I INTRODUCTION

There is significant interest in developing meaningful methods for measuring the electromagnetic (EM) shielding effectiveness (SE) of materials. Shielding effectiveness will here refer to the ability of the material to reduce the transmission of propagating EM fields. In this context, three incident-field types are typically considered; (1) plane wave (far-field), (2) high-impedance or electric-field dominant (near-field), and (3) low-impedance or magnetic-field dominant (near-field). The plane wave case is well simulated through the use of coaxial transmission-line holders [1-4]; however, near-field SE measurements are more problematic.

This paper presents a novel approach to the near-field SE-measurement problem based on the use of a small transverse electromagnetic (TEM) cell featuring an aperture in one of the walls. The aperture serves to couple energy into the TEM cell, and the process may be readily modeled using small-aperture theory. A reverberation chamber is used to generate the incident field. The aperture is covered with the material under test (MUT) and the power coupled to the TEM cell (\(P'\)) is compared to empty-aperture coupling (\(P\)) in order to establish an insertion-loss (IL) value

\[
IL = 20 \log \left| \frac{P}{P'} \right| \text{ (dB),}
\]

typically expressed in decibels. The TEM cell features two output ports. By monitoring the sum and difference of these two signals we may investigate the MUT's electric-field (IL\(_E\)) and magnetic-field (IL\(_H\)) shielding properties individually. These measurements are performed simultaneously using a hybrid junction; thus, a single measurement yields both high- and low-impedance data. A number of materials will be considered. Both theory and experiment will be emphasized with respect to the primary problem of measuring near-field SE.

II TEST CONFIGURATION

A TEM cell, depicted in figure 1a, is a section of expanded 50 ohm rectangular coaxial transmission line tapered at each end to match ordinary 50-ohm coaxial line [5]. For the present application an aperture is introduced in one of the walls lying parallel to the inner conductor. In principle any waveguide could be used. However, a coaxial transmission line propagating only the fundamental TEM mode has the advantages of a simple field distribution (one E-field and one H-field component) and broadband low-frequency coverage. The rectangular cross-section geometry creates a flat aperture surface and thus simplifies the mounting of the MUT. The TEM cell used here has dimensions \(a = 9\) cm, \(b = 6\) cm, \(g = 2.2\) cm (refer to fig. 1b), and the aperture is a 5.1 cm (2") square. A square brass ring is used to clamp the MUT over the aperture. Resonances associated with higher-order propagating modes appear starting at approximately 760 MHz and reasonable use of this cell is limited to below 1000 MHz [6]. A smaller cell should allow for SE testing to around 4 GHz; however, none was available for this study.

![Figure 1a. Top view of apertured TEM cell.](image1a.png)

![Figure 1b. Cross section of a TEM cell.](image1b.png)
A reverberation chamber, as shown in figure 2 (the equipment under test (EUT) is in this case the apertured TEM cell), begins as a simple shielded room with one significant modification. A paddle is added which may be turned continuously (mode stir) or in small discrete steps (mode tune). The paddle presence allows us to take advantage of multimoding in the chamber. In any given paddle position we simply have a shielded room with an added boundary condition. As the paddle positioning is varied, the field at any point away from the chamber walls yields a wave impedance whose average approaches the freespace value \( n_0 (377 \text{ ohms}) \) [7-8]. Thus in a statistical sense the reverberation chamber may be used to generate a far-field-like incident field. Proper average-field convergence depends on exciting a large number of modes in the chamber. Thus this technique, at least from the source point of view, works best at higher frequencies. The NBS chamber is 2.74 m by 3.05 m by 4.57 m and is used above 200 MHz into the GHz range. Unwanted scattering near the MUT, due to mounting hardware for example, should not be overly important since the reverberation chamber strives for a complicated boundary condition environment. The dynamic range, 90-100 decibels, is quite good. The chamber is a high-Q cavity; thus high field levels can be generated using only moderate input power. The primary difficulties are that the chamber will not give meaningful results if too few modes are present (in this case below 200 MHz), and that the technique can be very time consuming. Each frequency tested here requires measurements at 200 paddle positions. Although the operation may be automated and computer controlled, a typical curve presented here takes up to four hours to generate. At higher frequencies (above 1 GHz) where the mode-stir technique is appliable and loss input-output power normalization is required, the measurement time is considerably less. Nonetheless, this method is very data intensive and likely to remain so.

**II ANALYTICAL BACKGROUND**

The analysis of an apertured TEM cell in a reverberation chamber is similar to that for a dual TEM cell [9] except that the source field is distinctly different. With respect to the aperture plane, small aperture theory [10] predicts that coupling will result primarily from the presence of a normal electric-field component \( E_y \) and the tangential magnetic-field components \( H_x, H_z \). The x-y-z coordinates are as in figure 1b with the z direction lying along the central axis of the cell. The induced aperture fields will then excite modes in the coaxial transmission line both in the forward (+z), and backward (-z) directions. At frequencies below the cutoff of the first higher-order mode only the TEM mode delivers significant power to the output ports. For an electrically small aperture the excitation should behave as if due to a pair of dipole moments \( \vec{P} \) (electric) and \( \vec{M} \) (magnetic).

Denoting the TEM mode excitation coefficients \( a^\pm \), we find that [10]

\[
a^\pm = \frac{1}{2} \mu_0 \left[ H_0^+ \vec{M} - E_0^\mp \vec{P} \right],
\]

where \( E_0^\pm, H_0^\pm \) describe the TEM mode in the transmission line, an \( e^{-jut} \) time convention has been assumed, and \( \mu_0 \) is the free-space permeability.

The dipole moments depend on the generator field \( \vec{E}_g, \vec{H}_g \) exciting the aperture as well as the aperture characteristics themselves (size, shape, loading, etc.). Thus the dipole moments are normally expressed as the product of the incident field at the dipole location and an aperture polarizability dyadic. The polarizabilities are usually derived for the case of an aperture located in an infinite ground plane subject to a static impressed field. However, as is pointed out by Collin [10], in the case of coupling between dissimilar regions the geometry can significantly affect the dipole moments. He proposes that the dipole moments be expressed as

\[
\vec{P} = -\epsilon_0 \vec{\alpha}_e \cdot (\vec{E}_g + \vec{E}_{1sr} + \vec{E}_{2ar})
\]

\[
\vec{M} = -\alpha_m \cdot (\vec{H}_g + \vec{H}_{1sr} + \vec{H}_{2ar}),
\]

where \( \vec{E}_{1sr}, \vec{H}_{1sr} \) represent the scattered field in region (1) which we take to be the source region (reverberation chamber), \( \vec{E}_{2ar}, \vec{H}_{2ar} \) represent the scattered field in the receiving region (TEM cell), \( \alpha_e, \alpha_m \) are the standard, ideal, infinite ground plane, static-polarizability dyadics, and \( \epsilon_0 \) is the free-space permittivity. The \( \vec{ \cdot} \) indicates coupling either to the source region (+) or the receiving (-) region. The inclusion of the reaction fields serves the dual purpose of accounting for the dissimilar regions coupled by the aperture and also enforcing power conservation. Clearly, the reverberation chamber and a coaxial line will not be symmetric about the aperture; thus Collin's correction could be important. However, for the present geometry, frequencies, etc., we find that the reaction-field contribution to (3) is quite small and may be neglected, that is

\[
\vec{P} = -\epsilon_0 \vec{\alpha}_e \cdot \vec{E}_g
\]

\[
\vec{M} = -\alpha_m \cdot \vec{H}_g
\]
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This may not always be the case and a more detailed analysis may be found elsewhere [3].

Substituting (4) into (2) and noting that the (-) sign in (4) applies, we find that the excitation coefficients (2) are given by

\[ a^\pm = \frac{jk_0}{2\pi} \left( E_0^* e^{-j\theta} \pm \eta_0 H_0^* e^{-j\theta} \right), \]  

where \( k_0 = (2\pi/\lambda) \) is the free-space wave number. As discussed, \( a_0^* \) will have a nonzero component in the \( y \) direction only (\( a_{0y}^* = \hat{y} \cdot e^{-j\theta} \), \( \hat{y} \) denotes a unit vector) while \( a_m^* \) will have nonzero terms \( a_{mx}^* \) and \( a_{my}^* \).

The TEM mode has no \( z \)-component and the transverse fields are given by

\[ E_0^* = (x E_0 - y E_0) e^{-j\omega k_0 z}, \]
\[ H_0^* = - \frac{1}{\eta_0} (x H_0^* - y H_0^*) e^{-j\omega k_0 z}. \]

If for convenience we locate the aperture in the \( z = 0 \) plane, then combining the above mode expressions with the proper polarizability components yields

\[ a^\pm = \frac{jk_0}{2\pi} \left( a_{0y}^* E_0^* \pm a_{mx}^* H_0^* \right) \]

where \( E_{0y}^* = \hat{y} \cdot e^{-j\theta} \) and \( H_{0x}^* = \hat{x} \cdot H_0^* \).

The voltages excited in the lines are related via \( V^\pm = a^\pm A \),

\[ \begin{align*}
V(Z) &= V^+ = \frac{Jk_0}{\eta_0} a_{mx}^* H_0^* E_{0y}^* \\
V(A) &= V^- = -\frac{Jk_0}{\eta_0} a_{my}^* E_0^* H_{0x}^* 
\end{align*} \]

The sum and difference powers will thus be

\[ P(Z) = \frac{1}{2} \text{Re} \left\{ \frac{1}{Z} \left| \frac{Jk_0}{\eta_0} a_{mx}^* H_0^* E_{0y}^* \right|^2 \right\}, \]
\[ P(A) = \frac{1}{2} \text{Re} \left\{ \frac{1}{Z} \left| -\frac{Jk_0}{\eta_0} a_{my}^* E_0^* H_{0x}^* \right|^2 \right\}. \]

Typically, two types of power measurement are performed in the reverberation chamber, namely, peak output (max) and average output (avg). For the sum and difference powers these may be denoted

\[ \begin{align*}
P(Z)_{\text{max}} &= \frac{1}{2} \text{Re} \left\{ \frac{1}{Z} \left| \frac{Jk_0}{\eta_0} a_{mx}^* H_0^* E_{0y}^* \right|^2 \right\}, \\
P(A)_{\text{max}} &= \frac{1}{2} \text{Re} \left\{ \frac{1}{Z} \left| -\frac{Jk_0}{\eta_0} a_{my}^* E_0^* H_{0x}^* \right|^2 \right\}. 
\end{align*} \]

where \( Z_s, Z_\Lambda \) are the impedances of the sum and difference output lines. These expressions assume that the voltages \( V^* \) excited at the aperture are the same as those appearing at the mixer. This should be a reasonable assumption if low-loss cables are used and if the cable lengths are kept equal so that little relative phase change or attenuation are introduced.

We can now see that regardless of whether we monitor peak or average power, the insertion loss should behave like

\[ \begin{align*}
\text{IL}(Z) &= 20 \log \left| \frac{a_{my}}{a_{mx}} \right| = \text{IL}_E, \\
\text{IL}(A) &= 20 \log \left| \frac{a_{mx}}{a_{my}} \right| = \text{IL}_H 
\end{align*} \]

where \( \text{IL}_E \) denotes electric-field coupling, and \( \text{IL}_H \) denotes magnetic-field coupling through the MUT. Equation (13) also assumes that the peak and average driving fields \( E_{0y}^* (\vec{0}) \) and \( H_{0x}^* (\vec{0}) \) are the same in each case (loaded and unloaded). Measurements indicate that \( \text{IL} \) is indeed reasonably independent of whether the peak or average is monitored. We typically consider data based on averages; however, peak power data may have an advantage where dynamic range is a problem.

Equation (13) allows us to determine a measured value for the absolute value of the loaded polarizabilities \( a_{mx}^* \) and \( a_{my}^* \). Some theoretical work exists on this topic as well. We can adapt a result due to Casey [14] who examined a circular aperture of radius \( r \) backed by a good conductor of sheet impedance \( Z_s \). He finds that
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\[
a_{\text{mx}}/a_{\text{mx}}' = \left[ 1 + j \frac{4\alpha_0 \gamma}{3\left( Z_s + 2\pi R_c \right)} \right]
\]
\[
a_{ey}/a_{ey}' = \]

up to the order of terms like \((k \alpha)^2\), where \(R_c\) is the contact impedance between the MUT and the conductor containing the aperture. This result indicates that a good conductor should provide high levels of shielding against electric fields while magnetic-field shielding may be low, particularly as the frequency \((\omega = 2\pi f)\) tends toward zero. Although these results are for circular apertures and our study uses a square aperture, the above expressions may readily be adapted. Aperture polarizabilities are fairly insensitive to shape. Thus given a square aperture of side length \(s\) we choose an equivalent radius \(r\) such that the aperture polarizabilities would be the same in the unloaded case [3], or \(r = 0.58 s\) for the magnetic-aperture polarizability. The sheet impedance for a MUT is in general complex. However, if the MUT is a good conductor as assumed here and in addition is electrically thin, then \(Z_s\) may well be approximated by

\[
Z_s = 1/\sigma d,
\]

where \(\sigma\) is the MUT conductivity and \(d\) its thickness. Inserting (15) into (14) yields a simple expression for \(IL_H\) if the product \(\sigma d\) is known for the MUT. Unfortunately these approximations do not yield theoretical expressions for \(IL_E\) except to the extent that we expect \(IL_E\) to be large for a good conductor.

Having generated these descriptive equations we now may consider some \(IL\) measurements.

IV DATA AND DISCUSSION

The \(IL\) data obtained via the apertured TEM cell in the reverberation chamber is shown in figures 3 through 6. The initial three figures also show a theoretically determined \(IL_H\) curve based on (14) and (15). The product \(\sigma d\) has been experimentally determined using a flanged coaxial holder [3] for these three MUTs. Figure 3 shows \(IL\) data for a layered aluminum-mylar test material. As expected from (14) the electric field shielding \(IL_E\) is much greater than the magnetic field shielding \(IL_H\) at the lower frequencies. In addition the agreement between our theoretical and experimental \(IL_H\) curves is very good. At about 770 MHz the first cell resonance affects \(IL\) behavior. The \(IL_E\) data tend to fluctuate more than do the \(IL_H\) data. This is likely due to nearby objects such as the metal screws used to mount the MUT which tend to affect and scatter the electric field more than the magnetic field.

A layered plastic-aluminum-plastic fabric-like material yields the results shown in figure 4. Again the sum (\(IL_E\)) and difference (\(IL_H\)) curves behave as expected with good agreement to theory. We again see a resonance effect at about 770 MHz.

Figure 5 shows data for a gold-mylar test material. Here the agreement between theory and experiment is not good. Also the electric-field shielding \(IL_E\) is lower than would be expected since this sample exhibits a \(\sigma d\) value comparable to the previous two MUTs. By accident, the mylar side of the material was mated to the receiving cell for the loaded tests; thus the contact resistance \(R_c\) (14) was probably high. Put alternately, a shield should allow the currents excited on the cell exterior to flow over the aperture but in this case they were able to penetrate the cell interior.
Figure 6 shows results for a graphite-composite material. For this material a usable od value is not available. Thus there is no theoretical IL\(_H\) curve. Note that IL\(_G\) and IL\(_H\) are basically of the same order. This material shows significantly higher shielding levels, especially at the lower frequencies, leading one to suspect that the composite has some magnetic reflecting capability to it. The sample is also significantly thicker than are the others so we may be seeing an appreciable amount of absorption. The IL range found via this technique, 60–80 decibels, is similar to that found with a flanged coaxial holder [3]. Thus the graphite-composite material appears to be a very effective near- and far-field shield.

VI CONCLUSION

This paper has looked at the use of an apertured TEM cell in a reverberation chamber as a means to measure the near-field SE of materials. Measurements agreed well with theory. The advantages of this system are separate and simultaneous monitoring of both electric- and magnetic-field coupling, a high dynamic range, minimal input power requirements, and theoretical support for interpreting results. The disadvantages are the requirement of specialized equipment, fairly long measurement times, and frequency range. The latter consideration may not be so much of a problem at the high-frequency end if smaller TEM cells are available. Suitable cells should allow one to go up to around 4 GHz. Reducing the low-frequency limit would require a larger reverberation chamber which is certainly possible but for the most part not practical. Finally, the aperture is part of the IL data measured in addition to the MUT effect. The aperture partially determines the field level, and the field component (i.e. normal electric etc.) penetrating the MUT. These considerations should be recognized if data from this method are to be compared to those obtained via other methods. Nonetheless, this method holds promise as a broadband, near-field simulation SE-measurement approach.

VII ACKNOWLEDGEMENT

The authors wish to thank Galen H. Koepke and Myron L. Crawford for their help with the measurements presented in this paper, and C. K. Z. Miller for his support of this project.