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Shielding Effectiveness Against Electromagnetic Interference

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SHIELDING EFFECTIVENESS AGAINST ELECTROMAGNETIC INTERFERENCE

J. M. Googe
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ABSTRACT

The use of metal-filled and metal-coated plastics and other modified dielectric materials to replace metals for enclosures has created a need to test these materials for their electromagnetic interference (EMI) shielding effectiveness (SE). Shielding effectiveness involves a variety of electromagnetic environments, and useful data can be obtained from tests that carefully limit the environment to that of a plane wave. Such an environment can be created in a circular or rectangular transmission line.

Two such transmission line test fixtures, which hold samples of the material to be tested, have been developed. The fixtures described in this report are the National Bureau of Standards (NBS) coaxial transverse electromagnetic (TEM) cell, and a dual TEM cell constructed at ORNL from a design suggested by the NBS. The NBS coaxial fixture is an improved version of the device recommended by the American Society for Testing and Materials (ASTM).

The problems associated with measuring SE are well described in the literature. The two methods described here are the result of years of work to establish procedures and instrumentation that will produce acceptable data.

1. INTRODUCTION

The use of metal-filled and metal-coated plastics and other modified dielectric materials to replace metals for enclosures has created a need to test these materials for their electromagnetic interference (EMI) shielding effectiveness (SE). Although this parameter, SE, is well defined,[1,2] its measurement over broad frequency ranges is often difficult.

Shielding effectiveness involves a variety of electromagnetic environments, with useful results obtained from tests that carefully limit the environment to that of a plane wave. Such an environment may be created in a circular or rectangular transmission line.

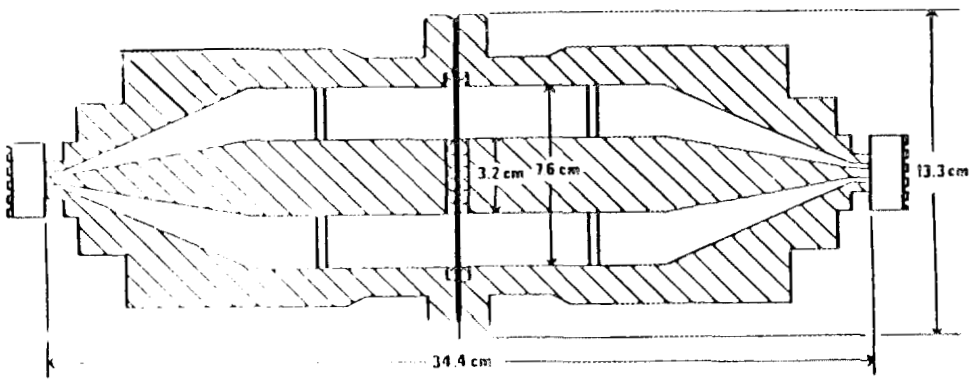
Two such transmission line test fixtures, which hold samples of the material to be tested, have been developed. Each of the fixtures attempts to maintain plane wave or far field conditions while allowing insertion loss data to be measured for the material under test (MUT). Tests are made on standard metallic samples with these fixtures for calibration and verification of analytical models. The fixtures described in the report are the National Bureau of Standards (NBS) coaxial transverse electromagnetic (TEM) cell and a dual TEM cell constructed at ORNL from a design suggested by the NBS. The NBS coaxial fixture is an improved version of the device recommended by the American Society for Testing and Materials (ASTM) in ASTM ES7-87.[3] All such test cells are useful only up to frequencies where modes of higher order occur.

The problems with measuring SE are well described in the literature, and these two methods are the result of years of work to establish procedures and instrumentation that will produce acceptable data.

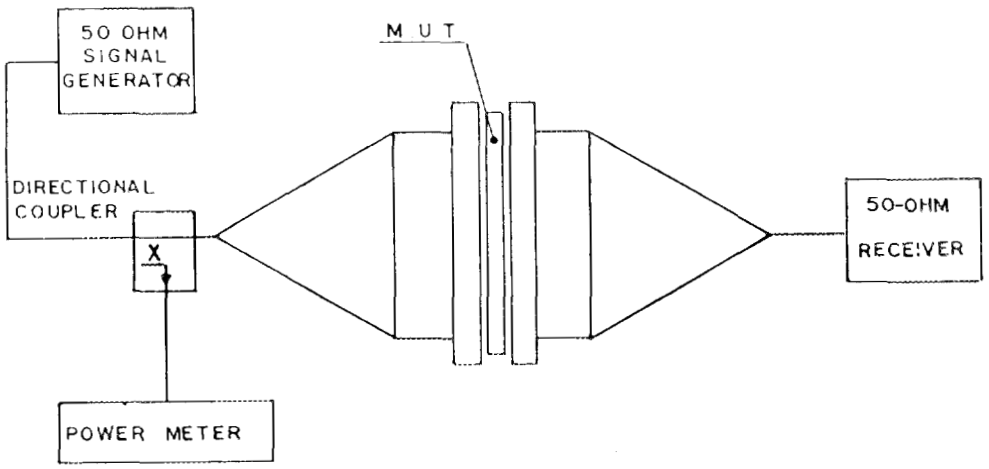
2. COAXIAL TEST METHOD USING THE TEM CELL

The basic idea for the coaxial test method is to measure the insertion loss caused by the sample of shield material inserted into the space between the outer and inner conductors of the coax. The sample of MUT presents a load across the line, causing a reflection of the plane wave at that point. The insertion loss of such a load can be calculated using transmission line theory.

The test fixture is made in the form of a tapered coaxial transmission line that comes apart in the middle so that a disk-shaped sample of the MUT can be inserted. Figure 1a shows a section of the NBS design for the TEM cell that is very similar to the ELGAL Instrumentation and Systems, Ltd., Model 19A,[4] which is in use at ORNL. Test data using this fixture will be discussed and compared with data from analytical models.



(a) Cross-section of NBS cell.



(b) Diagram of Model 19A measurement setup.

Fig. 1. Flanged coaxial holders for SE measurements.

The characteristic impedance of the TEM cell is kept at 50 Ω by maintaining the 2.3:1 ratio of the outer to inner conductors.

Measurements of the power transmitted through the TEM cell with and without the MUT inserted allow the calculation of insertion loss for the MUT.

An analysis of this configuration using transmission line theory follows. Insertion loss (I.L.) is defined as

$$\text{I.L.} = 10 \log P1/P2 \text{ dB} , \qquad (1)$$

where P1 is the power received without the MUT in place and P2 is the power received with the MUT in place.

Figure 2 shows approximate-equivalent circuits for the two cases.

The power delivered to the receiving end of the TEM cell in each case can be calculated using the appropriate circuit.

$$P1 = \left(\frac{Vg}{2\ Zo}\right)^2 Zo = \frac{Vg^2}{4\ Zo}\ , \tag{2}$$

$$P2 = \left(\frac{\dfrac{ZoZm}{Zo + Zm}}{Zo + \dfrac{ZoZm}{Zo + Zm}}\right)^2 \times Vg^2 \times \frac{1}{Zo} = \left(\frac{ZoZm}{Zo^2 + 2\ ZoZm}\right)^2 \times \frac{Vg^2}{Zo}\ , \tag{3}$$

and

$$I.L. = 10 \log \frac{\dfrac{Vg^2}{4\ Zo}}{\left(\dfrac{ZoZm}{Zo^2 + 2\ ZoZm}\right)^2 \dfrac{Vg^2}{Zo}} = 20 \log \left(1 + \frac{Zo}{2\ Zm}\right). \tag{4}$$

Equation (4) can be used to calculate the I.L. of the MUT if Zo and Zm are known, and of course, if the model for the system is correct. The model can be improved by including a term for the contact resistance between the sample holder and the bulk of the sample. This resistance, or any factor that adds to the bulk resistance of the MUT, will cause the predicted insertion loss to be larger than that measured. Since the value of Zm is small for good shields, the variability in contact resistance can cause large changes in insertion loss.

$$I.L. = 20 \log \left[1 + \frac{Zo}{2\ (Zm + Rc)}\right]. \tag{5}$$

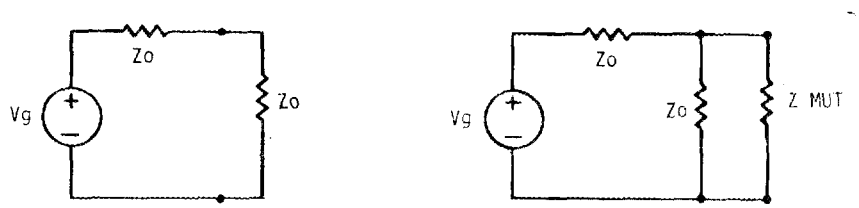


Fig. 2. Equivalent circuits.

The NBS flanged TEM cell is designed to eliminate or minimize the component of contact resistance that is in series with the Zm.[5] If this is true, the largest source of error in TEM coaxial cells has been eliminated. Ample published data are obtained using the NBS fixture[5] and the ASTM fixture, which highlight the problems with contact resistance and clearly demonstrate that the NBS fixture is better. Some of these data are shown in Fig. 3.[5] The agreement between the NBS results and those predicted by Eq. (4) is remarkable. The trick according to NBS is how the sample is held.

If Equation (4) is used to calculate insertion loss, it is necessary to know the characteristic impedance of the coaxial line test fixture and that of the sample which loads the otherwise matched line. The characteristic impedance of the coax is given by

$$Zo = 138 \log\left(\frac{b}{a}\right)\Omega \quad , \tag{6}$$

where b and a are the outer and inner radii of the coax. The load impedance, Zm, can be calculated as if it were a coaxial resistor made of material having the bulk conductivity of the MUT, as long as the frequency is such that the MUT is a thin disk. This fact will be true

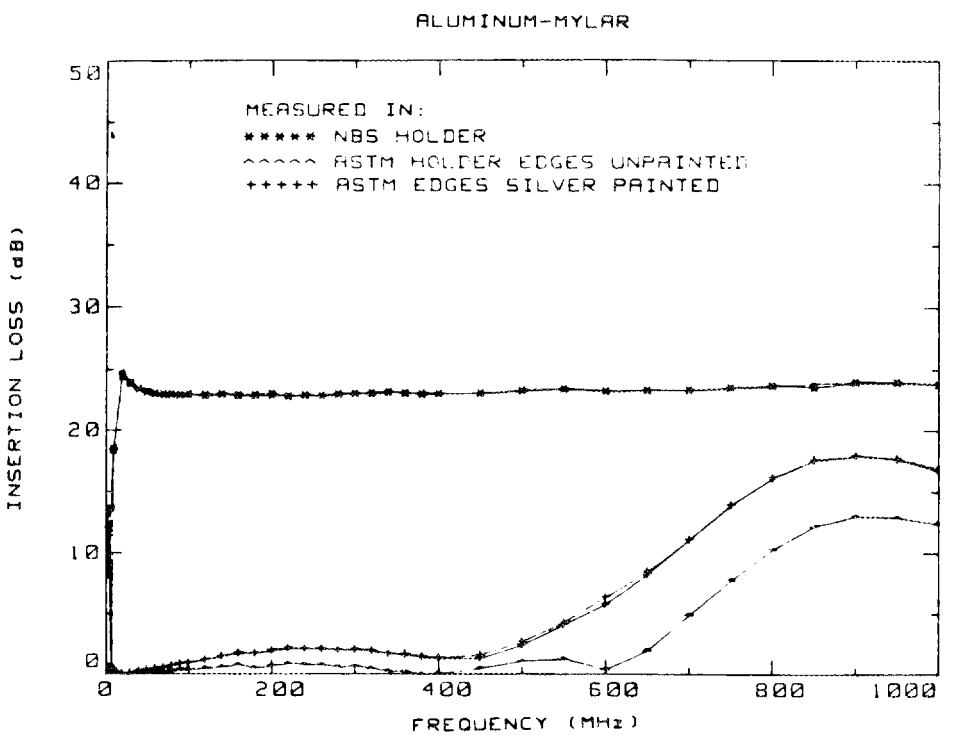


Fig. 3. Insertion loss for the aluminum-mylar sample measured in the ASTM proposed and NBS flanged coaxial holders.

as long as the skin depth at the frequency of interest is larger than the thickness of the MUT disk.

The resistance of a coaxial resistor can be calculated as follows: The resistance of an elementary ring is

$$dR = \frac{dr}{\sigma d \; 2 \; \pi r} \quad , \tag{7}$$

and the total resistance of the disk with radii b and a and thickness d is

$$R = \int_a^b \frac{dr}{\sigma 2\pi dr} = \frac{1}{2\pi\sigma d} \ln\left(\frac{b}{a}\right) = \frac{Rs}{2\pi} \ln\left(\frac{b}{a}\right) \quad . \tag{8}$$

Note that the factor σd is the reciprocal of the surface resistance, Rs, in ohms per square for a square sample of any size.

Using Eqs. (6), (8), and (4) yields

$$\frac{Zo}{2 \; Zm} = \frac{138 \log\left(\frac{b}{a}\right)}{2\left(\frac{1}{2\pi\sigma d}\right) \ln\left(\frac{b}{a}\right)} = 188.5 \; \sigma d \quad , \tag{9}$$

$$I.L. = 20 \log (1 + 188.5 \; \sigma d) = 20 \log \left(1 + \frac{188.5}{Rs}\right) \cdot \tag{10}$$

The surface resistance of the shield in ohms per square or the bulk conductivity and thickness of the shield is needed to predict insertion loss due to reflection of a plane wave up to frequencies where the skin depth approaches the thickness of the shield.

The skin depth at the frequency of interest can be calculated from

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \quad \text{meters} \quad . \tag{11}$$

The insertion loss predicted by Eq. (11) will be in error with any absorption loss, but absorption losses are small for thin shields.

3. SAMPLE CALCULATIONS

The data shown in Fig. 3 are for an aluminum-filled mylar sheet with $\sigma d = 0.079$.[6] The calculated I.L. for this material is

$$\text{I.L.} = 20 \log (1 + 188.5 \times 0.079) = 24 \text{ dB} \quad .$$

This 24 dB represents insertion loss due to reflection of the TEM mode only and compares well with test data obtained with the NBS fixture (Fig. 3).

If the MUT was a 1-mm-thick disk of copper with a bulk conductivity of 5.82×10^7 mho/m, the I.L. would be

$$\text{I.L.} = 20 \log (1 + 188.5 \times 5.82 \text{ E4}) = 140.8 \text{ dB} \quad .$$

This large attenuation is greater than the dynamic range of most test instrumentation. However, the best shielding metal-loaded plastics have bulk resistivity on the order of 1 Ω/cm, so the test equipment will not need as wide a dynamic range as when testing metals. It is important to have some thin metal samples of known conductivity and thickness for calibration standards.

Test set 19A came with a test sample of unknown metal-loaded plastic material with a certified insertion loss of 35 dB over the frequency range 10 MHz to 1 GHz. When the relationship of Eq. (10) for the I.L. of a thin disk is used to calculate the surface resistance, Rs, of this 35-dB sample, it yields a value of 3.4 Ω/square.

The total resistance of this concentric coaxial resistor measures 0.06 Ω. From this value one can calculate a surface resistance of 4.5 Ω/square for the low frequencies. There is some comfort in the relative agreement of these data.

It is useful to examine the relationship between thickness of a sample and insertion loss for a typical metal-loaded plastic material. For example, some of the best available metal-filled plastics have bulk resistivities on the order of 1 Ω/cm. Calculation of the insertion loss for increasing thicknesses yields the relationship shown in Fig. 4; increasing the shield thickness to 1 cm gives an I.L. of 45.6 dB, but further increases in thickness yield poor returns in shielding effectiveness. A 1-cm disk can be considered thin, as the skin depth of this material does not become 1 cm until a frequency of 39 GHz.

EMI shielding materials are subjected to EM radiation from fields other than plane waves of normal incidence. Each different set of boundary

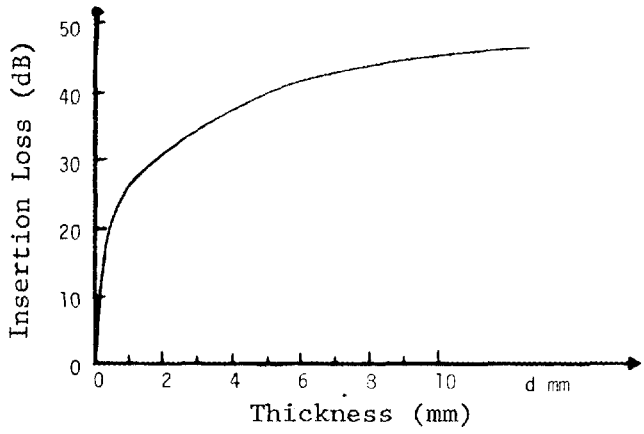


Fig. 4. I.L. vs thickness for 1 Ω/cm metal-loaded plastic.

conditions produces a unique equilibrium, and the shielding effectiveness for a given material will vary greatly depending on the case. Several methods for testing materials under different boundary conditions have become popular and are described in the literature.[6]

Two cases of special interest, plane wave normal incidence and plane wave tangential incidence, are often taken to be extremes that bracket the other cases of interest. Test conditions for these two cases can be established with a coaxial TEM cell such as the Set 19A and with a pair of rectangular TEM cells coupled by a common aperture. These coupled cells are often called a dual TEM cell.[7]

Figure 5 shows an arrangement for dual TEM cells with a common aperture. A design for such a system was suggested[8] and has been constructed at ORNL. Figures 6 and 7 are views of the ORNL dual TEM cell with the dimensions as shown in Fig. 8.

The rectangular TEM cell[9] is used to create a known broadband isolated test field of any desired size. Cells large enough to accommodate full-scale autos and aircraft are in use today. Similar to coaxial TEM cells, the size establishes the frequency where multiple modes appear and limit the use of the cell.

A natural development in the use of the rectangular TEM cell was to cut a hole in the wall of the cell and see how much power passed through this aperture into or out of the cell. By using two cells with the aperture in a common wall, boundary conditions can be carefully controlled. Fortunately, the resulting field problem has been solved for several cases of practical interest.[7,10] Shielding effectiveness measurement with a dual TEM cell involves the ratio of the amount of power that passes from one cell to the other through the aperture when open and when loaded with a sample of the MUT.

When rf power is applied to port 1 in the active cell with port 4 terminated in a matched load, a plane wave or TEM mode is established in this cell (Fig. 5). Power from this wave will be coupled to the

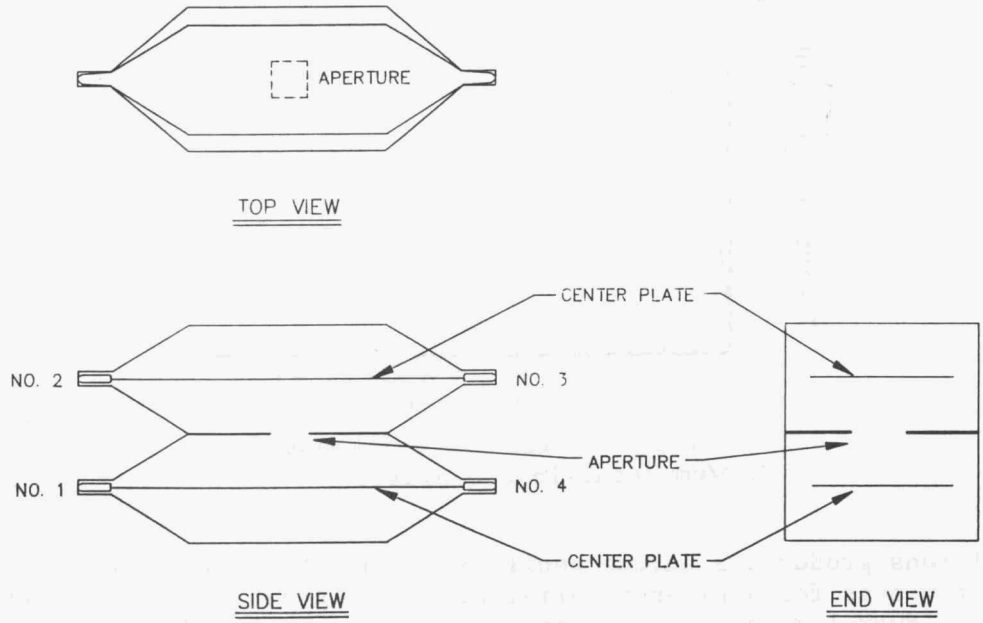


Fig. 5. Schematic diagram of dual TEM cell.

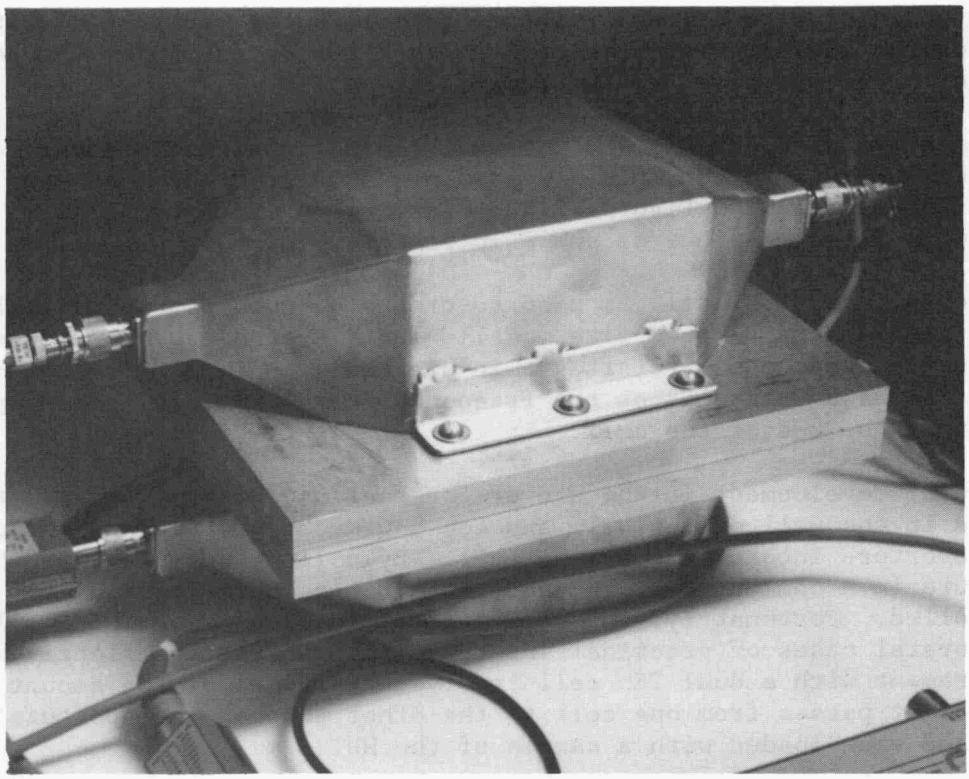


Fig. 6. Assembled dual TEM cell.

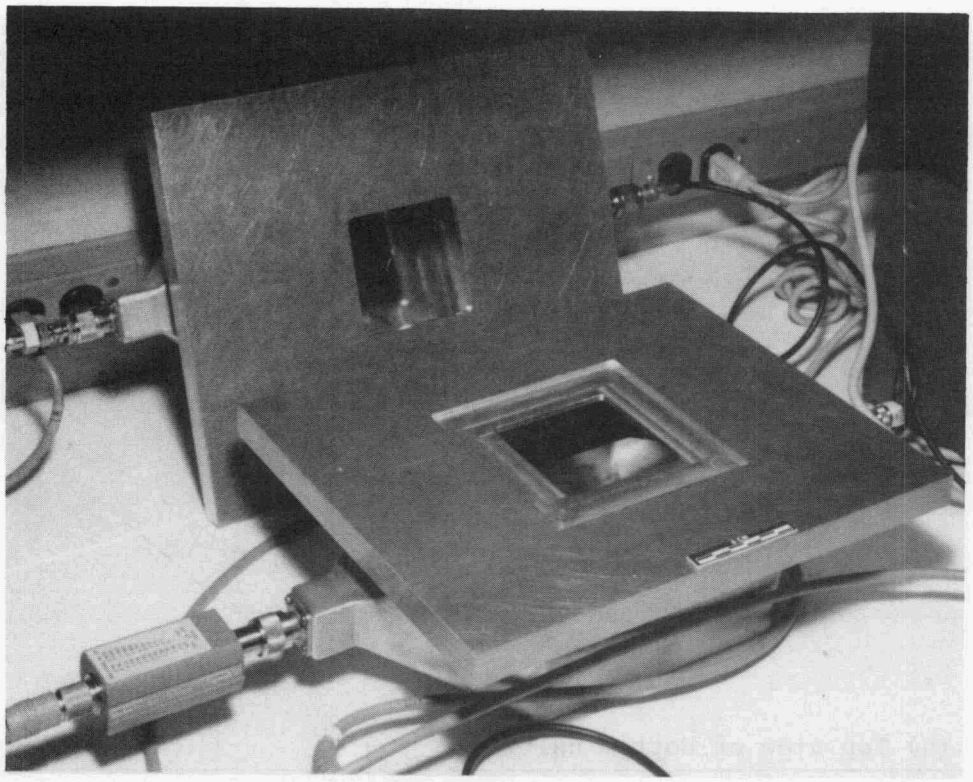


Fig. 7. Disassembled dual TEM cell.

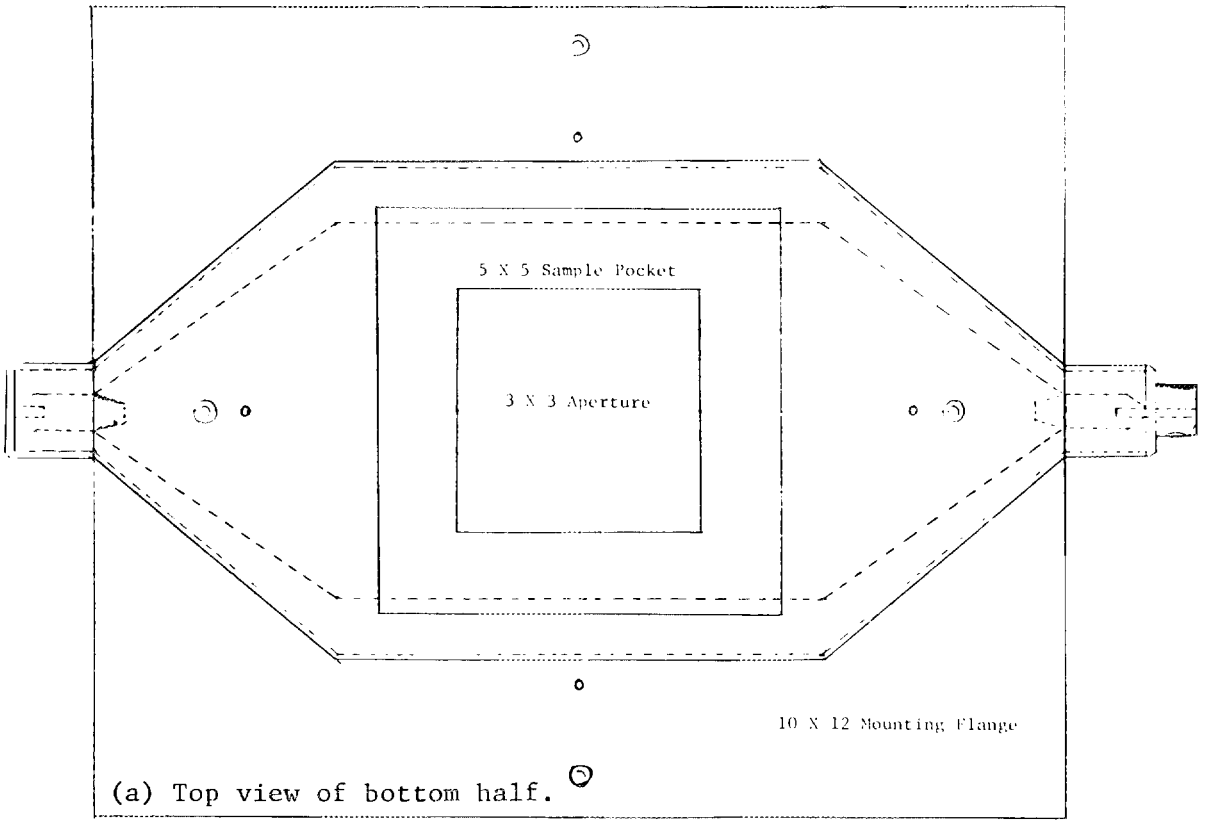
passive cell through the aperture. This power will propagate in both directions to be received by matched loads at ports 2 and 3.

Solutions to the resulting boundary value problem for the dual TEM cell with and without shielding material in the aperture have been published along with formula for insertion loss calculations.[7] Calculations made for the loss measured with respect to port 3 are called the forward insertion loss calculations, and those made with respect to port 2 are called the backward insertion loss calculations since the wave in the active cell is moving from port 1 to port 4.

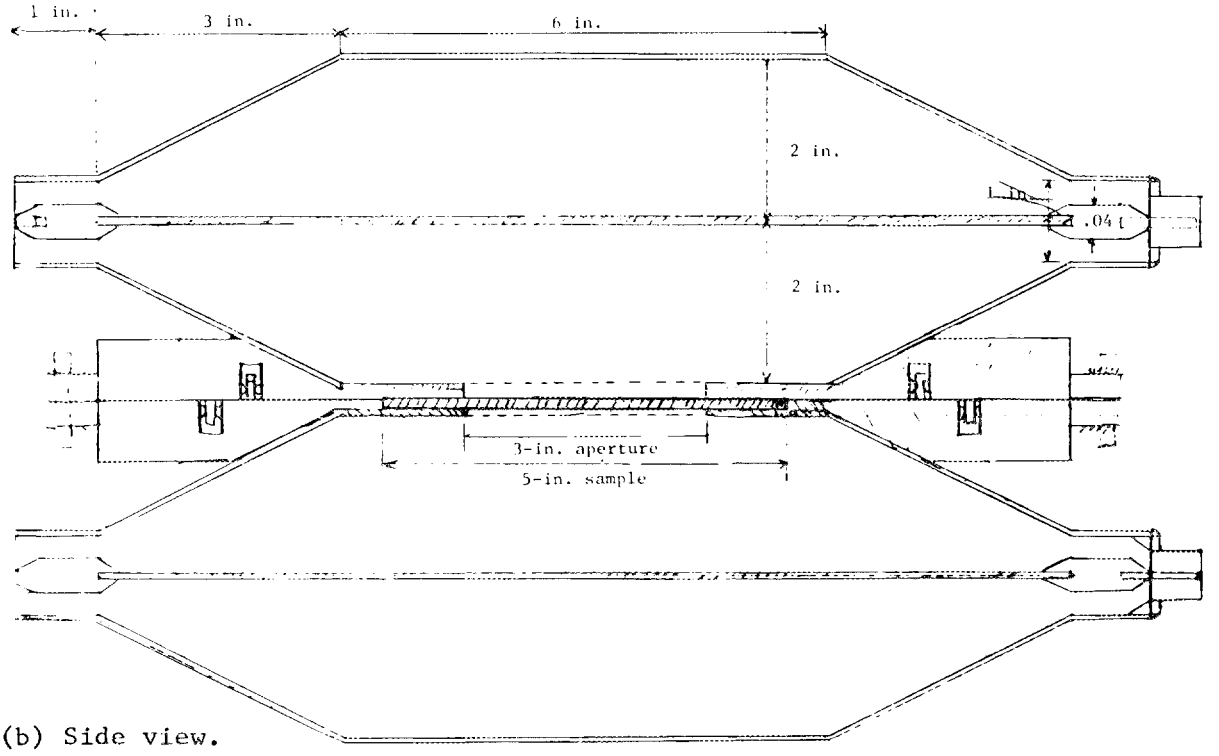
$$\mathrm{I.L.3} = -5.1 + 20 \log \left[1 + j \frac{4\,\omega\mu o r \sigma h}{3\pi(1 + 2\pi Rc\sigma h)} \right] , \tag{12}$$

$$\mathrm{I.L.4} = 3.2 + 20 \log \left[1 + j \frac{4\,\omega\mu o r \sigma h}{3\pi(1 + 2\pi Rc\sigma h)} \right] , \tag{13}$$

ω	Frequency	σ	Conductivity of MUT
μ	Permeability	h	Thickness of MUT
r	Aperture size factor	Rc	Contact resistance



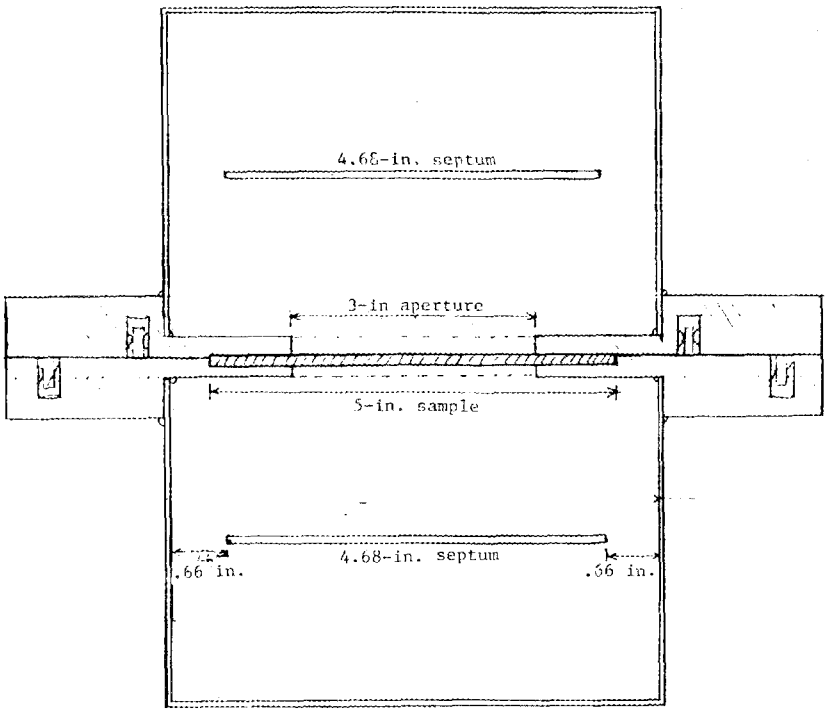
(a) Top view of bottom half.



(b) Side view.

Fig. 8. Detail drawings of ORNL dual TEM cell design.

Fig. 8 (continued)



(c) End through center.

The I.L. at the two ports is different and depends on the size and shape of the aperture as well as on the intrinsic properties of the MUT. The results are also very sensitive to the contact resistance between the MUT and the cell walls at the aperture. The literature contains widely varied data for similar materials and debates the usefulness of data obtained using the duel TEM cell.

4. CONCLUSIONS

A case can be made for preference of the dual cell in that measurements made at the forward and backward ports may be used to obtain separately the electric field insertion loss and the magnetic field insertion loss.[7] If this proves to be true, it will be helpful in the practical case for relating data obtained with the dual cell to data from other test methods.

Test data obtained using the ORNL dual TEM cell are not available at this time. Data in the open literature from dual TEM cells are meager and do not seem to agree well with analytical predictions. Work will continue with the ORNL dual TEM cell, and we look forward to the time when we have sufficient data to contribute to greater understanding of the dual cell.

REFERENCES

1. H. W. Ott, Noise Reduction Techniques in Electronic Systems, John Wiley and Sons, New York, 1976, p. 140.

2. E. F. Vance, Coupling to Shielded Cables, John Wiley and Sons, New York, 1978, p. 164.

3. ASTM ES7-83, Electromagnetic Shielding Effectiveness of Planar Materials, American Society for Testing Materials, Philadelphia (1983).

4. ELGAL Instrumentation Operation Manual, Set 19A, Elgal Instrumentation and Systems, Ltd. Israel, 1985.

5. J. W. Adams and E. J. Vangura. Shielding Effectiveness Measurements of Plastics, National Bureau of Standards, NBSIR 85-3035, Boulder, Colo., January 1986.

6. P. F. Wilson and M. T. Ma, "Methods for Measuring the Near-Field and Far-Field Shielding Effectiveness of Materials, Symp. Record Internat. Conf. on Electromag. Compatibility, EXPO-86, June 16-19, 1986, Washington, D.C., Paper No. T28.

7. P. F. Wilson and M. T. Ma. "Shielding-Effectiveness Measurements with a Dual TEM Cell," IEEE Trans. Electromag. Compatibility, Vol. EMC-27, No. 3, August 1985.

8. M. L. Crawford (NBS) Personal Communication to J. M. Googe (ORNL), November 1986.

9. M. L. Crawford, "Generation of Standard EM Fields Using TEM Transmission Cells," IEEE Trans. Electromag. Compatibility, Vol. EMC-16, No. 4, 189-95, November 1974.

10. P. F. Wilson and M. T. Ma, "Shielding Aperture Analysis of the Dual TEM Cell," Symp. Record, 1984 National Symp. Electromag. Compatibility, San Antonio, Texas, April 1984.

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