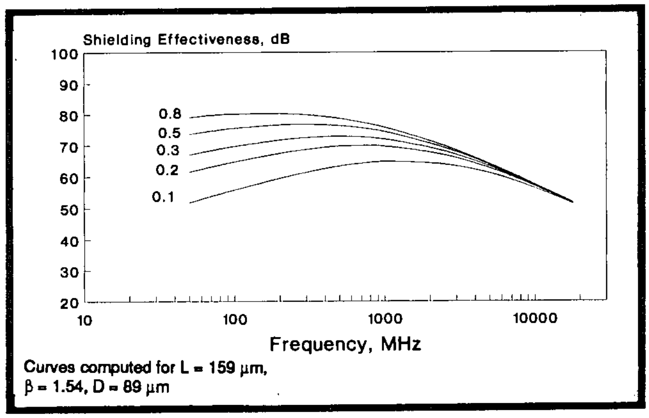


***FIGURE 2.*** *Variation of Fabric Shielding Effectiveness with Amount of Copper (in. oz./yd²).*

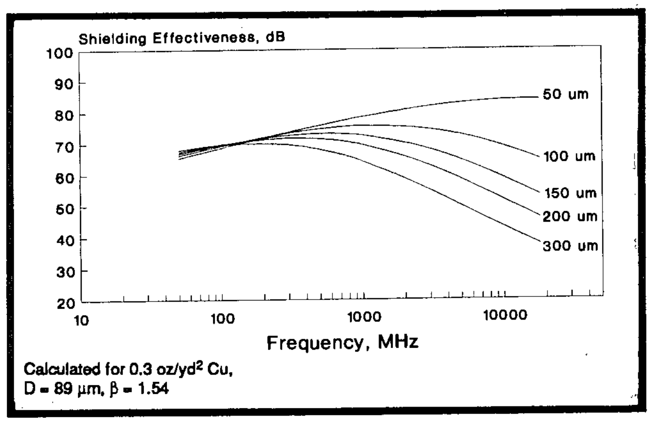


***FIGURE 3.*** *Effect of Maximum Pore Size on Shielding Effectiveness of Metallized Fabrics.*

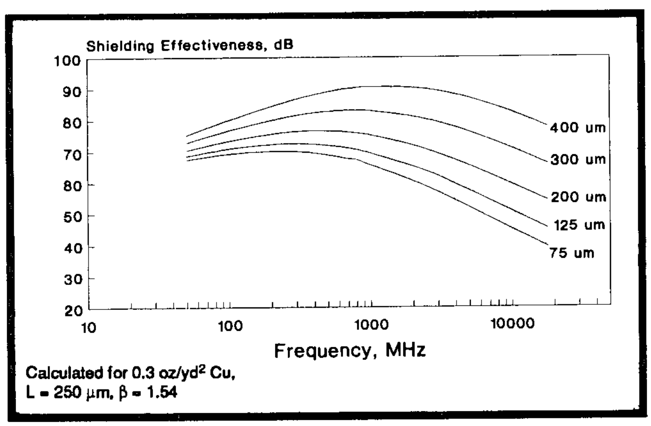


***FIGURE 4.*** *Effect of Thickness on Shielding Effectiveness of Metallized Fabrics.*

The fact that Equation (10) predicts a maximum in shielding effectiveness is very interesting. Fairly strong maxima have been observed in many of the sets of far-field shielding data obtained on certain metallized fabrics. These can be seen in some of the curves of experimental data to follow.

The important contribution of the thickness or caliper of the fabric is shown in Figure 4. In going from roughly 3 mils to 16 mils (51 μm to 254 μm) thick, with everything else held constant, the shielding of a copper-coated fabric is calculated to increase by about 12 dB at 100 MHz and approximately 38 dB at 17 MHz. Thickness clearly has a significant role in determining the SE of a fabric because of the waveguide-beyond-cutoff effect. It should again be noted that a maximum in shielding effectiveness is predicted when the caliper is large in relation to the pore size, which is what seems to be true for many metallized fabrics.

The average aspect ratio, β, of the fabric pores has a much smaller effect on shielding than does the amount of metal, the maximum pore size, or the fabric thickness. Furthermore, it does not vary as much between different fabrics as the other parameters. Therefore, its influence is not depicted here graphically. Nonwovens tend to have larger pore aspect ratios than wovens. As might be anticipated, the contribution does not become significant until higher frequencies. For instance, at 10 GHz, there is only a 4 dB difference between fabrics with pore aspect ratios of 2 and 6, the latter having the higher shielding effectiveness.

## RESULTS AND DISCUSSION

The far-field shielding effectiveness of four proprietary copper-plated fabrics was calculated according to Equation (10) as a function of frequency and plotted versus observed data in the following graphs. All of the data were obtained by Instrument Specialties (Delaware Water Gap, PA) according to modified MIL-STD-285 using a 2'x2' open port. Repeat measurements on the same fabric led to estimated experimental standard deviations of around 3 to 4 dB. The standard error is thus around ±8 dB at the 95 percent confidence limits for samples in triplicate. Error bars of ±8 dB are included in each of the following graphs.

The far-field attenuation of a copper-plated 1 oz/yd$^2$ nylon nonwoven is plotted in Figure 5. The calculated curve was generated by using actual data from the measured material; $L_{max}$=250 μm, b = 6.3 (both found from actual sizing of pores in a SEM micrograph collage), D = 4.6 mils (0.117 mm), and t, the thickness of equivalent foil, equals 1.7 microns. This last value corresponds to 0.45 oz/yd$^2$ (15 g/m$^2$) of Cu, which is a product containing almost 33% Cu on a 1 oz/yd$^2$ substrate. As shown in Figure 5, the predicted curve is a little low, and it tends to drop off too fast in the GHz region, but overall it agrees well with the scattered data.

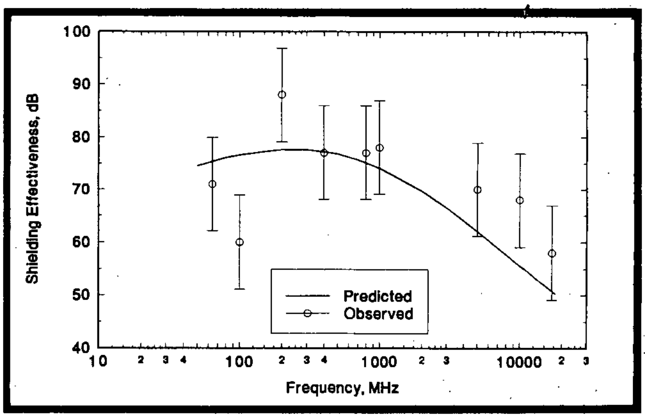


***FIGURE 5.*** *Far-field Shielding Effectiveness of Cu/nylon Nonwoven. Calculated for 0.45 oz/yd$^2$ Cu, L=250 μm, β=6.3, D=117μm.*

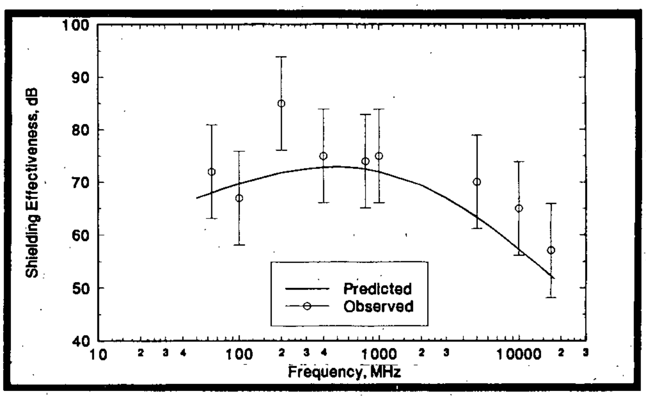


***FIGURE 6.*** *Far-field Shielding Effectiveness of Cu/nylon Ripstop. Calculated for 0.30 oz/yd$^2$ Cu, L=159 μm, β=1.5, D=89 μm.*

Figure 6 is the SE curve for Cu on 1 oz/yd$^2$ nylon ripstop (woven). Its thickness is 3.5 mils (0.089 mm), with a maximum pore dimension of 159 μm. The amount of Cu on the fabric is 0.30 oz/yd$^2$, which is equivalent to 1.13 μm thick Cu foil. An aspect ratio of 1.5 was used in the calculations. Agreement with observed shielding is very good considering the uncertainty in the measured data.

Figure 7 shows the SE curve for Cu on 1.25 oz/yd$^2$ polyester nonwoven. The amount of metal is 0.40 oz/yd$^2$, which corresponds to Cu foil 0.0015 mm thick. The maximum pore size is around 198 μm, with an average pore aspect ratio of approximately

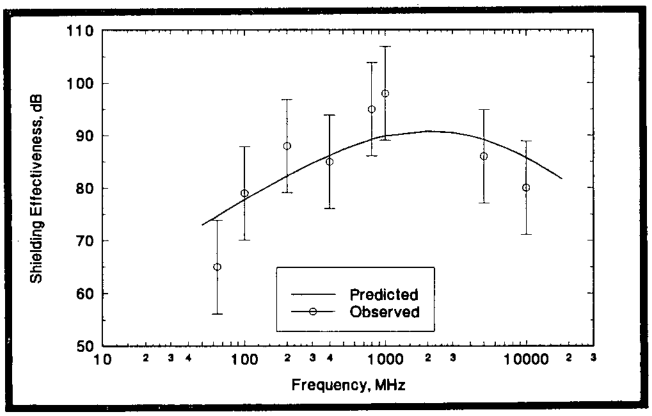


*FIGURE 7. Far-field Shielding Effectiveness of Cu/PET Nonwoven. Calculated for 0.40 oz/yd² Cu, L=198 μm, β=2.1, D=320 μm.*

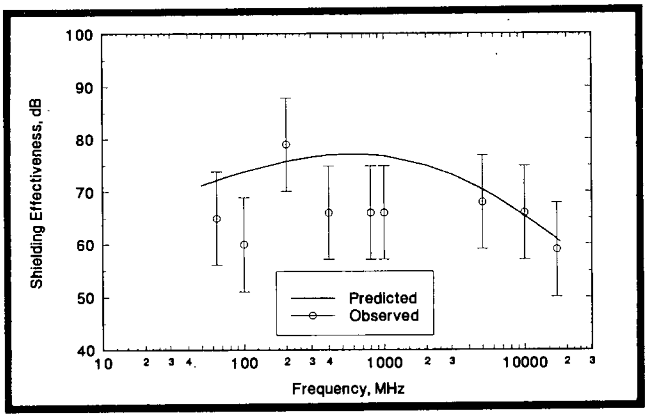


*FIGURE 8. Far-field Shielding Effectiveness of Cu/PET Taffeta. Calculated for 0.42 oz/yd² Cu, L=122 μm, β=1.3, D=100 μm.*

2.1. The thickness was measured to be 12.6 mils (320 μm). Except for a few points, the calculated values closely agree with the data given their uncertainty range.

Figure 8 is the SE curve for Cu on 1.55 oz/yd² polyester taffeta (woven). The maximum pore dimension found for this particular material from micrographs was about 122 μm. The average pore aspect ratio is approximately 1.3, and its thickness was measured as 4 mils (0.1 mm). The amount of metal is about 0.42 oz/yd², which translates to a foil thickness of 0.00159 mm. In contrast to the previous three examples, the predicted curve is perhaps a little high relative to the measured values.

Several sets of data are available for each one of the metallized products mentioned above. As might be expected, results show that the sets do not overlay each other because the amount of copper is slightly different in each case, and, more importantly, the critical variables of maximum pore size and caliper are known to vary greatly from even one section of the same fabric to another. This is seen with air permeability of a fabric, which is related to pore size and thickness of the fabric. For example, it is known that the air permeability of a sample of Cu/ 1 oz/yd² nylon nonwoven ranges from 235 to 497 cu. ft./min./sq. ft. depending on where one measures it within the sample.[12] Given the sensitivity of Equation (10) to maximum pore size and caliper, it is unlikely that two different samples of Cu/nylon nonwoven, or any other fabric, would ever have the exact same attenuation. This is something to keep in mind when looking for reproducibility of SE data from different samples of the same metallized fabric product.

## CONCLUSIONS

A straightforward, simple model for predicting the shielding effectiveness of metallized fabrics, both woven and nonwoven, has been developed using known equations and based on the geometry of the fabric and amount of metal on the fabric. Clearly, EMR shielding by metallized fabrics can be viewed as a weighted combination of shielding due to a thin foil with numerous, dissimilar apertures. Overall, agreement between the predicted and observed shielding effectiveness values for each of the copper-plated fabric examples is very good. Significantly, the model can predict the maximum in shielding effectiveness observed for metallized fabrics. The calculated attenuations tend to be slightly lower than the experimental results. This is probably due to the sensitivity of the model to the thickness of the fabric relative to the maximum pore size. As mentioned earlier, assignment of the proper thickness for use in the equation is subject to doubt, and it is unlikely that the number employed for the maximum pore size is always the true maximum considering that the SEM collages or optical micrographs used to determine the pore size sample only a very small portion of the fabric. A statistical study of the representativeness of selecting a maximum hole from such a small field would be illuminating.

Another possible factor in the slightly lower predicted values is the validity of the assumption that the total metal amount can be treated as a single, homogeneous foil. In reality, much of the radiation impinging on a metallized filament encounters multiple thin layers of metal often separated by dielectric filaments. Double layers of shielding materials separated by a dielectric layer have shown to provide greater shielding than a single layer of the same material with equal total thickness.*

Given the natural variation in air permeability of fabrics, which depends on pore size and fabric thickness, and the predicted sensitivity of the shielding effectiveness of metallized fabrics to those same parameters, sizable sample-to sample variation in shielding effectiveness is to be expected. This should be borne in mind when evaluating product performance reproducibility.

## ACKNOWLEDGMENTS

The authors would like to thank Sandy Vitt and Jerry Hook for providing pore size and thickness data, and Roy Johnson for obtaining air permeability data on metallized fabrics. Also, the many stimulating discussions with Dr. Bernard Silverman were greatly appreciated.

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*In-house measurements of metallized fabrics.



***IMPROVED SHIELDING*** . . . *(Continued from page 34)*

effectiveness of copper-alloy-copper shields is due to increased reflection at the boundaries between the metal layers.

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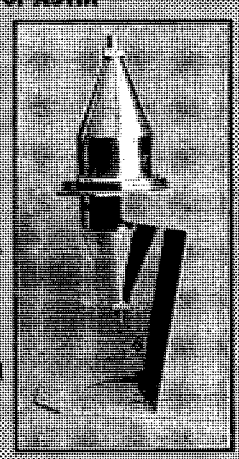

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