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Using a TEM Cell for EMC Measurements of Electronic Equipment

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Using a TEM Cell for EMC Measurements of Electronic Equipment

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CONTENTS

USING A TEM CELL FOR EMC MEASUREMENTS OF ELECTRONIC EQUIPMENT

M. L. Crawford and J. L. Workman

This publication describes the physical design and electrical evaluation of pertinent parameters which influence the use and operation of a transverse electromagnetic (TEM) cell. Detailed, step by step procedures are given for using a TEM cell for performing either radiated electromagnetic (EM) susceptibility testing or for measuring radiated EM emissions from electronic/ electro-mechanical equipment. These measurement procedures provide guidelines to potential users and also indicate precautions to observe to minimize problems often encountered when performing EMC measurements and hence to enhance the cell's usefulness. Where available, a brief error analysis associated with the measurement technique is included.

Key Words: Measurement procedures; susceptibility and emission measurements; transverse electromagnetic cell.

1. INTRODUCTION

Transverse electromagnetic (TEM) cells have shown great potential for performing electromagnetic interference/electromagnetic compatibility (EMI/EMC) measurements with substantially improved ease, versatility, and accuracy [1,2]. The TEM cell consists of a section of rectangular, coaxial line that serves as a broadband, linear phase and amplitude transducer (in the sense that it converts field strength to rf voltage or rf voltage to field strength) either to establish standard electromagnetic (EM) fields for susceptibility testing of electronic equipment or to detect radiated emanations from electronic equipment [3]. The cell is also a shielded enclosure, thus providing electrical isolation for the tests being performed; and, since it is a transducer, it eliminates the use of conventional antennas with their inherent measurement limitations (i.e., bandwidth, nonlinear phase, directivity, polarization, etc.). The newness of the TEM cell measurement technique and its increasing use, and sometimes misuse, have motivated the writing of this paper. This technical note gives physical and electrical descriptions of some TEM cells and provides a detailed step-by-step procedure for their use for both radiated susceptibility and emanation measurements. These measurement procedures are intended to provide guidelines for the potential user to minimize problems encountered with this technique, enhancing the cell's usefulness, and to insure that the results obtained are as meaningful as possible. Where available, a brief error analysis associated with the measurement techniques is included.

2. PHYSICAL DESCRIPTION OF A TEM CELL

The TEM cell is a rectangular, coaxial, 50-ohm transmission line, tapered at each end to adapt to conventional 50-ohm coaxial connectors. The center conductor, as shown in figure 1, is a flat sheet of metal supported by dielectric rods in the center of the cell. Access into the cell is by side doors located as shown in the figure. Conductive finger stock material is used around the edges of the doors and around cover panels for input/output connectors and AC power leads to insure the shielding integrity of the cell.

Fabrication details for constructing a large cell, similar to the 3 m x 3 m x 6 m cell shown in figure 2, are contained in reference [4]. A cell of any size could be fabricated using dimensional scaling and the procedures outlined in [4] with, of course, appropriate, minor modifications as required. The design of the cell, as a 50-ohm impedance transmission line, is derived approximately from the expression [5]:

$$Z_o = \frac{376.7}{4\left[\frac{a}{b} - \frac{2}{\pi}\ \ell n\left(\sinh\frac{\pi g}{2b}\right)\right] - \frac{\Delta C}{\varepsilon_o}}, \tag{1}$$

where a, b, and g are as shown in figure 3. The term $\Delta C/\varepsilon_0$ relates to the fringe capacitance between the edges of the septum and the side walls. For large gaps (i.e., $w/g \leq 5$) typically used in cell designs, this term is negligible and can be neglected. However, an exact expression for determining Z_0 can be obtained from reference [5] if required. Curves for designing a cell with arbitrary cross section and impedance are shown in figure 4. These curves are based on formulation developed by Tippet [6]. Final line impedance adjustments, to compensate for the cell's septum dielectric supports and transition angle impedance discontinuities, are made with the aid of a time-domain reflectometer by trimming the septum.

Cross-sectional drawings and a photograph of a 1.2 m x 1.2 m x 2.4 m cell are shown in figures 5 and 6. This cell is equipped with line filters to provide filtered ac power for use by equipment under test (EUT) inside the cell. The cell also has a bulkhead panel for feed-through connectors and rf filters to access the EUT via its input/output leads. If required, a shielded box can be installed over the bulkhead panel with the rf filters. This box may be necessary to prevent rf conducted on the EUT input/output leads, from radiating outside the cell or from being conducted into the cell.

3. ELECTRICAL DESCRIPTION

Electrically the TEM cell, as referred to earlier, is an expanded coaxial transmission line which propagates a TEM wave. This wave is characterized by orthogonal electric (E) and magnetic (H) fields which are perpendicular to the direction of propagation along the length of the cell or transmission line. Figure 7 shows the TEM mode field structure in the cell. The E and H field components are quite uniform over much of the volume between the septum and outer conductor, and simulate a planar field in free space (i.e., a wave impedance of 377 ohms). The TEM mode has no low frequency cut-off. This allows the cell to be used at frequencies as low as desired, limited only by the cell's magnetic shielding effectiveness which is determined by the material from which it is made. This TEM mode has the important linear phase and constant amplitude response as a function of frequency referred to earlier. This makes it possible to use the cell for broadband cw sweep testing as well as for complex wave-form simulation or detection without signal distortion; that is, as long as single TEM mode operation is maintained.

The upper useful frequency for a cell is limited by the distortion of the test signal caused by resonances and multimoding that occur within the cell at frequencies given by eqs (2) and (3).

$$f_{res} = \sqrt{f_c^2 + \left(\frac{c}{2\ell}\right)^2} = \text{cell resonant frequency in MHz}, \tag{2}$$

where f_c is the cell cut-off frequency for the TE_{10} mode, c is the wave propagation velocity (3.8×10^8m/sec) and ℓ is the resonant length of the cell. The cell cut-off frequency f_c is given as:

$$f_c = \frac{75}{a}\sqrt{1 + \frac{4ab}{\pi b_1 b_2 \, \ell n \left(\frac{8a}{\pi g}\right)}} \qquad (3)$$

The parameters a, b_1, b_2, and g are as defined earlier for equation 1 and as shown in figure 9 and 13. Progress has been made toward suppressing these adverse high-frequency effects by using rf absorber material placed in the cell as shown in figure 8 [7].

Many different cell shapes or form factors, which influence the field distribution of the cell, could be used for designing a cell. Two are shown in figures 9 and 10 with their electric field distributions. These field distributions were obtained using formulation derived by Tippet and Chang [5,6]. Tables 1 through 8 give the normalized field quantities at various transverse position locations in the cell as shown in figure 11. The normalized field, $\tilde{E}_{x,y}$, was obtained from the expression:

$$\tilde{E}_{x,y} = \frac{E_{x,y}}{\frac{V}{b}}, \qquad (4)$$

where $E_{x,y}$ is the magnitude of either the vertical or horizontal component of the electric field at the location of interest in the cell, V is the voltage between the septum of the cell, and b is the separation distance between the septum and cell upper or lower walls.

Various approaches have been investigated to find ways by which to increase the test volume available in a cell without reducing its upper useful frequency. One is to design the cell with an off-set septum. An asymmetric or offset septum cell was fabricated as shown in the cross-sectional drawings of figure 12. The E-field distributions above and below the septum of this cell are shown in figure 13. This cell offers approximately 25% greater test volume in its lower half space than a symmetric cell of similar size with an equivalent high-frequency cutoff and resonance limitation. This additional test space, however, comes at the price of less test field uniformity and greater difficulty in using the cell at multimode frequencies. A previous publication comparing the characteristics of this cell with a symmetric cell of similar size is available for further study, if desired [8].

A comparison of figures 9, 10, and 13 gives an indication of the electric field strength gradients in the area within which the EUT would be placed. For example, in the shaded area centered between the septum and lower or upper walls equal to 2a/3 x b/3, the cell of figure 9 has less than $\pm$1.4 dB E-field gradient, the cell of figure 10 has less than $\pm$0.6 dB E-field gradient and the cell of figure 13 has less than $\pm$0.5 dB above the septum and less than $\pm$2.6 dB below the septum. The cell of figure 10 or the upper half of the cell of figure 13 would be used for testing small items or calibrating small probes where good field uniformity was required. The cell of figure 9 or the lower half of the cell of figure 13 would be acceptable for testing larger objects at a maximum upper useful frequency where a loss (compromise) in the test-field uniformity could be tolerated. If a metal case (simulating an EUT) is placed in the center of one half of the cell, the field distribution is changed. The metal case disrupts the field and has a capacitive loading effect at that point in the cell. Figure 14 shows the relative field distribution with a metal case occupying one third of the volume between the septum and outer wall of a cell having the cross section of figure 10. Five transverse scans, across the width of the cell, are shown. The location of the scans are numbered on the side view of the cell and are indicated on the graph.

The field strength has increased by 3 dB and 6 dB, respectively, in the regions directly above and below the case. This increase in field strength must be taken into account as indicated in section 4.2.3 when determining the absolute test field, or the absolute level of the emitted field, if a significant cross section within the cell is occupied by the EUT.

The electrical characteristics of a cell as a transmission line can be determined simply by measuring the voltage standing wave ratios (VSWR) at the cell's measurement ports and by measuring its insertion loss. A typical empty cell's input VSWR, both with and without absorber loading, is shown in figure 15. These data were obtained by measuring the return loss (i.e., the ratio of the power incident to the cell's input port to the power reflected from the input port) of the cell shown in figure 4. The output port of the cell was terminated into a matched 50-ohm load. Resonant and multimode frequencies apparently start at approximately 220 MHz. Note how the VSWR is greatly reduced at these multimode/resonant frequencies by the rf absorber loading.

The insertion loss of a cell is obtained by measuring the difference in the net power applied at the cell's input port and the power available at the cell's output port. Inserting absorbers into the cell increases the loss substantially and must be limited to prevent excessive signal loss for both susceptibility and radiated emissions testing. The number, type, and placement location of absorbers inside the cell were experimentally determined to minimize the cell's insertion loss without significantly altering the TEM mode operation. The insertion loss of a typical cell (figure 5) is shown in figure 16. A loss of a few dB ($\leq$ 3 dB) in signal strength is reasonable for most applications; an upper frequency test limit for this particular cell, from figures 15 and 16, would be approximately 220 MHz.

Measurements can be made to determine the E-field characteristics within the test volume of the cell again with and without absorber loading for comparison, especially at high (multimode) frequencies. These measurements are made using an isotropic probe [9,10] located at the center of the test zones in the cell. The probe measures, as a function of frequency, the variation in the vertical E_y, transverse E_x, longitudinal E_z, and Hermitian magnitude S* of the electric field relative to vertical E-field component of the TEM electric field. Examples of the results of these measurements obtained in the test zones of the cell of figure 4 are shown in figures 17-20. The subscripts m and c in the ordinate of figures 17-20 refer to the <u>measured</u> as compared to the <u>computed</u> values of the amplitude of the appropriate field component in the cell. These results obviously will be influenced by inserting the EUT, especially at frequencies above the cell's resonances and multimode, and will require further evaluation if the cell is to be used above resonant/multimode frequencies. Ideally, the transverse, figure 18, and longitudinal, figure 19, components of the electric field measured at the center of the test zone should be zero. At multimode frequencies, the longitudinal and transverse components become significant, modifying the coupling and test-field characteristics of each cell and increasing the complexity of measuring the field patterns. This results in a measurement uncertainty that is difficult to define, and hence, limits the upper useful frequency range of the cell. Note that the variation in the normalized Hermitian magnitude, S, of the field ratios at multimode frequencies (above approximately 220 MHz for this cell) even for the absorber loaded case, would be quite large, resulting in large measurement uncertainties if the cell were used at these frequencies.

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*The Hermitian magnitude S is given as $S = \sqrt{E_x^2 + E_y^2 + E_z^2}$ where E_x is the transverse component, E_y is the the vertical component, and E_z is the longitudinal component, of the E-field strength inside the cell. For the TEM mode, $E_x = E_z = 0$ at the center of the cell's test zone.

The data shown for a 1.2 m x 1.2 m x 2.4 m symmetric cell are typical of any cell with the exceptions that larger cells would have proportionally lower multimode/resonant frequencies and hence lower upper useful frequency limits and that small cells would have proportionally higher upper useful frequency limits.

The upper useful frequency of any particular cell may be expanded by using a matrix of isotropic probes to map the complex field around an EUT inside the cell at multimode frequencies or by using metal blade tuners in the cell similar to what is used in reverberating enclosures [11], for mode stirring multimoded test fields. Each of these ideas is under evaluation at NBS with the additional objectives of reducing the measurement uncertainty, especially at frequencies above the cell multimode/resonant frequencies, and of increasing the size of the EUT that could be tested in a particular cell.

4. RADIATED SUSCEPTIBILITY MEASUREMENTS

One definition of susceptibility is the characteristic of being influenced or affected by electromagnetic energy. Radiated susceptibility measurements are performed by subjecting the EUT to a known test field while evaluating its performance. To make these measurements meaningful, they must be repeatable and relate to how the equipment will respond in its operational environment. The TEM cell was developed initially at the NBS as a device for accurately generating known fields for calibration purposes [12]. Because of its ability to excite a uniform, calculable, repeatable test field that can be related to free space, the cell has demonstrated that it is also a useful tool for susceptibility measurements. If a piece of equipment is placed in the cell, it can be subjected to fields of varying levels and waveforms, thus allowing a great deal of flexibility in the measurement plan.

4.1 Using the TEM Cell for Susceptibility Measurements

Both top and bottom halves of the cell can be used for making measurements, but generally the lower half is used. This allows the EUT to be supported on the bottom of the cell instead of on the center conductor. The EUT typically is placed so that its center is midway between the septum and the bottom of the cell and midway between the two side walls as shown in figure 21. This is the region where the TEM field is the most uniform. However, if required or desired, it can be placed almost at any location in the cell. For example, it may be advantageous to place it close to the bottom of the cell, as will be seen later. For best results, the size of the EUT should not exceed more than one third of the distance between the septum and the bottom or one third of the distance between the sides or length of the main body of the cell. This prevents excessive capacitive loading which shorts out part of the vertical test field and distorts the test-field pattern. The one-third criteria were selected because this corresponds to approximately a 2-ohm change in the cell's transmission line impedance and a 3- to 6-dB increase in the susceptibility test field, as shown earlier. This increase in level can be corrected as indicated in section 4.2.3 and Appendix A or with the use of calibrated probes. If a large EUT is inserted into the cell, the cell VSWR increases rapidly, as does the field distortion, making the correction progressively more difficult and less accurate. Not only should the EUT be placed in the cell in a way that does not exceed the size limits for the cell, but it should also be positioned to simulate, as nearly as possible, actual field exposure expected in the EUT's operational environment. This may require orienting the EUT in the cell's vertical E-field to obtain the desired polarization exposure. For example, if the maximum exposure is required and the EUT is rectangular, the edges of the EUT should be positioned vertically to give maximum coupling to the vertical field. Thus, the EUT would have to be repositioned or rotated along each orthogonal axis to assure that maximum coupling is acquired for each possible path of leakage. More details on placements of the EUT are contained in section 4.4, Measurement Procedures.

4.2 Measurement Plan

The test plan normally will be based on the EM environment and EUT operational requirements. The test plan will include selecting the measurement frequencies, characteristic and signal waveform levels, EUT exposure aspect angles, EUT input/output lead complement, and the measurement approach (swept, pulsed or discrete frequency measurements). The plan should also include defining EUT susceptibility criteria and requirements for monitoring failure modes.

4.2.1 Determine the Test Frequencies and Measurement Approach

If the operational environment of the EUT is known, then the selection of test frequencies simply becomes one of choosing frequencies that correspond with significant characteristics of the environment. Often, however, the environment is not sufficiently characterized such that specifications could be chosen, or the EUT may be mobile so that the environment is changing. Then more comprehensive testing may be required. Equipment susceptibility to EMI is primarily determined by the degree to which the interference field couples into and interacts with the equipment's components. This undesired coupling is influenced by a number of equipment parameters such as: input/output, power line, and circuit lead impedances and lead lengths; impedances of circuit components (especially those terminating lead wires); type of circuit components (particularly active components); and amount and type of EMI shielding and filtering used. The susceptibility of any particular equipment is frequently a function of frequency, suggesting resonance effects within the equipment with its input/output leads and other interconnected equipment. These resonance cases may be caused, for example, by the reactance of the connecting leads acting as an antenna, coupling with the input impedance of the terminating circuit components. The quality factor (Q) of such a resonant circuit determines the maximum spacing or increments between frequencies at which susceptibility tests must be performed. For example, a circuit Q of 40 (typical in many electronic systems) requires tests at increments of 18% in frequency between 0.5 to 10 MHz, 4.8% between 10 and 20 MHz, 2.4% between 20 and 50 MHz, 1.6% between 50 and 150 MHz, and 1.2% between 150 and 1000 MHz to characterize the circuit resonances. This calls for 310 measurements, perhaps not excessive for prototype evaluations, but certainly too many for production testing unless the total measurement process is automated.

Automated systems using minicomputer control are (by their digital nature) discrete frequency systems. The number of test points one can obtain using such a system is limited by the memory/storage capacity of the computer and the measurement system bandwidth. These limitations can be partially overcome by choosing frequency and amplitude measurement intervals compatible with the test system and the number of test points required. Computer-automated systems obviously are very efficient, effective tools for obtaining equipment susceptibility data; however, they can also be very costly.

Swept frequency susceptibility testing systems are also very useful in obtaining test data. These systems have the advantage of complete frequency coverage within the systems' bandwidths, but they lack computation capabilities for data analysis that are possible with computer-controlled systems.

An important precaution that must be exercised when using swept frequency testing is to insure that the frequency sweep rate is slow enough to allow adequate time for the EUT to respond, if susceptible, to the test field.

Some EUT's have components with relatively slow thermal time constants. This equipment must be exposed to test fields with sufficient duration to allow reaction/interaction; otherwise susceptibility tests may not be true indicators of the equipment's vulnerability. For example, some electronic systems require one to two seconds' exposure time for maximum response. Swept testing, however, has some obvious advantages over stepped or discrete frequency testing as demonstrated in figure 22. The solid line in the figure shows a typical plot of an EUT resonance response using swept measurements. The dashed line represents results of the the same tests performed using the stepped frequency approach. The stepped approach shows a peak at 102 MHz but has missed the resonant peak at 101.6 MHz. If the stepped approach were used and greater resolution were required, further testing with smaller frequency increments would have to be done in the frequency range 101 to 103 MHz.

Once again, determining the type of exposure fields to which an EUT should be subjected is very EUT dependent. Such determinations should be made for each type of equipment, considering its application and its planned operational environment. The waveform to which an EUT is exposed can have a pronounced effect upon its susceptibility. Some EUT's, for example, are not bothered by relatively strong cw fields but can be interfered with if the signal is modulated. An example of this type of interference is the demodulation of an amplitude modulated (AM) signal by a solid-state device. If the EUT uses AM and incorporates solid-state switching, the AM on the cw carrier can be demodulated by the switches and coupled into the audio circuits of the EUT. In this case, the cw carrier is not the cause of the interference, but rather the interference is a result of the interaction of the switches with the AM signal.

Another extremely important common source of interference is transient spikes on impulsive signals that get coupled into an EUT. These spikes can have considerable energy over large frequency bandwidths and are difficult to accurately simulate. TEM cells offer a useful tool for this type of testing.

4.2.2 Establish EUT Failure or Performance Degradation Criteria

Performance degradation or failure in an EUT typically relates to its compliance with a required performance specification. If the EUT's performance deviates outside these specification limits (for example, in its output or its ability to respond properly to input) when subjected to an interfering field, then it is termed susceptible. Susceptible modes for each EUT must be defined relative to a measurable response that can be monitored in a repeatable, meaningful way for a practical range of test conditions representative of typical operational environmental conditions.

4.2.3 Establishing the Exposure Field Levels as Required for the Tests

Normally, the electric field strength, E, is determined relative to the reference position at the center of the test zone in the cell. This determination is made with the cell empty. However, they represent the field exposure to which the EUT is subjected if the EUT is small (less than 2a/5, b/5, L/5).

The electric field strength, E_0, at the reference point halfway between the septum and floor in the center of the cell can be determined simply by measuring the voltage potential, V, between the center plate and the cell's outer wall. The electric field is given then as:

$$E_o = \frac{V}{b} , \tag{5}$$

where b is the separation distance between the center plate and the lower or upper wall. If the EUT is not small, the EUT will effectively short out part of the vertical separation, b, between the plates resulting in an increase in the exposure field. This new E_0' (with the EUT in the cell) can be found by determining the new effective separation distance, b', given as: b' = b - h, where h is the effective width of the EUT between the plates. E_0' then is equal to V/b'. Actually, unless the EUT's length and width occupied the full length and width dimensions of the cell, and the EUT case was metal (highly conductive), the effective height of the EUT is not as large as its physical height. The effective separation distance b' is then determined by measuring the distributed impedance of the TEM cell as a transmission line after inserting the EUT inside. This measurement is made using a time domain reflectometer (TDR). The value of the cell transmission line impedance in the section occupied the EUT is then used with eq (1) to compute b' and hence E_0'. An, example, computation of b' and E_0' based on TDR measurements is contained in Appendix A. If a TDR is not available or it is not convenient to make this impedance measurement, b' can be estimated by measuring the exposure field level at the center of the cell test zone, without the EUT in the cell, using a small dipole probe [10]. The probe's output voltage is then recorded and used as a reference to compare measurements of the exposure field made using the probe with the EUT in the cell similar to the example shown in figure 14.

If the test frequency is high enough that the wavelength, λ, is not significantly greater than the cell length ($\lambda \leq 10L$), the voltage, V, measured at the input or output port of the cell may be significantly different than the voltage potential at the center of the cell based upon the cell's VSWR. This would result in an error proportional to the VSWR or cell mismatch impedance. At frequencies for which $\lambda \leq 10L$, a more accurate determination of the E-field reference to the center of the test zone can be made by measuring the net input power to the cell, P_n, and its complex impedance. The E field is then given as:

$$E_o = \frac{\sqrt{P_n R_c}}{b}, \text{ or } E_o' = \frac{\sqrt{P_n R_c'}}{b'} \tag{6}$$

where R_c and R_c' are the real part of the cell's characteristic impedance referenced to the center of the cell with or without the EUT inserted in the cell.

P_n is determined from the power meter readings on the sidearms of a calibrated bi-directional coupler using the following equation

$$P_n = CR_f \cdot P_i - CR_R \cdot P_r \tag{7}$$

where CR_f and CR_R are the forward and reverse coupling ratios of the bi-directional coupler and P_i and P_r are the indicated incident and reflected coupler sidearm power meter readings.

The electric field, $E_{x,y}$ at any cross sectional location inside the cell can be determined, relative to the field, E_0, at the center of the test zone by the expression:

$$E_{x,y} = \frac{\sqrt{P_n R_c}}{b} \tilde{E}_{x,y} \text{ or } E'_{x,y} = \frac{\sqrt{P_n R_c'}}{b'} \tilde{E}_{x,y} \tag{8}$$

where P_n, R_c and b are as previously defined and $E_{x,y}$ can be obtained from tables 1 to 8. These tables can be used to calculate the transverse and vertical components of the electric field, as well as the magnitude and polarization angle of the electric field defined by:

$$E_{x,y} = \sqrt{E_x^2 + E_y^2}, \text{ and } \theta = \arctan \frac{E_y}{E_x} \tag{9}$$

For example, from table 3, $\tilde{E}_{x,y}$ is equal to 0.853 for the center of the EUT located at position A as shown in figure 27 inside a square cell. If the EUT is moved to position B, in figure 27, the correction factor is 1.157.

The absolute accuracy with which $E_{x,y}$ can be established is defined by the simple relationship

$$E''_{x,y} = E_{x,y} \pm \Delta E_{x,y} \tag{10}$$

where $\Delta\tilde{E}_{x,y}$ is the error in determining $E_{x,y}$.

The value of $\Delta E_{x,y}$ can be found by evaluating each independent variable, P_n, R_c, b, and $\tilde{E}_{x,y}$ in expression (8) as follows:

$$\Delta E_{x,y} = \frac{\partial E_{x,y}}{\partial P_n} \Delta P_n + \frac{\partial E_{x,y}}{\partial R_c} \Delta R_c + \frac{\partial E_{x,y}}{\partial b} \Delta b + \frac{\partial E_{x,y}}{\partial \tilde{E}_{x,y}} \Delta \tilde{E}_{x,y}. \tag{11}$$

where,

$$\frac{\partial E_{x,y}}{\partial P_n} = \frac{1}{2} E_{x,y} \frac{1}{P_n}, \quad \frac{\partial E_{x,y}}{\partial b} = -\frac{E_{x,y}}{b}$$

$$\frac{\partial E_{x,y}}{\partial R_c} = \frac{1}{2} E_{x,y} \frac{1}{R_c}, \quad \frac{E_{x,y}}{\tilde{E}_{x,y}} = \frac{E_{x,y}}{\tilde{E}_{x,y}} \tag{12}$$

Substituting eq (12) into (11) and assuming each independent variable could have a positive or negative value, gives the maximum fractional error in determining $E'_{x,y}$ or:

$$\varepsilon_E = \frac{\Delta E_{x,y}}{E_{x,y}} = \frac{1}{2}\left(|\varepsilon_P| + |\varepsilon_R|\right) + |\varepsilon_b| + \varepsilon_{\tilde{E}} \tag{13}$$

where

$$\varepsilon_P = \frac{\Delta P_n}{P_n}, \quad \varepsilon_R = \frac{\Delta R_c}{R_c}, \quad \varepsilon_b = \frac{\Delta b}{b}, \text{ and } \varepsilon_{\tilde{E}} = \frac{\Delta\tilde{E}_{x,y}}{\tilde{E}_{x,y}}$$

Higher order terms contributing to small erorrs were dropped in the derivation of eq (13).

The error ε_P, in determining P_n is due to uncertainties in coupler calibration, absolute measurement of rf power on the side arm of the coupler, and impedance mismatch between the cell, coupler, rf source, and cell termination. If a precision calibrated coupler and power meter are used and the cell and its termination are impedance matched (VSWR $\leq$ 1.05), ε_P should be less than $\pm$5%.

The error, ε_R, in determining R_c is a function of the measurement accuracy of the TDR, the impedance loading of the EUT inside the cell, and the test frequency. Obviously, if the test frequency is low enough that the electrical length of the cell is small, R_c will be the real part of the cell's termination impedance. As the frequency increases and the length of the cell becomes electrically significant, the impedance at the location of the EUT, as measured by the TDR, becomes significant. If the EUT occupies a small portion ($\leq$ one fifth) of the cross section of the cell, ε_R is small ($\leq$ 3%) and is typically neglected in the calculation of $E_{x,y}$. For larger EUT's (occupying up to one-third of the cross section of the cell) and at frequencies where the cell length is less than $\lambda/10$, the impedance loading effect must be determined with the TDR and used to correct R_c when using eq (6) to calculate E_o. ε_R for these cases can be much larger but typically would be less than 10% if the EUT were centered inside the cell. Exceeding the one-third load factor is not recommended. The error, ε_b, is proportional to the accuracy in physically measuring b or for significantly large EUT, in determining the effective separation distance, b'. This is estimated at approximately $\pm$1%. Error in excess of this is reflected in the estimate of $\varepsilon_{\tilde{E}}$.

Determining $\varepsilon_{\tilde{E}}$ can be difficult. Introducing the EUT inside the cell perturbs the electric field distribution as described in the section on field mapping. This loading factor (increase in E_v) can be determined using small calibrated probes, to measure the increase in the field around the EUT relative to the undisturbed field, or it can be approximated by estimating a new value for b' as discussed earlier.

The value of $\varepsilon_{\tilde{E}}$ is also influenced considerably by the form factor (ratio of cell width to the separation distance between the septum and its outside, parallel walls) and by the size of the EUT. If the EUT is small (less than b/5, 2W/5 and L/5; see figure 5 or 12), the cell's test-field distortion will be small, and the main contribution to $\varepsilon_{\tilde{E}}$ will be due to the test-field gradient between the septum and parallel wall. For this case, the sources of errors are summarized in table 9 for both asymmetric and symmetric cells. If the EUT exceeds the 1/5th factor, measurements of the field distribution around the EUT must be made in order to estimate ε_E. When making these measurements, one must realize that the EUT always interacts somewhat with the exposure field in any environment. Sorting out this open-field scattering effect, caused by the EUT/field interaction, from the perturbation. effect of the EUT/field/cell interaction is difficult and results in higher estimates of $\varepsilon_{\tilde{E}}$. These estimates, of course, are unique to each EUT and are not included in table 9.

The problem of EUT/test field/transducer interaction is not unique, of course, to using TEM cells for susceptibility testing. The problem exists to some degree (great or small) depending on how and in what environment test fields are created and thus, in which the EUT is tested. Susceptibility tests performed, for example, in conventional shielded enclosures using antennas to irradiate the EUT suffer serious errors from this effect, as mentioned in the introduction.

Equation (8) is applicable only to single-mode (TEM-mode) operation of the cell. If the cells are used with absorber loading at multimode frequencies, additional errors will exist that must be evaluated. Then, the most likely approach is to use calibrated isotropic probes to measure the field distribution in the cell rather than to calculate the field level from measured input parameters. This would be done in much the same manner as probing the field around the EUT to determine field perturbation for estimating ε_E. A careful evaluation of uncertainties involved in using a matrix of calibrated probes to determine the test field distribution around the EUT in the cell's test zone is needed and is anticipated in the near future.

The sources of errors for the three different cell geometries are summarized in table 9.

4.3 Susceptibility Measurement Set-Up

Figures 23 and 24 show two block diagrams of systems using the TEM cell for susceptibility measurements. Figure 23 is used for frequencies below 1 MHz and figure 24 is used for frequencies above 1 MHz. Both systems are configured for swept frequency testing; however, either system could be used for discrete frequency testing without the use of the xy recorder or a sweep-type generator.

The high-power generator generally consists of a variable frequency generator and high-power linear amplifier. Most of today's linear amplifiers have built-in protection circuits which protect them in the event the cell system becomes impedance mismatched. The low-pass filter is needed to keep unwanted higher frequency components (second, third, etc., harmonics) from being introduced into the cell. This is especially important if the harmonics or spurious frequencies are above the multimode or resonant frequency limit of the cell. A frequency counter is used to tell precisely at what frequency a failure occurs. This can be important if the signal generator frequency calibration is not sufficiently accurate since EUT susceptibility often is characterized by high Q-resonances which have very narrow frequency responses. The dual coupler and power meters are used to measure the incident and reflected power at the input of the cell. A test monitor is shown with the EUT and is used to determine failure of the EUT. A 50-ohm, high-power load is used to terminate the system.

The main difference between figures 23 and 25 is the use of an rf voltmeter with monitor tee in place of the directional coupler and power meters. This is required at frequencies below 1 MHz because of the lack of availability of low-frequency, high-directivity (below 1 MHz), bidirectional couplers. At frequencies below 1 MHz, the cell is electrically small (i.e., much less than one wavelength), and accurate voltmeter measurements, which can be referred to the EUT location at the center of the cell, can be made.

Automated, interactive, susceptibility measurements can be made by using a minicomputer controlled system as shown in figure 25. This system places the testing operation under control of the computer which progressively increases the test-field level in the cell at selected test frequencies while monitoring the test-field level around the EUT and the performance of the EUT. If degradation occurs as determined from preestablished, programmed criteria, the computer can respond by limiting the test-field level to prevent damage to the EUT. The computer, also according to software instruction and format, will print out the susecptibility information. Such a system using a large 3 m x 3 m x 6 m TEM cell is under development at NBS and will be operational in the near future.

4.4 Radiated Susceptibility Measurement Procedures

The following measurement procedures are suggested as a systematic approach for evaluating the EM radiated susceptibility of equipment using a TEM cell.

Step 1. Place the EUT inside the cell.

> Normally the cell is placed in one of two locations in the lower half space (below the septum) centered in the cell. The first location (location 1) is halfway between the septum and the cell bottom as was shown in figure 21. The EUT is supported on dielectric material with as low a dielectric constant as possible. For example, plastic foams with a dielectric constant of approximately 1.04 to 1.08 are almost invisible electrically and make good support material.

The second common location (location 2) for placing the EUT is on the floor of the cell (fig. 26), but insulated from it (unless grounding the EUT case to the cell is desired). This position is used to minimize exposure of the EUT's input/output leads and monitor leads to the test field as explained in step 5. If the EUT is placed near the floor of the cell, the test field will be lower, relative to the field at the center (midway between the septum and floor) of the cell test zone. A correction for determining this field can easily be made as discussed in section 4.2.3.

Place the EUT in either location 1 or 2 and orient the EUT as desired relative to the cell's TEM field. Normally, the first orientation position is with the EUT lying flat as in normal use.

Step 2. Access the EUT as required for operation and performance monitoring.

The EUT input/output and ac power leads should be as nearly the same as in its anticipated use. Leads should be the same length, if possible, and be terminated into their equivalent operational impedances so as to stimulate the EUT in its operational configuration. Care must be taken in routing the leads including monitor leads (if nontransparent to the rf field) inside the cell for the most meaningful, repeatable results (i.e., desired lead exposure, minimum field perturbation/interaction, etc.). To minimize exposure of the leads to the test field, the EUT should be lowered as close to the cell floor as possible and its leads should be routed along the floor of the cell in appropriate holders, to the bulkhead panel and ac receptacle, as shown in figure 26. Shield the leads by either taping the leads to the cell floor with 2" wide conductive tape or by using braided wire slipped over the lead. Note, keep the leads separate; do not bundle input/output, monitor, and ac power line leads together. Twist the leads if they cannot be kept separated. If braided wire is used be sure braid is in electrical contact with the cell floor. However, care must be taken to prevent the braided shield or tape from contacting the case of the EUT unless, once again, a common ground between the EUT and cell is required. Grounding the two together will obviously influence the results of the susceptibility measurements. Connect the EUT input/output and monitor leads to appropriate feed-through, filtered connectors for accessing and operating the EUT. Input/output leads should be filtered to prevent rf leakage into or out of the cell, which would reduce the shielding integrity of the measurement system. The monitor leads must also be accessed through the bulkhead as appropriate for the measurement requirement. These leads, which are used for sensing and telemetering the performance of the EUT while exposed to the test fields, may require special "invisible," high-resistance leads made of carbon-impregnated plastic [10] or fiber optics lines to prevent perturbation of or interaction with the test environment. DC signals or signals with frequency components below 1 KHz may be monitored via the high-resistance lines. RF signals should be monitored via fiber optic lines.

If the monitor signal is at a frequency or frequencies sufficiently different from the susceptibility test frequency or frequencies, conductive (hard wire) leads may be used with appropriate filtering (high-pass, low-pass, band-pass, etc.) at the bulkhead. Note that a separate, shielded filter compartment should be provided on the outside of the cell for housing the filters as shown in figures 21 and 26.

Step 3. Connect up the measurement system as shown in figure 23 or figure 24.

Step 4. With the cell rf input source turned <u>off</u> and the EUT turned on in the desired operational mode, record the EUT monitor response and initialize (zero) the test-field measurement instrumentation.

Step 5. Select the first test frequency, modulation rate, test waveform, etc., turn the cell rf source on, and slowly bring up the field level inside the cell until: a) the EUT response monitor(s) indicate susceptibilityθ or b) the maximum required test level is obtained. Note: Do not increase test level too fast. Sufficient time must be spent at each test level to allow the EUT to respond. Record the monitored response.

Step 6. Select the next test frequency, modulation rate or test waveform, etc., and repeat procedures of step 5 until all frequencies, modulation levels and rates, and waveforms required by the test plan are complete. Note: It may be desirable to select specific test levels and sweep the frequency range of interest at these levels while monitoring the EUT response. If this procedure is used, the following precautions must be exercised: a) the sweep rate must be slow enough to allow the EUT to respond (remember, susceptibility often is due to resonance in the EUT circuits, leads, or apertures in its case); and b) the selected test level must not be too high or damage may occur to the EUT.

Step 7. If exposure to interference fields of the EUT input/output and ac power line leads occurs in actual use, these leads should be raised from the floor of the cell and extended inside the cell, matching polarization as much as allowed. Care must be taken to clamp the leads with dielectric supports so they can be placed in the same location (exposure) if the EUT is taken out and then returned to the cell. Both the EUT placement locations and orientation, and the input/output ac power line leads placement locations and orientations must be carefully recorded in order to obtain repeatability when reevaluating the susceptibility characteristics of an EUT. This is true no matter what the test environment (e.g., shielded enclosure, TEM cell, anechoic chamber, etc.) since EUT susceptibility obviously is a function of how the interference is coupled into the EUT (e.g., EUT exposure aspect angle relative to interference polarization, etc.). With the EUT leads now exposed to the test field, steps 4 through 6 should be repeated. NOTE: Performing step 7 as a separate procedure provides information on how the interference fields are coupled into the EUT.

Step 8. Next, the EUT should be reoriented from position 1 (flat, normal operating position) by laying it on its side or on its end. All three orthogonal orientations of the EUT may need to be tested in the cell. This is required to expose each surface of the EUT, matching polarization to the TEM field of the cell. After changing the EUT orientation, steps 2, 4, 5, 6, and 7 should be repeated.

Note: If the field close to the EUT is monitored, using, for example, small calibrated electric and/or magnetic field probes, the measured results must be interpreted carefully. This is because such measurements are made in the near field of the scattered field from the EUT and its leads. This field can be stronger than the test field (TEM field) launched inside the cell, and erroneous results or conclusions may result.

Not all the tests outlined in this measurement procedure may be required, and only those required by the test plan should be performed. For example, if the objective of the measurement program is to reduce the vulnerability (susceptibility) of the EUT, one EUT orientation with one input/output lead configuration could be tested in one particular operational mode to a preselected susceptibility test-field waveform and amplitude. Then, if corrective measures were made to the EUT and placement of the EUT and its leads inside the cell were carefully duplicated, repeat measurements could be made. These measurements could then be compared to determine degree of improvement.

5.0 RADIATED EMANATIONS MEASUREMENTS

Electronic or electromechanical equipment or components may emit energy which interferes or interacts with the normal operation of either the system and/or other receptors. To insure the electromagnetic compatibility (EMC) of such systems, it is important to determine the amplitude levels of these emanations and to characterize their waveform, polarization, etc. This is apparent since equipment performance degradation or failure is often dependent upon the interference signal waveform and the signal's amplitude.

A TEM cell is especially useful for emitted signal waveform characterization because of its characteristic as a TEM transducer which permits detection of the signal with little or no distortion in the signal waveform.

5.1 Using the Cell for Radiated Emanations Measurements

TEM cells are reciprocal devices (i.e., can receive or detect radiated fields from equipment as well as establishing fields for testing). Thus, energy radiated from an EUT placed inside the cell will couple via the TEM mode characteristics to the cell's output/input ports. If both cell ports are terminated into 50-ohm matched impedances (detectors or terminations) and if the cell is symmetric and has negligible insertion loss, one half of the EUT's radiated energy will appear at each port. This energy can be measured, for example, by using a spectrum analyzer or receiver (frequency-domain measurements) on one port and an oscilloscope (time-domain measurements) on the other port. The voltage measured at the ports, V_m, is then given as:

$$V_m = \sqrt{\frac{P'_R \times Z_o}{2}} \tag{14}$$

where P'_R is the power radiated by the EUT inside the cell, and Z_o is the cell characteristic impedance.

5.2 Determining the Free-space Equivalent Radiated Field Strength from the EUT Based on Measurements Made with the EUT Inside the TEM Cell.

The radiation characteristics of an EUT mounted inside a shielded, reflective environment will change relative to the EUT's free-space radiation characteristics. This change can be determined approximately when using a TEM cell as follows:

Experience with measuring the directivity of radiation sources (EUT's) indicates that they can be approximated reasonably well as electrically small dipole sources for frequencies at which the cell is normally used. With this assumption, the change in radiation resistance due to inserting the EUT onto the cell becomes [5]:

$$\frac{R'_a}{R_a} = \frac{3\pi}{2}\frac{Z_o}{\eta_o}\left[\frac{\tilde{E}\cos\theta}{K_o b}\right]^2 \tag{15}$$

where:

R_a' is the radiation resistance of the EUT when mounted inside the TEM cell;

R_a is the radiation resistance of the EUT in a free-space environment;

Z_o is the cell characteristic impedance;

η_o is the intrinsic wave impedance = 120π ohms in the cell;

$\tilde{E}$ is the normalized electric field inside the cell relative to the field strength at the center of the cell test region, (i.e., $E = (E_o)/(V/b)$;
cos θ corresponds to the polarization match between the radiated field from the EUT and the TEM mode field characteristics of the cell (maximum coupling occurs if the radiated energy from the EUT is polarization matched to the TEM field of the cell, or $\cos\theta = 1$);

K_o is equal to $2\pi/\lambda_o$ where λ_o is the wavelength of the radiated signal; and

b = separation distance between septum and lower or upper wall.

If P_R is the power radiated by the EUT in a free-space environment and P_R' is the power radiated by the EUT in the TEM cell, then:

$$P_R' = P_R \, K^2(I) \frac{R_a'}{R_a} \tag{16}$$

where

$$K(I) = \frac{I_R'}{I_R} , \tag{17}$$

and corresponds to the change in the EUT radiation current caused by enclosing the EUT inside the confining environment of the TEM cell. The value of K(I) is affected by the size of the EUT relative to the size of the cell. If the radiation aperture is small, the EUT radiation current distribution will be essentially the same as for open-space conditions and K will be approximately equal to one. One can determine the open-space radiated electric field strength, E_D, at a distance, d, from the EUT, assuming far-field conditions, from the expressions:

$$E_D = \sqrt{\eta_o P_D} , \tag{18}$$

$$P_D = \frac{GP_R}{4\pi d^2} , \tag{19}$$

where:

P_D is the radiated power density at the distance, d;

P_R is the power radiated from the EUT;

G is the gain characteristics of the EUT; and

$_0$ again is the instrinsic wave impedance.

Combining eqs (14 through (19) gives:

$$E_D \cong \frac{2b\ \eta_0 V_m}{\lambda_0\ dZ_0\ K(I)\ \tilde{E}\cos\theta} \sqrt{\frac{G}{3}} \tag{20}$$

This equation then gives the field intensity in the direction of maximum radiation (i.e., maximum E_D) assuming far-field conditions. An example computation of E_D based on the measurement of emissions from a spherical dipole emitter placed in a TEM cell is contained in Appendix B. The radiation intensity very close to the EUT (small d) is influenced by the reactive near-field components; hence, E_D will be in error. Equation (20), however, should be valid for separation distances as small as $\lambda/2$, since the EUT must be electrically small (longest dimension less than $\lambda/6$) in order to satisfy the criteria that the EUT dimension be less than b/3, 2a/3 and L/3, when placed inside a TEM cell at frequencies below the cell's multimode cutoff. Some work has been done to test experimentally the validity of eq (20) and the limitations of the assumptions applicable to its use for correlating TEM cell measurements to open-space measurements [13]. However, additional work is needed. Work is progressing to develop a "standard radiator" that can be analytically characterized and used to empirically determine the change of its radiation characteristics (relative to open space) by inserting it into a cell. This radiator is completely self-contained (i.e., housing its own power supply, rf source, amplifier, and impedance matching network inside its radiating structure). Results of this development should be available in the near future.

It should also be noted that eq (20) is not valid at frequencies above the first resonant frequency of the cell. At these higher frequencies, distortion in the TEM field characteristics exists. This distortion, however, can be minimized by using rf absorber to suppress the cell resonance and higher order multimoding.

Additional work is also needed to determine analytically the change in the current distribution of the radiator (EUT structure, wiring harness, etc.) as a function of its electrical size caused by confining it inside the TEM cell. This problem is a very complex one and will require simplifying approximations, at least initially. A second effort will be to evaluate this change experimentally. This will require the use of special current and field measuring probes to determine the current distribution of the complex, radiated near field of the radiator, before and after it is confined in the cell, for comparison. Once this effort is completed, an error analysis will be performed to establish the absolute measurement uncertainties of the TEM cell radiated emanation technique.

5.3 Formulating the Measurement Plan

Formulating the measurement plan requires determining the EUT's operational modes and orientations for which tests are to be performed. It also presumes anticipating the types of tests to be performed (frequency domain; spectrum, or time-domain waveform analyses) and the detection system requirements such as bandwidth, sensitivity, etc. If the type of emanation from an EUT is known, the measurements can be simplified, and the selection of an rf detector that will give the most accurate, meaningful information can be made.

There are, in general, two types of interference emanations, narrowband and broadband. There are a great many definitions for each of these terms. However, for our purposes, narrowband means that the emanations are contained in a limited portion of the frequency spectrum, normally within the bandwidth of the detection system. Broadband emanations are produced over a large portion of the spectrum and may have signficant amounts of energy extending beyond the detection system's bandwidth. For example, the signal shown in figure 28 would be classified as a narrowband signal if the difference in frequency between f_1 and f_2 were only a few KHz. This type of signal could be the carrier of an AM broadcast station or the emanation from a local oscillator in a receiver.

Examples of broadband emanations are shown in figure 29. These emanations are impulsive signals which may be periodic or random in time with varying or constant amplitude. Some impulsive emitters are: the brushes of AC motors, switching transients created by turning equipment on or off, keying transients in digital systems, or transmit keying of tranceivers. Such emanations may cover a frequency spectrum from a few KHz to over 1 GHz.

In general, the detector and transducer selected to comply with the measurement plan requirements must have sufficient bandwidths and sensitivities to measure the amplitude and frequency or frequencies of the emanations and also must be capable of preserving the waveform characteristics of the emanations. If only the amplitude and spectrum of the emanations are required and the bandwidth of the emissions is less than 3 MHz, spectrum analyzers can be used. If additional detection bandwidth or sensitivity is required, broadband tunable receivers (field intensity meters) may be required. If the emanations are periodic, a real-time oscilloscope can be used either connected directly to the cell to measure the time-domain response or connected to the predetection or postdetection outputs of the broadband tunable detectors, which are connected to the cell, to obtain a real-time display of the emanation. If, however, the emanations are random, special sample and hold detection or statistical sampling may be required to obtain meaningful information [14].

5.4 Measurement Set-Up

The block diagram of a typical measurement system is shown in figure 30. As mentioned earlier, the choice of detectors connected to the cell measurement port is determined by the measurement requirements such as bandwidth, frequency range, and/or time-domain response, sensitivity, etc. If the detector is not sufficiently well matched to 50 ohms, an attenuator can be inserted as shown to provide the equivalent matched termination required by the cell.

Equipment required to operate the EUT inside the cell or to which the EUT must be connected for proper operation is obviously dependent upon the particular EUT and its test requirements. Access to the EUT's input/output leads is by rf-filtered, fed-through connectors located on the outer wall of the cell near the floor as shown in figure 26. (See sec. 4.4, step 2.) Again, this lead complement is EUT dependent and must be established in the measurement plan. Filtered, ac power to operate the EUT (if required) is provided at a shielded receptacle recessed into the outer wall near the bottom of the cell.

5.5 Radiated Emanations Measurement Procedures

The following measurement procedures are suggested for making radiated emanations measurements.

Step 1. Select type of test or measurements to perform (e.g., measurement plan). This includes selection of EUT operational modes for testing, lead complement, and signal detection requirements such as bandwidth, sensitivity, waveform analysis, time domain, etc., and hence detector requirements.

Step 2. Place the EUT inside the cell with desired location and orientation to the TEM field. Instructions for placing the EUT inside the cell are the same as those used for susceptibility testing. See section 4.4, step 1 for details.

Step 3. Access the EUT as required for operation and monitoring. Again, this is similar to instructions described in section 4.4, step 2, for susceptibility testing. The only exceptions would be due to operational requirements of the EUT. For example, waveform analysis of the emitted signal from the EUT may require hardline synchronizing of the detected signal with the input signal to the EUT or to internal signals being processed by the EUT. This requires additional leads to the EUT which must be filtered and routed to minimize their interaction with the EUT and its emitted signal. Routing of these leads should be along the floor of the cell with minimum exposure (polarization mismatched) to the cell's TEM field characteristic. This would be the same as discussed in section 4.4 for placement of the EUT leads for minimum interaction with the test field.

Step 4. Connect the measurement system as shown in figure 30. The detectors (receivers, spectrum analyzer, power meters) should be calibrated as per their instruction manuals and impedance matched to the TEM cell. The 10 dB attenuator shown in figure 30 is connected between the cell and the detector to improve the impedance match.

Step 5. With the EUT switched off, determine the ambient signal level in the cell. This procedure verifies the shielding and filtering integrity of the cell and the EUT input/output leads. It also provides baseline data for the measurement system to establish minimum, detectable signal levels (sensitivity), common mode or grounding problems, and spurious signal determination, which is characteristic of the measurement (detection) equipment. If ground problems or undesired signals exist, efforts should be made to correct for or minimize them. This may require, for example, additional filtering, ac line isolators or conditioners, common or single point grounding, etc.

Step 6. Turn the EUT on in the desired operational mode and measure its radiated emanations as follows.

a) First, determine the amplitude and spectrum of the radiated emanations from the EUT. This can be done with either a spectrum analyzer or a tuned receiver (field intensity meter) connected to one port of the cell with the cell's opposite port terminated into 50 ohms.

b) Using the data obtained in a) perform the required analysis of the emanations at specific frequencies of interest. This can be done, for example, by selecting an emanation of interest, tuning the receiver or spectrum analyzer to it, and then adjusting the measurement bandwidth as required for signal definition and resolution, and recording the measurement results.

c) If time-domain analysis or emanation characterization is required, use the block diagram shown in either figure 31 with the oscilloscope connected directly to the cell measurement port, or the block diagram shown in figure 32, with the oscilloscope connected to the predetection or postdetection outputs of the receiving instrument. The arrangement shown in figure 32 provides greater measurement sensitivity. In both measurement systems (fig. 31 or fig. 32), the oscilloscope must be synchronized with either the periodic detected signal from the cell or with an EUT-monitored periodic signal represented by the dashed line from the EUT. The measurement results can then be recorded by photographing the oscilloscope display.)

d) If the emanation is random, the oscilloscope cannot be synchronized properly. Then the detected signal must be either: 1) recorded with a video disk or tape recorder and played back frame by frame to analyze the emanation; or 2) analyzed statistically using amplitude probability distribution analyzers, etc.

Complete step 6 for each EUT operational mode required.

Step 7. Reorient the EUT as required by the test plan and repeat steps 3, 5, and 6.

Step 8. If required, change orientation of EUT input/output and ac power cords used in the cell and repeat step 3, 5, and 6. Note, keep in mind the importance of careful placement of the lead to assure repeatability of measurement results.

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Appendix A

Sample calculations of b' and $E'_{x,y}$ for Susceptibility Testing (correcting test field level for loading effect of EUT).

The following is a sample calculation for determining the corrected, effective separation distance b' and hence the electric field, $E'_{x,y}$ inside a TEM cell after inserting an EUT.

From equation (1) of this technical note, the empty cell's impedance was given as:

$$Z_o = \frac{376.7}{4\left[\frac{a}{b} - \frac{2}{\pi}\,\ell n\left(\sinh\frac{\pi g}{2b}\right)\right] - \frac{\Delta c}{\varepsilon_o}} \tag{A-1}$$

The equation parameters a, b, and g were defind in the main body of the text.

The cell's impedance after inserting an EUT with its image in the oposite half space of the cell as shown, for example in figure A-1 is:

$$Z'_o = \frac{376.7}{4\left[\frac{a}{b'} - \frac{2}{\pi}\,\ell n\left(\sinh\frac{\pi g}{2b'}\right)\right] - \frac{\Delta c}{\varepsilon_o}} \tag{A-2}$$

The parameter, b', is the effective separation distance between the cell septum and outer wall, and is the parameter to be determined. Taking the ratio of Z_o/Z_o' and assuming $\frac{\Delta c}{\varepsilon_o}$ is negligible gives the expression:

$$\frac{Z_o}{Z'_o} = \frac{\frac{a}{b'} - \frac{2}{\pi}\,\ell n\left(\sinh\frac{\pi g}{2b'}\right)}{\frac{a}{b} - \frac{2}{\pi}\,\ell n\left(\sinh\frac{\pi g}{2b}\right)} \tag{A-3}$$

To find b', measure the distributed impedance of both the empty cell and the cell with the EUT and its image using a time domain reflectometer (TDR). Assume for the purpose of this example that the EUT is to be susceptibility tested in the cell of figure 5. Assume that the impedance of this cell, measured by the TDR in the section of the cell to be occupied by the EUT, is 50.5 ohm with the cell empty and 48.3 ohms with the EUT and its image inside the cell. We can compute the effective separation distance b' as follows:

For this cell, a = 0.6 m, b = 0.6 m, and g = 0.104 m.

Substituting these values along with the measured value for Z_o and Z'_o into equation (A-3) we obtain:

$$\frac{50.5}{48.3} = \frac{\frac{0.6}{b'} - \frac{2}{\pi}\ln\left(\sinh\frac{0.104\pi}{2b'}\right)}{1 - \frac{2}{\pi}\ln\left(\sinh\frac{0.104\pi}{1.2}\right)}$$

or

$$1.902 = \frac{0.6}{b'} - .637\left(\ln \sinh \frac{0.163}{b'}\right) \quad \text{(A-4)}$$

Equation A-4 can now be solved numerically to obtain the value of b', which is approximately 0.50.

If it is inconvient to place a second equivalent EUT inside the cell to serve as an image for the principle EUT when measuring Z_0', the following approximation can be used. Measure the distributed impedance Z_0'', with only the EUT (no image) inside the cell.

Then:

$$Z_0 - 2\Delta Z_0 \cong Z_0' \quad \text{(A-5)}$$

where

$$\Delta Z_0 = Z_0 - Z_0''$$

or

$$Z_0' \cong 2Z_0'' - Z_0$$

The approximate value, Z_0', the symmetrically loaded impedance, can then be calculated and used to obtain the corrected equivalent separation distance b'. For example, Z_0'' measured, for the sample calcuation of b' given above was 49.4 ohms. or computing the approximate value of Z_0'gives

$$Z_0' \simeq 2(49.4) - 50.5 = 48.3\ \Omega$$

If the EUT is centered in the test zone of the cell, midway between the septum and floor, we can obtain the value of $E'_{x,y}$ from equation (8) as.

$$E'_{x,y} = \frac{\sqrt{P_n R_c'}}{b'}\tilde{E}_{x,y} = \frac{\sqrt{48.3\ P_n}}{0.5} = 13.9\sqrt{P_n}\ \text{volts/meter} \quad \text{(A-6)}$$

where $\tilde{E}_{x,y}'$ is equal to 1 at this location in the cell. For the empty cell, $E_{x,y}$ is given as.

$$E_{x,y} = \frac{\sqrt{P_n R_c}}{b}\tilde{E}_{x,y} = \frac{\sqrt{50.5\ P_n}}{0.6} = 11.8\sqrt{P_n}\ \text{volts/meter} \quad \text{(A-7)}$$

the ratio of

$$\frac{E'_{x,y}}{E_{x,y}} = 1.18$$

This represents again for this particular EUT located at the center of the test zone, inside this particular cell, a 1.44 dB correction to the E-field, $E_{x,y}$, computed from the power measured at the cell's input port.

If the EUT was located in the center of the cell, but near the cell floor (position A indicated in figure 27) and if the impedance loading caused by the EUT inside the cell is the same as the above example, the corrected electric field strength, $E'_{x,y}$ is:

$$E'_{x,y} = 13.9 \quad P_n \; (.853) = 11.86 \quad P_n \text{ volts/}_{\text{meter}} \qquad \text{(A-8)}$$

where $\tilde{E}_{x,y}$ is equal to 0.853 at this location in the cell. This value, for $\tilde{E}_{x,y}$ was obtained from table 3 of this technical note which gives the magnitude of the normalized electric field as a function of cross section location in a square TEM cell.

The value of the electric field strength, $E_{x,y}$ at postion A in the empty cell is:

$$E_{x,y} = 11.8 \sqrt{P_n} \; (.853) = 10.07 \sqrt{P_n} \text{ volts/}_{\text{meter}} \qquad \text{(A-9)}$$

The ratio, $\dfrac{E'_{x,y}}{E_{x,y}}$ then is $\dfrac{11.86\sqrt{P_n}}{10.07\sqrt{P_n}} = 1.18$

This correction factor, for the loading effect of the EUT, is the same for either test location of the EUT.

Appendix B

Evaluation of cell reciprocity and calculation of field intensity, E_D relative to open space for radiated emissions testing.

The following demonstrates the reciprocity of the TEM Cell for use in performing radiated emissions measurements. It also gives a sample calculation for determining the field intensity, E_D, relative to open space, of radiated emissions measurements made with an EUT placed inside a TEM Cell. For this example, a 10 cm spherical dipole radiator was placed at four different locations inside the cell of figure 5 as shown in figure B-1. The dipole radiator operates at a fundamental frequency of 30 MHz with harmonics up to approximately 500 MHz. Spectrum analyzer displays of the detected emissions from the dipole, measured at one of the output ports of the cell are shown in figure B-2. The opposite port of the cell was terminated into 50 ohms. Note, that the relative amplitudes of the four traces are comparable at frequencies below the multimode/resonance frequencies (240 MHz) of this cell. The small differences in detected amplitude as a function of dipole placement location in the cell, at frequencies below 240 MHz, corresponds to the TEM field distribtuions shown for this cell in figure 9 and tables 1-4. This demonstrates the reciprocity of the TEM cell.

To calculate the field intensity, E_D, relative to open-space, for the radiated emissions from the EUT, we use equation (20) from section 5.2.

$$E_D \cong \frac{2b\,\eta_o\,V_m}{\lambda_o\,d\,Z_o\,K(I)\,\tilde{E}\cos\theta}\sqrt{\frac{G}{3}} \qquad \text{(B-1)}$$

For measurements made using the cell of figure 5, equation (20) or (B-1) simplifies to

$$E_D \cong \frac{(2)\,(0.6)\,(376.7)\,V_m}{(50)\,\lambda_o\,d\,\;K(I)\,\tilde{E}\cos\theta}\sqrt{\frac{G}{3}}$$

For the spherical dipole radiator, the maximum directive gain, G, is 1.5. Also, if the polarization of the dipole is matched to the TEM field polarization in the cell, Cos θ will be 1. In addition, since the dipole is small compared to the test volume inside the cell, the dipole current distribution for the radiator will be essentially the same as for open-space conditions, hence K(I) will be approximately 1.0. Then equation (B-1) becomes (for this cell and EUT).

$$E_D \cong \frac{(1.2)\,(376.7)\,V_m}{(50)\,\lambda_o\,\;d\,\;(1)\,\tilde{E}(1)}\sqrt{\frac{1.5}{3}}$$

$$\frac{6.39\,V_m}{\lambda_o\,d\,\tilde{E}} \qquad \text{(B-2)}$$

The detected, measured voltage, V_m at the cell port for the dipole centered in the cell test zone (trace A, figure B-2) is -28 dBM at 30 MHz. This corresponds to a voltage measured with a 50 ohm analyzer of 8.9 mV. At the center of the test zone, E equals 1.0 and at 30 MHz, λ_o is 10 meters.

This equation (B-2) again for this specific emission measured from the spherical dipole ratio inside the 1.2 m x 2.4 m cell yields;

$$E_D \cong \frac{0.00569}{d}$$

or for a separation distance or 10 meters

$$\boxed{E_D \cong 0.569\ \mathrm{mV}/_{\mathrm{meter}}} \qquad \text{(B-3)}$$

This same 30 MHz emission measured with the dipole close to the floor the cell (trace C) has a detected voltage of -30 dBM or 7.07 m/V. For this case E, interpolated from table 2 of this report, is 0.839 and the calculated field intensity, E_D, relative to open-space is:

$$E_D \cong \frac{(6.39)\ (.00707)}{(10)\ d(.839)}$$

$$\cong \frac{0.00538}{d}$$

or for a separation distance of 10 meters,

$$E_D \cong 0.538\ \mathrm{mV}/_{\mathrm{meter}}$$

The value obtain for E_D (eqs B-3 and B-4) for the two locations of the dipole inside the cell compares well within the measurement resolution and accuracy of this technique. This demonstrate the independence of placement location of the EUT inside the cell on the computed equivalent open-space radiated emissions results.

Table 1.

x-component of the electric field in a square symmetric TEM cell. (fig. 9, a=b, w=0.83a)

	center	a/5	2a/5	3a/5	4a/5	wall
Floor	0.000	0.000	0.000	0.000	0.000	0.000
b/5	0.000	0.060	0.129	0.208	0.278	0.307
2b/5	0.000	0.108	0.245	0.422	0.600	0.680
3b/5	0.000	0.127	0.311	0.620	1.029	1.237
4b/5	0.000	0.090	0.248	0.647	1.684	2.285
Septum	0.000	0.000	0.000	0.000	0.000	3.603

center of TEM cell

Table 2.

y-component of the electric field in a square symmetric TEM cell. (fig. 9, a=b, w=0.83a)

	center	a/5	2a/5	3a/5	4a/5	wall
Floor	0.824	0.793	0.698	0.530	0.289	0.000
b/5	0.853	0.825	0.736	0.568	0.315	0.000
2b/5	0.935	0.917	0.852	0.699	0.410	0.000
3b/5	1.049	1.052	1.051	0.977	0.652	0.000
4b/5	1.153	1.186	1.298	1.499	1.343	0.000
Septum	1.196	1.245	1.431	1.986	6.640	0.000

center of TEM cell

Table 3.

Magnitude of the electric field in a square symmetric TEM cell. (fig. 9, a=b, w = 0.83a)

	center	a/5	2a/5	3a/5	4a/5	wall
Floor	0.824	0.793	0.698	0.530	0.289	0.000
b/5	0.853	0.827	0.747	0.605	0.420	0.307
2b/5	0.935	0.924	0.886	0.817	0.727	0.680
3b/5	1.049	1.060	1.096	1.157	1.218	1.237
4b/5	1.153	1.189	1.321	1.633	2.154	2.285
Septum	1.196	1.245	1.431	1.986	6.640	3.603

center of TEM cell

Table 4.

Polarization angle of the electric field in degrees in a square, symmetric TEM cell.

	center	a/5	2a/5	3a/5	4a/5	wall
Floor	90.00	90.00	90.00	90.00	90.00	--
b/5	90.00	85.86	80.05	69.89	48.54	00.00
2b/5	90.00	83.27	73.97	58.89	34.35	00.00
3b/5	90.00	83.14	73.50	57.60	32.36	00.00
4b/5	90.00	85.64	79.20	66.67	38.56	00.00
Septum	90.00	90.00	90.00	90.00	90.00	00.00

center of TEM cell

Table 5.

x-component of the electric field in a rectangular symmetric TEM cell. (fig. 10, 0.6a = b, w = 0.72a)

	center	a/5	2a/5	3a/5	4a/5	wall
Floor	0.000	0.000	0.000	0.000	0.000	0.000
b/5	0.000	0.024	0.067	0.143	0.220	0.249
2b/5	0.000	0.040	0.121	0.284	0.462	0.517
3b/5	0.000	0.043	0.141	0.410	0.763	0.817
4b/5	0.000	0.028	0.101	0.440	1.247	1.112
Septum	0.000	0.000	0.000	0.000	1.969	1.254

center of
TEM cell

Table 6.

y-component of the electric field in a rectangular symmetric TEM cell. (fig. 10, 0.6a = b, w = 0.72a)

	center	a/5	2a/5	3a/5	4a/5	wall
Floor	0.966	0.946	0.872	0.698	0.394	0.000
b/5	0.972	0.956	0.890	0.724	0.411	0.000
2b/5	0.989	0.981	0.944	0.807	0.464	0.000
3b/5	1.010	1.015	1.028	0.979	0.557	0.000
4b/5	1.028	1.046	1.120	1.311	0.645	0.000
Septum	1.035	1.058	1.164	1.664	0.000	0.000

center of
TEM cell

Table 7.

Magnitude of the electric field in a rectangular symmetric TEM cell. (fig. 10, 0.6a = b, w = 0.72a

	center	a/5	2a/5	3a/5	4a/5	wall
Floor	0.966	0.946	0.872	0.698	0.394	0.000
b/5	0.972	0.956	0.892	0.738	0.466	0.249
2b/5	0.989	0.982	0.951	0.856	0.655	0.517
3b/5	1.010	1.016	1.038	1.062	0.945	0.817
4b/5	1.028	1.046	1.125	1.383	1.404	1.112
Septum	1.035	1.058	1.164	1.664	1.969	1.254

center of
TEM cell

Table 8.

Polarization angle of the electric field in degrees in a rectangular, symmetric TEM cell.

	center	a/5	2a/5	3a/5	4a/5	wall
Floor	90.00	90.00	90.00	90.00	90.00	--
b/5	90.00	88.58	85.68	78.80	61.76	00.00
2b/5	90.00	87.66	82.70	70.61	45.12	00.00
3b/5	90.00	87.60	82.20	67.26	36.15	00.00
4b/5	90.00	88.48	84.82	71.43	27.36	00.00
Septum	90.00	90.00	90.00	90.00	90.00	00.00

center of
TEM cell

TABLE 9.

SUMMARY OF MEASUREMENT ERRORS FOR SUSCEPTIBILITY MEASUREMENTS

Source of Error	Percent Uncertainty: Symmetric a = b (Fig. 9)	Asymmetric (Fig. 13): Above Septum	Asymmetric (Fig. 13): Below Septum	Rectangular 0.6a = b (Fig. 10)
a) Absolute measurement of incident RF power on side arm of Coupler	$\mp$ 3%	$\mp$ 3%	$\mp$ 3%	$\mp$ 3%
b) Coupler Calibration	$\mp$ 2%	$\mp$ 2%	$\mp$ 2%	$\mp$ 2%
ϵ_P, total error in determining the net power passing through cell.	$\mp$ 5%	$\mp$ 5%	$\mp$ 5%	$\mp$ 5%
c) ϵ_R determination of the Real part of the cell complex impedance.	$\mp$ 3%	$\mp$ 3%	$\mp$ 3%	$\mp$ 3%
d) ϵ_b Cell center plate separation distance from upper or lower wall.	$\mp$ 1%	$\mp$ 1%	$\mp$ 1%	$\mp$ 1%
e) $\epsilon_{\tilde{E}}$ Nonuniformity or pertubation of the electric field inside the cell test zone.	$\mp$ 20%	$\mp$ 5%	$\mp$ 30%	$\mp$ 6%
* ϵ_E, Total maximum field strength error	$\mp$ 25% $\mp$ 2dB	$\mp$ 10% $\mp$ 1dB	$\mp$ 35% $\mp$ 3dB	$\mp$ 11% $\mp$ 1dB

* For example $\epsilon_E = \mp \left| \frac{1}{2}(0.03 + 0.05) + 0.01 + 0.20 \right| \times 100 = \mp 25\%$

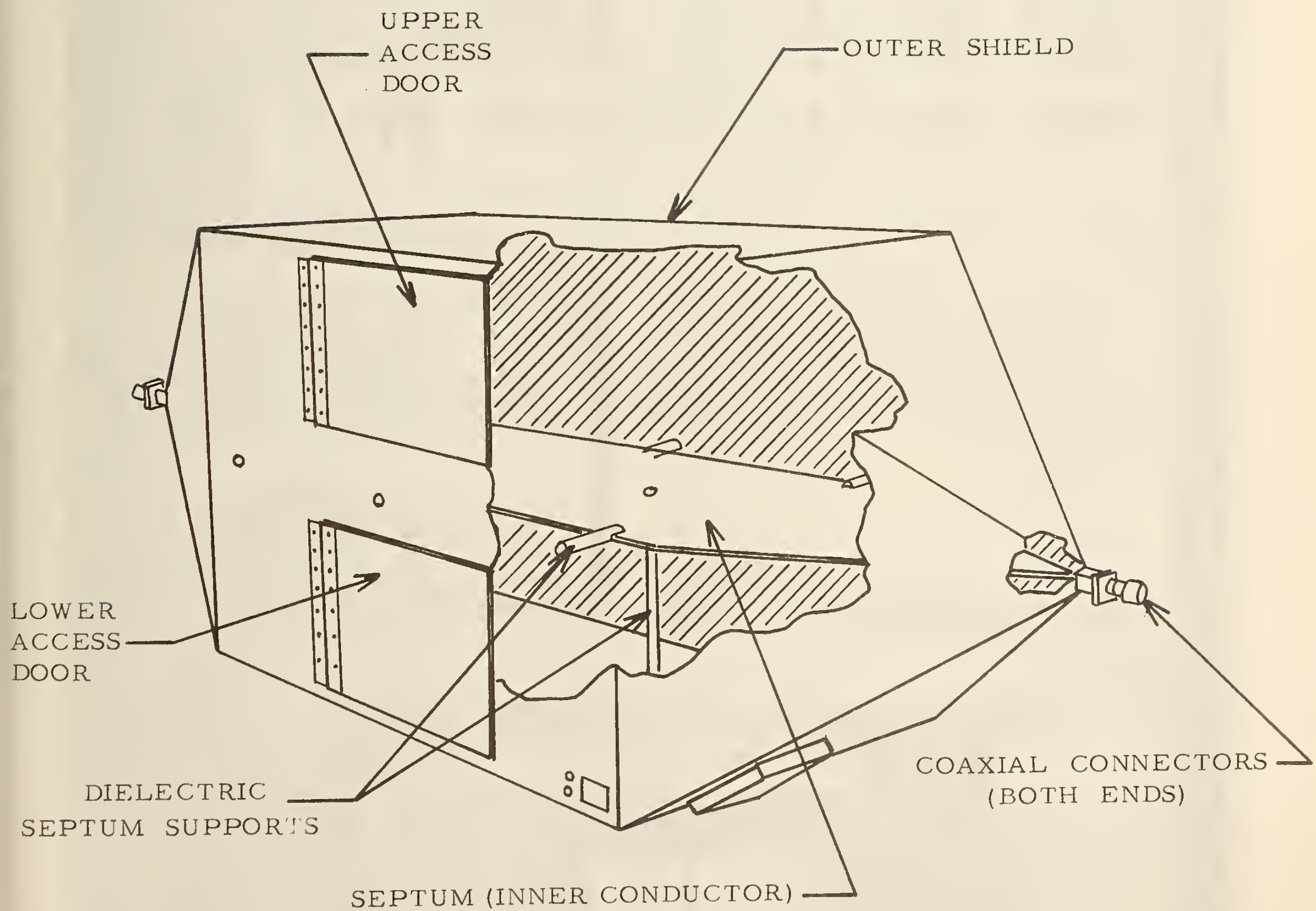


Figure 1. View of transverse electromagnetic (TEM) cell.

Figure 2. NBS 3m x 3m x 6m TEM cell

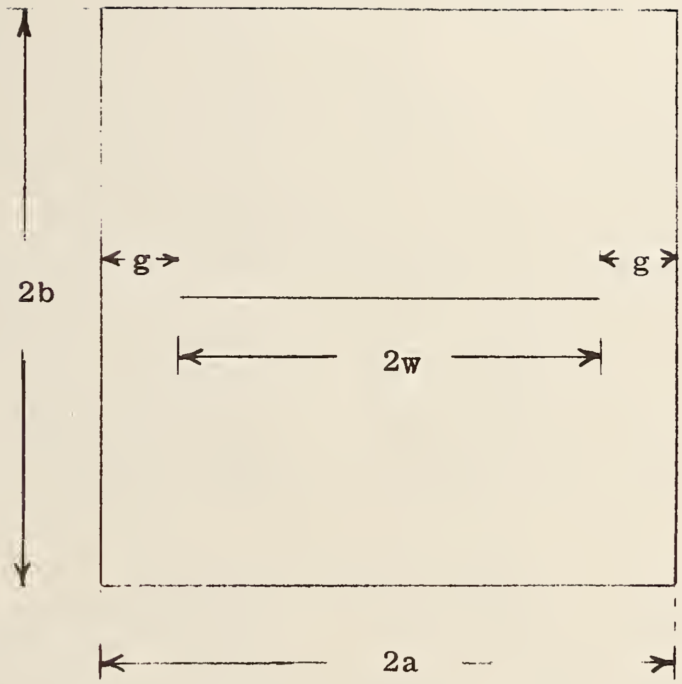


Figure 3. Cross-section of a TEM cell.

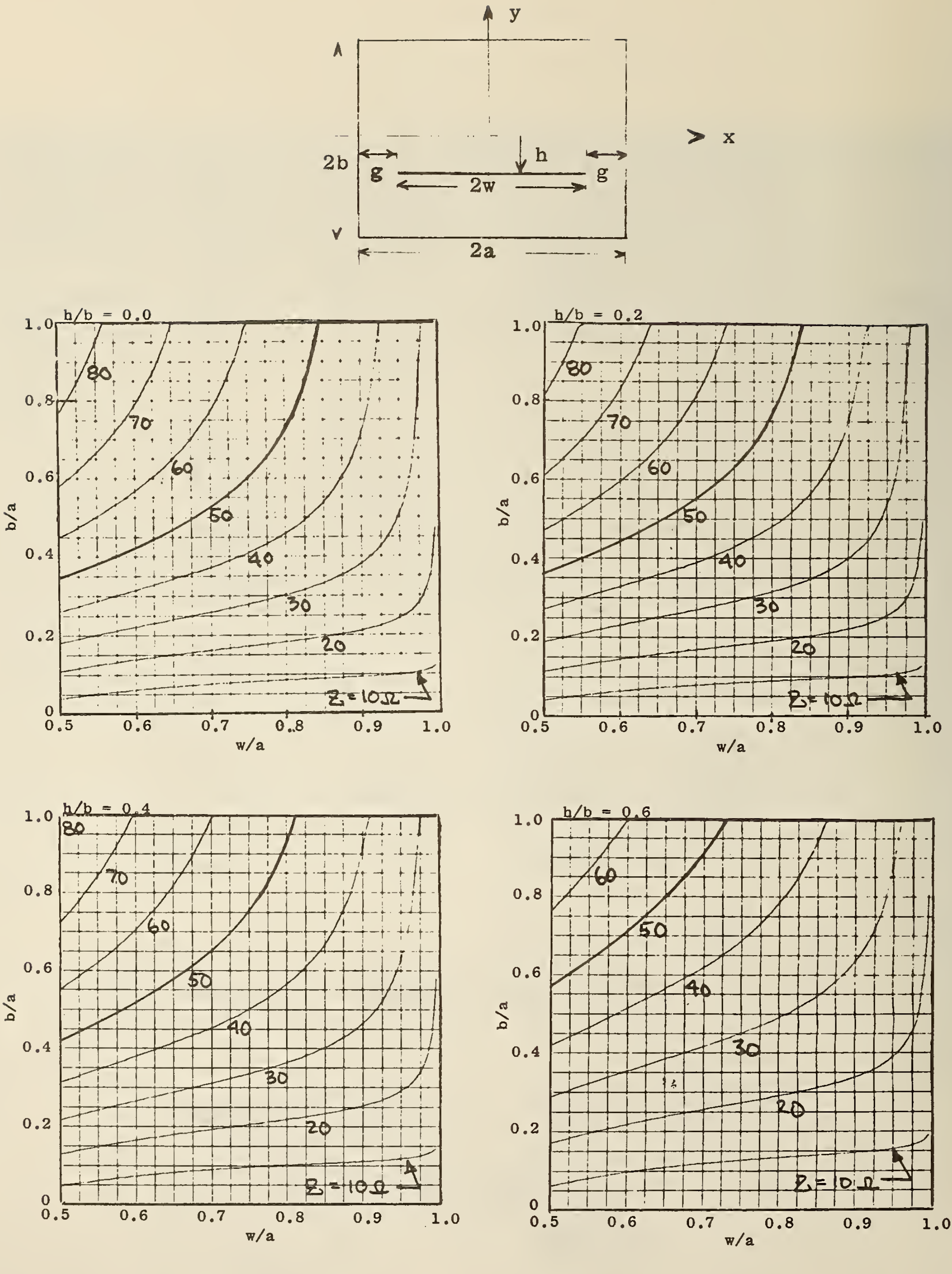


Figure 4. Transverse electromagnetic (TEM) cell design curves showing ratio of cell outer conductor dimensions to ratio of center plate width to cell width for various transmission line characteristic impedances and vertical center plate locations.

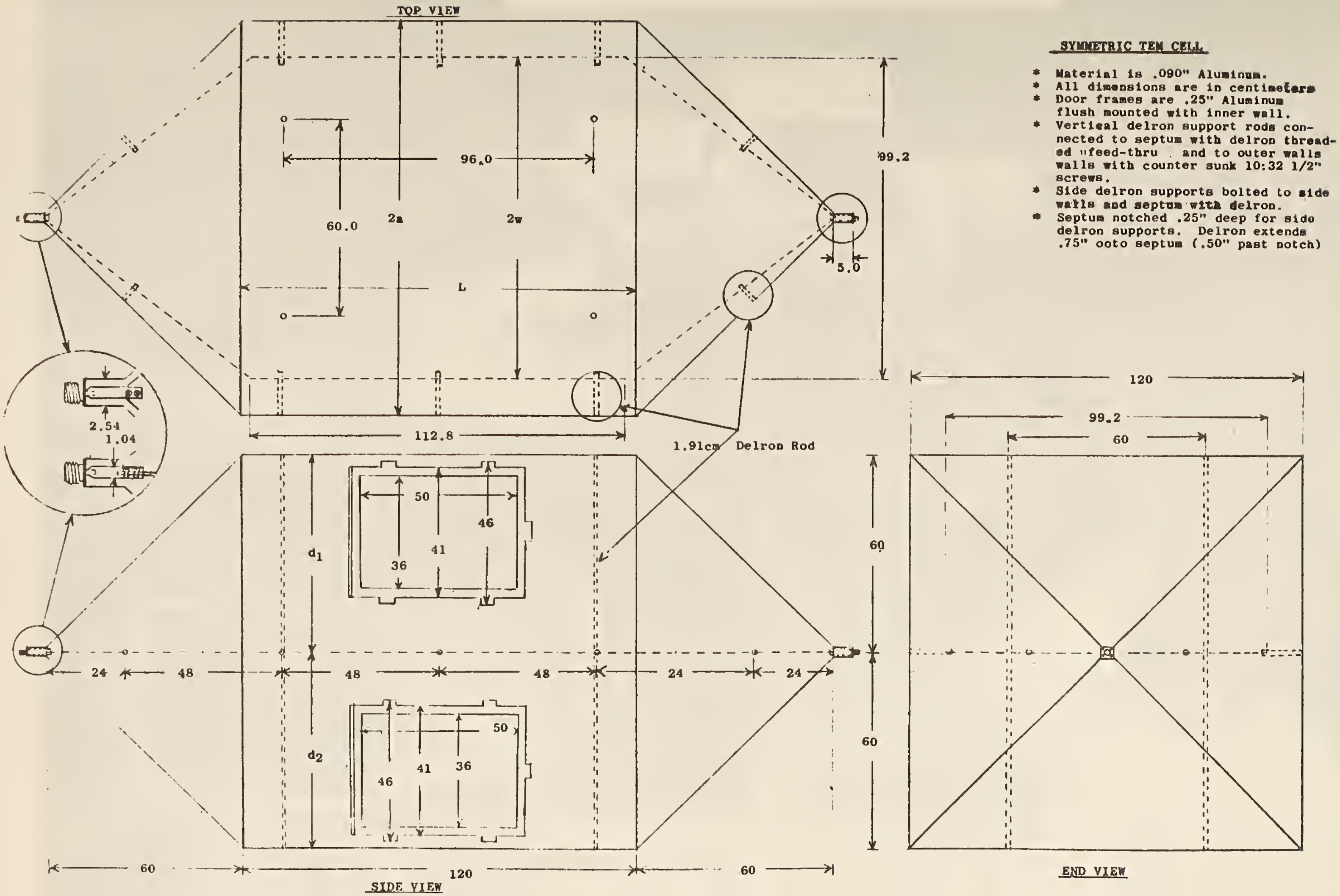


Figure 5. Cross sectional views of symmetric rectangular TEM cell.

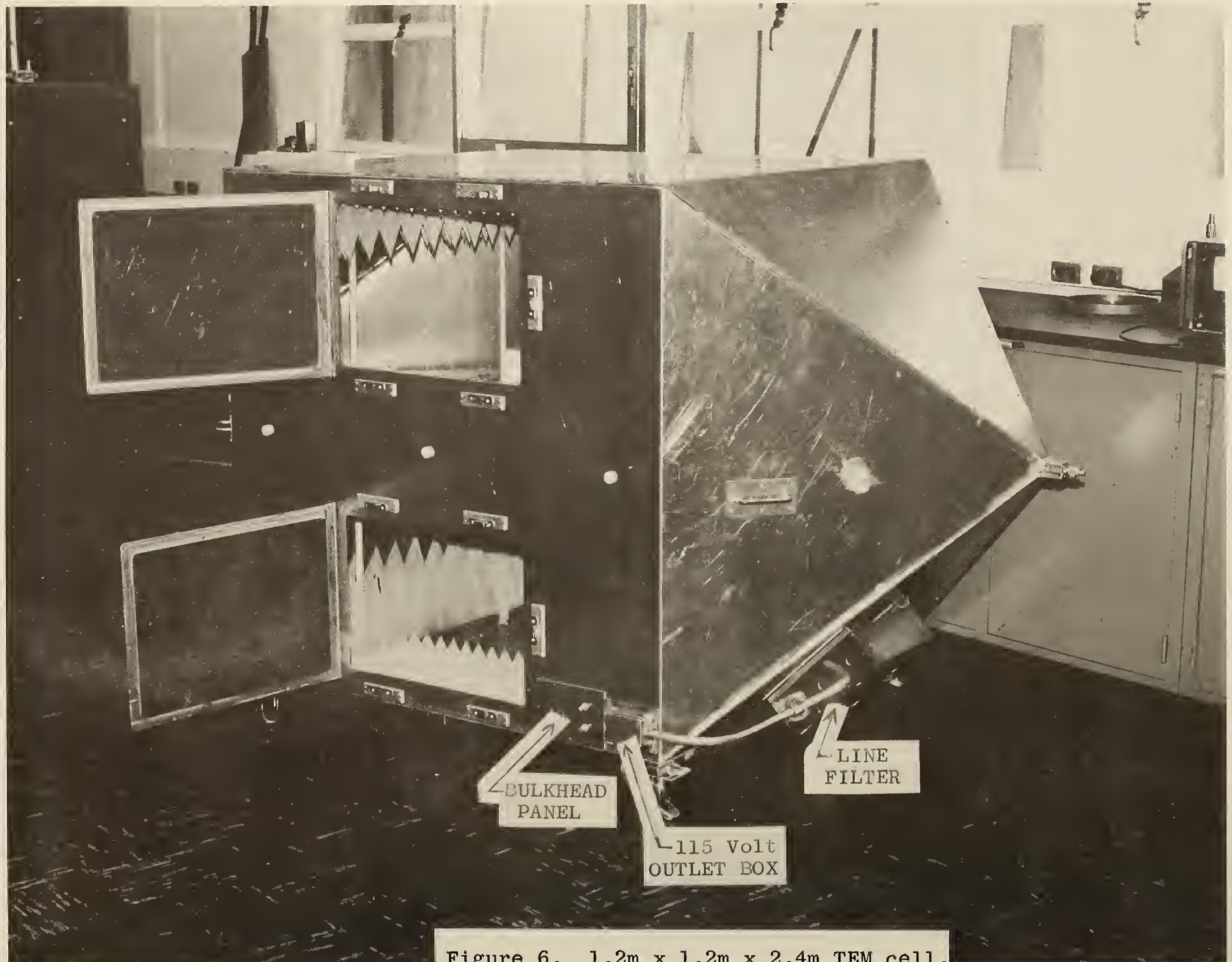


Figure 6. 1.2m x 1.2m x 2.4m TEM cell.

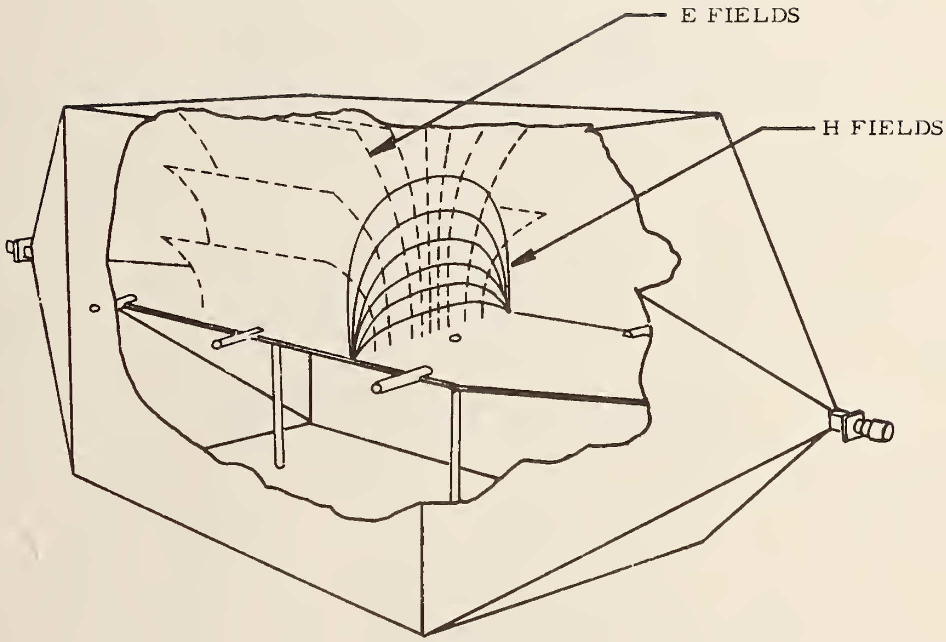


Figure 7. Trnsverse electromagnetic (TEM) field distribution inside a TEM cell.

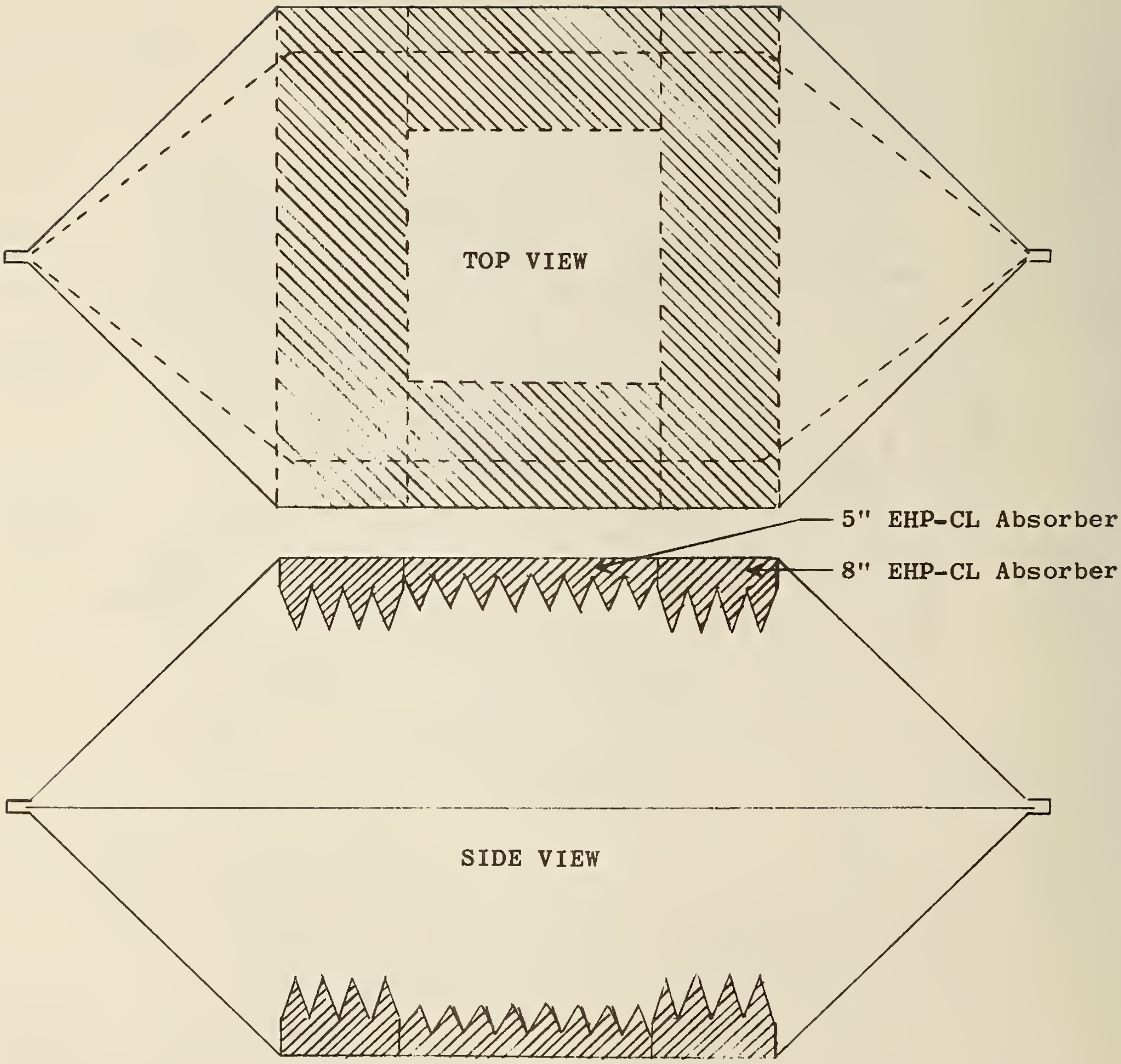


Figure 8. Diagram for absorber loading symmetric TEM cell. (Shaded areas indicate placement of anechoic material.

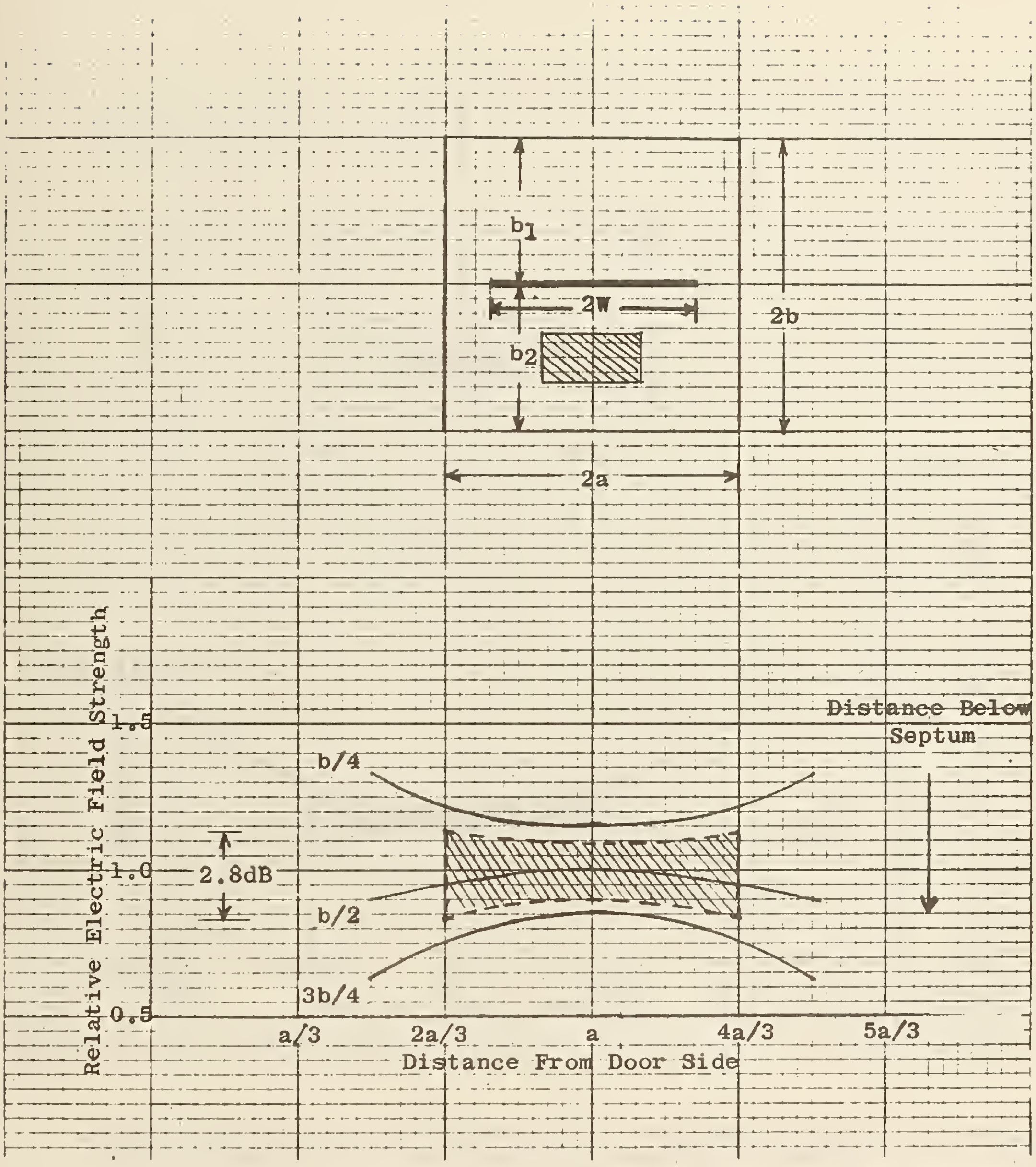


Figure 9. Relative electric field distribution inside symmetric cell. Shaded area corresponds to 1/3 cross-section area shown in top view.

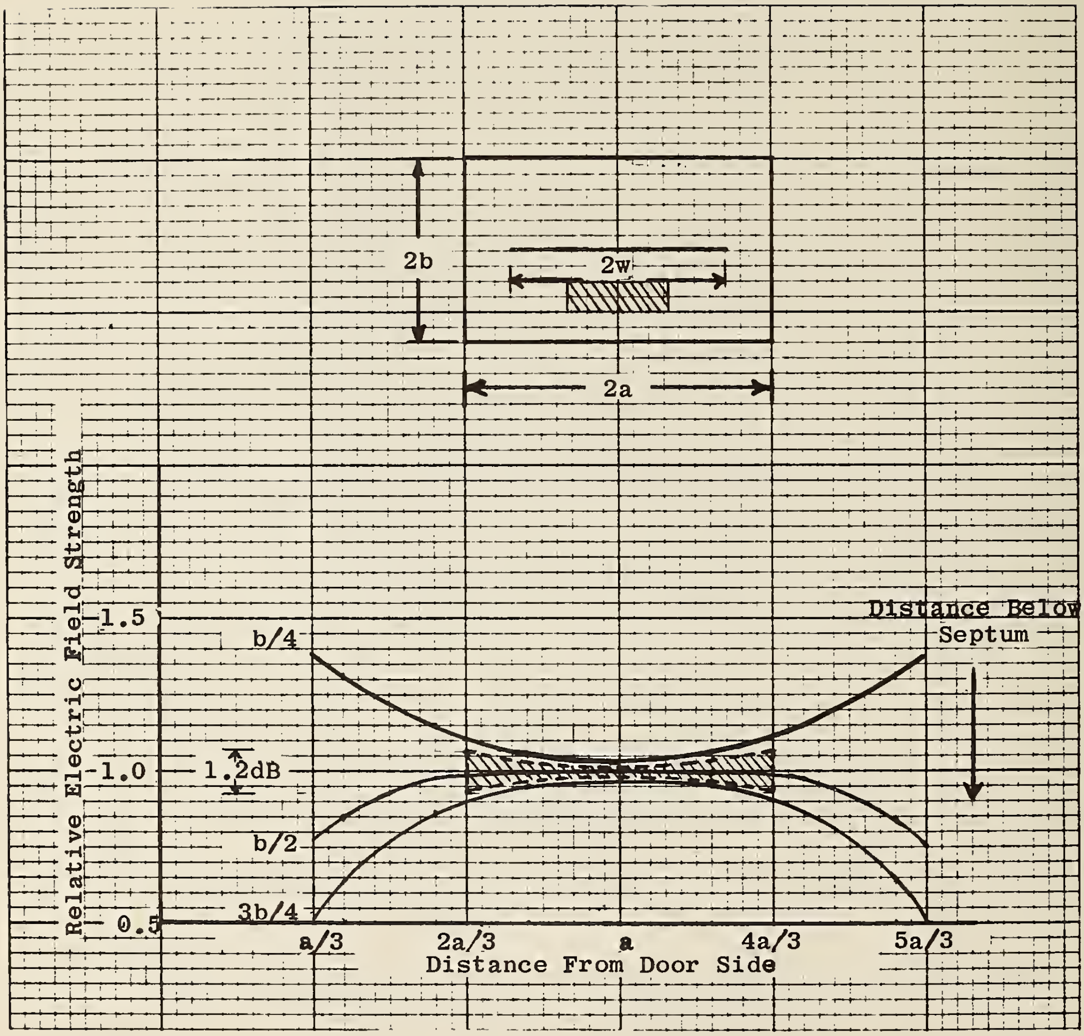


Figure 10. Relative electric field distribution inside rectangular (0.6 a = b), symmetric TEM cell. Shaded area corresponds to 1/3 cross-section area shown in top view.

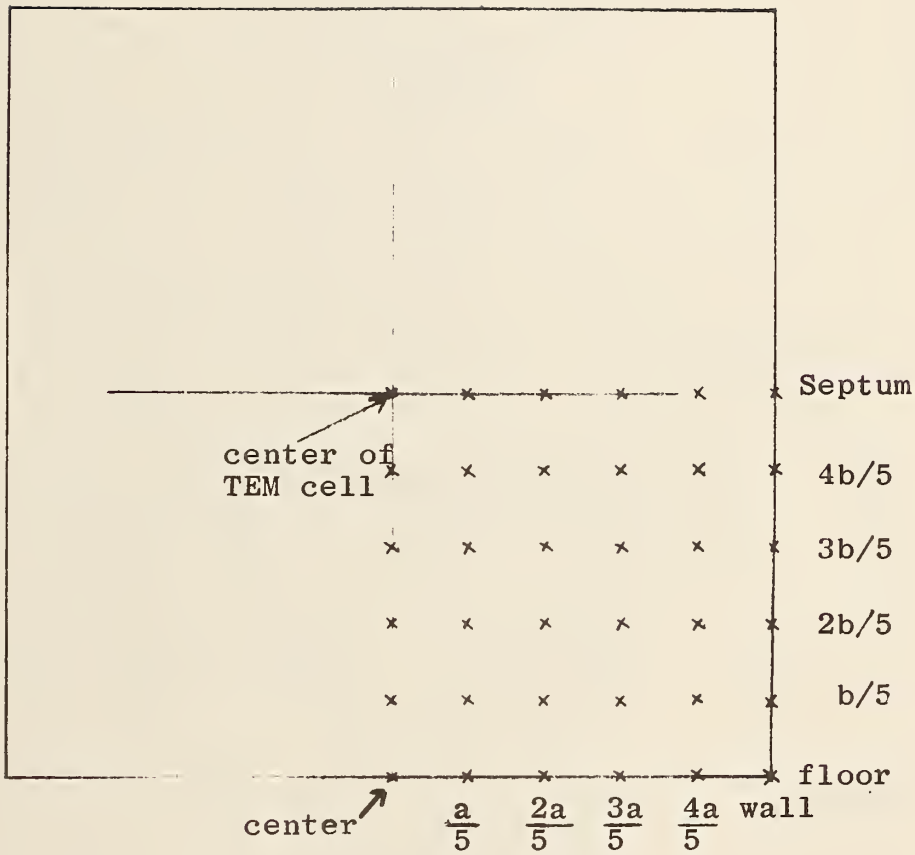


Figure 11. Field distribution locations shown in tables 1-8.

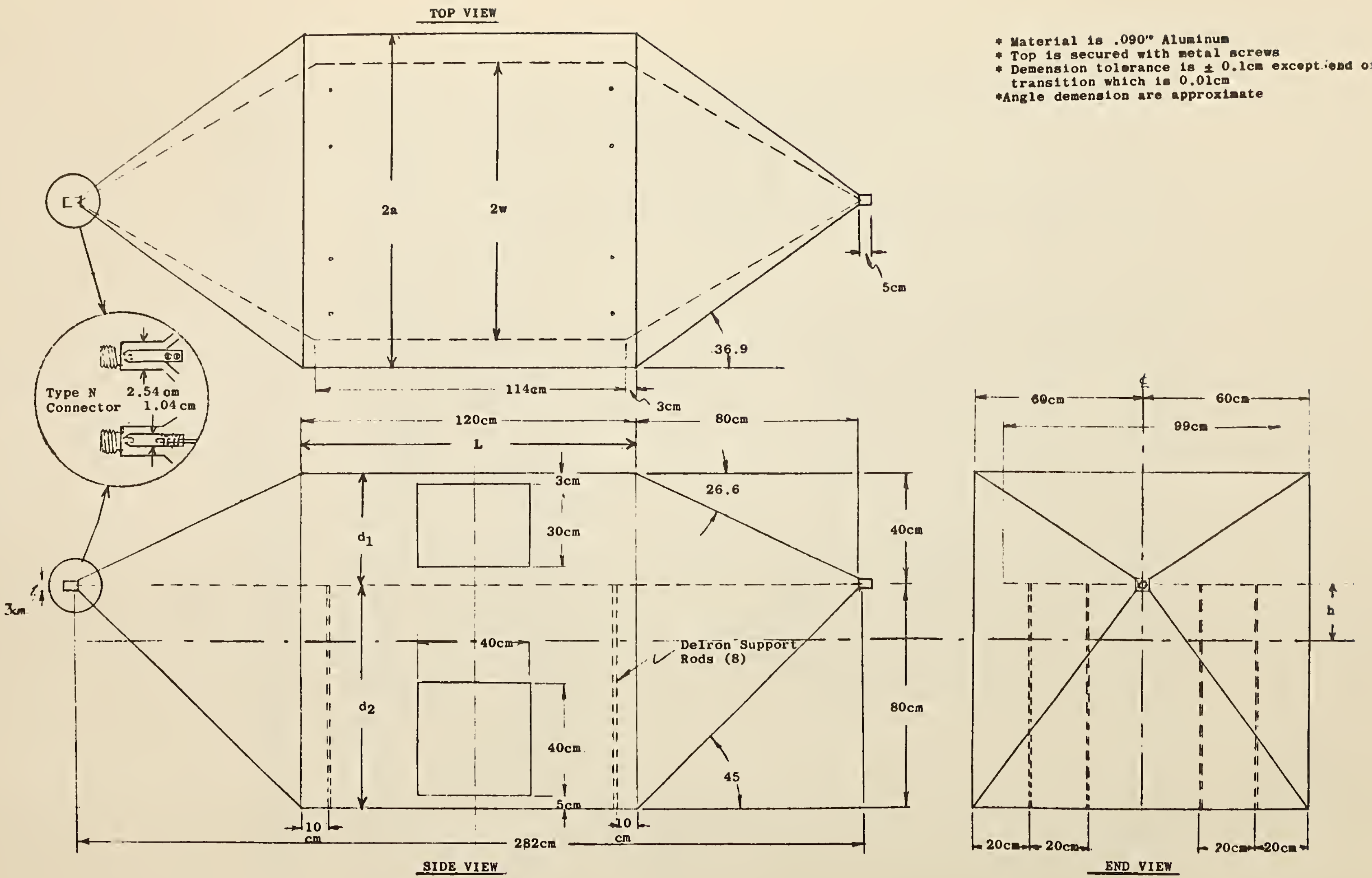


Figure 12. Cross sectional views for design of 1.2m x 1.2m x 2.8m asymmetric TEM cell.

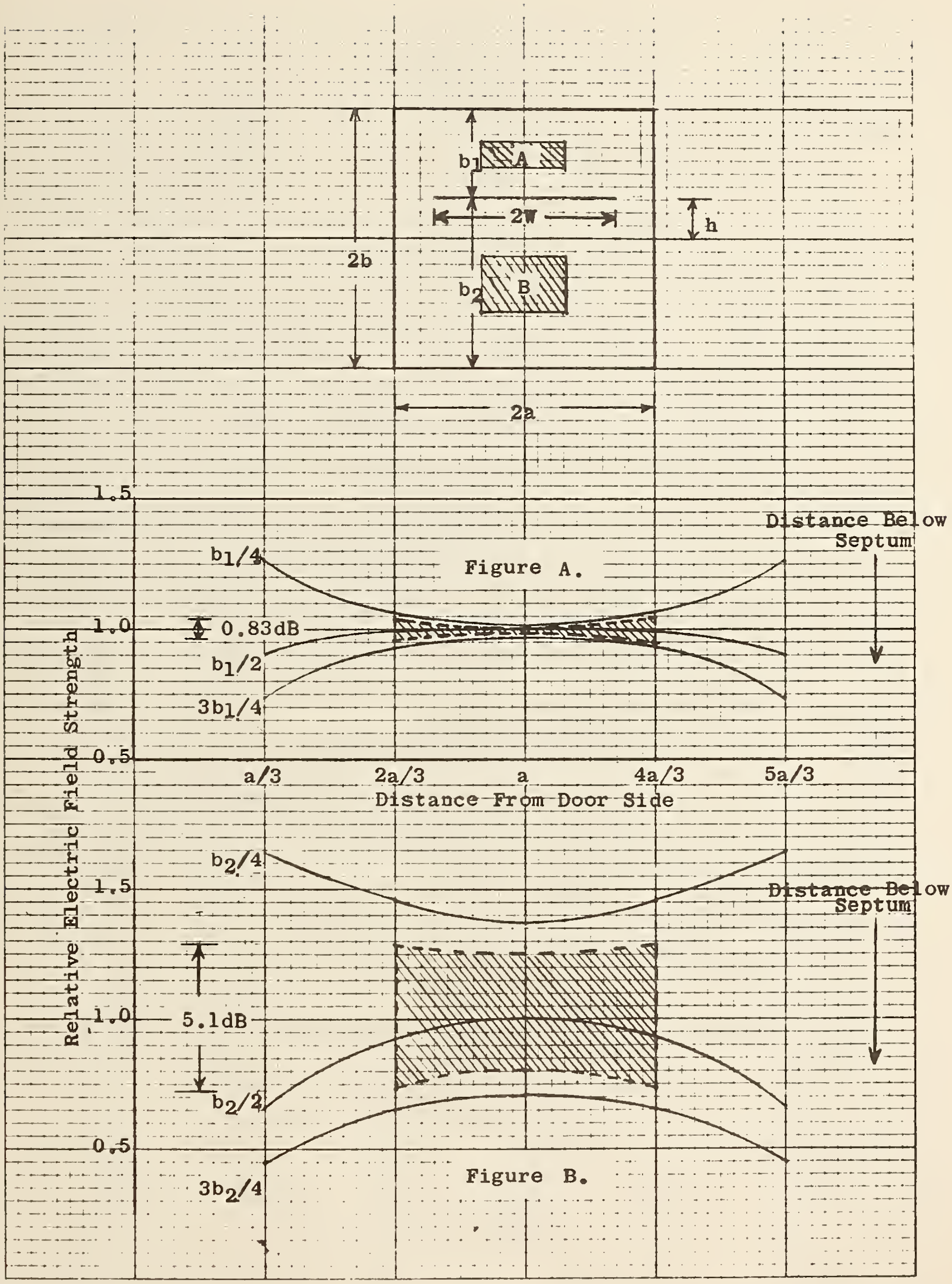


Figure 13. Relative electric field distribution inside asymmetric cell. (h = b/3) Shaded area corresponds to 1/3 cross-section area shown in cross sectional view of cell. Figure A and B data corresponds to area labeled A and B in top view.

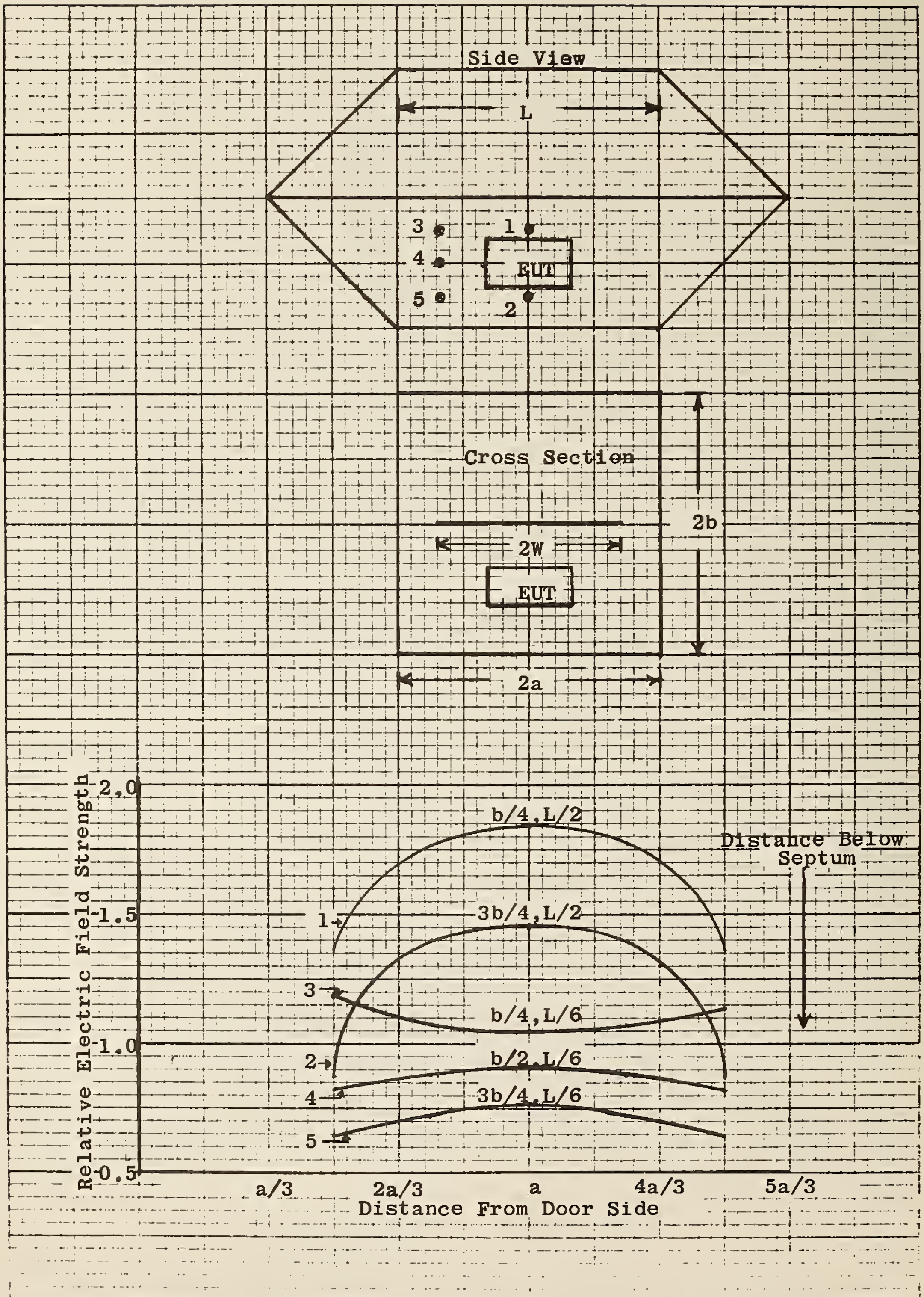


Figure 14. Relative electric field distribution inside cell with EUT (metal case) occupying 1/3 vertical separation distance between septum and floor. (Cross sectional cuts at center (L/2) and off end (L/6) of EUT as indicated by numbers in top view.

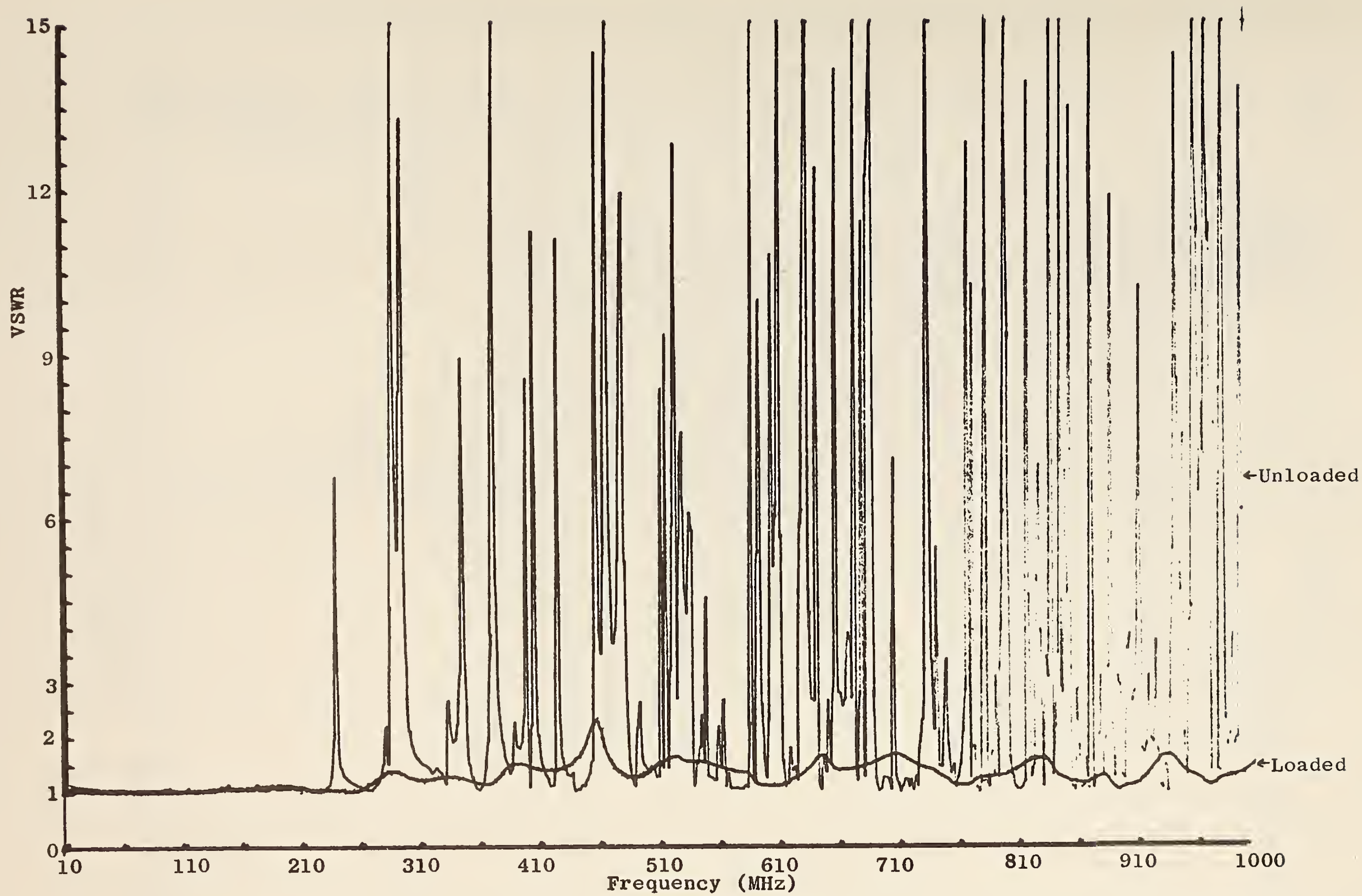


Figure 15. Input VSWR of NBS 1.2m x 1.2m x 2.4m symmetric TEM cell with and without absorber loading.

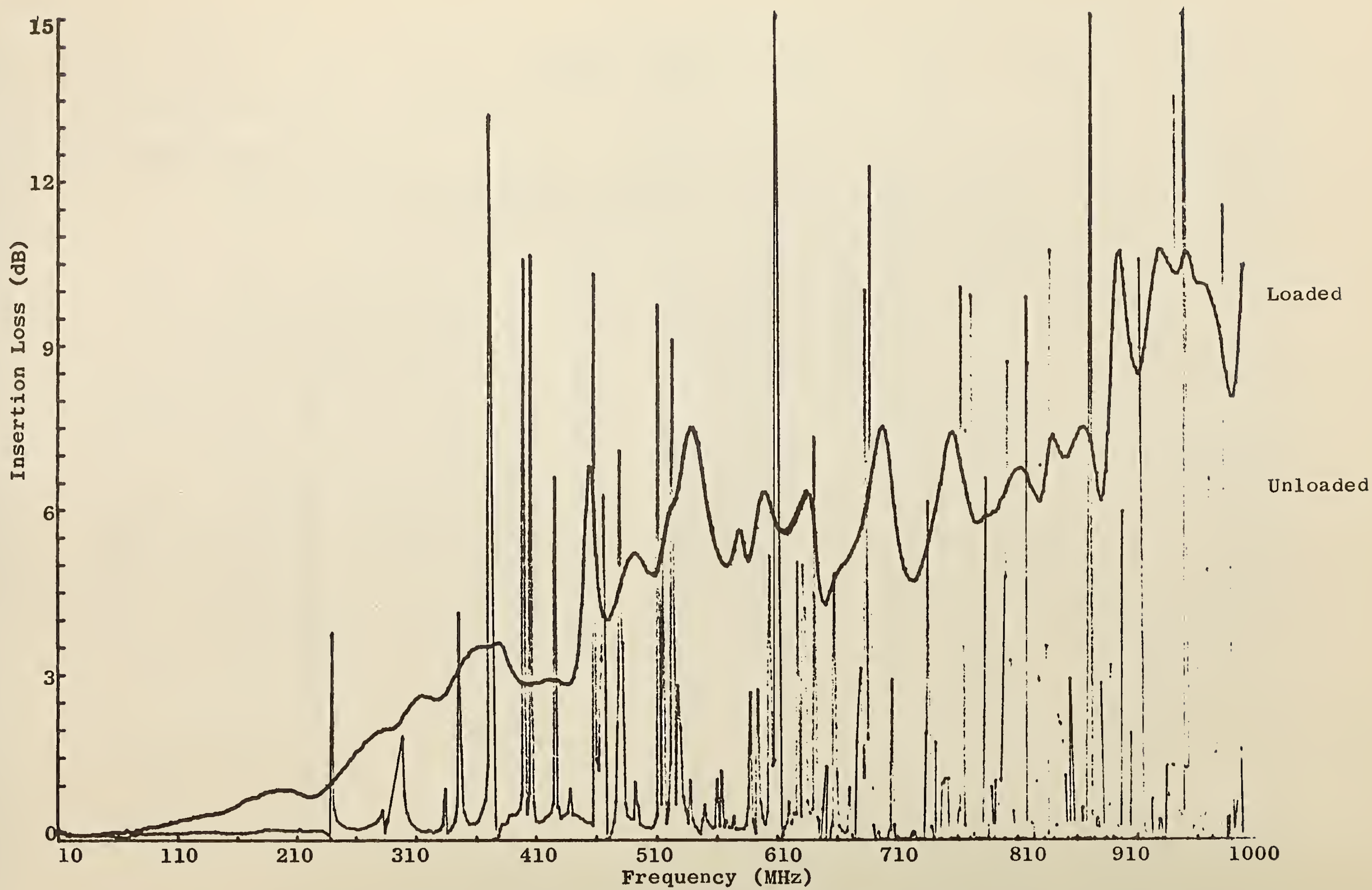


Figure 16. Insertion loss of NES 1.2m x 1.2m x 2.4m symmetric TEM cell with and without absorber loading.

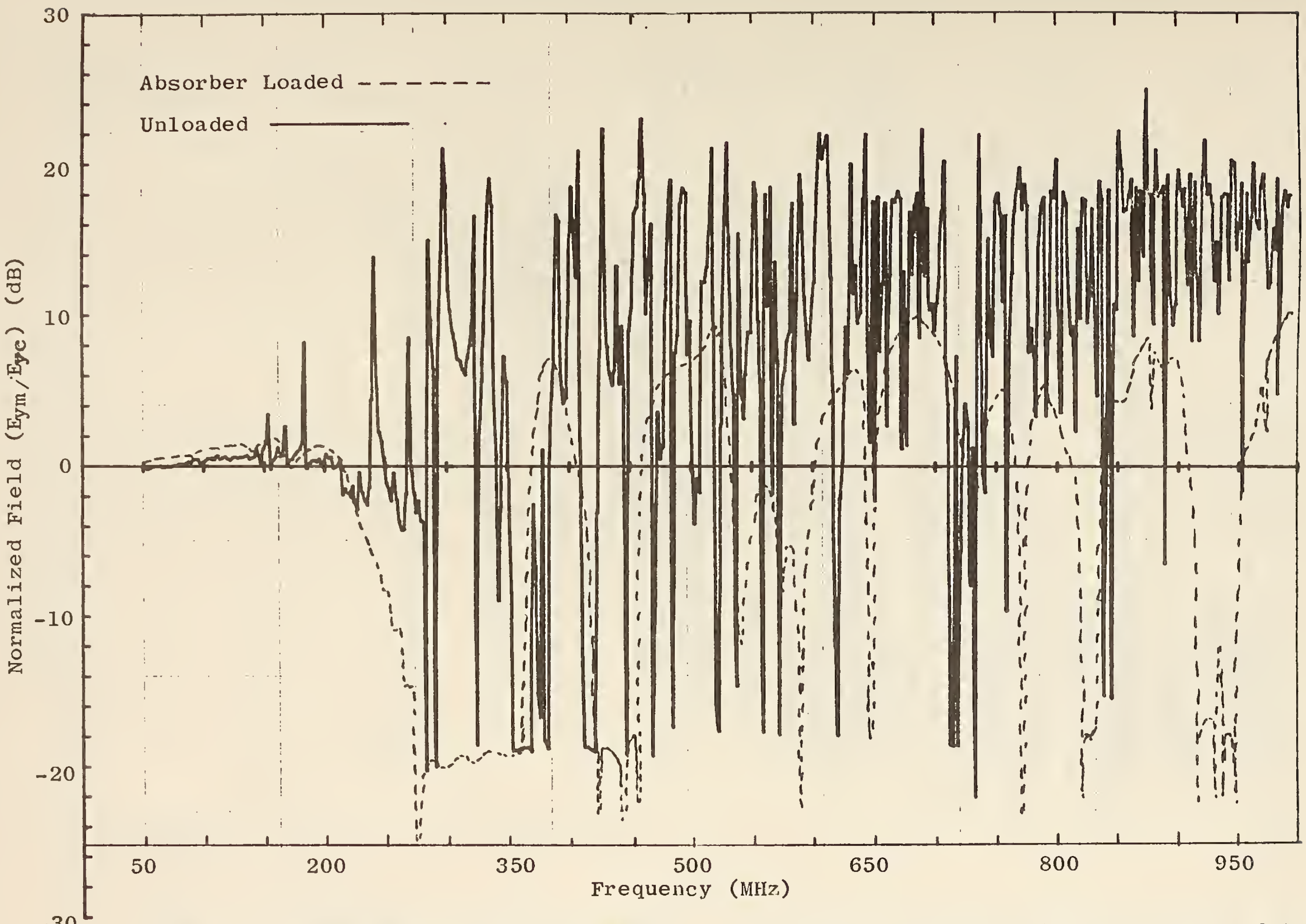


Figure 17. Normalized variation in magnitude of vertical electric field at center of test zone inside 1.2m x 1.2m x 2.4m symmetric TEM cell with and without absorber loading.

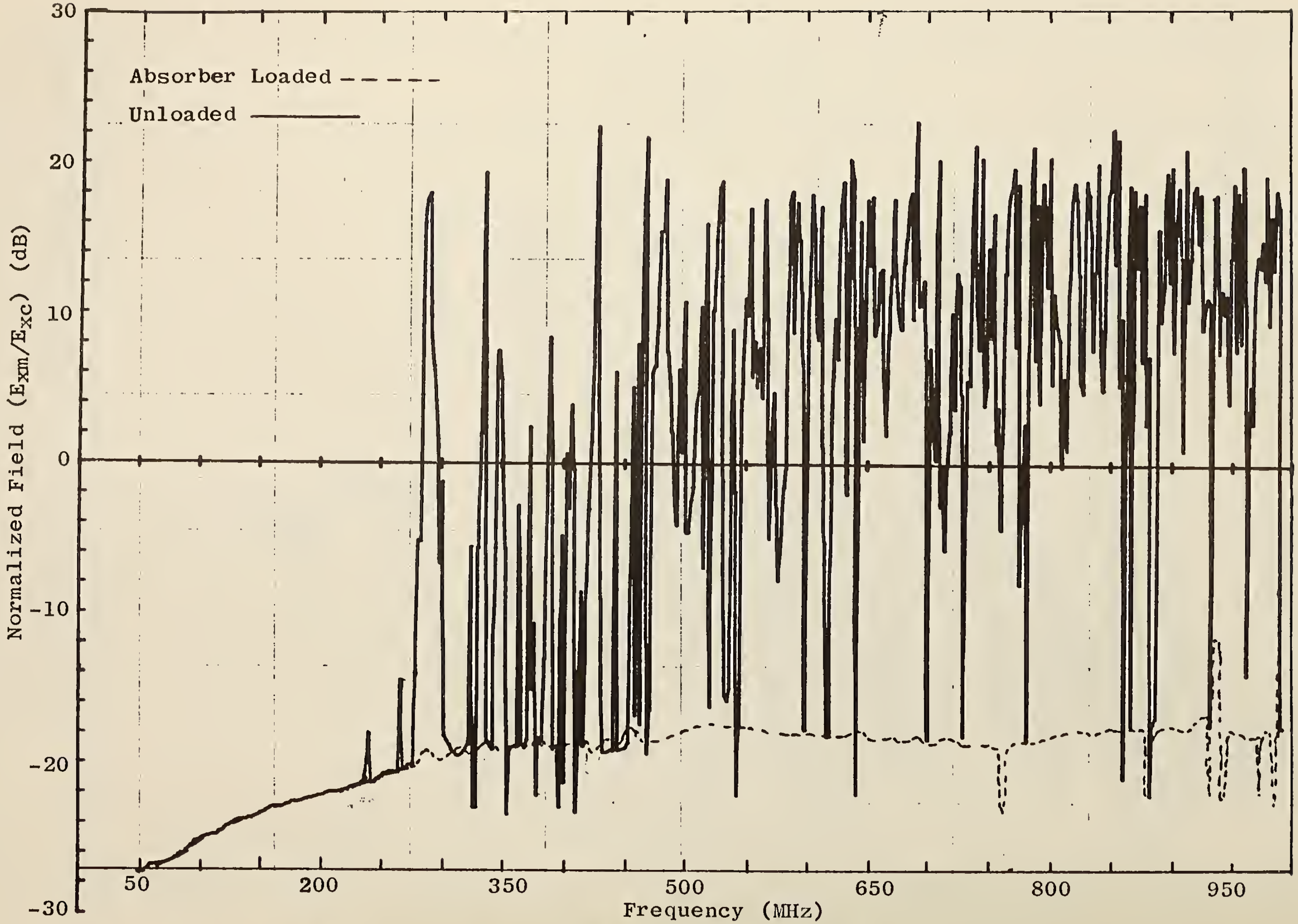


Figure 18. Normalized variation in magnitude of transverse electric field at center of test zone inside 1.2m x 1.2m x 2.4m symmetric TEM cell with and without absorber loading.

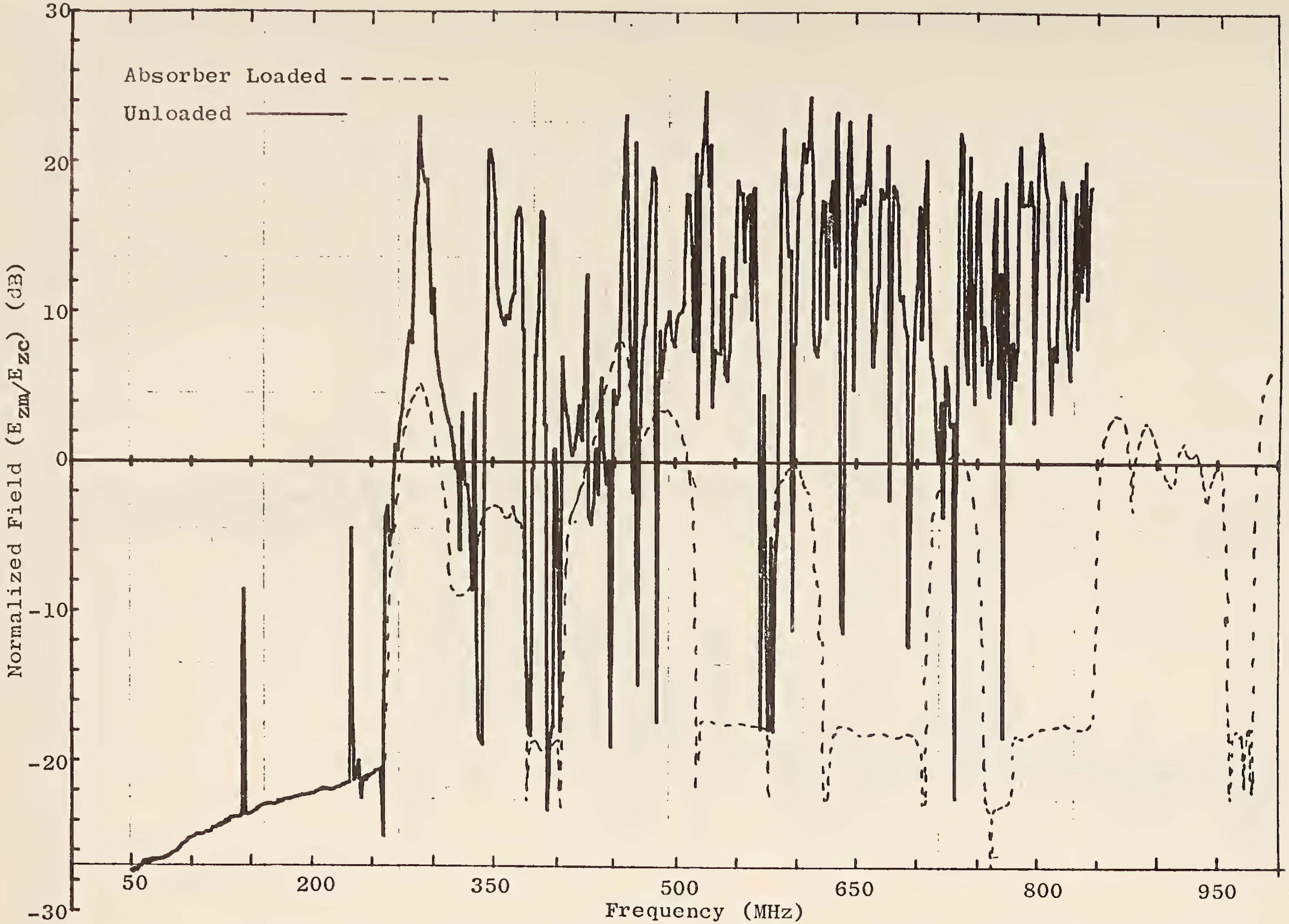


Figure 19. Normalized variation in magnitude of longitudinal electric field at center of test zone inside 1.2m x 1.2m x 2.4m symmetric TEM cell with and without absorber loading.

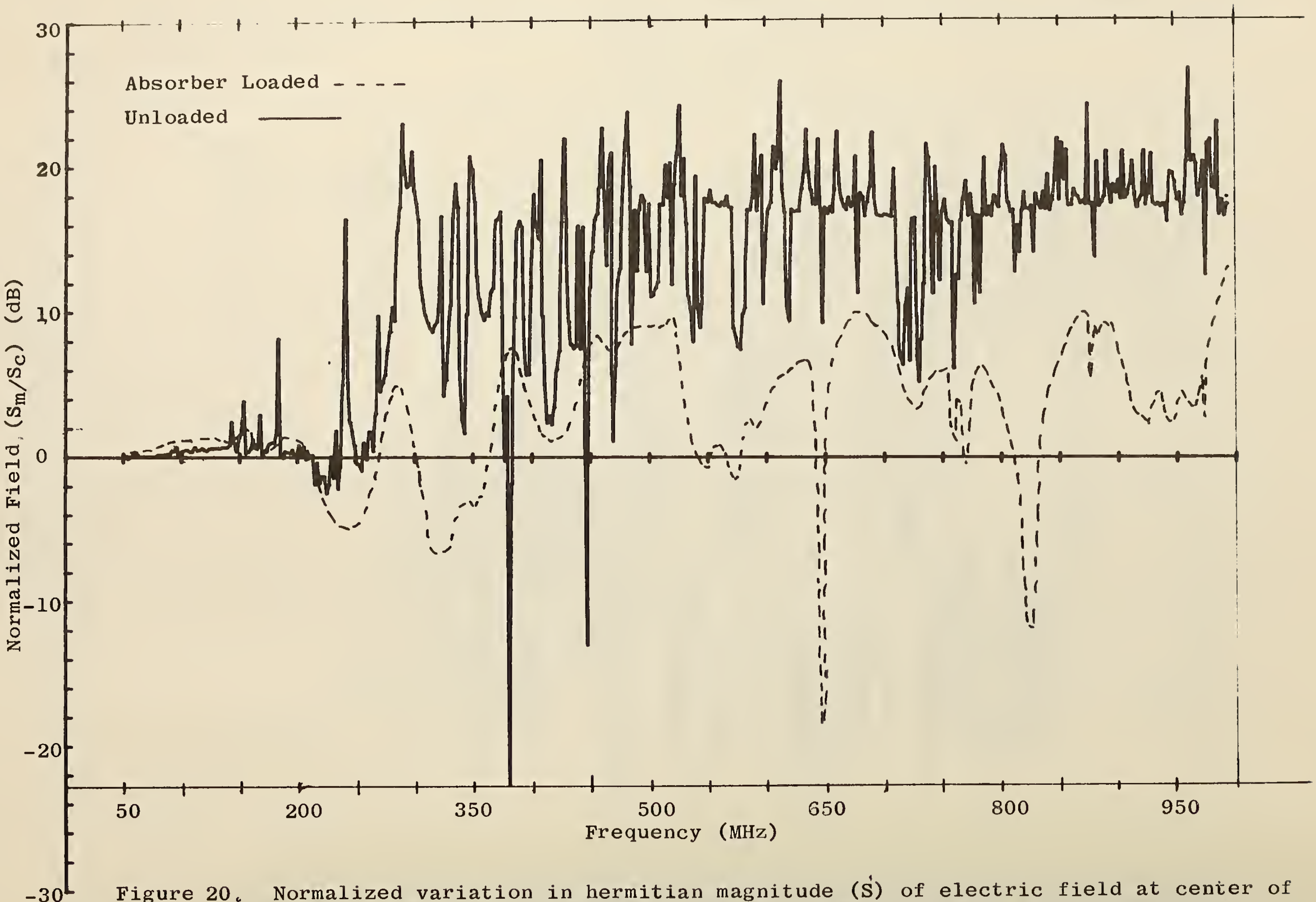


Figure 20. Normalized variation in hermitian magnitude ($\dot{S}$) of electric field at center of test zone inside 1.2m x 1.2m x 2.4m symmetric TEM cell with and without absorber loading.

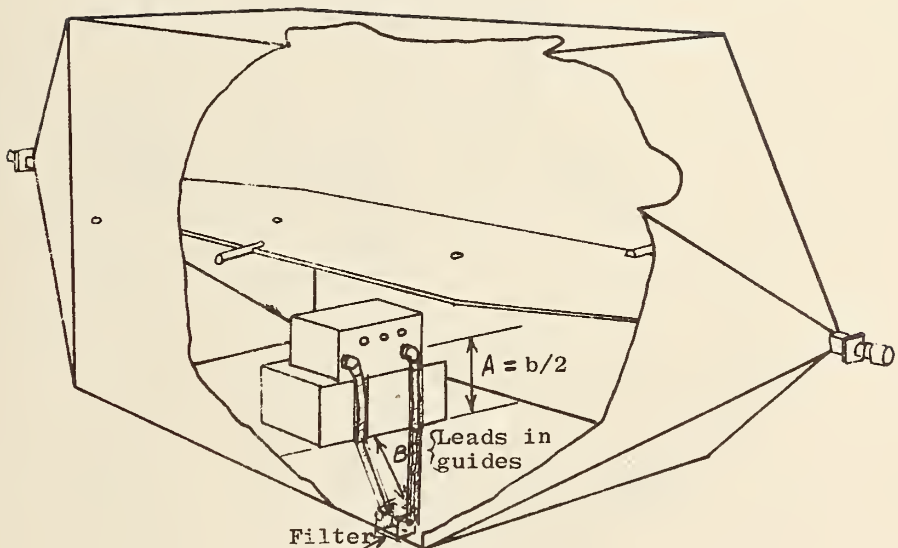


Figure 21. Placement of EUT in cell for EMC measurements.

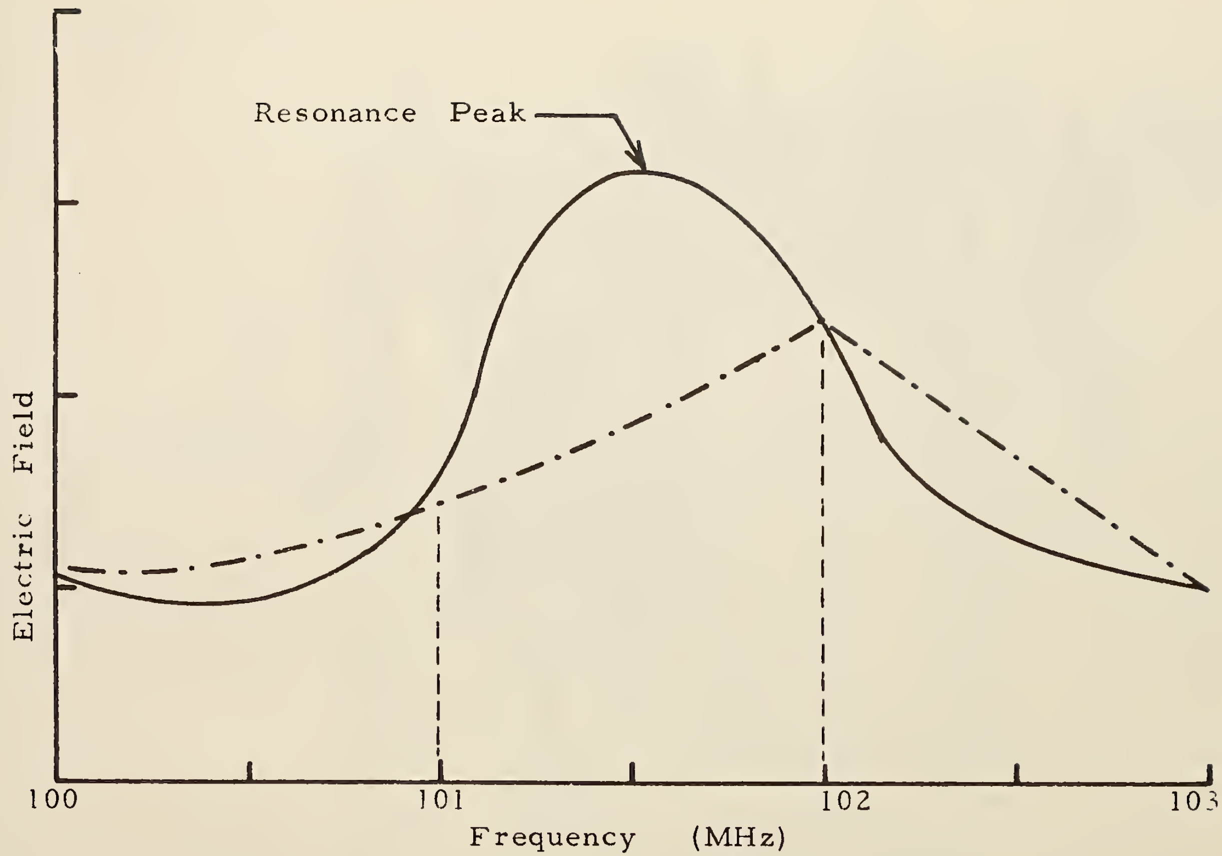
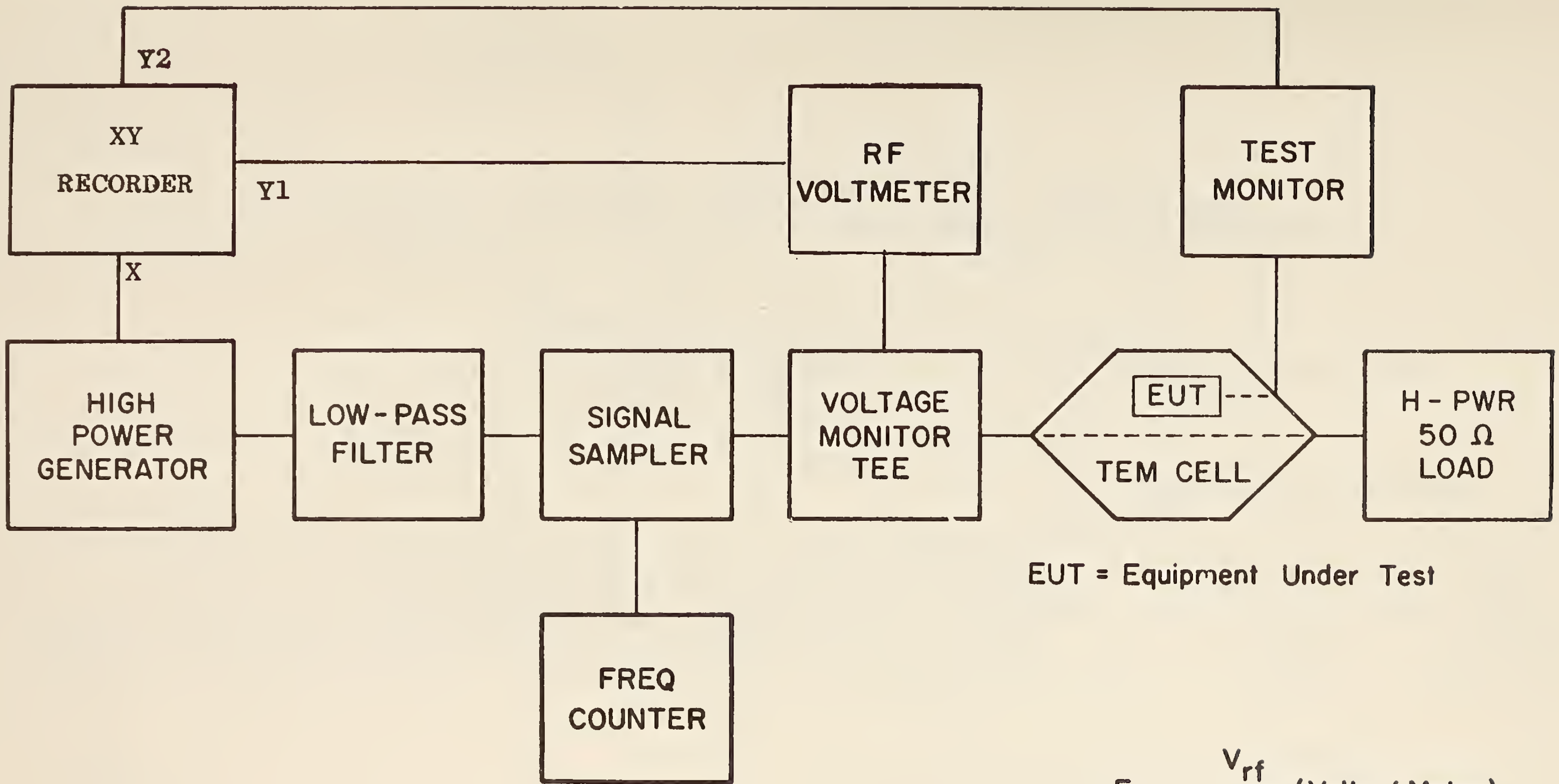
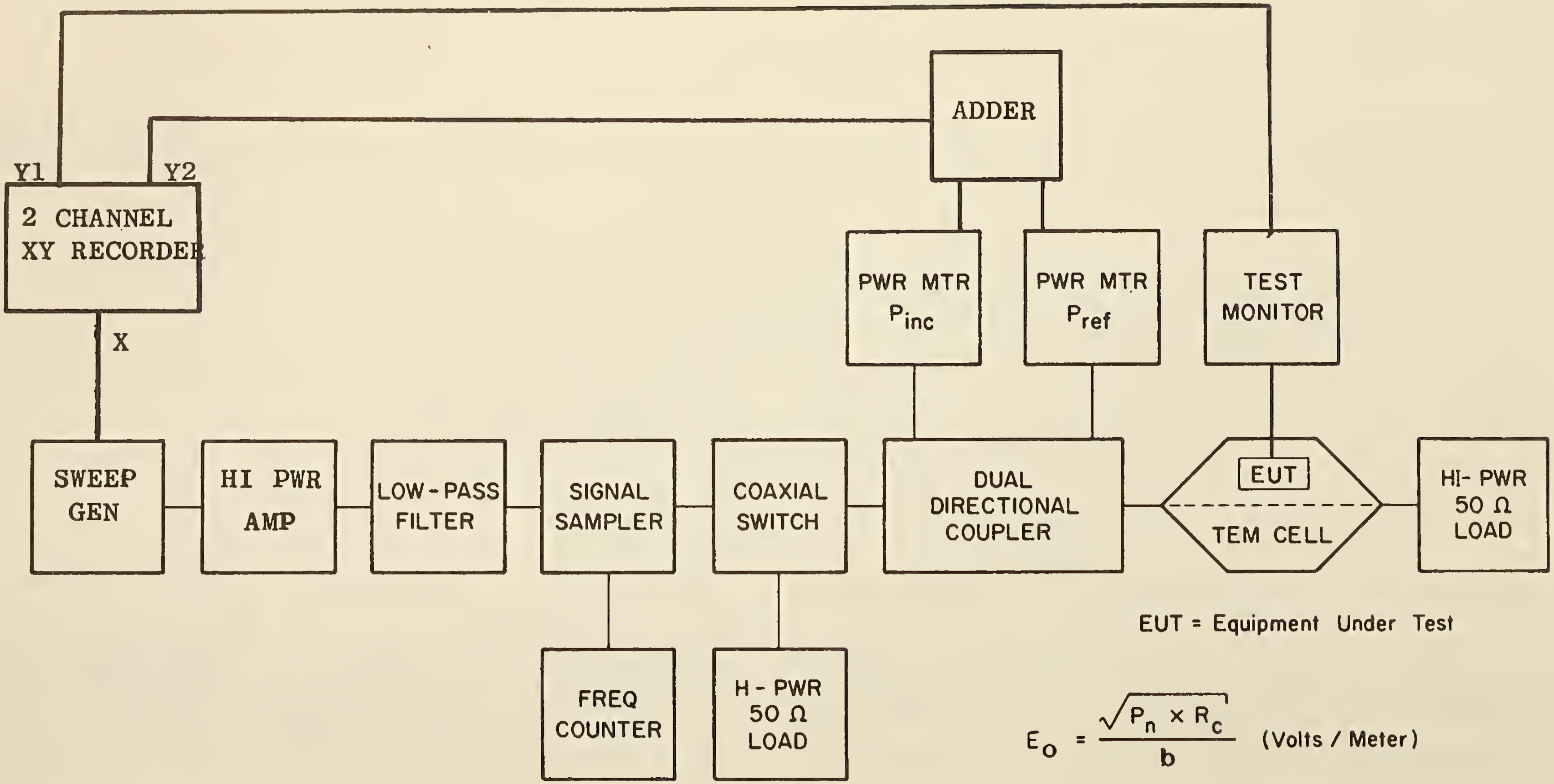


Figure 22. Susceptibility function of Eut demonstrating swept compared to discrete frequency measurements.



$$E_o = \frac{V_{rf}}{b} \text{ (Volts / Meter)}$$

Figure 23. Block diagram of system for susceptibility testing of equipment (used typically below 1 MHz).



EUT = Equipment Under Test

$$E_o = \frac{\sqrt{P_n \times R_c}}{b} \quad \text{(Volts / Meter)}$$

Figure 24. Block Diagram of System for Susceptibility Testing of Equipment (1 MHz to 500 MHz)

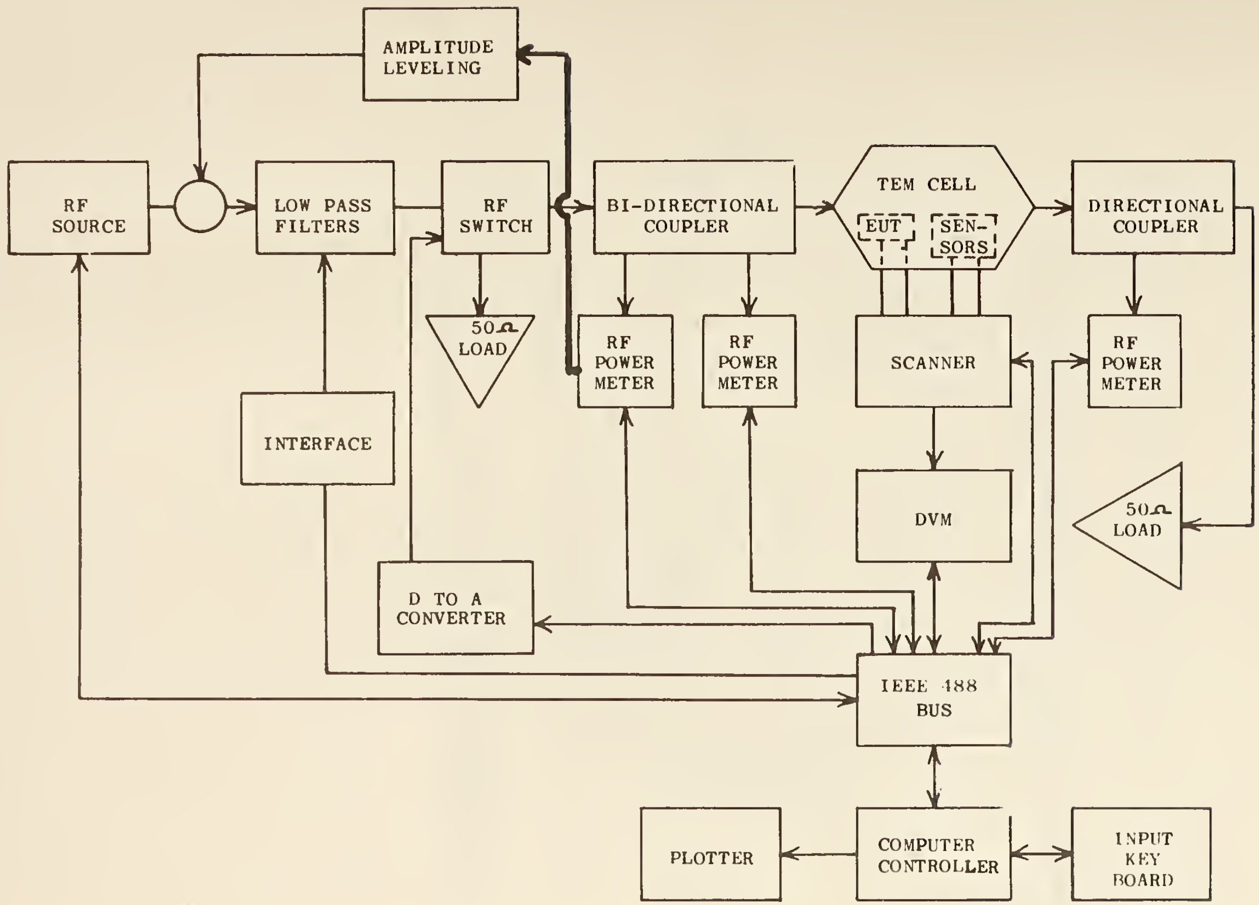


Figure 25. Block diagram of automated TEM cell susceptibility measurement system.

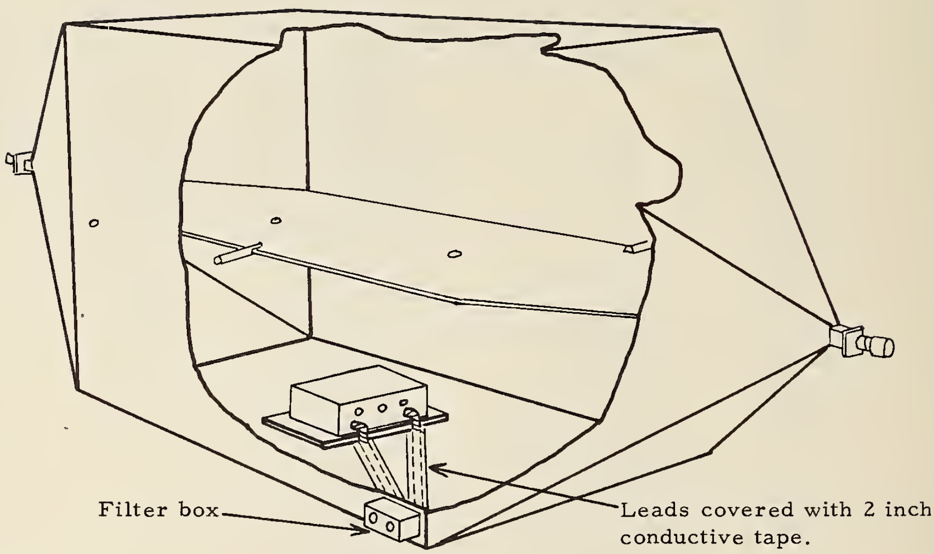


Fig. 26. Placement of EUT in cell for minimum exposure of leads to the TEM field.

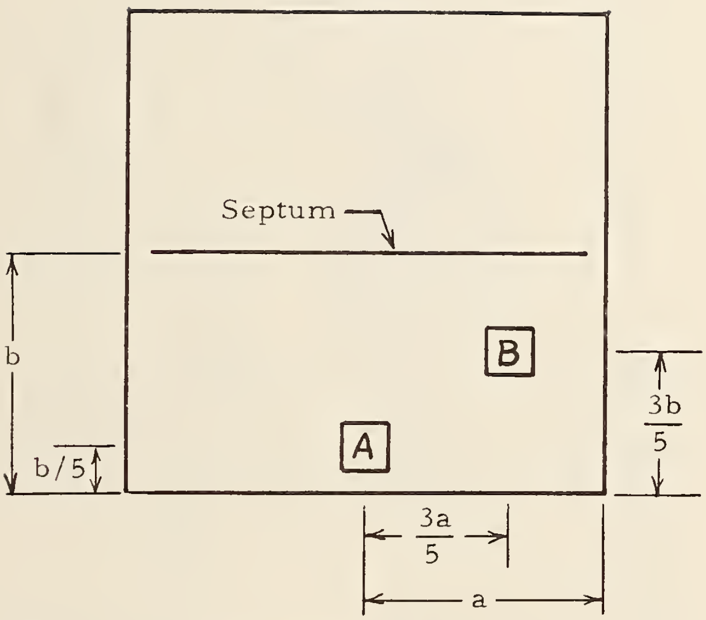


Fig. 27. Determination of E field correction factor as a function of the EUT location inside the cell.

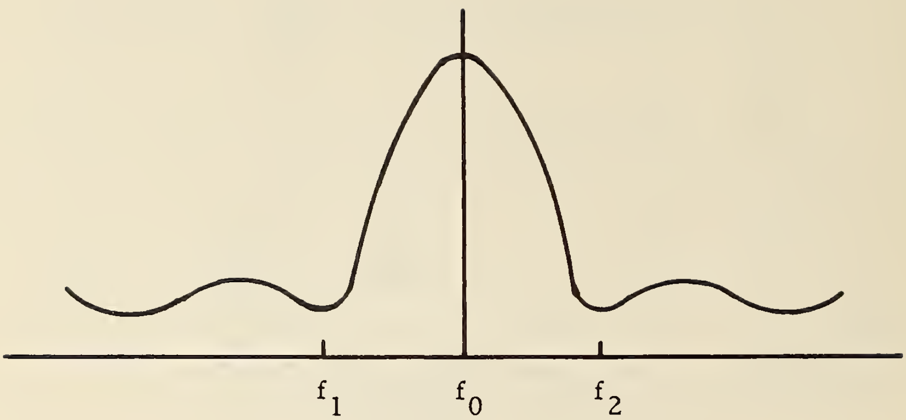
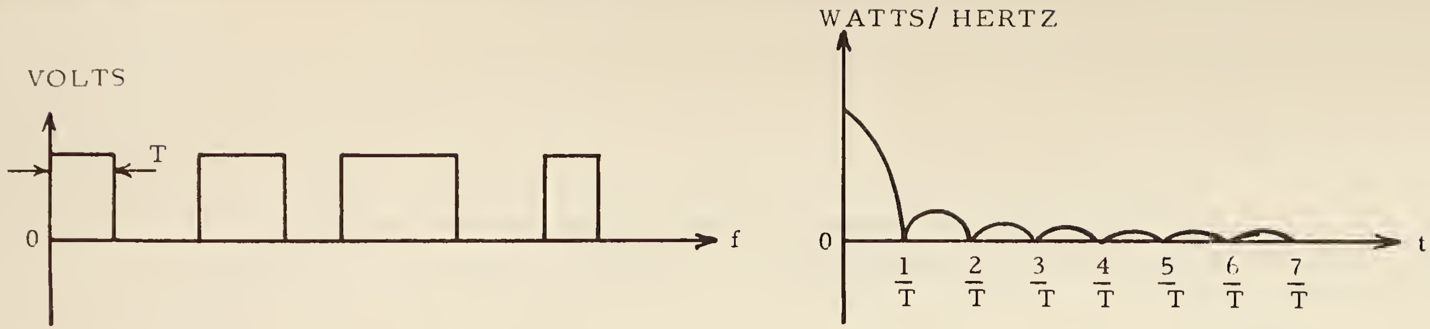
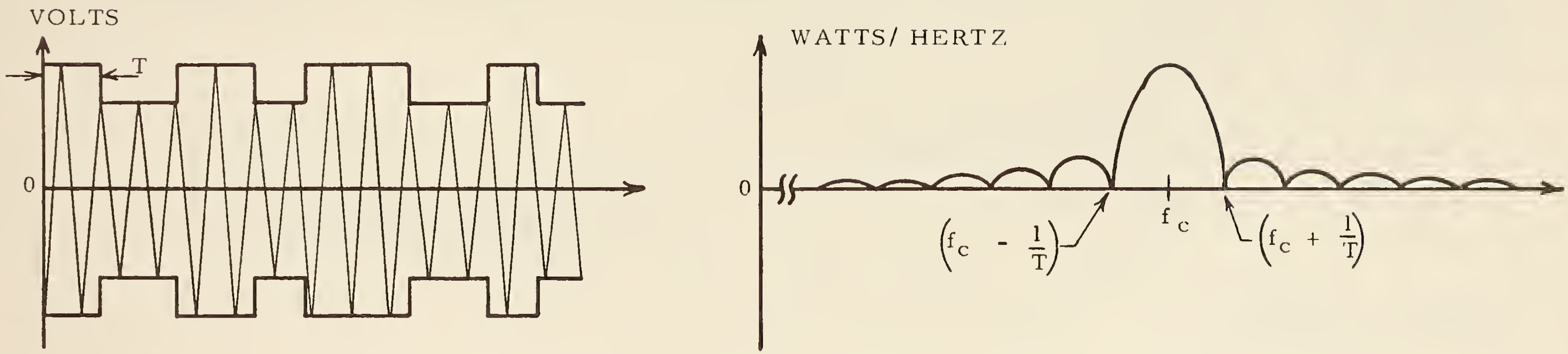


Figure 28. Example of narrowband emanation. (frequency domain)



a. DIGITAL BASEBAND EMANATION



b. SPURIOUS CARRIER f_c MODULATED BY DIGITAL BASEBAND SIGNAL.

Figure 29. Examples of broadband emanations. (frequency and time domain representations)

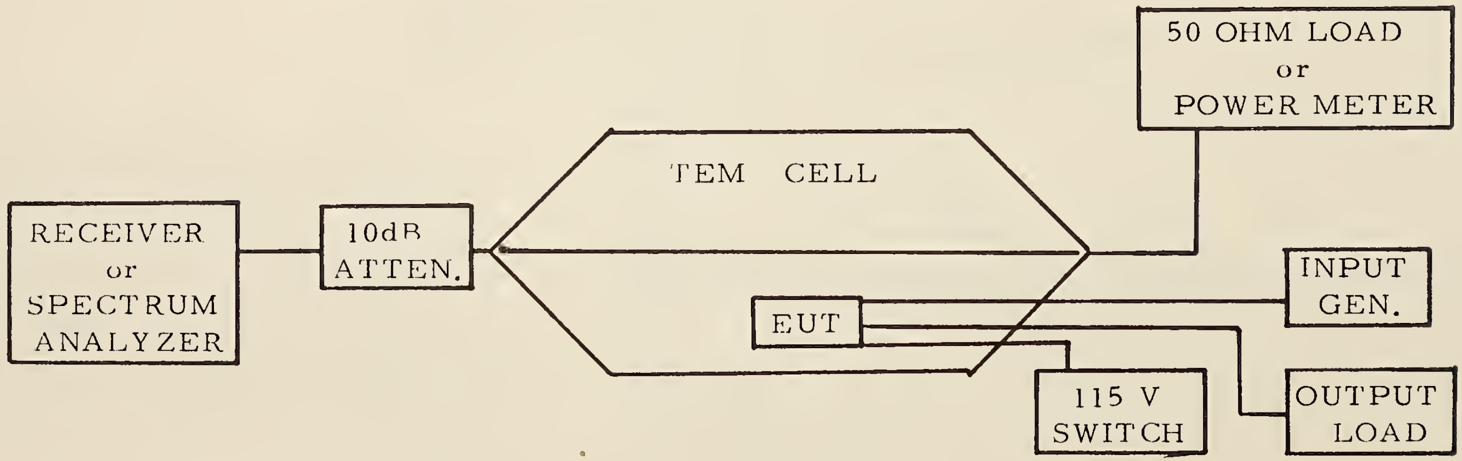


Figure 30. Block diagram of measurement system for frequency domain analysis of radiated emanations from EUT using a TEM cell.

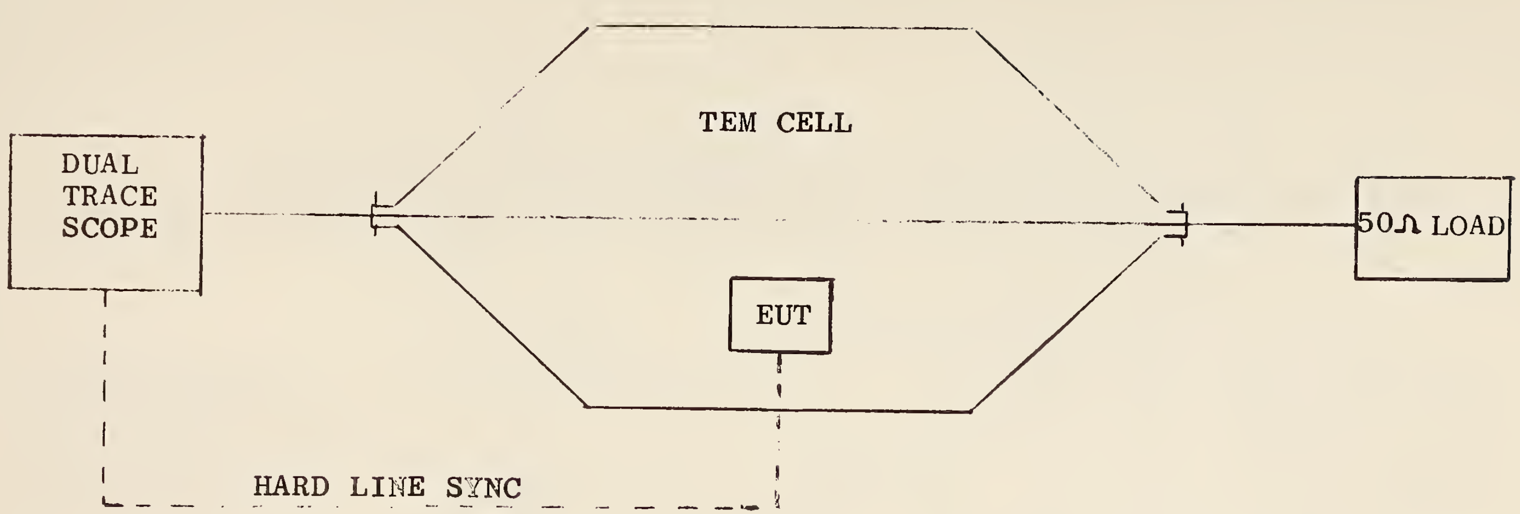


Figure 31. Block diagram of measurement system for time domain analysis of radiated emanations form EUT using a TEM cell.

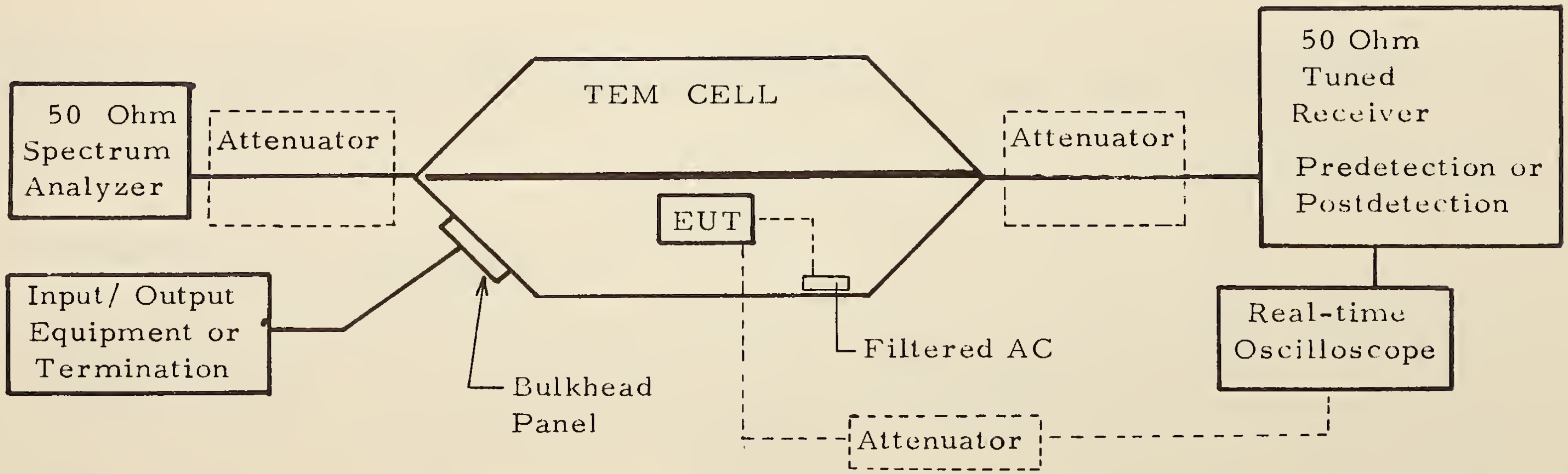


Figure 32. Block diagram of measurement system for time domain evaluation of radiated emanations from EUT using a TEM cell. (Attenuator required for hard line sync of some EUT).

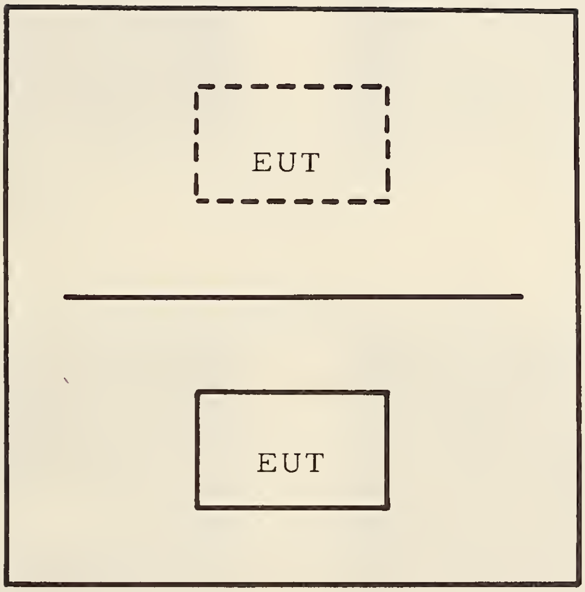


Figure A-1. Placement of EUT and its image (second identical EUT) in cell for measurement of loaded impedance, Z_0'.

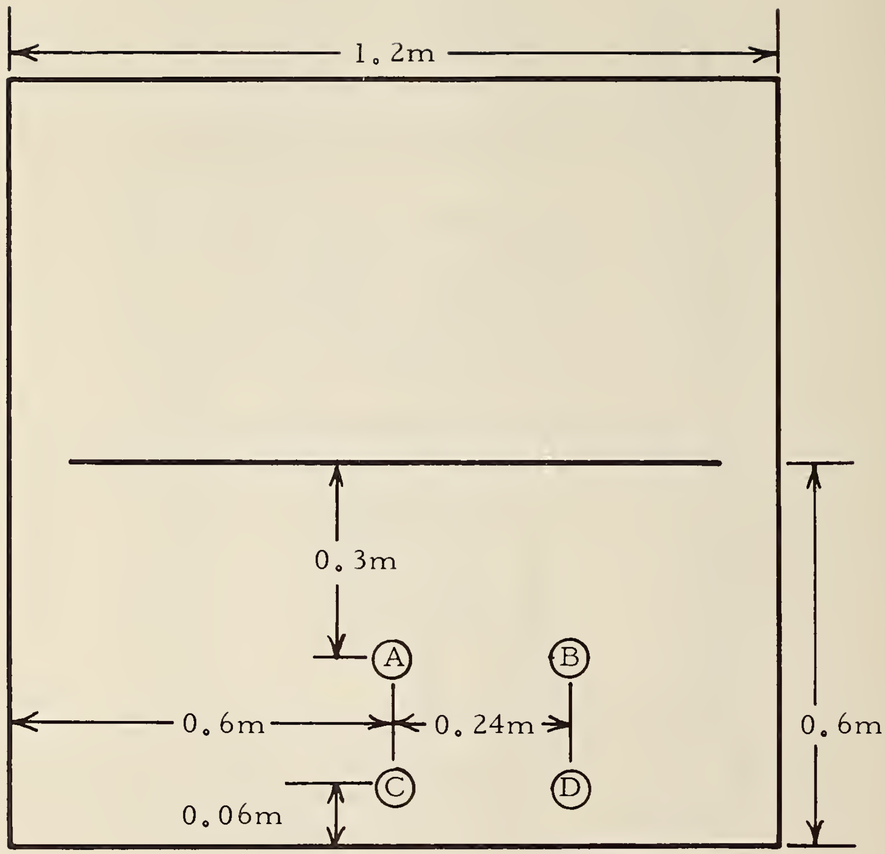


Figure B-1. Placement locations of the spherical dipole radiator inside the 1.2m x 1.2m x 2.4m symmetric TEM cell for radiated emissions measurements.

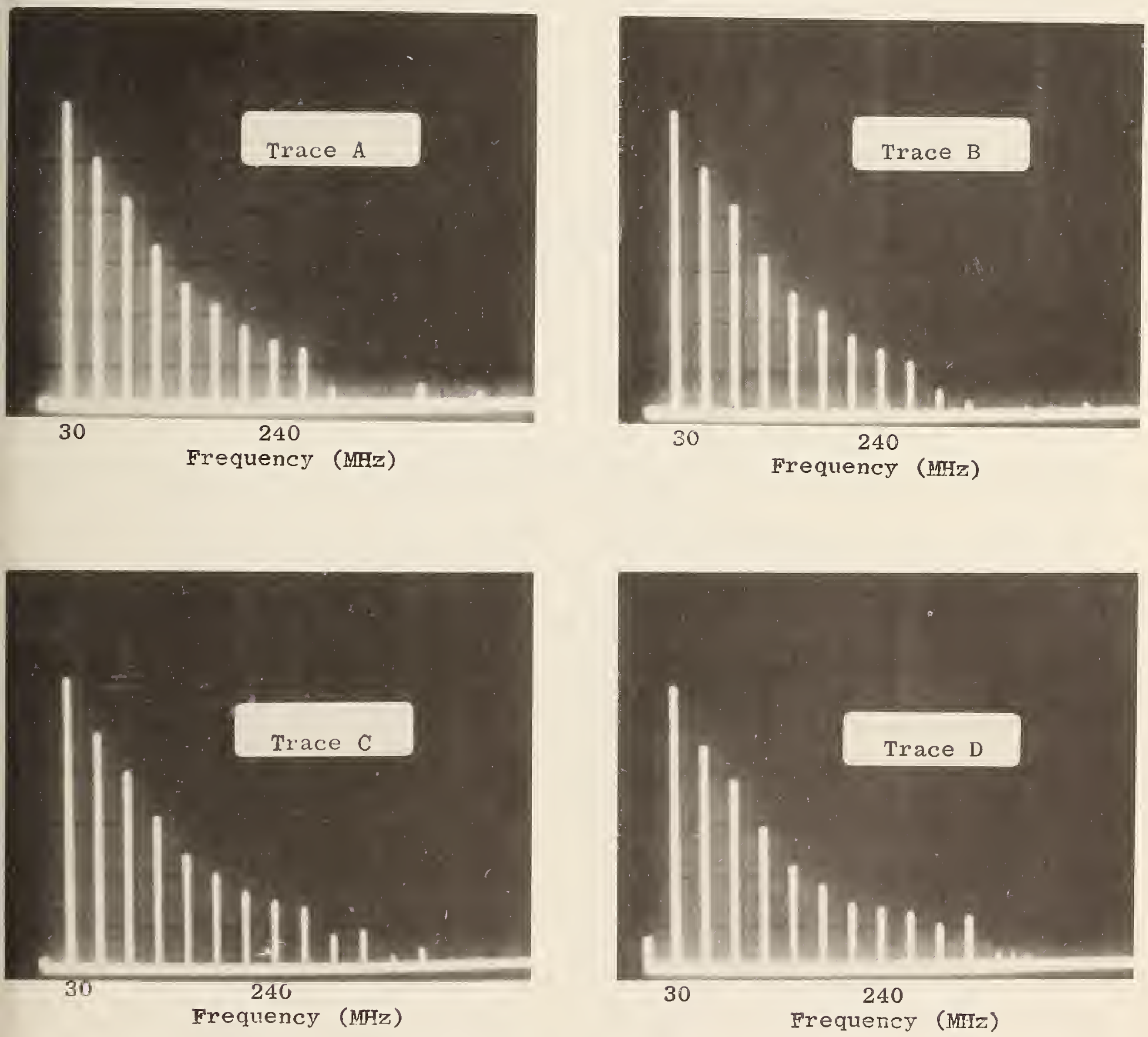


Figure B-2. Radiated emissions from 10cm spherical dipole measured inside a 1.2m x 1.2m x 2.4m TEM cell. Spectrum analyzer display (0-500)MHz. 50MHz/div. Reference level = -10dBM, 10 dB/div. Trace A obtained with dipole centered in test zone midway between septum and outer walls. Trace B same as trace A, except dipole was moved to 36cm from door side. Trace C same as trace A except dipole lowered to 6cm from floor. Trace D obtained with dipole 6cm above floor and 36cm from door side. (Location measurement referred to center of spherical dipole.)

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This publication describes the physical design and electrical evaluation of pertinent parameters which influence the use and operation of a transverse electromagnetic (TEM) cell. Detailed, step by step procedures are given for using a TEM cell for performing either radiated EM susceptibility testing or for measuring radiated EM emissions from electronic/electro-mechanical equipment. These measurement procedures provide guidelines to potential users and also indicate precautions to observe to minimize problems often encountered when performing EMC measurements and hence to enhance the cell's usefulness. Where available, a brief error analysis associated with the measurement technique is included.

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Key Words: Measurement procedures; susceptibility and emission measurements; transverse electromagnetic cell.

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Using a TEM Cell for EMC Measurements of Electronic Equipment

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Using a TEM Cell for EMC Measurements of Electronic Equipment

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CONTENTS

USING A TEM CELL FOR EMC MEASUREMENTS OF ELECTRONIC EQUIPMENT

M. L. Crawford and J. L. Workman

This publication describes the physical design and electrical evaluation of pertinent parameters which influence the use and operation of a transverse electromagnetic (TEM) cell. Detailed, step by step procedures are given for using a TEM cell for performing either radiated electromagnetic (EM) susceptibility testing or for measuring radiated EM emissions from electronic/electro-mechanical equipment. These measurement procedures provide guidelines to potential users and also indicate precautions to observe to minimize problems often encountered when performing EMC measurements and hence to enhance the cell's usefulness. Where available, a brief error analysis associated with the measurement technique is included.

Key Words: Measurement procedures; susceptibility and emission measurements; transverse electromagnetic cell.

1. INTRODUCTION

Transverse electromagnetic (TEM) cells have shown great potential for performing electromagnetic interference/electromagnetic compatibility (EMI/EMC) measurements with substantially improved ease, versatility, and accuracy [1,2]. The TEM cell consists of a section of rectangular, coaxial line that serves as a broadband, linear phase and amplitude transducer (in the sense that it converts field strength to rf voltage or rf voltage to field strength) either to establish standard electromagnetic (EM) fields for susceptibility testing of electronic equipment or to detect radiated emanations from electronic equipment [3]. The cell is also a shielded enclosure, thus providing electrical isolation for the tests being performed; and, since it is a transducer, it eliminates the use of conventional antennas with their inherent measurement limitations (i.e., bandwidth, nonlinear phase, directivity, polarization, etc.). The newness of the TEM cell measurement technique and its increasing use, and sometimes misuse, have motivated the writing of this paper. This technical note gives physical and electrical descriptions of some TEM cells and provides a detailed step-by-step procedure for their use for both radiated susceptibility and emanation measurements. These measurement procedures are intended to provide guidelines for the potential user to minimize problems encountered with this technique, enhancing the cell's usefulness, and to insure that the results obtained are as meaningful as possible. Where available, a brief error analysis associated with the measurement techniques is included.

2. PHYSICAL DESCRIPTION OF A TEM CELL

The TEM cell is a rectangular, coaxial, 50-ohm transmission line, tapered at each end to adapt to conventional 50-ohm coaxial connectors. The center conductor, as shown in figure 1, is a flat sheet of metal supported by dielectric rods in the center of the cell. Access into the cell is by side doors located as shown in the figure. Conductive finger stock material is used around the edges of the doors and around cover panels for input/output connectors and AC power leads to insure the shielding integrity of the cell.

Fabrication details for constructing a large cell, similar to the 3 m x 3 m x 6 m cell shown in figure 2, are contained in reference [4]. A cell of any size could be fabricated using dimensional scaling and the procedures outlined in [4] with, of course, appropriate, minor modifications as required. The design of the cell, as a 50-ohm impedance transmission line, is derived approximately from the expression [5]:

$$Z_o = \frac{376.7}{4\left[\frac{a}{b} - \frac{2}{\pi}\,\ell n\left(\sinh\frac{\pi g}{2b}\right)\right] - \frac{\Delta C}{\varepsilon_o}}, \qquad (1)$$

where a, b, and g are as shown in figure 3. The term $\Delta C/\varepsilon_0$ relates to the fringe capacitance between the edges of the septum and the side walls. For large gaps (i.e., $w/g \leq 5$) typically used in cell designs, this term is negligible and can be neglected. However, an exact expression for determining Z_0 can be obtained from reference [5] if required. Curves for designing a cell with arbitrary cross section and impedance are shown in figure 4. These curves are based on formulation developed by Tippet [6]. Final line impedance adjustments, to compensate for the cell's septum dielectric supports and transition angle impedance discontinuities, are made with the aid of a time-domain reflectometer by trimming the septum.

Cross-sectional drawings and a photograph of a 1.2 m x 1.2 m x 2.4 m cell are shown in figures 5 and 6. This cell is equipped with line filters to provide filtered ac power for use by equipment under test (EUT) inside the cell. The cell also has a bulkhead panel for feed-through connectors and rf filters to access the EUT via its input/output leads. If required, a shielded box can be installed over the bulkhead panel with the rf filters. This box may be necessary to prevent rf conducted on the EUT input/output leads, from radiating outside the cell or from being conducted into the cell.

3. ELECTRICAL DESCRIPTION

Electrically the TEM cell, as referred to earlier, is an expanded coaxial transmission line which propagates a TEM wave. This wave is characterized by orthogonal electric (E) and magnetic (H) fields which are perpendicular to the direction of propagation along the length of the cell or transmission line. Figure 7 shows the TEM mode field structure in the cell. The E and H field components are quite uniform over much of the volume between the septum and outer conductor, and simulate a planar field in free space (i.e., a wave impedance of 377 ohms). The TEM mode has no low frequency cut-off. This allows the cell to be used at frequencies as low as desired, limited only by the cell's magnetic shielding effectiveness which is determined by the material from which it is made. This TEM mode has the important linear phase and constant amplitude response as a function of frequency referred to earlier. This makes it possible to use the cell for broadband cw sweep testing as well as for complex wave-form simulation or detection without signal distortion; that is, as long as single TEM mode operation is maintained.

The upper useful frequency for a cell is limited by the distortion of the test signal caused by resonances and multimoding that occur within the cell at frequencies given by eqs (2) and (3).

$$f_{res} = \sqrt{f_c^2 + \left(\frac{c}{2\pounds}\right)^2} = \text{cell resonant frequency in MHz}, \qquad (2)$$

where f_c is the cell cut-off frequency for the TE_{10} mode, c is the wave propagation velocity (3.8×10^8m/sec) and £ is the resonant length of the cell. The cell cut-off frequency f_c is given as:

$$f_c = \frac{75}{a}\sqrt{1 + \frac{4ab}{\pi b_1 b_2 \ \ell n \left(\frac{8a}{\pi g}\right)}} \qquad (3)$$

The parameters a, b_1, b_2, and g are as defined earlier for equation 1 and as shown in figure 9 and 13. Progress has been made toward suppressing these adverse high-frequency effects by using rf absorber material placed in the cell as shown in figure 8 [7].

Many different cell shapes or form factors, which influence the field distribution of the cell, could be used for designing a cell. Two are shown in figures 9 and 10 with their electric field distributions. These field distributions were obtained using formulation derived by Tippet and Chang [5,6]. Tables 1 through 8 give the normalized field quantities at various transverse position locations in the cell as shown in figure 11. The normalized field, $\tilde{E}_{x,y}$, was obtained from the expression:

$$\tilde{E}_{x,y} = \frac{E_{x,y}}{\frac{V}{b}}, \qquad (4)$$

where $E_{x,y}$ is the magnitude of either the vertical or horizontal component of the electric field at the location of interest in the cell, V is the voltage between the septum of the cell, and b is the separation distance between the septum and cell upper or lower walls.

Various approaches have been investigated to find ways by which to increase the test volume available in a cell without reducing its upper useful frequency. One is to design the cell with an off-set septum. An asymmetric or offset septum cell was fabricated as shown in the cross-sectional drawings of figure 12. The E-field distributions above and below the septum of this cell are shown in figure 13. This cell offers approximately 25% greater test volume in its lower half space than a symmetric cell of similar size with an equivalent high-frequency cutoff and resonance limitation. This additional test space, however, comes at the price of less test field uniformity and greater difficulty in using the cell at multimode frequencies. A previous publication comparing the characteristics of this cell with a symmetric cell of similar size is available for further study, if desired [8].

A comparison of figures 9, 10, and 13 gives an indication of the electric field strength gradients in the area within which the EUT would be placed. For example, in the shaded area centered between the septum and lower or upper walls equal to 2a/3 x b/3, the cell of figure 9 has less than $\pm$1.4 dB E-field gradient, the cell of figure 10 has less than $\pm$0.6 dB E-field gradient and the cell of figure 13 has less than $\pm$0.5 dB above the septum and less than $\pm$2.6 dB below the septum. The cell of figure 10 or the upper half of the cell of figure 13 would be used for testing small items or calibrating small probes where good field uniformity was required. The cell of figure 9 or the lower half of the cell of figure 13 would be acceptable for testing larger objects at a maximum upper useful frequency where a loss (compromise) in the test-field uniformity could be tolerated. If a metal case (simulating an EUT) is placed in the center of one half of the cell, the field distribution is changed. The metal case disrupts the field and has a capacitive loading effect at that point in the cell. Figure 14 shows the relative field distribution with a metal case occupying one third of the volume between the septum and outer wall of a cell having the cross section of figure 10. Five transverse scans, across the width of the cell, are shown. The location of the scans are numbered on the side view of the cell and are indicated on the graph.

The field strength has increased by 3 dB and 6 dB, respectively, in the regions directly above and below the case. This increase in field strength must be taken into account as indicated in section 4.2.3 when determining the absolute test field, or the absolute level of the emitted field, if a significant cross section within the cell is occupied by the EUT.

The electrical characteristics of a cell as a transmission line can be determined simply by measuring the voltage standing wave ratios (VSWR) at the cell's measurement ports and by measuring its insertion loss. A typical empty cell's input VSWR, both with and without absorber loading, is shown in figure 15. These data were obtained by measuring the return loss (i.e., the ratio of the power incident to the cell's input port to the power reflected from the input port) of the cell shown in figure 4. The output port of the cell was terminated into a matched 50-ohm load. Resonant and multimode frequencies apparently start at approximately 220 MHz. Note how the VSWR is greatly reduced at these multimode/resonant frequencies by the rf absorber loading.

The insertion loss of a cell is obtained by measuring the difference in the net power applied at the cell's input port and the power available at the cell's output port. Inserting absorbers into the cell increases the loss substantially and must be limited to prevent excessive signal loss for both susceptibility and radiated emissions testing. The number, type, and placement location of absorbers inside the cell were experimentally determined to minimize the cell's insertion loss without significantly altering the TEM mode operation. The insertion loss of a typical cell (figure 5) is shown in figure 16. A loss of a few dB ($\leq$ 3 dB) in signal strength is reasonable for most applications; an upper frequency test limit for this particular cell, from figures 15 and 16, would be approximately 220 MHz.

Measurements can be made to determine the E-field characteristics within the test volume of the cell again with and without absorber loading for comparison, especially at high (multimode) frequencies. These measurements are made using an isotropic probe [9,10] located at the center of the test zones in the cell. The probe measures, as a function of frequency, the variation in the vertical E_y, transverse E_x, longitudinal E_z, and Hermitian magnitude S* of the electric field relative to vertical E-field component of the TEM electric field. Examples of the results of these measurements obtained in the test zones of the cell of figure 4 are shown in figures 17-20. The subscripts m and c in the ordinate of figures 17-20 refer to the <u>measured</u> as compared to the <u>computed</u> values of the amplitude of the appropriate field component in the cell. These results obviously will be influenced by inserting the EUT, especially at frequencies above the cell's resonances and multimode, and will require further evaluation if the cell is to be used above resonant/multimode frequencies. Ideally, the transverse, figure 18, and longitudinal, figure 19, components of the electric field measured at the center of the test zone should be zero. At multimode frequencies, the longitudinal and transverse components become significant, modifying the coupling and test-field characteristics of each cell and increasing the complexity of measuring the field patterns. This results in a measurement uncertainty that is difficult to define, and hence, limits the upper useful frequency range of the cell. Note that the variation in the normalized Hermitian magnitude, S, of the field ratios at multimode frequencies (above approximately 220 MHz for this cell) even for the absorber loaded case, would be quite large, resulting in large measurement uncertainties if the cell were used at these frequencies.

---

*The Hermitian magnitude S is given as $S = \sqrt{E_x^2 + E_y^2 + E_z^2}$ where E_x is the transverse component, E_y is the the vertical component, and E_z is the longitudinal component, of the E-field strength inside the cell. For the TEM mode, $E_x = E_z = 0$ at the center of the cell's test zone.

The data shown for a 1.2 m x 1.2 m x 2.4 m symmetric cell are typical of any cell with the exceptions that larger cells would have proportionally lower multimode/resonant frequencies and hence lower upper useful frequency limits and that small cells would have proportionally higher upper useful frequency limits.

The upper useful frequency of any particular cell may be expanded by using a matrix of isotropic probes to map the complex field around an EUT inside the cell at multimode frequencies or by using metal blade tuners in the cell similar to what is used in reverberating enclosures [11], for mode stirring multimoded test fields. Each of these ideas is under evaluation at NBS with the additional objectives of reducing the measurement uncertainty, especially at frequencies above the cell multimode/resonant frequencies, and of increasing the size of the EUT that could be tested in a particular cell.

4. RADIATED SUSCEPTIBILITY MEASUREMENTS

One definition of susceptibility is the characteristic of being influenced or affected by electromagnetic energy. Radiated susceptibility measurements are performed by subjecting the EUT to a known test field while evaluating its performance. To make these measurements meaningful, they must be repeatable and relate to how the equipment will respond in its operational environment. The TEM cell was developed initially at the NBS as a device for accurately generating known fields for calibration purposes [12]. Because of its ability to excite a uniform, calculable, repeatable test field that can be related to free space, the cell has demonstrated that it is also a useful tool for susceptibility measurements. If a piece of equipment is placed in the cell, it can be subjected to fields of varying levels and waveforms, thus allowing a great deal of flexibility in the measurement plan.

4.1 Using the TEM Cell for Susceptibility Measurements

Both top and bottom halves of the cell can be used for making measurements, but generally the lower half is used. This allows the EUT to be supported on the bottom of the cell instead of on the center conductor. The EUT typically is placed so that its center is midway between the septum and the bottom of the cell and midway between the two side walls as shown in figure 21. This is the region where the TEM field is the most uniform. However, if required or desired, it can be placed almost at any location in the cell. For example, it may be advantageous to place it close to the bottom of the cell, as will be seen later. For best results, the size of the EUT should not exceed more than one third of the distance between the septum and the bottom or one third of the distance between the sides or length of the main body of the cell. This prevents excessive capacitive loading which shorts out part of the vertical test field and distorts the test-field pattern. The one-third criteria were selected because this corresponds to approximately a 2-ohm change in the cell's transmission line impedance and a 3- to 6-dB increase in the susceptibility test field, as shown earlier. This increase in level can be corrected as indicated in section 4.2.3 and Appendix A or with the use of calibrated probes. If a large EUT is inserted into the cell, the cell VSWR increases rapidly, as does the field distortion, making the correction progressively more difficult and less accurate. Not only should the EUT be placed in the cell in a way that does not exceed the size limits for the cell, but it should also be positioned to simulate, as nearly as possible, actual field exposure expected in the EUT's operational environment. This may require orienting the EUT in the cell's vertical E-field to obtain the desired polarization exposure. For example, if the maximum exposure is required and the EUT is rectangular, the edges of the EUT should be positioned vertically to give maximum coupling to the vertical field. Thus, the EUT would have to be repositioned or rotated along each orthogonal axis to assure that maximum coupling is acquired for each possible path of leakage. More details on placements of the EUT are contained in section 4.4, Measurement Procedures.

4.2 Measurement Plan

The test plan normally will be based on the EM environment and EUT operational requirements. The test plan will include selecting the measurement frequencies, characteristic and signal waveform levels, EUT exposure aspect angles, EUT input/output lead complement, and the measurement approach (swept, pulsed or discrete frequency measurements). The plan should also include defining EUT susceptibility criteria and requirements for monitoring failure modes.

4.2.1 Determine the Test Frequencies and Measurement Approach

If the operational environment of the EUT is known, then the selection of test frequencies simply becomes one of choosing frequencies that correspond with significant characteristics of the environment. Often, however, the environment is not sufficiently characterized such that specifications could be chosen, or the EUT may be mobile so that the environment is changing. Then more comprehensive testing may be required. Equipment susceptibility to EMI is primarily determined by the degree to which the interference field couples into and interacts with the equipment's components. This undesired coupling is influenced by a number of equipment parameters such as: input/output, power line, and circuit lead impedances and lead lengths; impedances of circuit components (especially those terminating lead wires); type of circuit components (particularly active components); and amount and type of EMI shielding and filtering used. The susceptibility of any particular equipment is frequently a function of frequency, suggesting resonance effects within the equipment with its input/output leads and other interconnected equipment. These resonance cases may be caused, for example, by the reactance of the connecting leads acting as an antenna, coupling with the input impedance of the terminating circuit components. The quality factor (Q) of such a resonant circuit determines the maximum spacing or increments between frequencies at which susceptibility tests must be performed. For example, a circuit Q of 40 (typical in many electronic systems) requires tests at increments of 18% in frequency between 0.5 to 10 MHz, 4.8% between 10 and 20 MHz, 2.4% between 20 and 50 MHz, 1.6% between 50 and 150 MHz, and 1.2% between 150 and 1000 MHz to characterize the circuit resonances. This calls for 310 measurements, perhaps not excessive for prototype evaluations, but certainly too many for production testing unless the total measurement process is automated.

Automated systems using minicomputer control are (by their digital nature) discrete frequency systems. The number of test points one can obtain using such a system is limited by the memory/storage capacity of the computer and the measurement system bandwidth. These limitations can be partially overcome by choosing frequency and amplitude measurement intervals compatible with the test system and the number of test points required. Computer-automated systems obviously are very efficient, effective tools for obtaining equipment susceptibility data; however, they can also be very costly.

Swept frequency susceptibility testing systems are also very useful in obtaining test data. These systems have the advantage of complete frequency coverage within the systems' bandwidths, but they lack computation capabilities for data analysis that are possible with computer-controlled systems.

An important precaution that must be exercised when using swept frequency testing is to insure that the frequency sweep rate is slow enough to allow adequate time for the EUT to respond, if susceptible, to the test field.

Some EUT's have components with relatively slow thermal time constants. This equipment must be exposed to test fields with sufficient duration to allow reaction/interaction; otherwise susceptibility tests may not be true indicators of the equipment's vulnerability. For example, some electronic systems require one to two seconds' exposure time for maximum response. Swept testing, however, has some obvious advantages over stepped or discrete frequency testing as demonstrated in figure 22. The solid line in the figure shows a typical plot of an EUT resonance response using swept measurements. The dashed line represents results of the the same tests performed using the stepped frequency approach. The stepped approach shows a peak at 102 MHz but has missed the resonant peak at 101.6 MHz. If the stepped approach were used and greater resolution were required, further testing with smaller frequency increments would have to be done in the frequency range 101 to 103 MHz.

Once again, determining the type of exposure fields to which an EUT should be subjected is very EUT dependent. Such determinations should be made for each type of equipment, considering its application and its planned operational environment. The waveform to which an EUT is exposed can have a pronounced effect upon its susceptibility. Some EUT's, for example, are not bothered by relatively strong cw fields but can be interfered with if the signal is modulated. An example of this type of interference is the demodulation of an amplitude modulated (AM) signal by a solid-state device. If the EUT uses AM and incorporates solid-state switching, the AM on the cw carrier can be demodulated by the switches and coupled into the audio circuits of the EUT. In this case, the cw carrier is not the cause of the interference, but rather the interference is a result of the interaction of the switches with the AM signal.

Another extremely important common source of interference is transient spikes on impulsive signals that get coupled into an EUT. These spikes can have considerable energy over large frequency bandwidths and are difficult to accurately simulate. TEM cells offer a useful tool for this type of testing.

4.2.2 Establish EUT Failure or Performance Degradation Criteria

Performance degradation or failure in an EUT typically relates to its compliance with a required performance specification. If the EUT's performance deviates outside these specification limits (for example, in its output or its ability to respond properly to input) when subjected to an interfering field, then it is termed susceptible. Susceptible modes for each EUT must be defined relative to a measurable response that can be monitored in a repeatable, meaningful way for a practical range of test conditions representative of typical operational environmental conditions.

4.2.3 Establishing the Exposure Field Levels as Required for the Tests

Normally, the electric field strength, E, is determined relative to the reference position at the center of the test zone in the cell. This determination is made with the cell empty. However, they represent the field exposure to which the EUT is subjected if the EUT is small (less than 2a/5, b/5, L/5).

The electric field strength, E_0, at the reference point halfway between the septum and floor in the center of the cell can be determined simply by measuring the voltage potential, V, between the center plate and the cell's outer wall. The electric field is given then as:

$$E_0 = \frac{V}{b} , \tag{5}$$

where b is the separation distance between the center plate and the lower or upper wall. If the EUT is not small, the EUT will effectively short out part of the vertical separation, b, between the plates resulting in an increase in the exposure field. This new E_0' (with the EUT in the cell) can be found by determining the new effective separation distance, b', given as: b' = b - h, where h is the effective width of the EUT between the plates. E_0' then is equal to V/b'. Actually, unless the EUT's length and width occupied the full length and width dimensions of the cell, and the EUT case was metal (highly conductive), the effective height of the EUT is not as large as its physical height. The effective separation distance b' is then determined by measuring the distributed impedance of the TEM cell as a transmission line after inserting the EUT inside. This measurement is made using a time domain reflectometer (TDR). The value of the cell transmission line impedance in the section occupied the EUT is then used with eq (1) to compute b' and hence E_0'. An, example, computation of b' and E_0' based on TDR measurements is contained in Appendix A. If a TDR is not available or it is not convenient to make this impedance measurement, b' can be estimated by measuring the exposure field level at the center of the cell test zone, without the EUT in the cell, using a small dipole probe [10]. The probe's output voltage is then recorded and used as a reference to compare measurements of the exposure field made using the probe with the EUT in the cell similar to the example shown in figure 14.

If the test frequency is high enough that the wavelength, λ, is not significantly greater than the cell length ($\lambda \leq 10L$), the voltage, V, measured at the input or output port of the cell may be significantly different than the voltage potential at the center of the cell based upon the cell's VSWR. This would result in an error proportional to the VSWR or cell mismatch impedance. At frequencies for which $\lambda \leq 10L$, a more accurate determination of the E-field reference to the center of the test zone can be made by measuring the net input power to the cell, P_n, and its complex impedance. The E field is then given as:

$$E_o = \frac{\sqrt{P_n/G_c}}{b}, \text{ or } E_o' = \frac{\sqrt{P_n/G_c'}}{b'} \tag{6}$$

where G_c and G_c' are the real part of the cell's characteristic admittance referenced to the center of the cell with or without the EUT inserted in the cell.

P_n is determined from the power meter readings on the sidearms of a calibrated bi-directional coupler using the following equation

$$P_n = CR_f \cdot P_i - CR_R \cdot P_r \tag{7}$$

where CR_f and CR_R are the forward and reverse coupling ratios of the bi-directional coupler and P_i and P_r are the indicated incident and reflected coupler sidearm power meter readings.

The electric field, $E_{x,y}$ at any cross sectional location inside the cell can be determined, relative to the field, E_o, at the center of the test zone by the expression:

$$E_{x,y} = \frac{\sqrt{P_n/G_c}}{b} \tilde{E}_{x,y} \text{ or } E_{x,y}' = \frac{\sqrt{P_n/G_c'}}{b'} \tilde{E}_{x,y} \tag{8}$$

where P_n, G_c and b are as previously defined and $\tilde{E}_{x,y}$ can be obtained from tables 1 to 8. These tables can be used to calculate the transverse and vertical components of the electric field, as well as the magnitude and polarization angle of the electric field defined by:

$$E_{x,y} = \sqrt{E_x^2 + E_y^2}, \text{ and } \theta = \arctan \frac{E_y}{E_x} \quad (9)$$

For example, from table 3, $\tilde{E}_{x,y}$ is equal to 0.853 for the center of the EUT located at position A as shown in figure 27 inside a square cell. If the EUT is moved to position B, in figure 27, the correction factor is 1.157.

The absolute accuracy with which $E_{x,y}$ can be established is defined by the simple relationship

$$E''_{x,y} = E_{x,y} \pm \Delta E_{x,y} \quad (10)$$

where $\Delta\tilde{E}_{x,y}$ is the error in determining $E_{x,y}$.

The value of $\Delta E_{x,y}$ can be found by evaluating each independent variable, P_n, G_c, b, and $\tilde{E}_{x,y}$ in expression (8) as follows:

$$\Delta E_{x,y} = \frac{\partial E_{x,y}}{\partial P_n} \Delta P_n + \frac{\partial E_{x,y}}{\partial G_c} \Delta G_c + \frac{\partial E_{x,y}}{\partial b} \Delta b + \frac{\partial E_{x,y}}{\partial \tilde{E}_{x,y}} \Delta \tilde{E}_{x,y}. \quad (11)$$

where,

$$\frac{\partial E_{x,y}}{\partial P_n} = \frac{1}{2} E_{x,y} \frac{1}{P_n}, \qquad \frac{\partial E_{x,y}}{\partial b} = -\frac{E_{x,y}}{b}$$

$$\frac{\partial E_{x,y}}{\partial G_c} = \frac{-1}{2} E_{x,y} \frac{1}{G_c}, \qquad \frac{E_{x,y}}{\tilde{E}_{x,y}} = \frac{E_{x,y}}{\tilde{E}_{x,y}} \quad (12)$$

Substituting eq (12) into (11) and assuming each independent variable could have a positive or negative value, gives the maximum fractional error in determining $E'_{x,y}$ or:

$$\varepsilon_E = \frac{\Delta E_{x,y}}{E_{x,y}} = \frac{1}{2}\left(|\varepsilon_P| + |\varepsilon_G|\right) + |\varepsilon_b| + |\varepsilon_{\tilde{E}}| \quad (13)$$

where

$$\varepsilon_P = \frac{\Delta P_n}{P_n}, \quad \varepsilon_G = \frac{\Delta G_c}{G_c}, \quad \varepsilon_b = \frac{\Delta b}{b}, \text{ and } \varepsilon_{\tilde{E}} = \frac{\Delta\tilde{E}_{x,y}}{\tilde{E}_{x,y}}$$

Higher order terms contributing to small erorrs were dropped in the derivation of eq (13).

The error ε_P, in determining P_n is due to uncertainties in coupler calibration, absolute measurement of rf power on the side arm of the coupler, and impedance mismatch between the cell, coupler, rf source, and cell termination. If a precision calibrated coupler and power meter are used and the cell and its termination are impedance matched (VSWR $\leq$ 1.05), ε_P should be less than $\pm$5%.

The error, ε_G, in determining G_c is a function of the measurement accuracy of the TDR, the impedance loading of the EUT inside the cell, and the test frequency. Obviously, if the test frequency is low enough that the electrical length of the cell is small, G_c will be the real part of the cell's termination admittance. As the frequency increases and the length of the cell becomes electrically significant, the impedance at the location of the EUT, as measured by the TDR, becomes significant. If the EUT occupies a small portion ($\leq$ one fifth) of the cross section of the cell, ε_G is small ($\leq$ 3%) and is typically neglected in the calculation of $E_{x,y}$. For larger EUT's (occupying up to one-third of the cross section of the cell) and at frequencies where the cell length is less than $\lambda/10$, the impedance loading effect must be determined with the TDR and used to correct G_c when using eq (6) to calculate E_0. ε_G for these cases can be much larger but typically would be less than 10% if the EUT were centered inside the cell. <u>Exceeding the one-third load factor is not recommended</u>. The error, ε_b, is proportional to the accuracy in physically measuring b or for significantly large EUT, in determining the effective separation distance, b'. This is estimated at approximately $\pm$1%. Error in excess of this is reflected in the estimate of $\varepsilon_{\tilde{E}}$.

Determining $\varepsilon_{\tilde{E}}$ can be difficult. Introducing the EUT inside the cell perturbs the electric field distribution as described in the section on field mapping. This loading factor (increase in E_v) can be determined using small calibrated probes, to measure the increase in the field around the EUT relative to the undisturbed field, or it can be approximated by estimating a new value for b' as discussed earlier.

The value of $\varepsilon_{\tilde{E}}$ is also influenced considerably by the form factor (ratio of cell width to the separation distance between the septum and its outside, parallel walls) and by the size of the EUT. If the EUT is small (less than b/5, 2W/5 and L/5; see figure 5 or 12), the cell's test-field distortion will be small, and the main contribution to $\varepsilon_{\tilde{E}}$ will be due to the test-field gradient between the septum and parallel wall. For this case, the sources of errors are summarized in table 9 for both asymmetric and symmetric cells. If the EUT exceeds the 1/5th factor, measurements of the field distribution around the EUT must be made in order to estimate ε_E. When making these measurements, one must realize that the EUT always interacts somewhat with the exposure field in any environment. Sorting out this open-field scattering effect, caused by the EUT/field interaction, from the perturbation effect of the EUT/field/cell interaction is difficult and results in higher estimates of $\varepsilon_{\tilde{E}}$. These estimates, of course, are unique to each EUT and are not included in table 9.

The problem of EUT/test field/transducer interaction is not unique, of course, to using TEM cells for susceptibility testing. The problem exists to some degree (great or small) depending on how and in what environment test fields are created and thus, in which the EUT is tested. Susceptibility tests performed, for example, in conventional shielded enclosures using antennas to irradiate the EUT suffer serious errors from this effect, as mentioned in the introduction.

Equation (8) is applicable only to single-mode (TEM-mode) operation of the cell. If the cells are used with absorber loading at multimode frequencies, additional errors will exist that must be evaluated. Then, the most likely approach is to use calibrated isotropic probes to measure the field distribution in the cell rather than to calculate the field level from measured input parameters. This would be done in much the same manner as probing the field around the EUT to determine field perturbation for estimating ε_E. A careful evaluation of uncertainties involved in using a matrix of calibrated probes to determine the test field distribution around the EUT in the cell's test zone is needed and is anticipated in the near future.

The sources of errors for the three different cell geometries are summarized in table 9.

4.3 Susceptibility Measurement Set-Up

Figures 23 and 24 show two block diagrams of systems using the TEM cell for susceptibility measurements. Figure 23 is used for frequencies below 1 MHz and figure 24 is used for frequencies above 1 MHz. Both systems are configured for swept frequency testing; however, either system could be used for discrete frequency testing without the use of the xy recorder or a sweep-type generator.

The high-power generator generally consists of a variable frequency generator and high-power linear amplifier. Most of today's linear amplifiers have built-in protection circuits which protect them in the event the cell system becomes impedance mismatched. The low-pass filter is needed to keep unwanted higher frequency components (second, third, etc., harmonics) from being introduced into the cell. This is especially important if the harmonics or spurious frequencies are above the multimode or resonant frequency limit of the cell. <u>A frequency counter is used to tell precisely at what frequency a failure occurs.</u> This can be important if the signal generator frequency calibration is not sufficiently accurate since EUT susceptibility often is characterized by high Q-resonances which have very narrow frequency responses. The dual coupler and power meters are used to measure the incident and reflected power at the input of the cell. A test monitor is shown with the EUT and is used to determine failure of the EUT. A 50-ohm, high-power load is used to terminate the system.

The main difference between figures 23 and 25 is the use of an rf voltmeter with monitor tee in place of the directional coupler and power meters. This is required at frequencies below 1 MHz because of the lack of availability of low-frequency, high-directivity (below 1 MHz), bidirectional couplers. At frequencies below 1 MHz, the cell is electrically small (i.e., much less than one wavelength), and accurate voltmeter measurements, which can be referred to the EUT location at the center of the cell, can be made.

Automated, interactive, susceptibility measurements can be made by using a minicomputer controlled system as shown in figure 25. This system places the testing operation under control of the computer which progressively increases the test-field level in the cell at selected test frequencies while monitoring the test-field level around the EUT and the performance of the EUT. If degradation occurs as determined from preestablished, programmed criteria, the computer can respond by limiting the test-field level to prevent damage to the EUT. The computer, also according to software instruction and format, will print out the susecptibility information. Such a system using a large 3 m x 3 m x 6 m TEM cell is under development at NBS and will be operational in the near future.

4.4 Radiated Susceptibility Measurement Procedures

The following measurement procedures are suggested as a systematic approach for evaluating the EM radiated susceptibility of equipment using a TEM cell.

Step 1. Place the EUT inside the cell.

Normally the cell is placed in one of two locations in the lower half space (below the septum) centered in the cell. The first location (location 1) is halfway between the septum and the cell bottom as was shown in figure 21. The EUT is supported on dielectric material with as low a dielectric constant as possible. For example, plastic foams with a dielectric constant of approximately 1.04 to 1.08 are almost invisible electrically and make good support material.

The second common location (location 2) for placing the EUT is on the floor of the cell (fig. 26), but insulated from it (unless grounding the EUT case to the cell is desired). This position is used to minimize exposure of the EUT's input/output leads and monitor leads to the test field as explained in step 5. If the EUT is placed near the floor of the cell, the test field will be lower, relative to the field at the center (midway between the septum and floor) of the cell test zone. A correction for determining this field can easily be made as discussed in section 4.2.3.

Place the EUT in either location 1 or 2 and orient the EUT as desired relative to the cell's TEM field. Normally, the first orientation position is with the EUT lying flat as in normal use.

Step 2. Access the EUT as required for operation and performance monitoring.

The EUT input/output and ac power leads should be as nearly the same as in its anticipated use. Leads should be the same length, if possible, and be terminated into their equivalent operational impedances so as to stimulate the EUT in its operational configuration. Care must be taken in routing the leads including monitor leads (if nontransparent to the rf field) inside the cell for the most meaningful, repeatable results (i.e., desired lead exposure, minimum field perturbation/interaction, etc.). To minimize exposure of the leads to the test field, the EUT should be lowered as close to the cell floor as possible and its leads should be routed along the floor of the cell in appropriate holders, to the bulkhead panel and ac receptacle, as shown in figure 26. Shield the leads by either taping the leads to the cell floor with 2" wide conductive tape or by using braided wire slipped over the lead. Note, keep the leads separate; do not bundle input/output, monitor, and ac power line leads together. Twist the leads if they cannot be kept separated. If braided wire is used be sure braid is in electrical contact with the cell floor. However, care must be taken to prevent the braided shield or tape from contacting the case of the EUT unless, once again, a common ground between the EUT and cell is required. Grounding the two together will obviously influence the results of the susceptibility measurements. Connect the EUT input/output and monitor leads to appropriate feed-through, filtered connectors for accessing and operating the EUT. Input/output leads should be filtered to prevent rf leakage into or out of the cell, which would reduce the shielding integrity of the measurement system. The monitor leads must also be accessed through the bulkhead as appropriate for the measurement requirement. These leads, which are used for sensing and telemetering the performance of the EUT while exposed to the test fields, may require special "invisible," high-resistance leads made of carbon-impregnated plastic [10] or fiber optics lines to prevent perturbation of or interaction with the test environment. DC signals or signals with frequency components below 1 KHz may be monitored via the high-resistance lines. RF signals should be monitored via fiber optic lines.

If the monitor signal is at a frequency or frequencies sufficiently different from the susceptibility test frequency or frequencies, conductive (hard wire) leads may be used with appropriate filtering (high-pass, low-pass, band-pass, etc.) at the bulkhead. Note that a separate, shielded filter compartment should be provided on the outside of the cell for housing the filters as shown in figures 21 and 26.

Step 3. Connect up the measurement system as shown in figure 23 or figure 24.

Step 4. With the cell rf input source turned <u>off</u> and the EUT turned on in the desired operational mode, record the EUT monitor response and initialize (zero) the test-field measurement instrumentation.

Step 5. Select the first test frequency, modulation rate, test waveform, etc., turn the cell rf source on, and slowly bring up the field level inside the cell until: a) the EUT response monitor(s) indicate susceptibilityθ or b) the maximum required test level is obtained. Note: Do not increase test level too fast. Sufficient time must be spent at each test level to allow the EUT to respond. Record the monitored response.

Step 6. Select the next test frequency, modulation rate or test waveform, etc., and repeat procedures of step 5 until all frequencies, modulation levels and rates, and waveforms required by the test plan are complete. Note: It may be desirable to select specific test levels and sweep the frequency range of interest at these levels while monitoring the EUT response. If this procedure is used, the following precautions must be exercised: a) the sweep rate must be slow enough to allow the EUT to respond (remember, susceptibility often is due to resonance in the EUT circuits, leads, or apertures in its case); and b) the selected test level must not be too high or damage may occur to the EUT.

Step 7. If exposure to interference fields of the EUT input/output and ac power line leads occurs in actual use, these leads should be raised from the floor of the cell and extended inside the cell, matching polarization as much as allowed. Care must be taken to clamp the leads with dielectric supports so they can be placed in the same location (exposure) if the EUT is taken out and then returned to the cell. Both the EUT placement locations and orientation, and the input/output ac power line leads placement locations and orientations must be carefully recorded in order to obtain repeatability when reevaluating the susceptibility characteristics of an EUT. This is true no matter what the test environment (e.g., shielded enclosure, TEM cell, anechoic chamber, etc.) since EUT susceptibility obviously is a function of how the interference is coupled into the EUT (e.g., EUT exposure aspect angle relative to interference polarization, etc.). With the EUT leads now exposed to the test field, steps 4 through 6 should be repeated. NOTE: Performing step 7 as a separate procedure provides information on how the interference fields are coupled into the EUT.

Step 8. Next, the EUT should be reoriented from position 1 (flat, normal operating position) by laying it on its side or on its end. All three orthogonal orientations of the EUT may need to be tested in the cell. This is required to expose each surface of the EUT, matching polarization to the TEM field of the cell. After changing the EUT orientation, steps 2, 4, 5, 6, and 7 should be repeated.

Note: If the field close to the EUT is monitored, using, for example, small calibrated electric and/or magnetic field probes, the measured results must be interpreted carefully. This is because such measurements are made in the near field of the scattered field from the EUT and its leads. This field can be stronger than the test field (TEM field) launched inside the cell, and erroneous results or conclusions may result.

Not all the tests outlined in this measurement procedure may be required, and only those required by the test plan should be performed. For example, if the objective of the measurement program is to reduce the vulnerability (susceptibility) of the EUT, one EUT orientation with one input/output lead configuration could be tested in one particular operational mode to a preselected susceptibility test-field waveform and amplitude. Then, if corrective measures were made to the EUT and placement of the EUT and its leads inside the cell were carefully duplicated, repeat measurements could be made. These measurements could then be compared to determine degree of improvement.

5.0 RADIATED EMANATIONS MEASUREMENTS

Electronic or electromechanical equipment or components may emit energy which interferes or interacts with the normal operation of either the system and/or other receptors. To insure the electromagnetic compatibility (EMC) of such systems, it is important to determine the amplitude levels of these emanations and to characterize their waveform, polarization, etc. This is apparent since equipment performance degradation or failure is often dependent upon the interference signal waveform and the signal's amplitude.

A TEM cell is especially useful for emitted signal waveform characterization because of its characteristic as a TEM transducer which permits detection of the signal with little or no distortion in the signal waveform.

5.1 Using the Cell for Radiated Emanations Measurements

TEM cells are reciprocal devices (i.e., can receive or detect radiated fields from equipment as well as establishing fields for testing). Thus, energy radiated from an EUT placed inside the cell will couple via the TEM mode characteristics to the cell's output/input ports. If both cell ports are terminated into 50-ohm matched impedances (detectors or terminations) and if the cell is symmetric and has negligible insertion loss, one half of the EUT's radiated energy will appear at each port. This energy can be measured, for example, by using a spectrum analyzer or receiver (frequency-domain measurements) on one port and an oscilloscope (time-domain measurements) on the other port. The voltage measured at the ports, V_m, is then given as:

$$V_m = \frac{\sqrt{P_R' \times Z_o}}{2} \tag{14}$$

where P_R' is the power radiated by the EUT inside the cell, and Z_o is the cell characteristic impedance.

5.2 Determining the Free-space Equivalent Radiated Field Strength from the EUT Based on Measurements Made with the EUT Inside the TEM Cell.

The radiation characteristics of an EUT mounted inside a shielded, reflective environment will change relative to the EUT's free-space radiation characteristics. This change can be determined approximately when using a TEM cell as follows:

Experience with measuring the directivity of radiation sources (EUT's) indicates that they can be approximated reasonably well as electrically small dipole sources for frequencies at which the cell is normally used. With this assumption, the change in radiation resistance due to inserting the EUT onto the cell becomes [5]:

$$\frac{R_a'}{R_a} = 3\pi \frac{Z_o}{\eta_o} \left[\frac{\tilde{E} \cos \theta}{K_o b}\right]^2 \tag{15}$$

where:

R_a' is the radiation resistance of the EUT when mounted inside the TEM cell;

R_a is the radiation resistance of the EUT in a free-space environment;

Z_o is the cell characteristic impedance;

η_o is the intrinsic wave impedance = 120π ohms in the cell;

$\tilde{E}$ is the normalized electric field inside the cell relative to the field strength at the center of the cell test region, (i.e., $E = (E_o)/(V/b)$;
$\cos\theta$ corresponds to the polarization match between the radiated field from the EUT and the TEM mode field characteristics of the cell (maximum coupling occurs if the radiated energy from the EUT is polarization matched to the TEM field of the cell, or $\cos\theta = 1$);

K_o is equal to $2\pi/\lambda_o$ where λ_o is the wavelength of the radiated signal; and

b = separation distance between septum and lower or upper wall.

If P_R is the power radiated by the EUT in a free-space environment and P_R' is the power radiated by the EUT in the TEM cell, then:

$$P_R' = P_R \, K^2(I) \, \frac{R_a'}{R_a} \tag{16}$$

where

$$K(I) = \frac{I_R'}{I_R} , \tag{17}$$

and corresponds to the change in the EUT radiation current caused by enclosing the EUT inside the confining environment of the TEM cell. The value of K(I) is affected by the size of the EUT relative to the size of the cell. If the radiation aperture is small, the EUT radiation current distribution will be essentially the same as for open-space conditions and K will be approximately equal to one. One can determine the open-space radiated electric field strength, E_D, at a distance, d, from the EUT, assuming far-field conditions, from the expressions:

$$E_D = \sqrt{\eta_o P_D} , \tag{18}$$

$$P_D = \frac{GP_R}{4\pi d^2} , \tag{19}$$

where:

P_D is the radiated power density at the distance, d;

P_R is the power radiated from the EUT;

G is the gain characteristics of the EUT; and

$_o$ again is the instrinsic wave impedance.

Combining eqs (14 through (19) gives:

$$E_D \cong \frac{b\ \eta_o V_m}{\lambda_o\ dZ_o\ K(I)\ \tilde{E}\ \cos\theta} \sqrt{\frac{2G}{3}} \tag{20}$$

This equation then gives the field intensity in the direction of maximum radiation (i.e., maximum E_D) assuming far-field conditions. An example computation of E_D based on the measurement of emissions from a spherical dipole emitter placed in a TEM cell is contained in Appendix B. The radiation intensity very close to the EUT (small d) is influenced by the reactive near-field components; hence, E_D will be in error. Equation (20), however, should be valid for separation distances as small as $\lambda/2$, since the EUT must be electrically small (longest dimension less than $\lambda/6$) in order to satisfy the criteria that the EUT dimension be less than b/3, 2a/3 and L/3, when placed inside a TEM cell at frequencies below the cell's multimode cutoff. Some work has been done to test experimentally the validity of eq (20) and the limitations of the assumptions applicable to its use for correlating TEM cell measurements to open-space measurements [13]. However, additional work is needed. Work is progressing to develop a "standard radiator" that can be analytically characterized and used to empirically determine the change of its radiation characteristics (relative to open space) by inserting it into a cell. This radiator is completely self-contained (i.e., housing its own power supply, rf source, amplifier, and impedance matching network inside its radiating structure). Results of this development should be available in the near future.

It should also be noted that eq (20) is not valid at frequencies above the first resonant frequency of the cell. At these higher frequencies, distortion in the TEM field characteristics exists. This distortion, however, can be minimized by using rf absorber to suppress the cell resonance and higher order multimoding.

Additional work is also needed to determine analytically the change in the current distribution of the radiator (EUT structure, wiring harness, etc.) as a function of its electrical size caused by confining it inside the TEM cell. This problem is a very complex one and will require simplifying approximations, at least initially. A second effort will be to evaluate this change experimentally. This will require the use of special current and field measuring probes to determine the current distribution of the complex, radiated near field of the radiator, before and after it is confined in the cell, for comparison. Once this effort is completed, an error analysis will be performed to establish the absolute measurement uncertainties of the TEM cell radiated emanation technique.

5.3 Formulating the Measurement Plan

Formulating the measurement plan requires determining the EUT's operational modes and orientations for which tests are to be performed. It also presumes anticipating the types of tests to be performed (frequency domain; spectrum, or time-domain waveform analyses) and the detection system requirements such as bandwidth, sensitivity, etc. If the type of emanation from an EUT is known, the measurements can be simplified, and the selection of an rf detector that will give the most accurate, meaningful information can be made.

There are, in general, two types of interference emanations, narrowband and broadband. There are a great many definitions for each of these terms. However, for our purposes, narrowband means that the emanations are contained in a limited portion of the frequency spectrum, normally within the bandwidth of the detection system. Broadband emanations are produced over a large portion of the spectrum and may have signficant amounts of energy extending beyond the detection system's bandwidth. For example, the signal shown in figure 28 would be classified as a narrowband signal if the difference in frequency between f_1 and f_2 were only a few KHz. This type of signal could be the carrier of an AM broadcast station or the emanation from a local oscillator in a receiver.

Examples of broadband emanations are shown in figure 29. These emanations are impulsive signals which may be periodic or random in time with varying or constant amplitude. Some impulsive emitters are: the brushes of AC motors, switching transients created by turning equipment on or off, keying transients in digital systems, or transmit keying of tranceivers. Such emanations may cover a frequency spectrum from a few KHz to over 1 GHz.

In general, the detector and transducer selected to comply with the measurement plan requirements must have sufficient bandwidths and sensitivities to measure the amplitude and frequency or frequencies of the emanations and also must be capable of preserving the waveform characteristics of the emanations. If only the amplitude and spectrum of the emanations are required and the bandwidth of the emissions is less than 3 MHz, spectrum analyzers can be used. If additional detection bandwidth or sensitivity is required, broadband tunable receivers (field intensity meters) may be required. If the emanations are periodic, a real-time oscilloscope can be used either connected directly to the cell to measure the time-domain response or connected to the predetection or postdetection outputs of the broadband tunable detectors, which are connected to the cell, to obtain a real-time display of the emanation. If, however, the emanations are random, special sample and hold detection or statistical sampling may be required to obtain meaningful information [14].

5.4 Measurement Set-Up

The block diagram of a typical measurement system is shown in figure 30. As mentioned earlier, the choice of detectors connected to the cell measurement port is determined by the measurement requirements such as bandwidth, frequency range, and/or time-domain response, sensitivity, etc. If the detector is not sufficiently well matched to 50 ohms, an attenuator can be inserted as shown to provide the equivalent matched termination required by the cell.

Equipment required to operate the EUT inside the cell or to which the EUT must be connected for proper operation is obviously dependent upon the particular EUT and its test requirements. Access to the EUT's input/output leads is by rf-filtered, fed-through connectors located on the outer wall of the cell near the floor as shown in figure 26. (See sec. 4.4, step 2.) Again, this lead complement is EUT dependent and must be established in the measurement plan. Filtered, ac power to operate the EUT (if required) is provided at a shielded receptacle recessed into the outer wall near the bottom of the cell.

5.5 Radiated Emanations Measurement Procedures

The following measurement procedures are suggested for making radiated emanations measurements.

Step 1. Select type of test or measurements to perform (e.g., measurement plan). This includes selection of EUT operational modes for testing, lead complement, and signal detection requirements such as bandwidth, sensitivity, waveform analysis, time domain, etc., and hence detector requirements.

Step 2. Place the EUT inside the cell with desired location and orientation to the TEM field. Instructions for placing the EUT inside the cell are the same as those used for susceptibility testing. See section 4.4, step 1 for details.

Step 3. Access the EUT as required for operation and monitoring. Again, this is similar to instructions described in section 4.4, step 2, for susceptibility testing. The only exceptions would be due to operational requirements of the EUT. For example, waveform analysis of the emitted signal from the EUT may require hardline synchronizing of the detected signal with the input signal to the EUT or to internal signals being processed by the EUT. This requires additional leads to the EUT which must be filtered and routed to minimize their interaction with the EUT and its emitted signal. Routing of these leads should be along the floor of the cell with minimum exposure (polarization mismatched) to the cell's TEM field characteristic. This would be the same as discussed in section 4.4 for placement of the EUT leads for minimum interaction with the test field.

Step 4. Connect the measurement system as shown in figure 30. The detectors (receivers, spectrum analyzer, power meters) should be calibrated as per their instruction manuals and impedance matched to the TEM cell. The 10 dB attenuator shown in figure 30 is connected between the cell and the detector to improve the impedance match.

Step 5. With the EUT switched off, determine the ambient signal level in the cell. This procedure verifies the shielding and filtering integrity of the cell and the EUT input/output leads. It also provides baseline data for the measurement system to establish minimum, detectable signal levels (sensitivity), common mode or grounding problems, and spurious signal determination, which is characteristic of the measurement (detection) equipment. If ground problems or undesired signals exist, efforts should be made to correct for or minimize them. This may require, for example, additional filtering, ac line isolators or conditioners, common or single point grounding, etc.

Step 6. Turn the EUT on in the desired operational mode and measure its radiated emanations as follows.

a) First, determine the amplitude and spectrum of the radiated emanations from the EUT. This can be done with either a spectrum analyzer or a tuned receiver (field intensity meter) connected to one port of the cell with the cell's opposite port terminated into 50 ohms.

b) Using the data obtained in a) perform the required analysis of the emanations at specific frequencies of interest. This can be done, for example, by selecting an emanation of interest, tuning the receiver or spectrum analyzer to it, and then adjusting the measurement bandwidth as required for signal definition and resolution, and recording the measurement results.

c) If time-domain analysis or emanation characterization is required, use the block diagram shown in either figure 31 with the oscilloscope connected directly to the cell measurement port, or the block diagram shown in figure 32, with the oscilloscope connected to the predetection or postdetection outputs of the receiving instrument. The arrangement shown in figure 32 provides greater measurement sensitivity. In both measurement systems (fig. 31 or fig. 32), the oscilloscope must be synchronized with either the periodic detected signal from the cell or with an EUT-monitored periodic signal represented by the dashed line from the EUT. The measurement results can then be recorded by photographing the oscilloscope display.)

d) If the emanation is random, the oscilloscope cannot be synchronized properly. Then the detected signal must be either: 1) recorded with a video disk or tape recorder and played back frame by frame to analyze the emanation; or 2) analyzed statistically using amplitude probability distribution analyzers, etc.

Complete step 6 for each EUT operational mode required.

Step 7. Reorient the EUT as required by the test plan and repeat steps 3, 5, and 6.

Step 8. If required, change orientation of EUT input/output and ac power cords used in the cell and repeat step 3, 5, and 6. Note, keep in mind the importance of careful placement of the lead to assure repeatability of measurement results.

6. REFERENCES

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Appendix A

Sample calculations of b' and $E'_{x,y}$ for Susceptibility Testing (correcting test field level for loading effect of EUT).

The following is a sample calculation for determining the corrected, effective separation distance b' and hence the electric field, $E'_{x,y}$ inside a TEM cell after inserting an EUT.

From equation (1) of this technical note, the empty cell's impedance was given as:

$$Z_o = \frac{376.7}{4\left[\frac{a}{b} - \frac{2}{\pi} \ell n\left(\sinh \frac{\pi g}{2b}\right)\right] - \frac{\Delta c}{\varepsilon_o}} \qquad \text{(A-1)}$$

The equation parameters a, b, and g were defind in the main body of the text.

The cell's impedance after inserting an EUT with its image in the oposite half space of the cell as shown, for example in figure A-1 is:

$$Z'_o = \frac{376.7}{4\left[\frac{a}{b'} - \frac{2}{\pi} \ell n\left(\sinh \frac{\pi g}{2b'}\right)\right] - \frac{\Delta c}{\varepsilon_o}} \qquad \text{(A-2)}$$

The parameter, b', is the effective separation distance between the cell septum and outer wall, and is the parameter to be determined. Taking the ratio of Z_o/Z_o' and assuming $\frac{\Delta c}{\varepsilon_o}$ is negligible gives the expression:

$$\frac{Z_o}{Z'_o} = \frac{\frac{a}{b'} - \frac{2}{\pi} \ell n\left(\sinh \frac{\pi g}{2b'}\right)}{\frac{a}{b} - \frac{2}{\pi} \ell n\left(\sinh \frac{\pi g}{2b}\right)} \qquad \text{(A-3)}$$

To find b', measure the distributed impedance of both the empty cell and the cell with the EUT and its image using a time domain reflectometer (TDR). Assume for the purpose of this example that the EUT is to be susceptibility tested in the cell of figure 5. Assume that the impedance of this cell, measured by the TDR in the section of the cell to be occupied by the EUT, is 50.5 ohm with the cell empty and 48.3 ohms with the EUT and its image inside the cell. We can compute the effective separation distance b' as follows:

For this cell, a = 0.6 m, b = 0.6 m, and g = 0.104 m.

Substituting these values along with the measured value for Z_o and Z'_o into equation (A-3) we obtain:

$$\frac{50.5}{48.3} = \frac{\frac{0.6}{b'} - \frac{2}{\pi} \ln\left(\sinh \frac{0.104\pi}{2b'}\right)}{1 - \frac{2}{\pi} \ln\left(\sinh \frac{0.104\pi}{1.2}\right)}$$

or

$$1.902 = \frac{0.6}{b'} - .637\left(\ln \sinh \frac{0.163}{b'}\right) \qquad \text{(A-4)}$$

Equation A-4 can now be solved numerically to obtain the value of b', which is approximately 0.50.

If it is inconvient to place a second equivalent EUT inside the cell to serve as an image for the principle EUT when measuring Z_0', the following approximation can be used. Measure the distributed impedance Z_0'', with only the EUT (no image) inside the cell.

Then:

$$Z_0 - 2\Delta Z_0 \cong Z_0' \qquad \text{(A-5)}$$

where

$$\Delta Z_0 = Z_0 - Z_0''$$

or

$$Z_0' \cong 2Z_0'' - Z_0$$

The approximate value, Z_0', the symmetrically loaded impedance, can then be calculated and used to obtain the corrected equivalent separation distance b'. For example, Z_0'' measured, for the sample calcuation of b' given above was 49.4 ohms. or computing the approximate value of Z_0'gives

$$Z_0' \simeq 2(49.4) - 50.5 = 48.3\ \Omega$$

If the EUT is centered in the test zone of the cell, midway between the septum and floor, we can obtain the value of $E'_{x,y}$ from equation (8) as.

$$E'_{x,y} = \frac{\sqrt{P_n R_c'}}{b'} \tilde{E}_{x,y} = \frac{\sqrt{48.3\ P_n}}{0.5} = 13.9\sqrt{P_n}\ \text{volts/meter} \qquad \text{(A-6)}$$

where $\tilde{E}_{x,y}'$ is equal to 1 at this location in the cell. For the empty cell, $E_{x,y}$ is given as.

$$E_{x,y} = \frac{\sqrt{P_n R_c}}{b} \tilde{E}_{x,y} = \frac{\sqrt{50.5\ P_n}}{0.6} = \underline{11.8\sqrt{P_n}}\ \text{volts/meter} \qquad \text{(A-7)}$$

the ratio of

$$\frac{E'_{x,y}}{E_{x,y}} = 1.18$$

This represents again for this particular EUT located at the center of the test zone, inside this particular cell, a 1.44 dB correction to the E-field, $E_{x,y}$, computed from the power measured at the cell's input port.

If the EUT was located in the center of the cell, but near the cell floor (position A indicated in figure 27) and if the impedance loading caused by the EUT inside the cell is the same as the above example, the corrected electric field strength, $E'_{x,y}$ is:

$$E'_{x,y} = 13.9 \quad P_n \ (.853) = 11.86 \quad P_n \ \text{volts}/_{\text{meter}} \qquad \text{(A-8)}$$

where $\tilde{E}_{x,y}$ is equal to 0.853 at this location in the cell. This value, for $\tilde{E}_{x,y}$ was obtained from table 3 of this technical note which gives the magnitude of the normalized electric field as a function of cross section location in a square TEM cell.

The value of the electric field strength, $E_{x,y}$ at postion A in the empty cell is:

$$E_{x,y} = 11.8 \sqrt{P_n} \ (.853) = 10.07 \sqrt{P_n} \ \text{volts}/_{\text{meter}} \qquad \text{(A-9)}$$

The ratio, $\dfrac{E'_{x,y}}{E_{x,y}}$ then is $\dfrac{11.86\sqrt{P_n}}{10.07\sqrt{P_n}} = 1.18$

This correction factor, for the loading effect of the EUT, is the same for either test location of the EUT.

Appendix B

Evaluation of cell reciprocity and calculation of field intensity, E_D relative to open space for radiated emissions testing.

The following demonstrates the reciprocity of the TEM Cell for use in performing radiated emissions measurements. It also gives a sample calculation for determining the field intensity, E_D, relative to open space, of radiated emissions measurements made with an EUT placed inside a TEM Cell. For this example, a 10 cm spherical dipole radiator was placed at four different locations inside the cell of figure 5 as shown in figure B-1. The dipole radiator operates at a fundamental frequency of 30 MHz with harmonics up to approximately 500 MHz. Spectrum analyzer displays of the detected emissions from the dipole, measured at one of the output ports of the cell are shown in figure B-2. The opposite port of the cell was terminated into 50 ohms. Note, that the relative amplitudes of the four traces are comparable at frequencies below the multimode/resonance frequencies (240 MHz) of this cell. The small differences in detected amplitude as a function of dipole placement location in the cell, at frequencies below 240 MHz, corresponds to the TEM field distribtuions shown for this cell in figure 9 and tables 1-4. This demonstrates the reciprocity of the TEM cell.

To calculate the field intensity, E_D, relative to open-space, for the radiated emissions from the EUT, we use equation (20) from section 5.2.

$$E_D \cong \frac{b\,\eta_o\,V_m}{\lambda_o\,d\,Z_o\,K(I)\,\tilde{E}\cos\theta}\sqrt{\frac{2G}{3}} \qquad \text{(B-1)}$$

For measurements made using the cell of figure 5, equation (20) or (B-1) simplifies to

$$E_D \cong \frac{(0.6)\,(376.7)\,V_m}{(50)\,\lambda_o\,d\,K(I)\,\tilde{E}\cos\theta}\sqrt{\frac{2G}{3}}$$

For the spherical dipole radiator, the maximum directive gain, G, is 1.5. Also, if the polarization of the dipole is matched to the TEM field polarization in the cell, Cos θ will be 1. In addition, since the dipole is small compared to the test volume inside the cell, the dipole current distribution for the radiator will be essentially the same as for open-space conditions, hence K(I) will be approximately 1.0. Then equation (B-1) becomes (for this cell and EUT).

$$E_D \cong \frac{(0.6)(376.7)\,V_m}{(50)\,\lambda_o\,d\,(1)\,\tilde{E}(1)}\sqrt{\frac{(1.5)\,2}{3}}$$

$$\frac{4.52\,V_m}{\lambda_o\,d\,\tilde{E}} \qquad \text{(B-2)}$$

The detected, measured voltage, V_m at the cell port for the dipole centered in the cell test zone (trace A, figure B-2) is -28 dBM at 30 MHz. This corresponds to a voltage measured with a 50 ohm analyzer of 8.9 mV. At the center of the test zone, E equals 1.0 and at 30 MHz, λ_o is 10 meters.

This equation (B-2) again for this specific emission measured from the spherical dipole ratio inside the 1.2 m x 2.4 m cell yields;

$$E_D \cong \frac{0.00402}{d}$$

or for a separation distance or 10 meters

$$\boxed{E_D \cong 0.402 \, \mathrm{mV}/_{\mathrm{meter}}} \qquad \text{(B-3)}$$

This same 30 MHz emission measured with the dipole close to the floor the cell (trace C) has a detected voltage of -30 dBM or 7.07 m/V. For this case E, interpolated from table 2 of this report, is 0.839 and the calculated field intensity, E_D, relative to open-space is:

$$E_D \cong \frac{(6.39)\ (.00707)}{(10)\ d(.839)(1.41)}$$

$$\cong \frac{0.00380}{d}$$

or for a separation distance of 10 meters,

$$E_D \cong 0.380 \, \mathrm{mV}/_{\mathrm{meter}}$$

The value obtain for E_D (eqs B-3 and B-4) for the two locations of the dipole inside the cell compares well within the measurement resolution and accuracy of this technique. This demonstrate the independence of placement location of the EUT inside the cell on the computed equivalent open-space radiated emissions results.

Table 1.

x-component of the electric field in a square symmetric TEM cell. (fig. 9, a=b, w=0.83a)

	center	a/5	2a/5	3a/5	4a/5	wall
Floor	0.000	0.000	0.000	0.000	0.000	0.000
b/5	0.000	0.060	0.129	0.208	0.278	0.307
2b/5	0.000	0.108	0.245	0.422	0.600	0.680
3b/5	0.000	0.127	0.311	0.620	1.029	1.237
4b/5	0.000	0.090	0.248	0.647	1.684	2.285
Septum	0.000	0.000	0.000	0.000	0.000	3.603

center of TEM cell

Table 2.

y-component of the electric field in a square symmetric TEM cell. (fig. 9, a=b, w=0.83a)

	center	a/5	2a/5	3a/5	4a/5	wall
Floor	0.824	0.793	0.698	0.530	0.289	0.000
b/5	0.853	0.825	0.736	0.568	0.315	0.000
2b/5	0.935	0.917	0.852	0.699	0.410	0.000
3b/5	1.049	1.052	1.051	0.977	0.652	0.000
4b/5	1.153	1.186	1.298	1.499	1.343	0.000
Septum	1.196	1.245	1.431	1.986	6.640	0.000

center of TEM cell

Table 3.

Magnitude of the electric field in a square symmetric TEM cell. (fig. 9, a=b, w = 0.83a)

	center	a/5	2a/5	3a/5	4a/5	wall
Floor	0.824	0.793	0.698	0.530	0.289	0.000
b/5	0.853	0.827	0.747	0.605	0.420	0.307
2b/5	0.935	0.924	0.886	0.817	0.727	0.680
3b/5	1.049	1.060	1.096	1.157	1.218	1.237
4b/5	1.153	1.189	1.321	1.633	2.154	2.285
Septum	1.196	1.245	1.431	1.986	6.640	3.603

center of TEM cell

Table 4.

Polarization angle of the electric field in degrees in a square, symmetric TEM cell.

	center	a/5	2a/5	3a/5	4a/5	wall
Floor	90.00	90.00	90.00	90.00	90.00	--
b/5	90.00	85.86	80.05	69.89	48.54	00.00
2b/5	90.00	83.27	73.97	58.89	34.35	00.00
3b/5	90.00	83.14	73.50	57.60	32.36	00.00
4b/5	90.00	85.64	79.20	66.67	38.56	00.00
Septum	90.00	90.00	90.00	90.00	90.00	00.00

center of TEM cell

Table 5.

x-component of the electric field in a rectangular symmetric TEM cell. (fig. 10, 0.6a = b, w = 0.72a)

	center	a/5	2a/5	3a/5	4a/5	wall
Floor	0.000	0.000	0.000	0.000	0.000	0.000
b/5	0.000	0.024	0.067	0.143	0.220	0.249
2b/5	0.000	0.040	0.121	0.284	0.462	0.517
3b/5	0.000	0.043	0.141	0.410	0.763	0.817
4b/5	0.000	0.028	0.101	0.440	1.247	1.112
Septum	0.000	0.000	0.000	0.000	1.969	1.254

center of TEM cell

Table 7.

Magnitude of the electric field in a rectangular symmetric TEM cell. (fig. 10, 0.6a = b, w = 0.72a

	center	a/5	2a/5	3a/5	4a/5	wall
Floor	0.966	0.946	0.872	0.698	0.394	0.000
b/5	0.972	0.956	0.892	0.738	0.466	0.249
2b/5	0.989	0.982	0.951	0.856	0.655	0.517
3b/5	1.010	1.016	1.038	1.062	0.945	0.817
4b/5	1.028	1.046	1.125	1.383	1.404	1.112
Septum	1.035	1.058	1.164	1.664	1.969	1.254

center of TEM cell

Table 6.

y-component of the electric field in a rectangular symmetric TEM cell. (fig. 10, 0.6a = b, w = 0.72a)

	center	a/5	2a/5	3a/5	4a/5	wall
Floor	0.966	0.946	0.872	0.698	0.394	0.000
b/5	0.972	0.956	0.890	0.724	0.411	0.000
2b/5	0.989	0.981	0.944	0.807	0.464	0.000
3b/5	1.010	1.015	1.028	0.979	0.557	0.000
4b/5	1.028	1.046	1.120	1.311	0.645	0.000
Septum	1.035	1.058	1.164	1.664	0.000	0.000

center of TEM cell

Table 8.

Polarization angle of the electric field in degrees in a rectangular, symmetric TEM cell.

	center	a/5	2a/5	3a/5	4a/5	wall
Floor	90.00	90.00	90.00	90.00	90.00	--
b/5	90.00	88.58	85.68	78.80	61.76	00.00
2b/5	90.00	87.66	82.70	70.61	45.12	00.00
3b/5	90.00	87.60	82.20	67.26	36.15	00.00
4b/5	90.00	88.48	84.82	71.43	27.36	00.00
Septum	90.00	90.00	90.00	90.00	90.00	00.00

center of TEM cell

TABLE 9.

SUMMARY OF MEASUREMENT ERRORS FOR SUSCEPTIBILITY MEASUREMENTS

Source of Error	Percent Uncertainty: Symmetric a = b (Fig. 9)	Asymmetric (Fig. 13): Above Septum	Asymmetric (Fig. 13): Below Septum	Rectangular 0.6a = b (Fig. 10)
a) Absolute measurement of incident RF power on side arm of Coupler	∓ 3%	∓ 3%	∓ 3%	∓ 3%
b) Coupler Calibration	∓ 2%	∓ 2%	∓ 2%	∓ 2%
ϵ_P, total error in determining the net power passing through cell.	∓ 5%	∓ 5%	∓ 5%	∓ 5%
c) ϵ_R determination of the Real part of the cell complex impedance.	∓ 3%	∓ 3%	∓ 3%	∓ 3%
d) ϵ_b Cell center plate separation distance from upper or lower wall.	∓ 1%	∓ 1%	∓ 1%	∓ 1%
e) $\epsilon_{\tilde{E}}$ Nonuniformity or pertubation of the electric field inside the cell test zone.	∓ 20%	∓ 5%	∓ 30%	∓ 6%
* ϵ_E, Total maximum field strength error	∓ 25% ∓ 2dB	∓ 10% ∓ 1dB	∓ 35% ∓ 3dB	∓ 11% ∓ 1dB

* For example $\epsilon_E = \mp \left| \frac{1}{2}(0.03 + 0.05) + 0.01 + 0.20 \right| \times 100 = \mp 25\%$

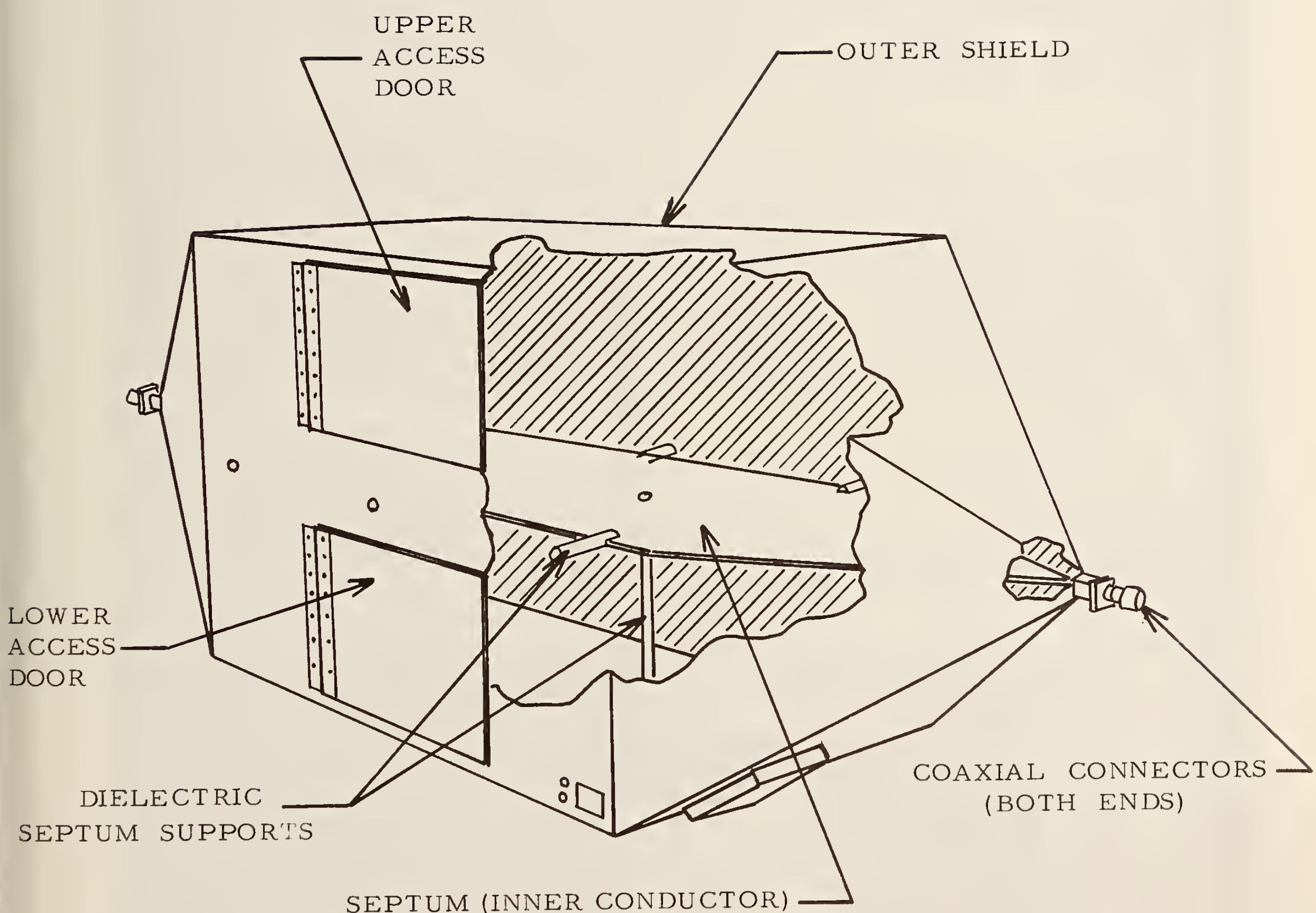


Figure 1. View of transverse electromagnetic (TEM) cell.

Figure 2. NBS 3m x 3m x 6m TEM cell

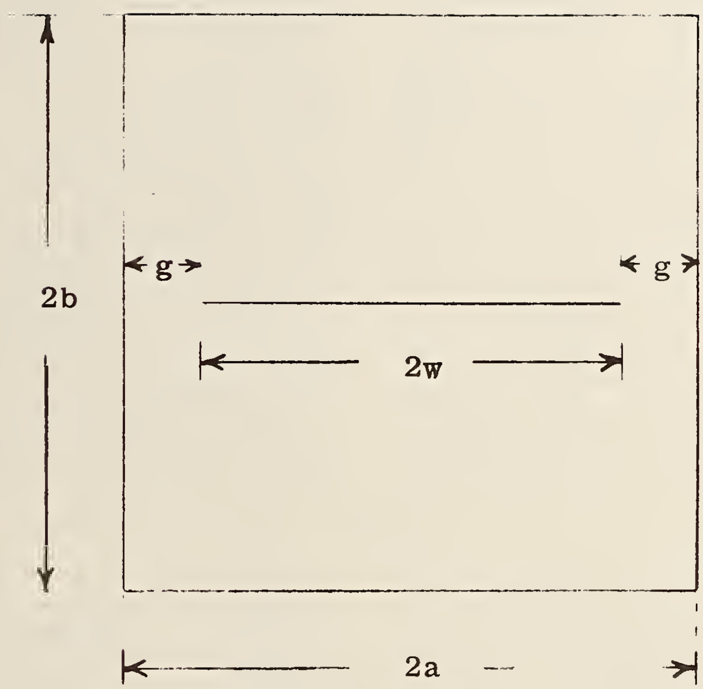


Figure 3. Cross-section of a TEM cell.

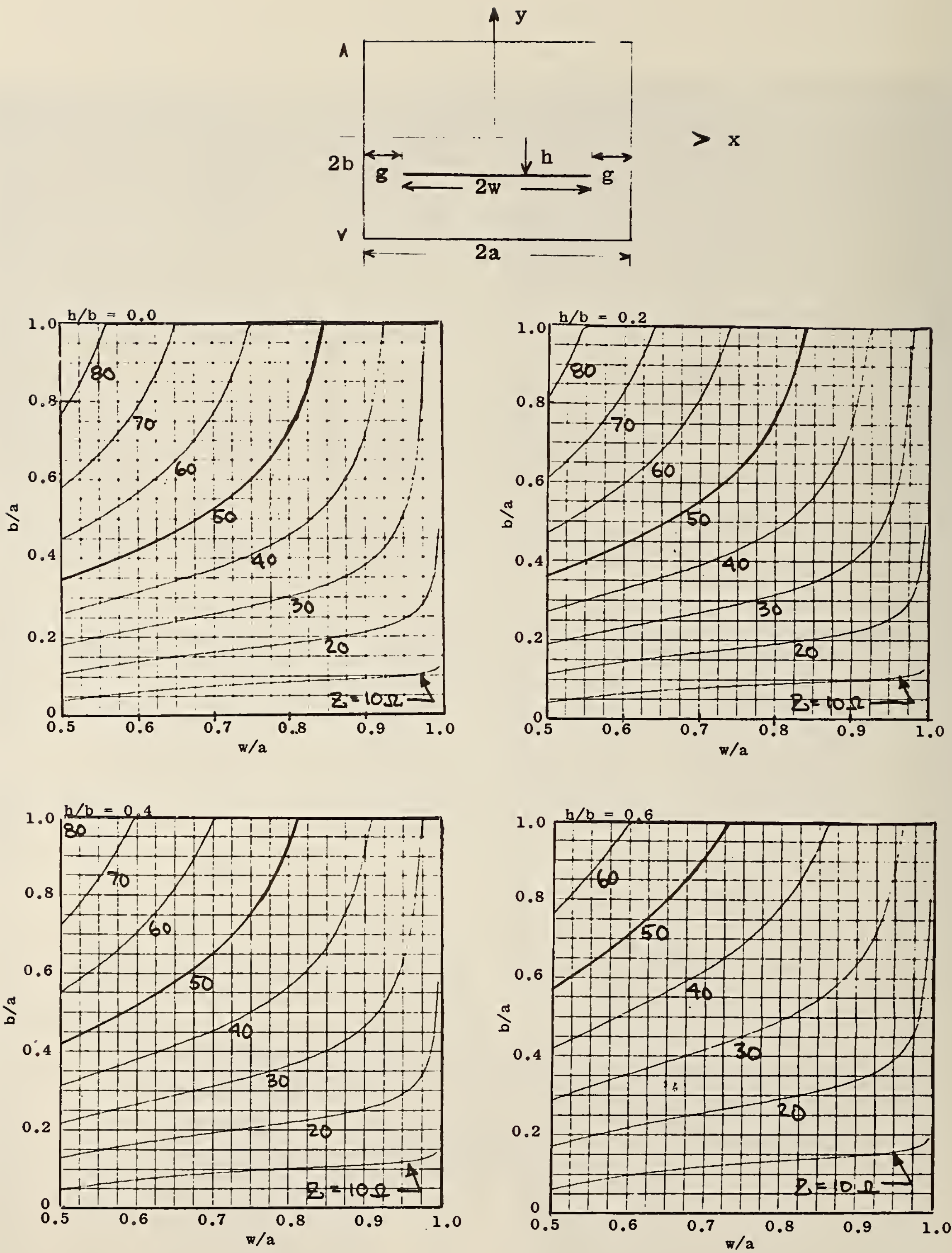


Figure 4. Transverse electromagnetic (TEM) cell design curves showing ratio of cell outer conductor dimensions to ratio of center plate width to cell width for various transmission line characteristic impedances and vertical center plate locations.

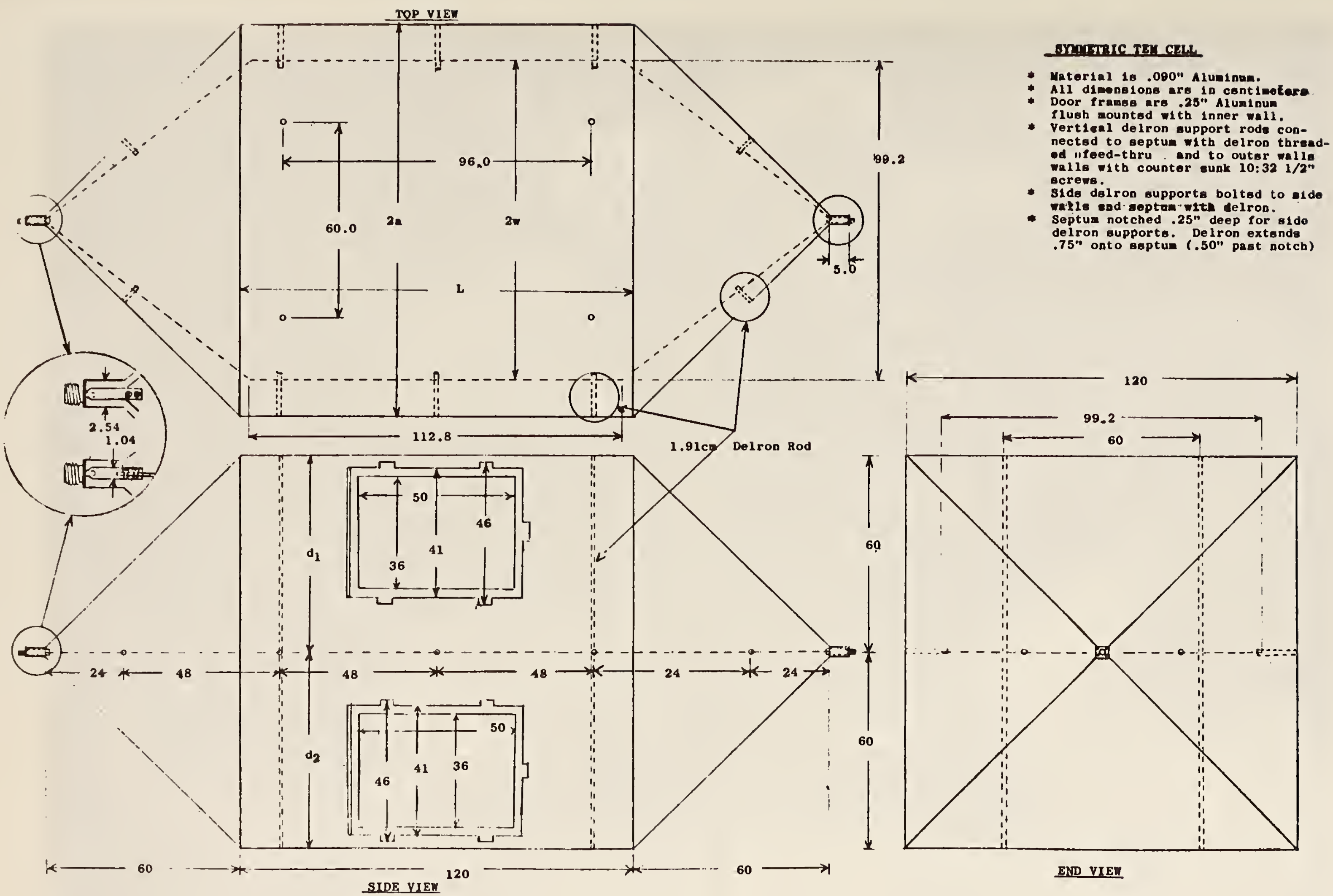


Figure 5. Cross sectional views of symmetric rectangular TEM cell.

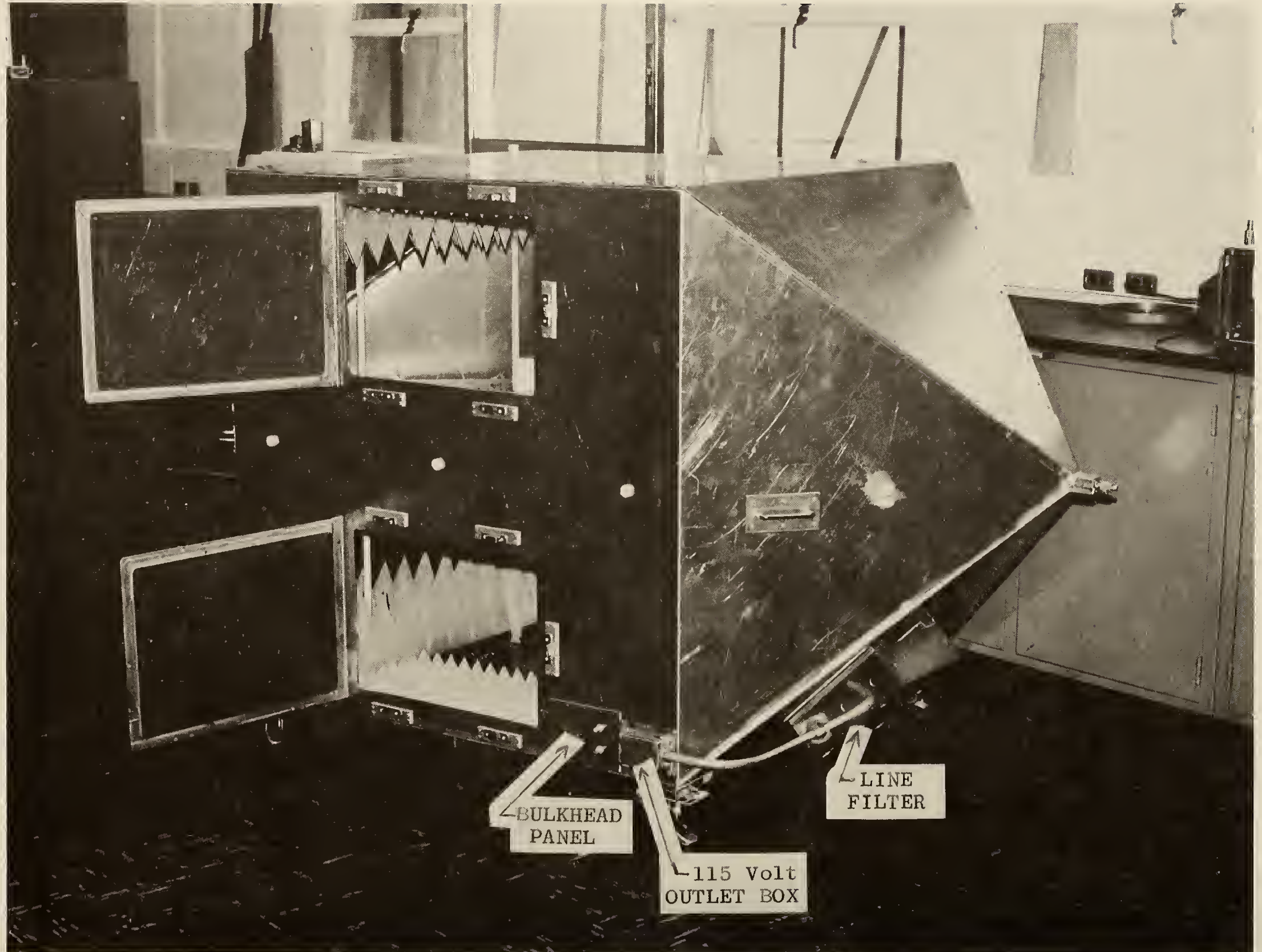


Figure 6. 1.2m x 1.2m x 2.4m TEM cell.

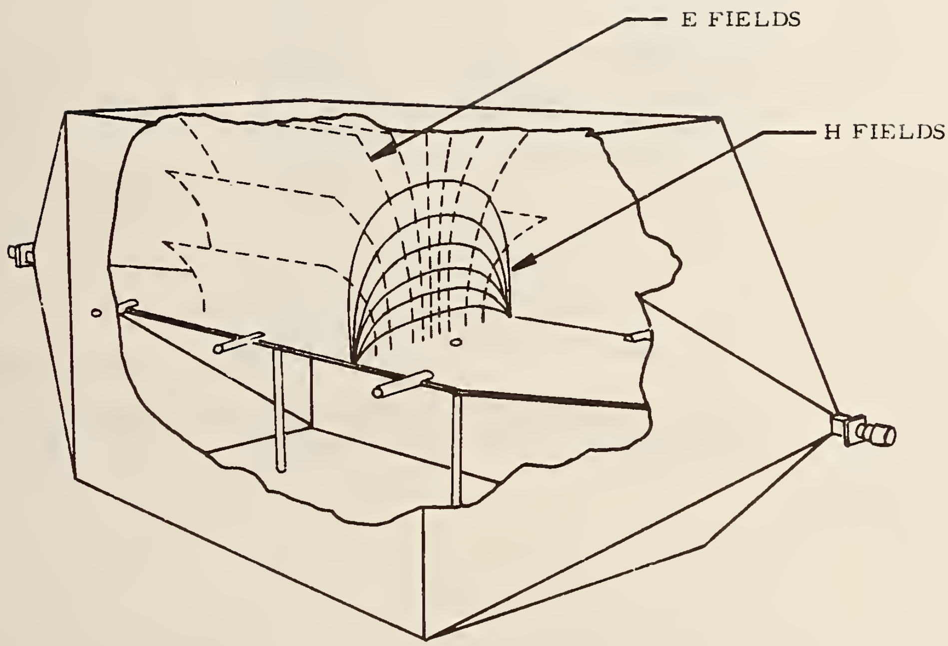


Figure 7. Trnsverse electromagnetic (TEM) field distribution inside a TEM cell.

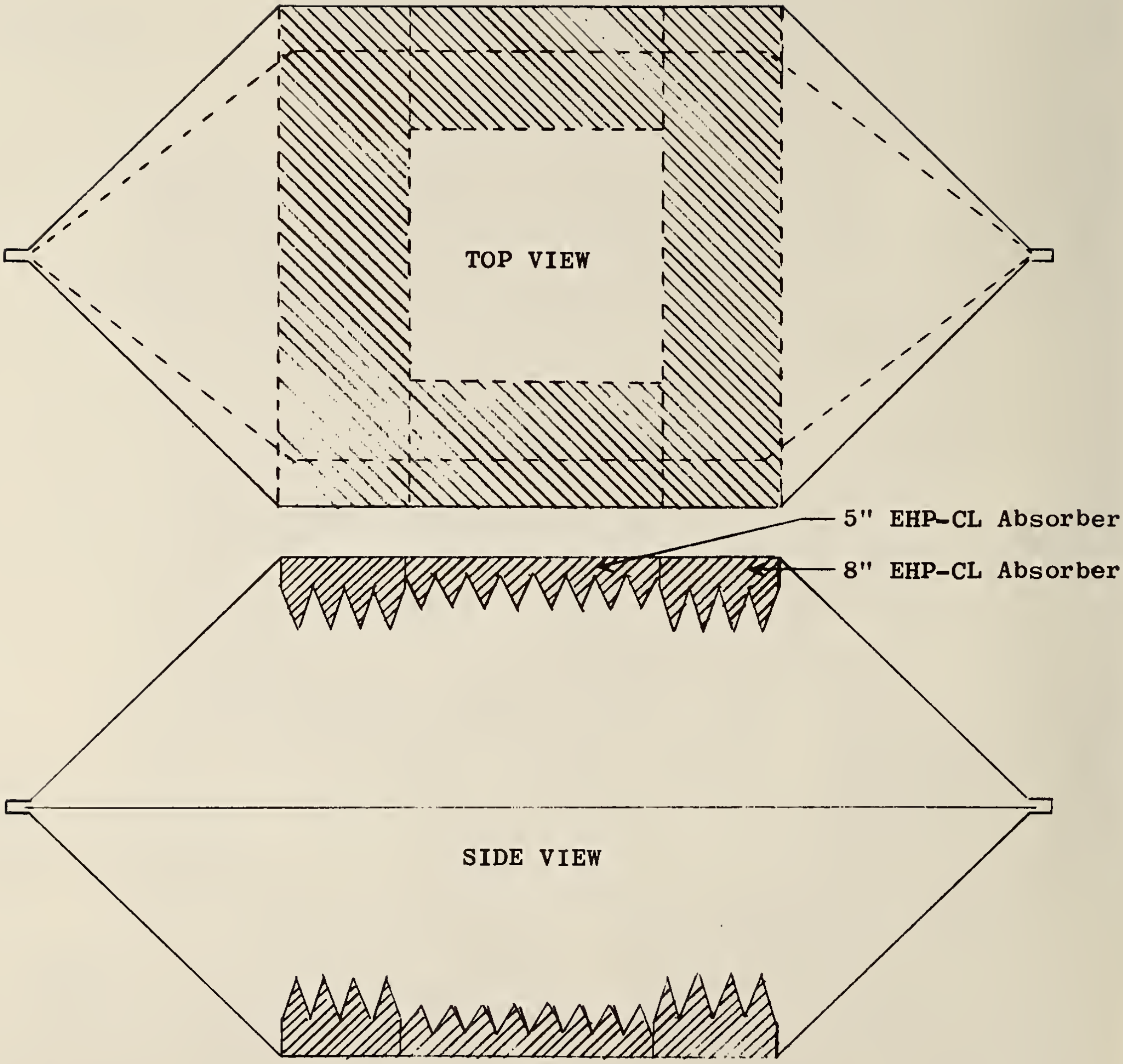


Figure 8. Diagram for absorber loading symmetric TEM cell.
(Shaded areas indicate placement of anechoic material.

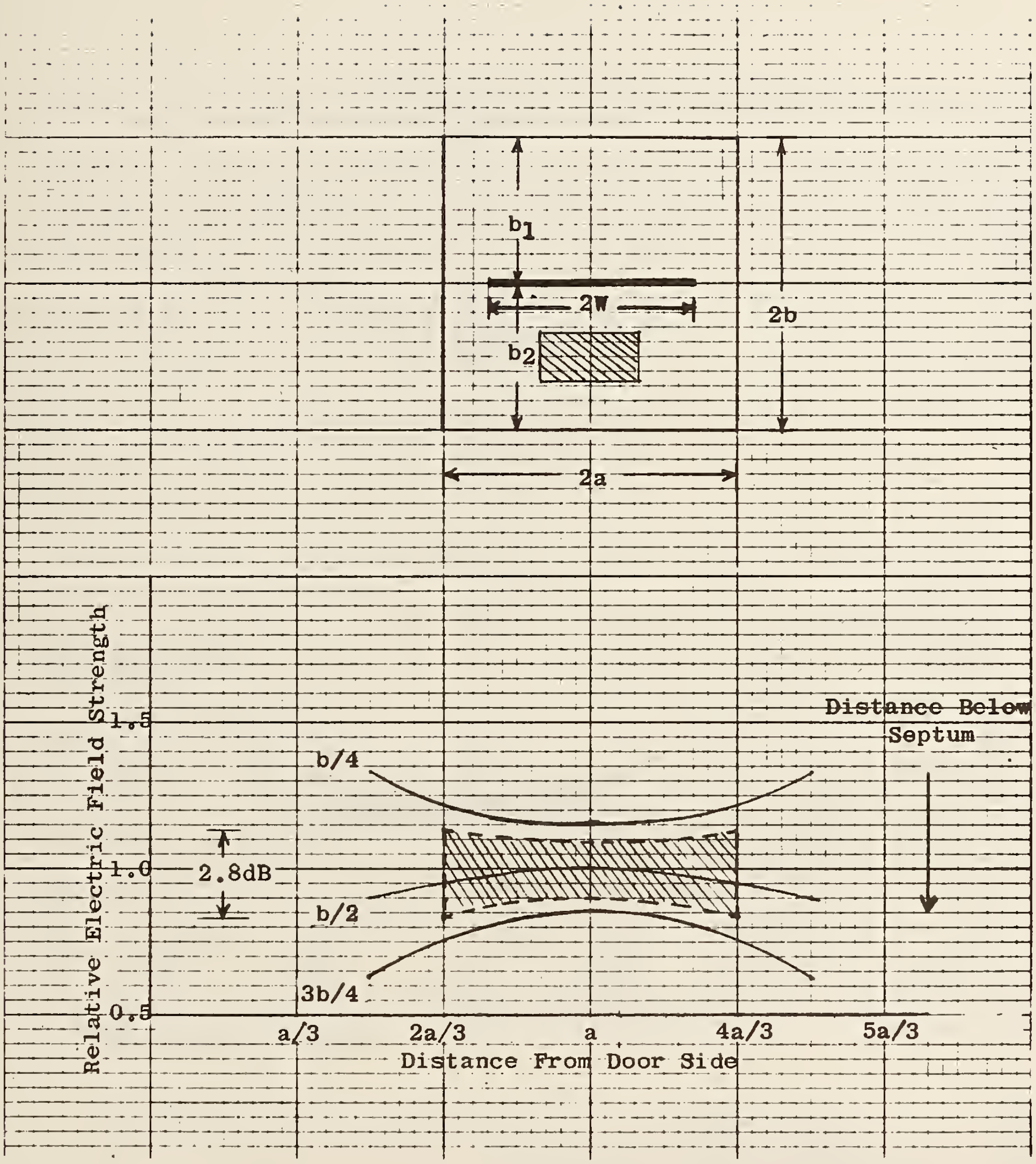


Figure 9. Relative electric field distribution inside symmetric cell. Shaded area corresponds to 1/3 cross-section area shown in top view.

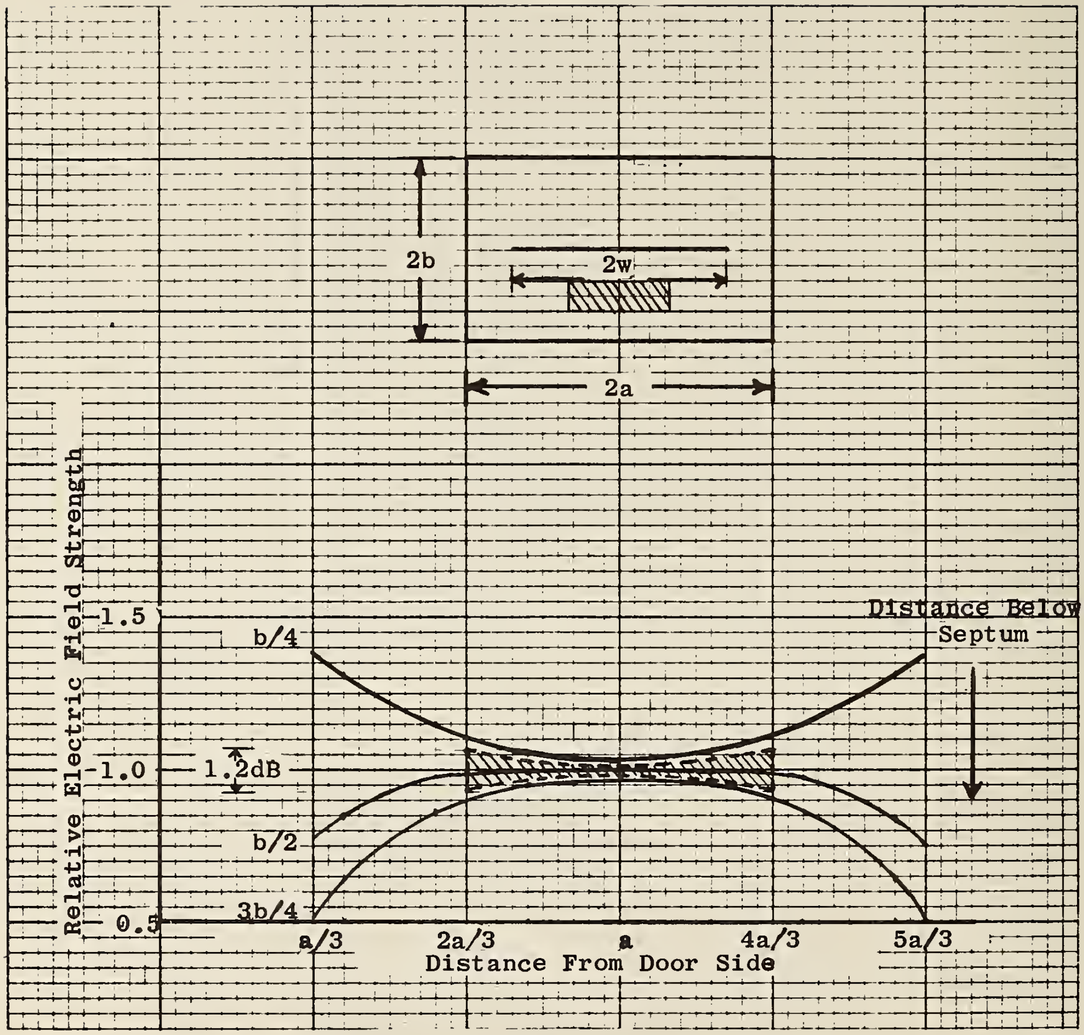


Figure 10. Relative electric field distribution inside rectangular (0.6 a = b), symmetric TEM cell. Shaded area corresponds to 1/3 cross-section area shown in top view.

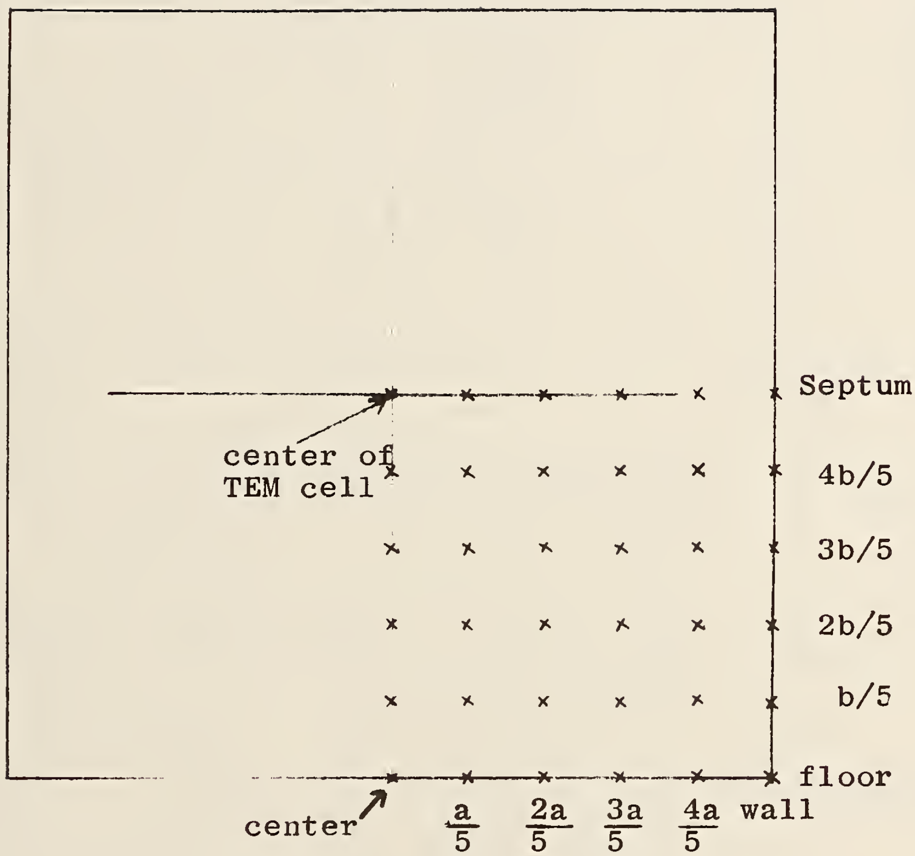


Figure 11. Field distribution locations shown in tables 1-8.

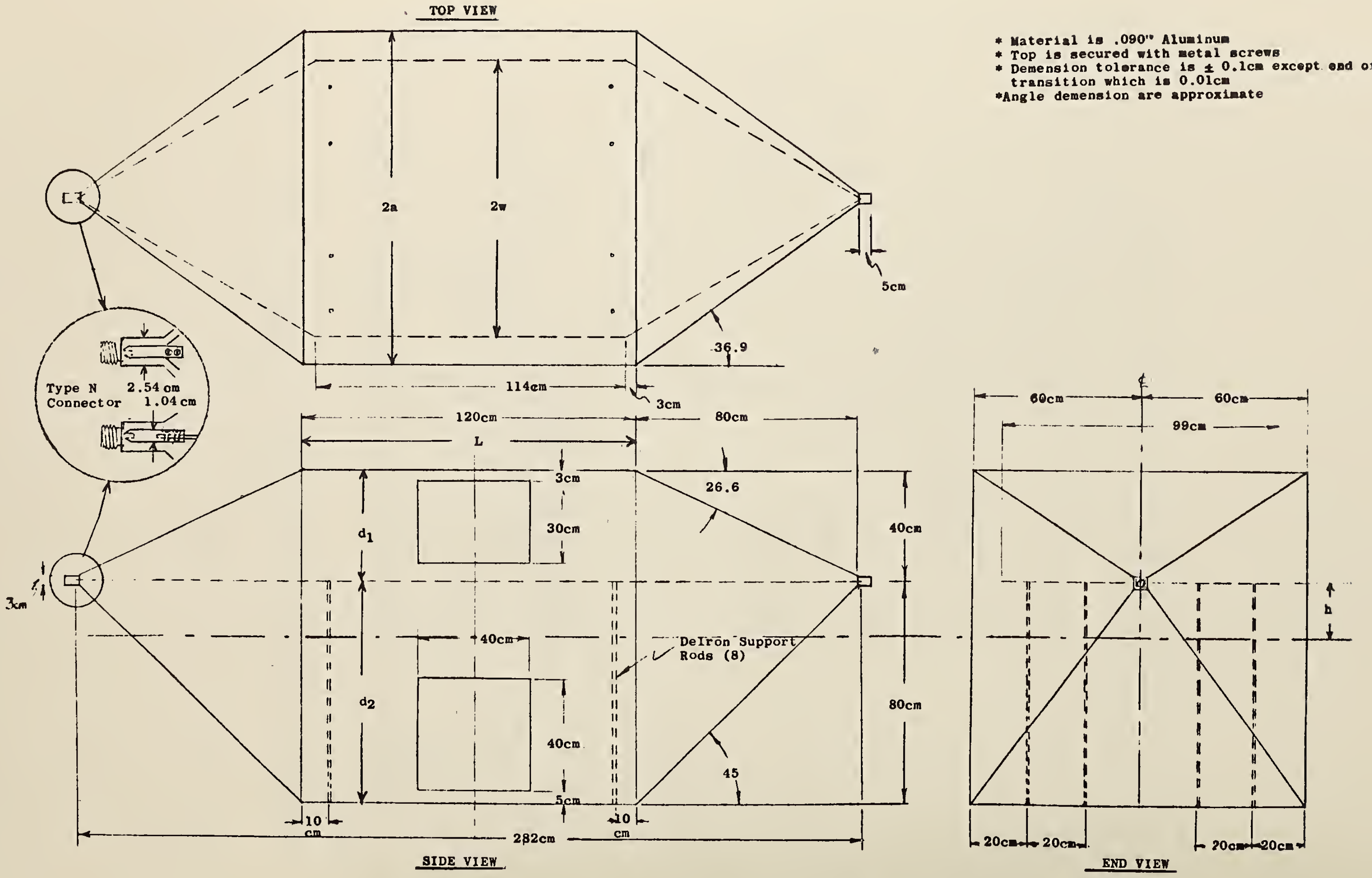


Figure 12, Cross sectional views for design of 1.2m x 1.2m x 2.8m asymmetric TEM cell.

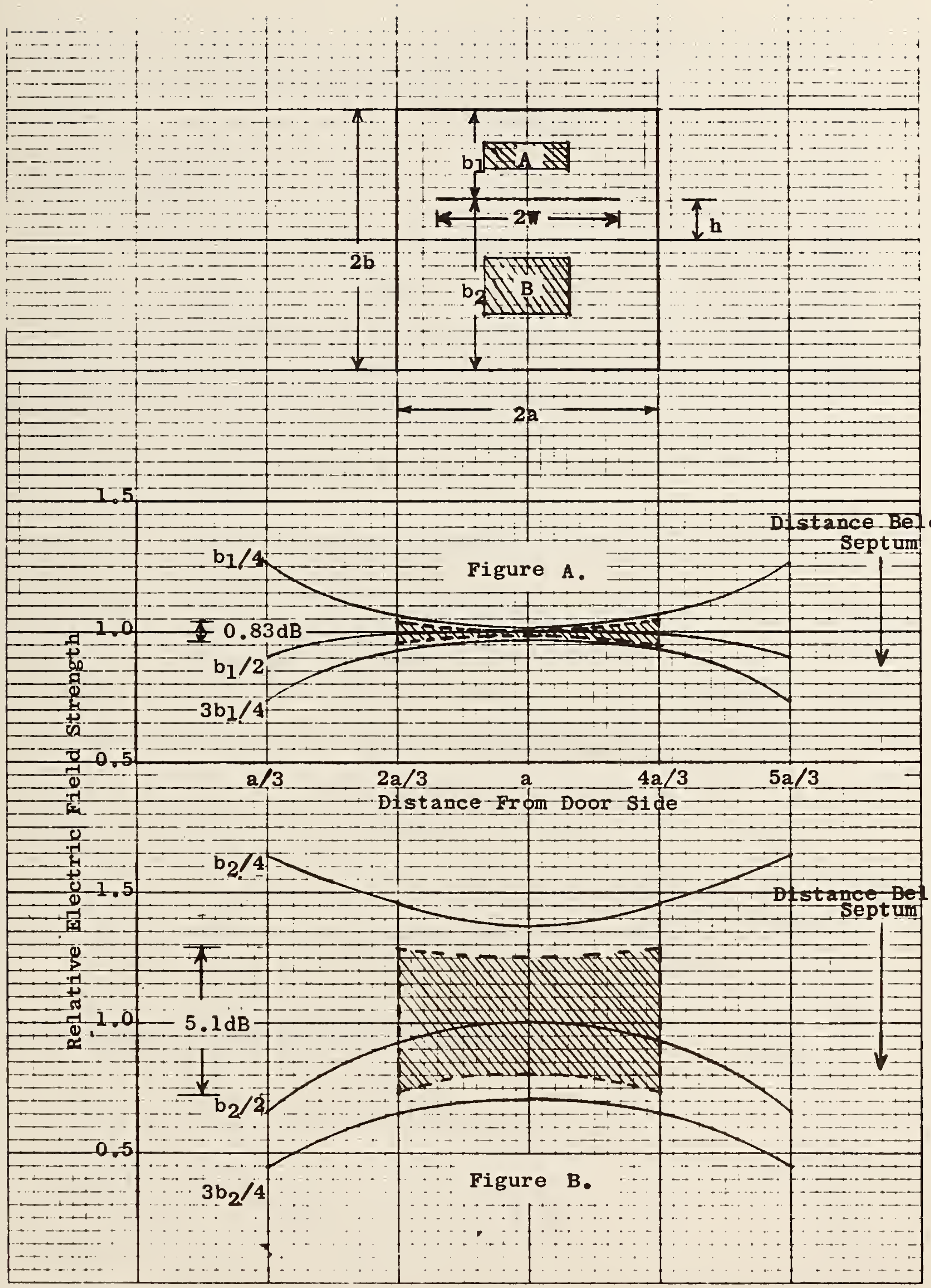


Figure 13. Relative electric field distribution inside asymmetric cell. (h = b/3) Shaded area corresponds to 1/3 cross-section area shown in cross sectional view of cell. Figure A and B data corresponds to area labeled A and B in top view.

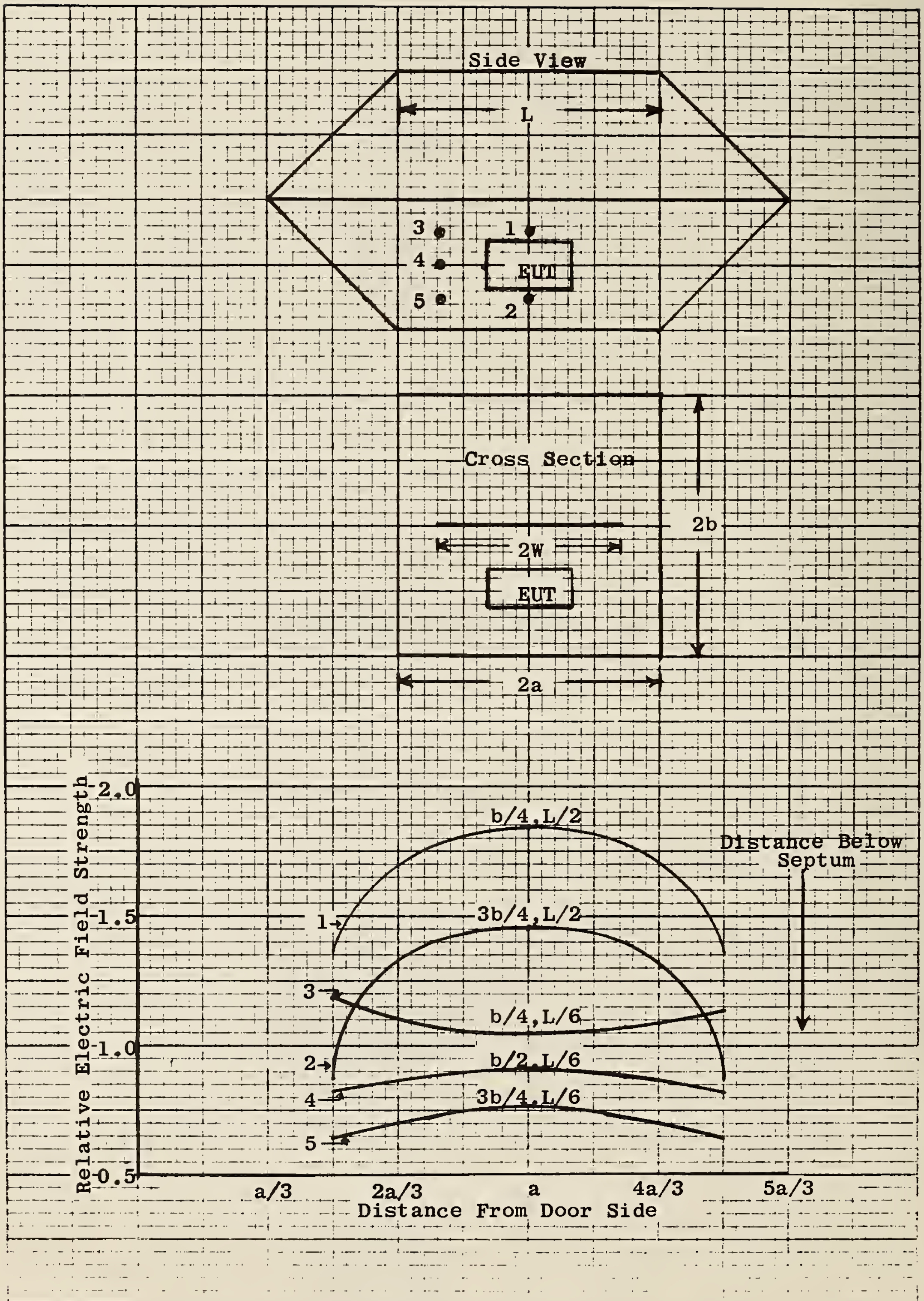


Figure 14. Relative electric field distribution inside cell with EUT (metal case) occupying 1/3 vertical separation distance between septum and floor. (Cross sectional cuts at center (L/2) and off end (L/6) of EUT as indicated by numbers in top view.

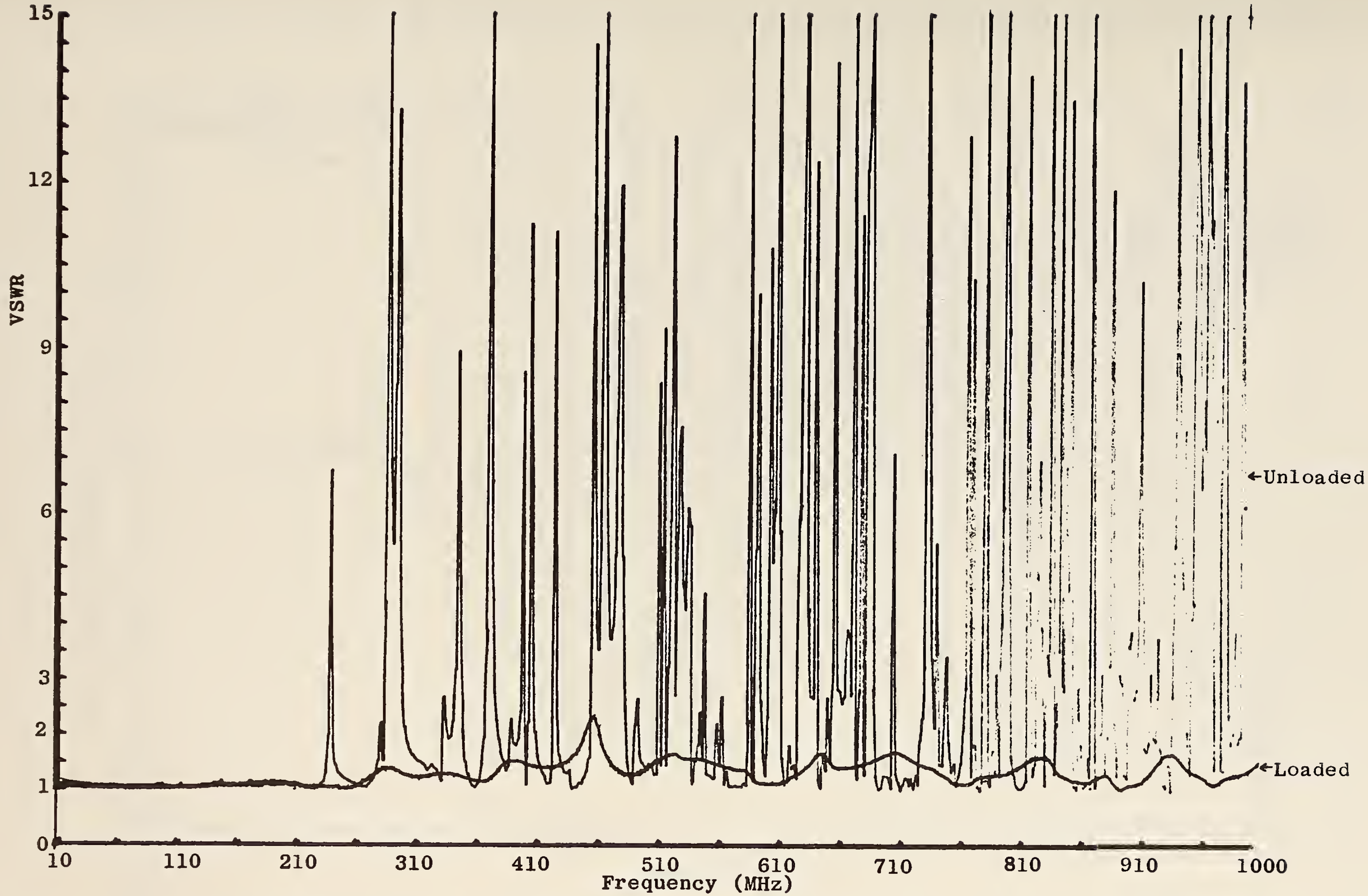


Figure 15. Input VSWR of NBS 1.2m x 1.2m x 2.4m symmetric TEM cell with and without absorber loading.

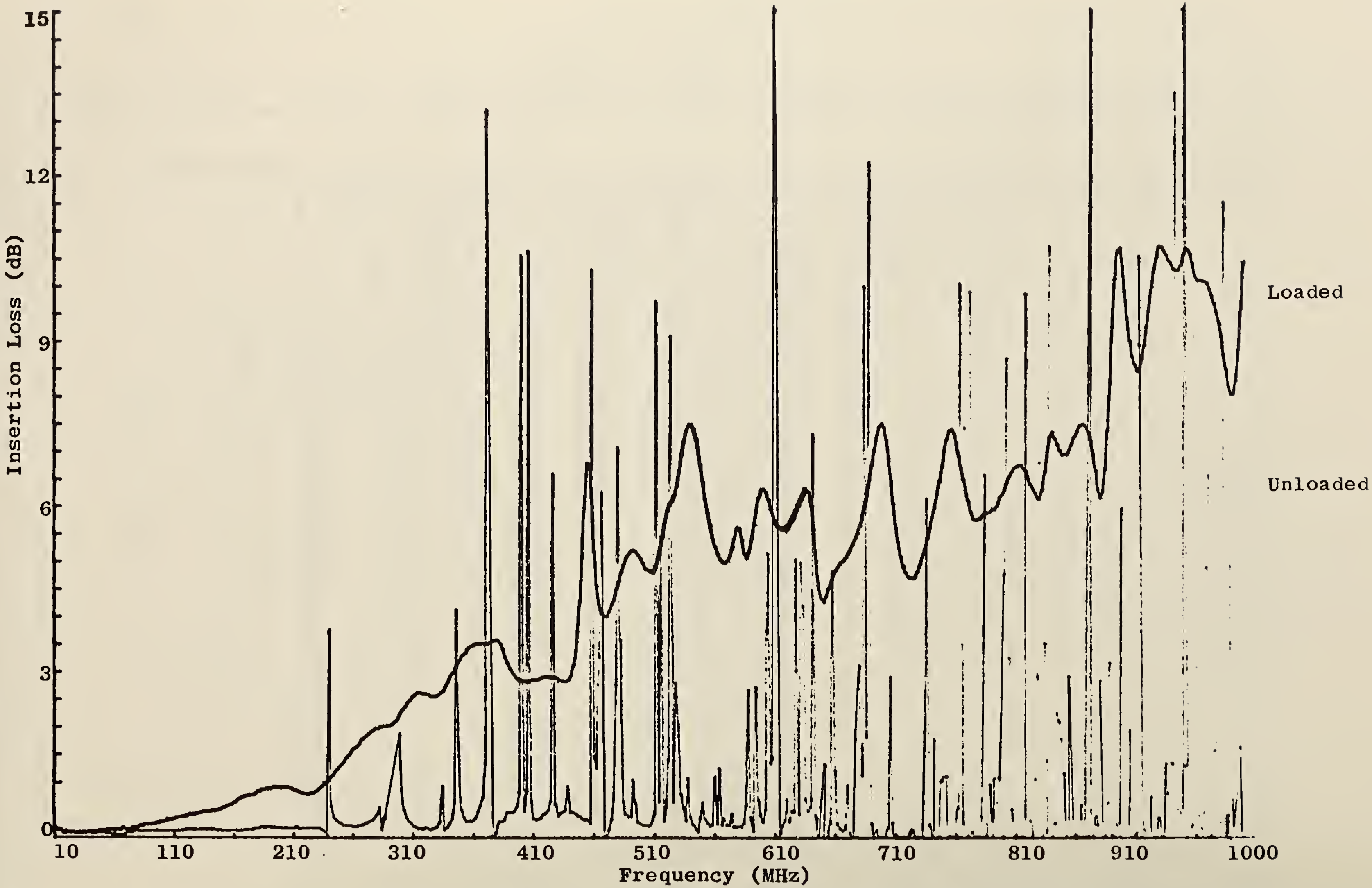


Figure 16. Insertion loss of NES 1.2m x 1.2m x 2.4m symmetric TEM cell with and without absorber loading.

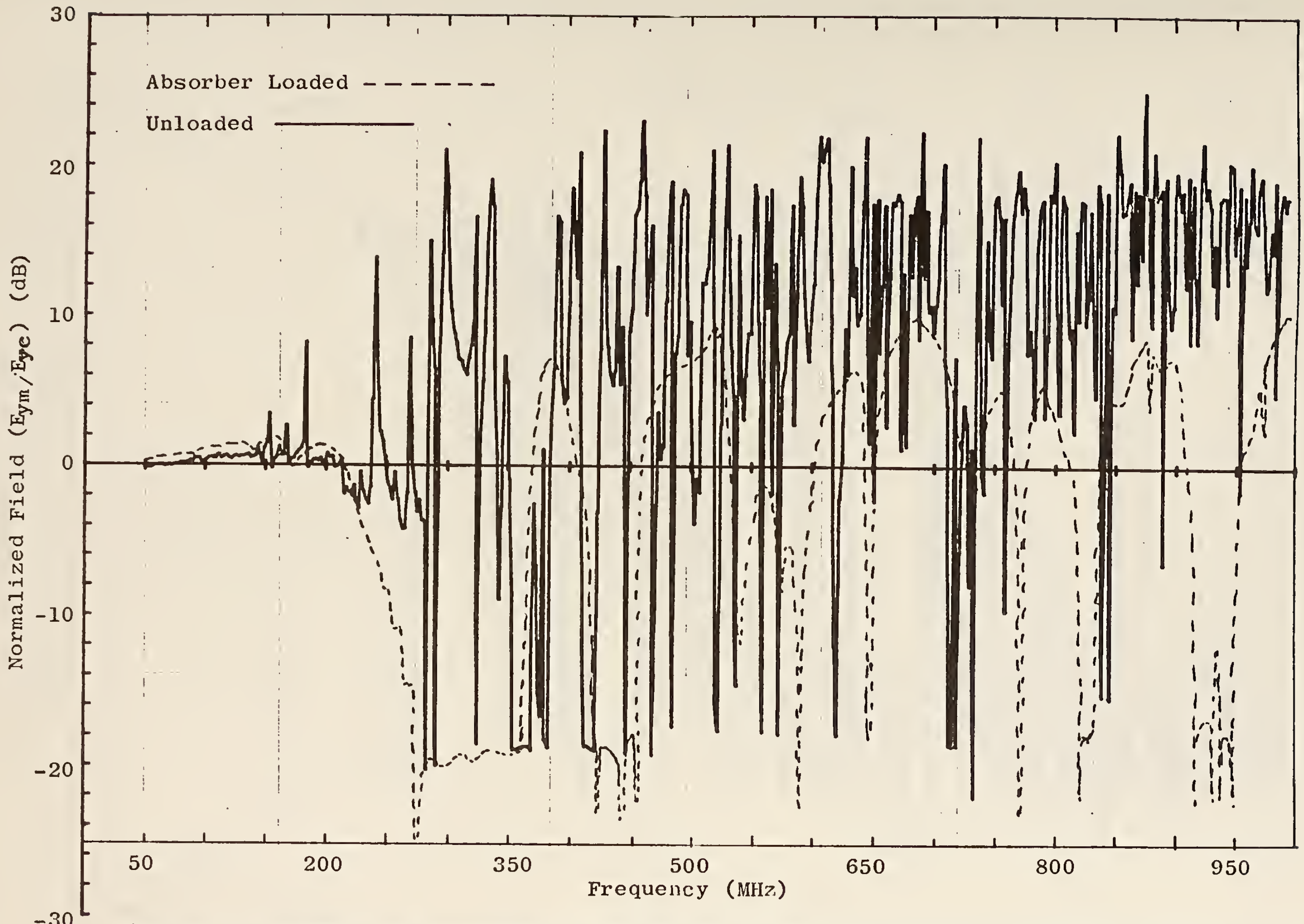


Figure 17. Normalized variation in magnitude of vertical electric field at center of test zone inside 1.2m x 1.2m x 2.4m symmetric TEM cell with and without absorber loading.

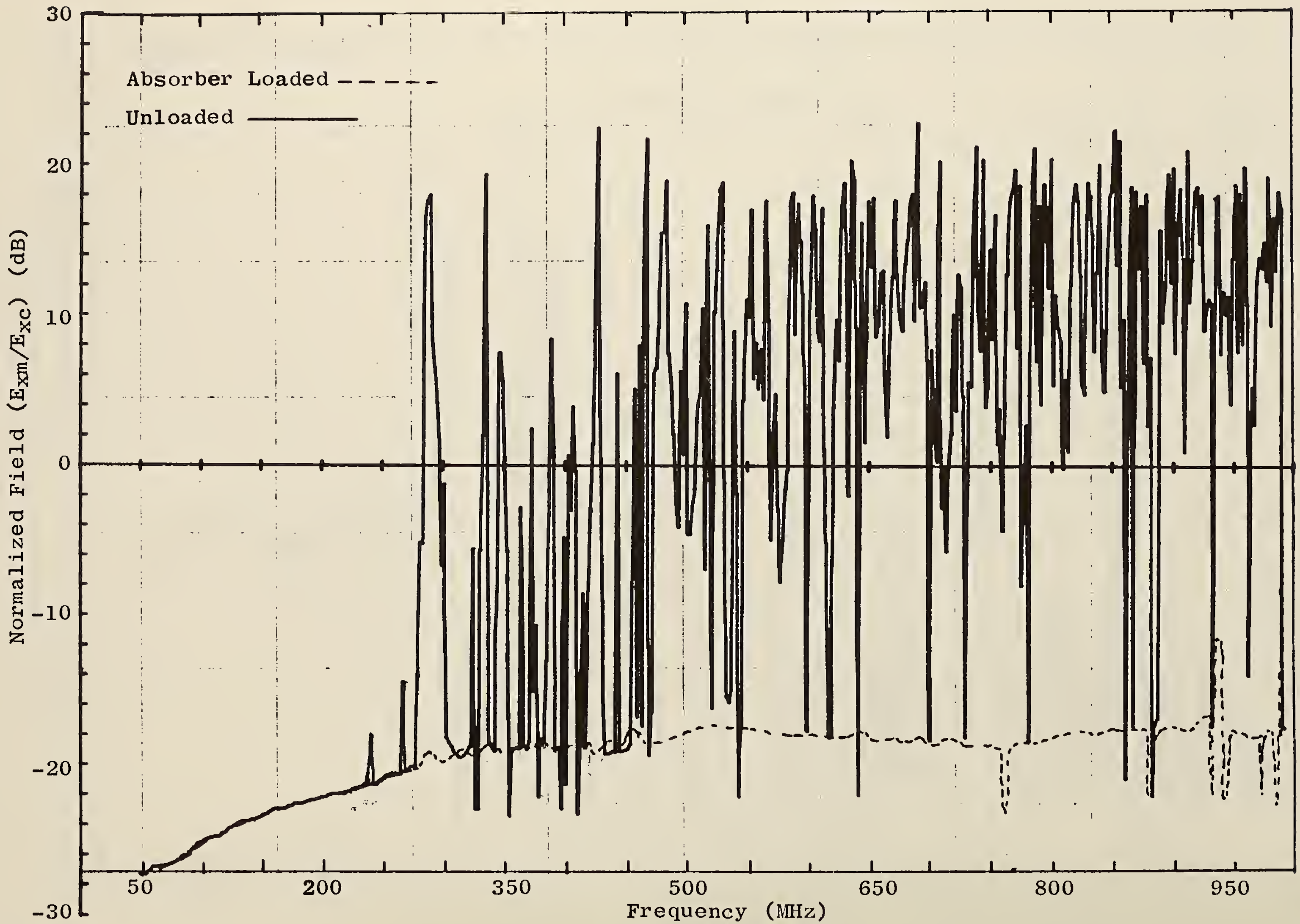


Figure 18. Normalized variation in magnitude of transverse electric field at center of test zone inside 1.2m x 1.2m x 2.4m symmetric TEM cell with and without absorber loading.

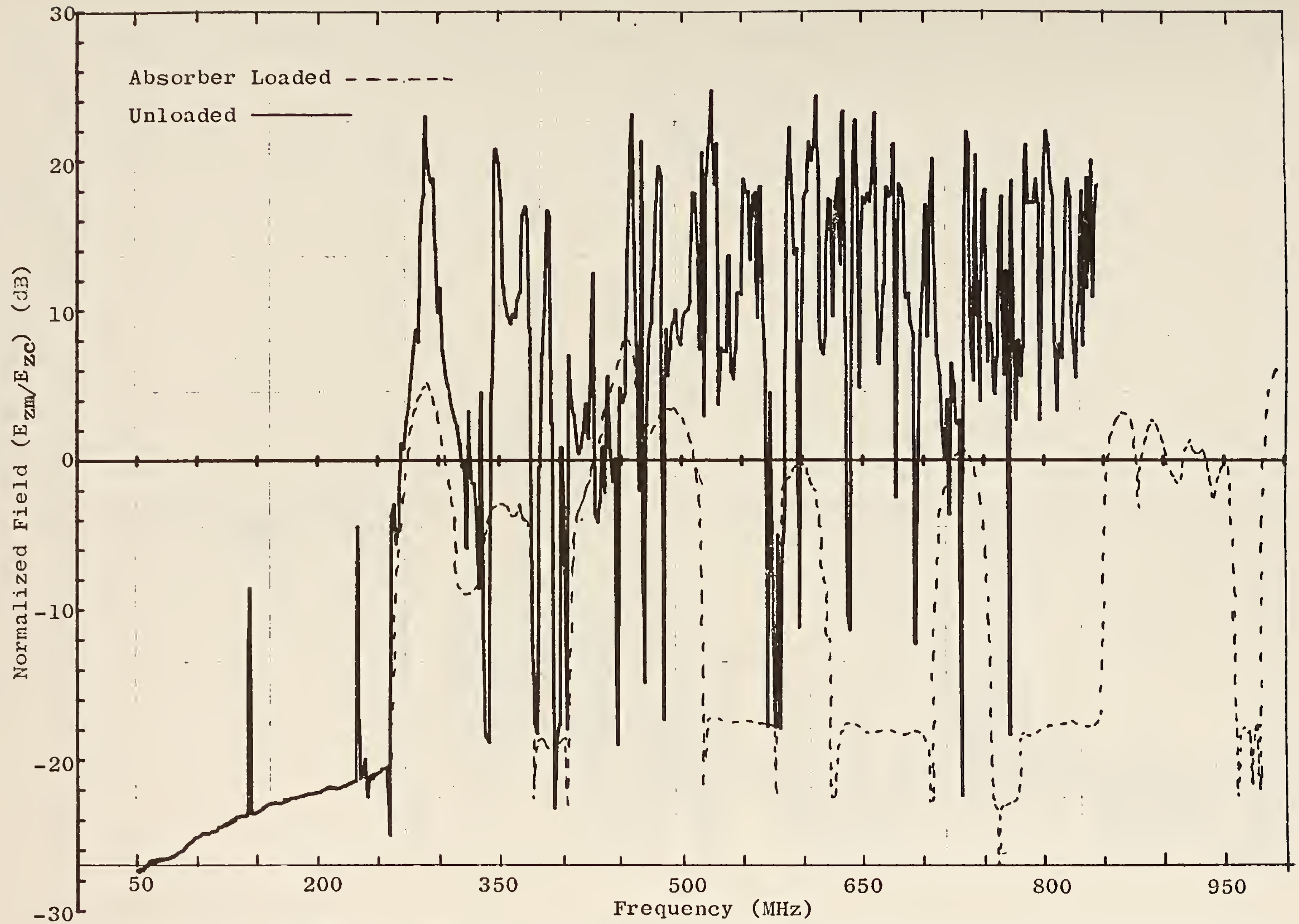


Figure 19. Normalized variation in magnitude of longitudinal electric field at center of test zone inside 1.2m x 1.2m x 2.4m symmetric TEM cell with and without absorber loading.

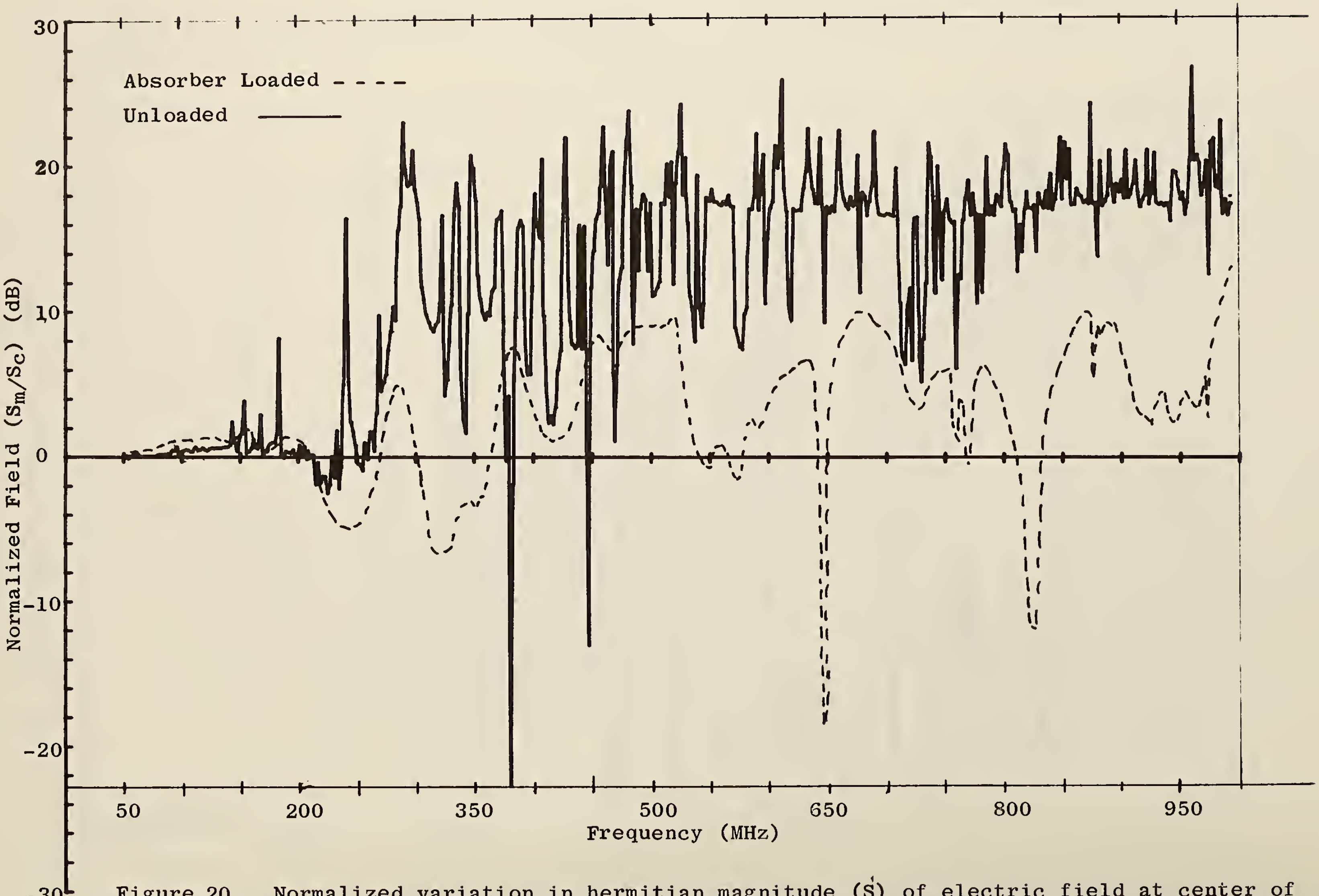


Figure 20. Normalized variation in hermitian magnitude ($\dot{S}$) of electric field at center of test zone inside 1.2m x 1.2m x 2.4m symmetric TEM cell with and without absorber loading.

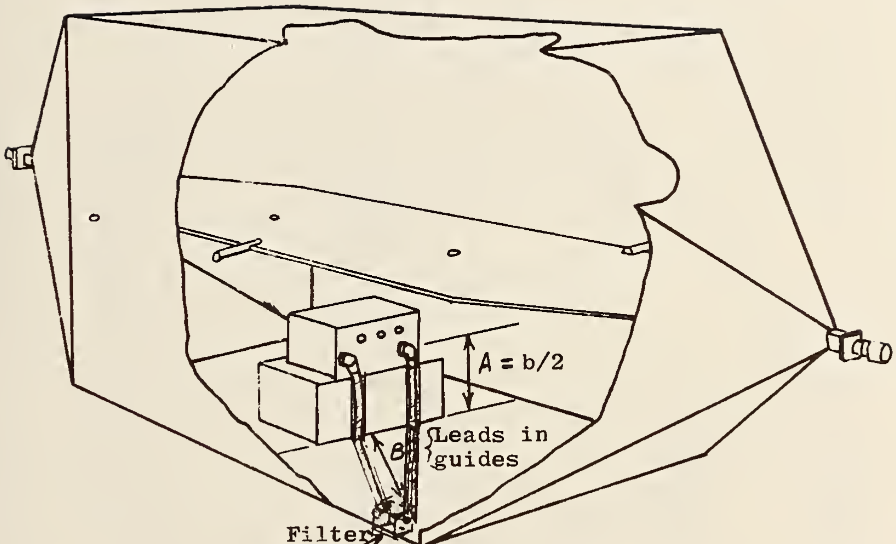


Figure 21. Placement of EUT in cell for EMC measurements.

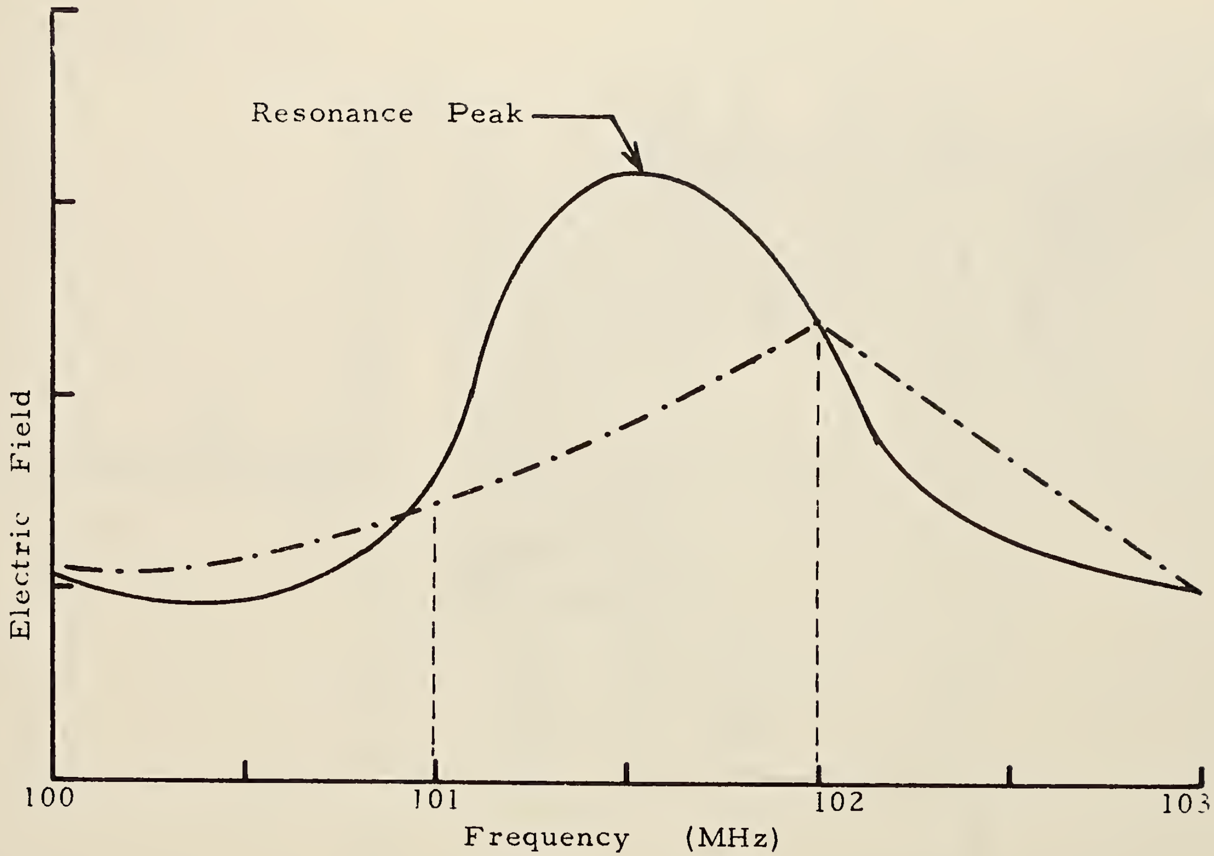
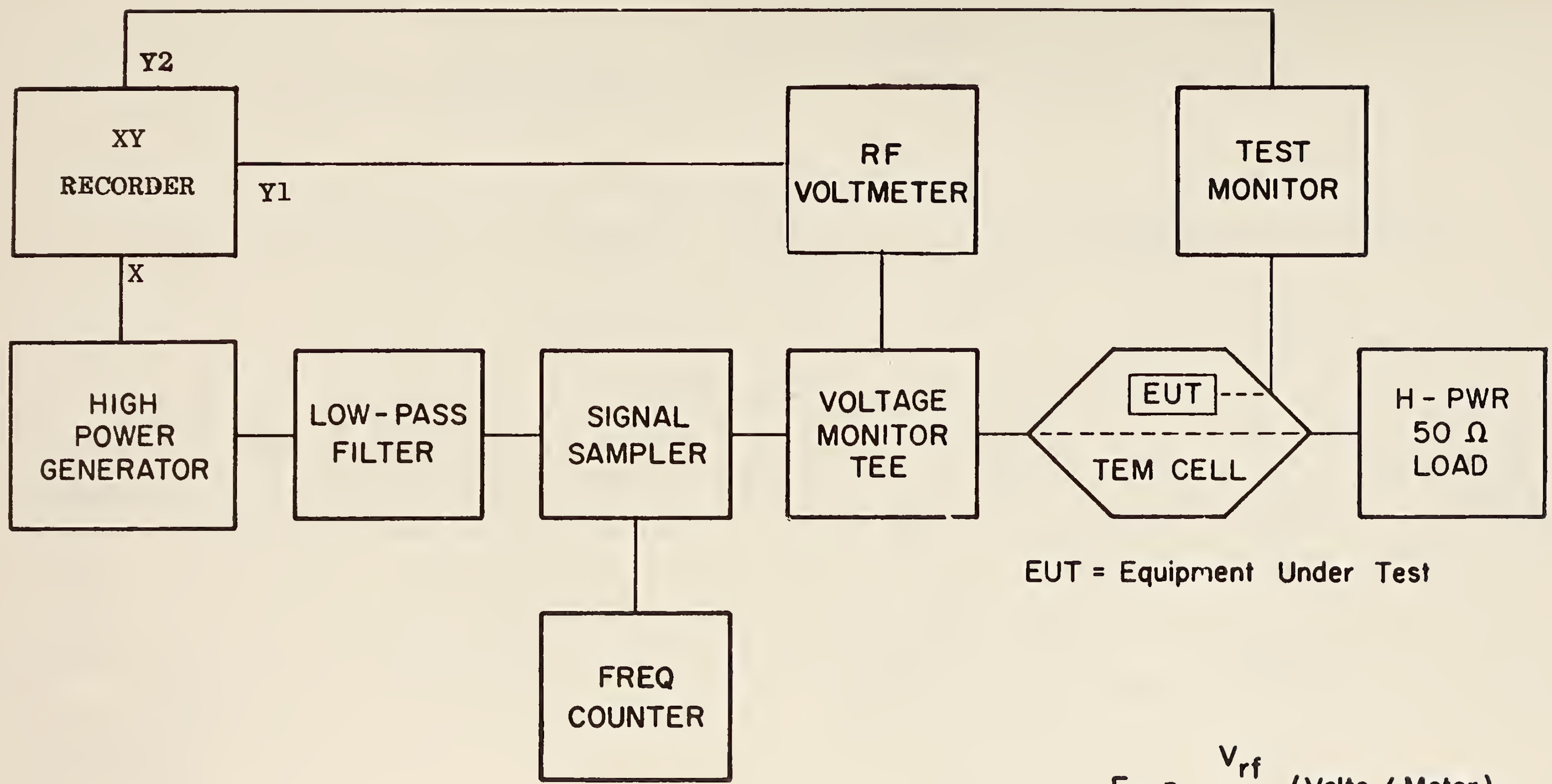
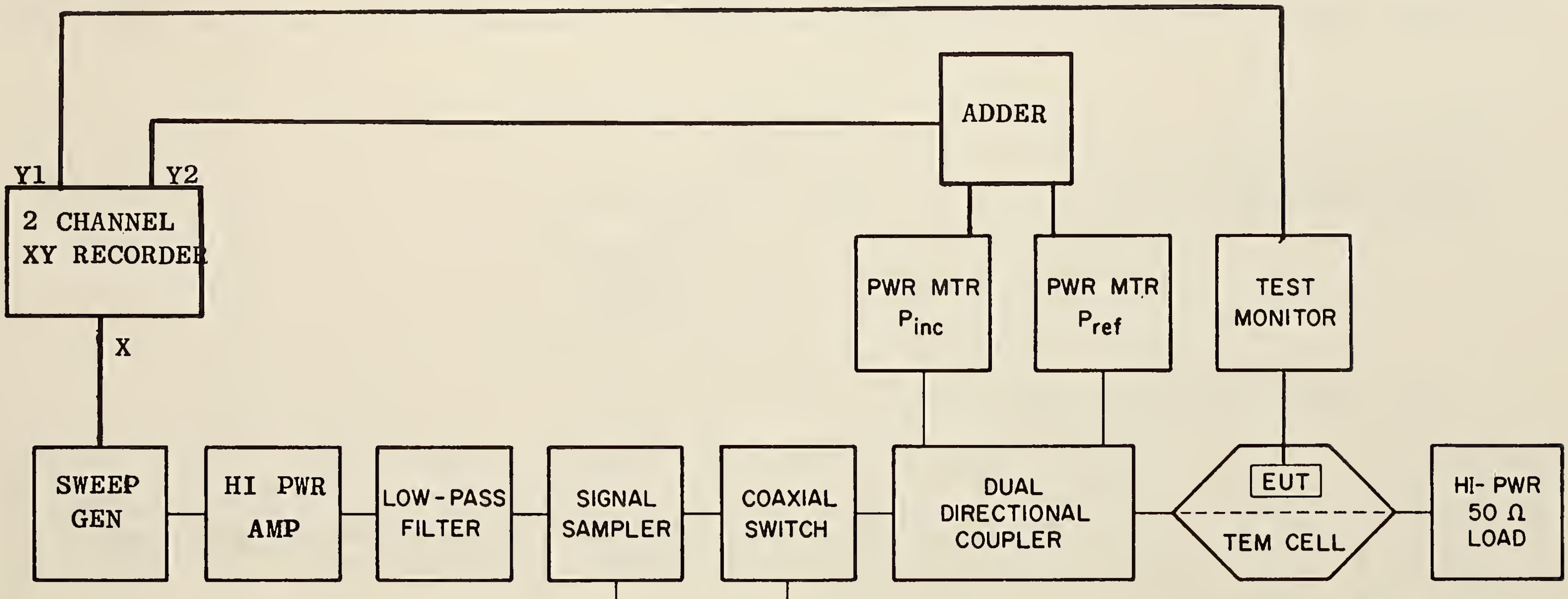


Figure 22. Susceptibility function of Eut demonstrating swept compared to discrete frequency measurements.



$$E_o = \frac{V_{rf}}{b} \text{ (Volts / Meter)}$$

Figure 23. Block diagram of system for susceptibility testing of equipment (used typically below 1 MHz).



EUT = Equipment Under Test

$$E_o = \frac{\sqrt{P_n \times R_c}}{b} \quad \text{(Volts / Meter)}$$

Figure 24. Block Diagram of System for Susceptibility Testing of Equipment (1 MHz to 500 MHz)

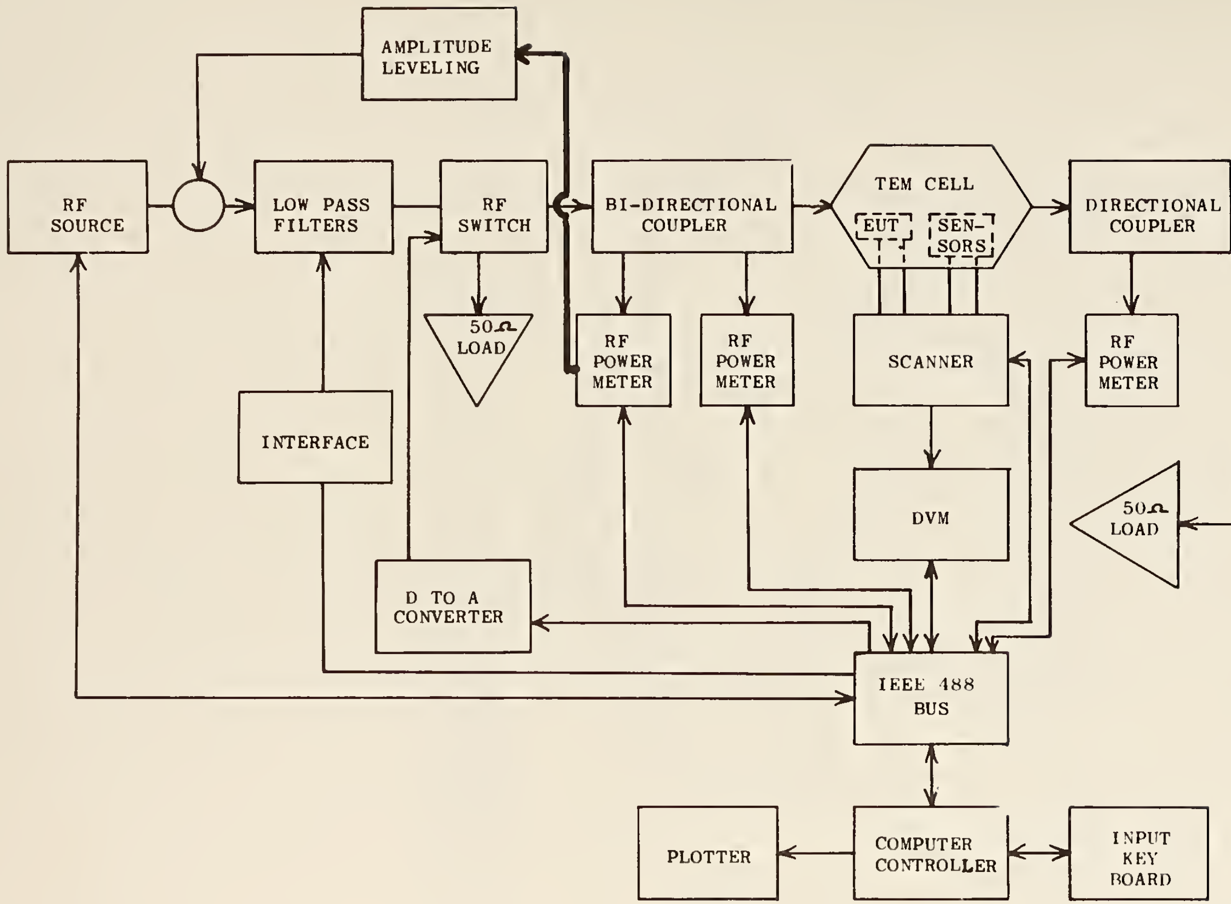


Figure 25. Block diagram of automated TEM cell susceptibility measurement system.

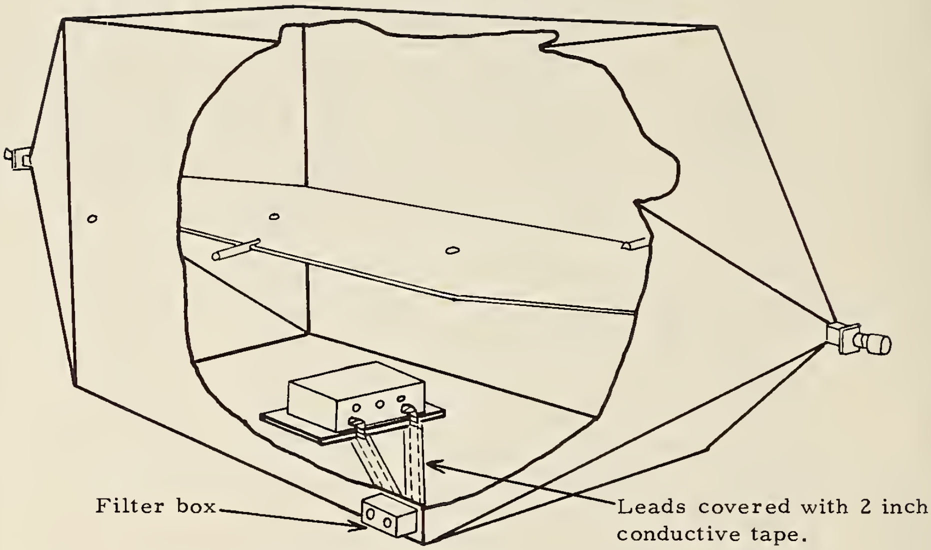


Fig. 26. Placement of EUT in cell for minimum exposure of leads to the TEM field.

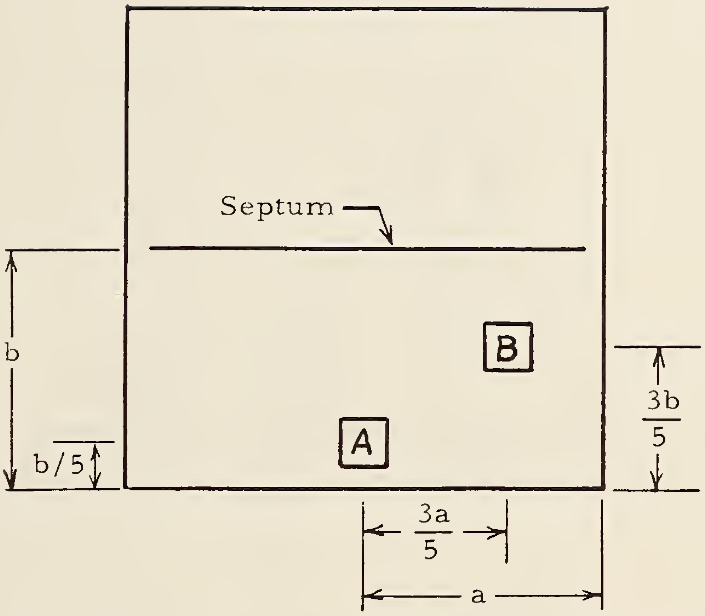


Fig. 27. Determination of E field correction factor as a function of the EUT location inside the cell.

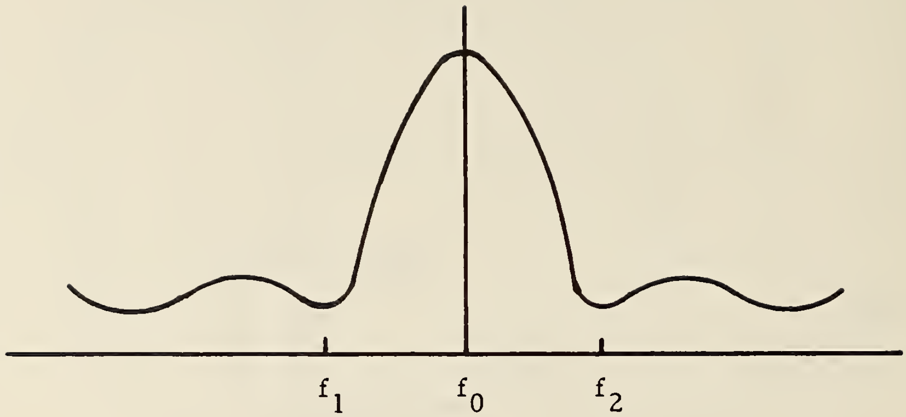
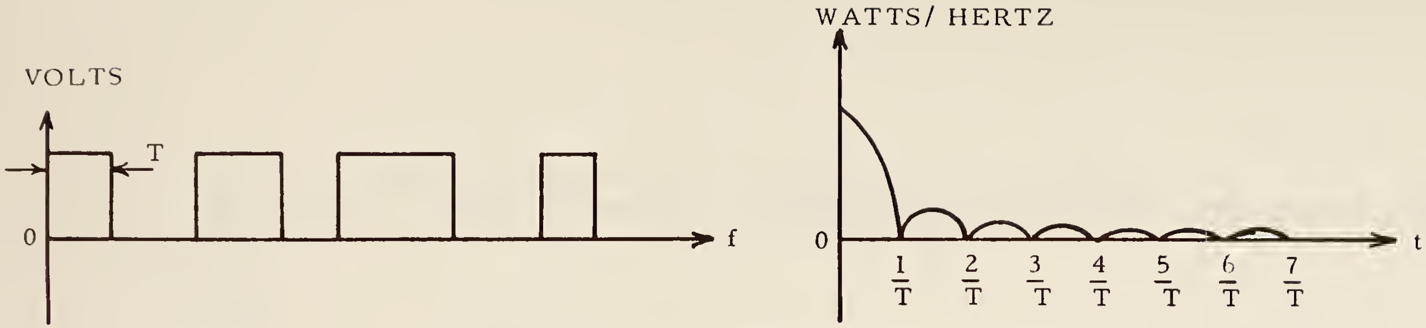
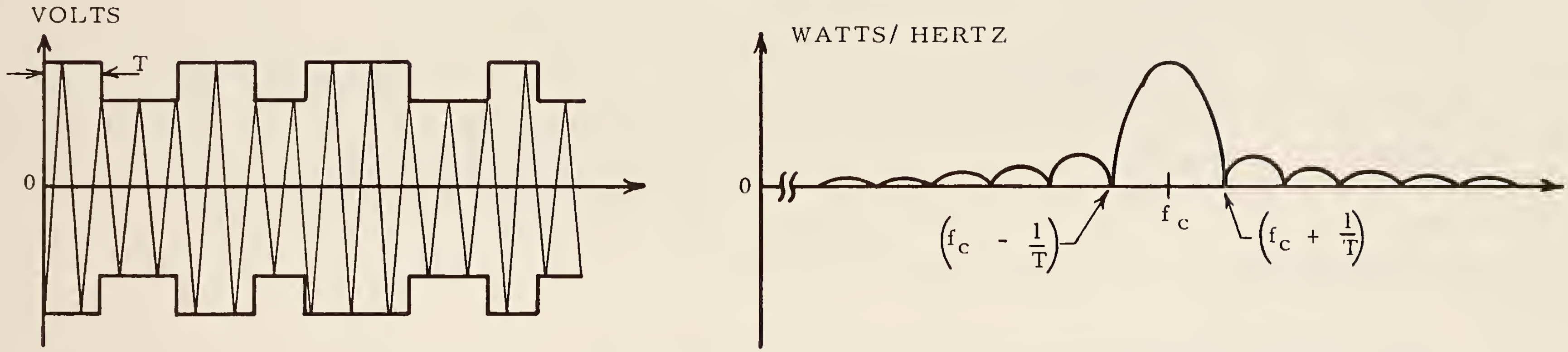


Figure 28. Example of narrowband emanation. (frequency domain)



a. DIGITAL BASEBAND EMANATION



b. SPURIOUS CARRIER f_c MODULATED BY DIGITAL BASEBAND SIGNAL.

Figure 29. Examples of broadband emanations. (frequency and time domain representations)

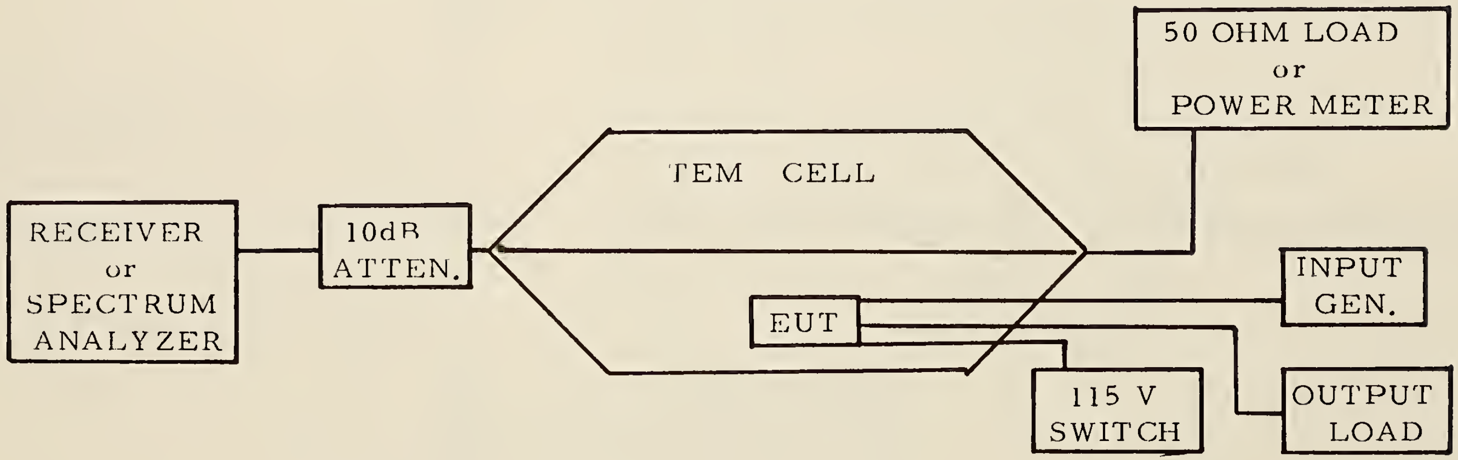


Figure 30. Block diagram of measurement system for frequency domain analysis of radiated emanations from EUT using a TEM cell.

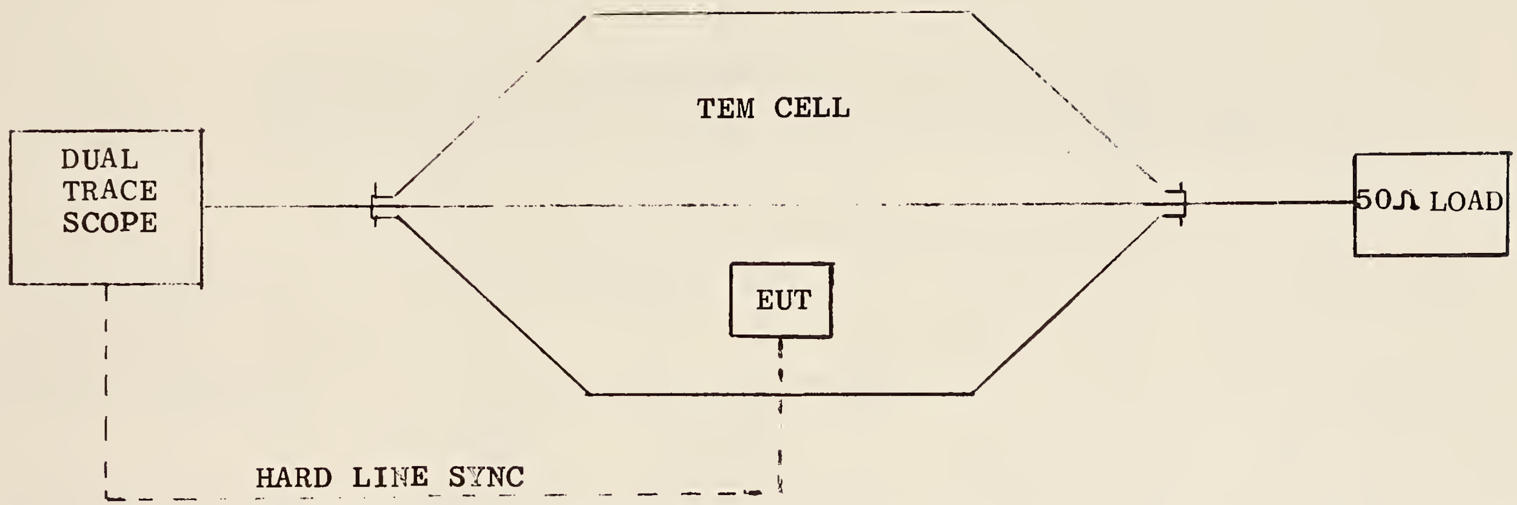


Figure 31. Block diagram of measurement system for time domain analysis of radiated emanations form EUT using a TEM cell.

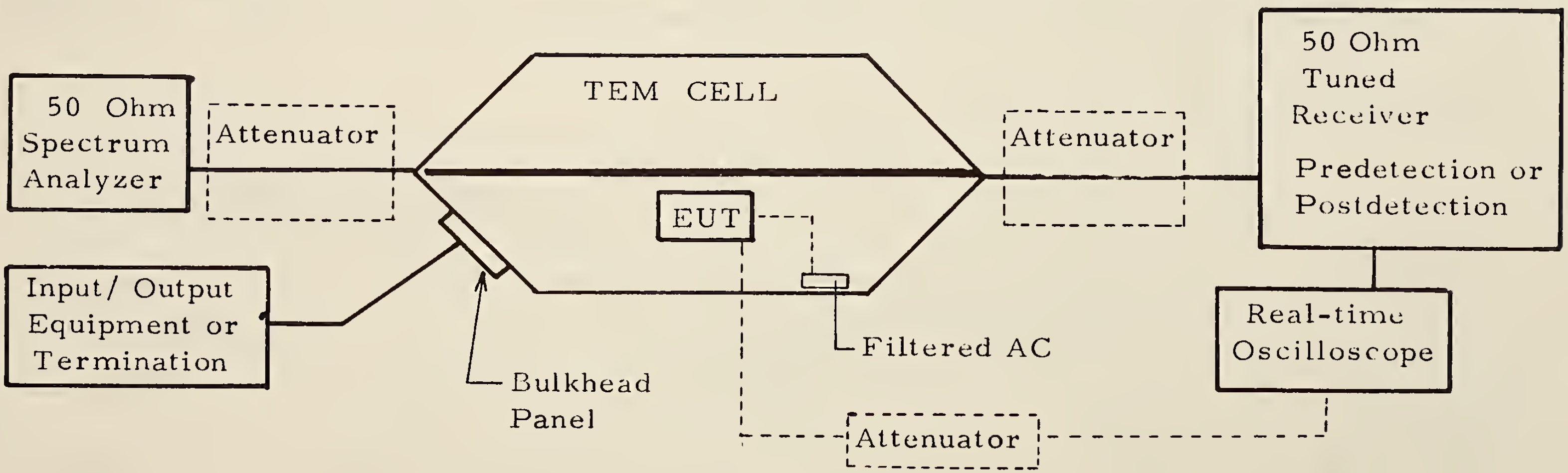


Figure 32. Block diagram of measurement system for time domain evaluation of radiated emanations from EUT using a TEM cell. (Attenuator required for hard line sync of some EUT).

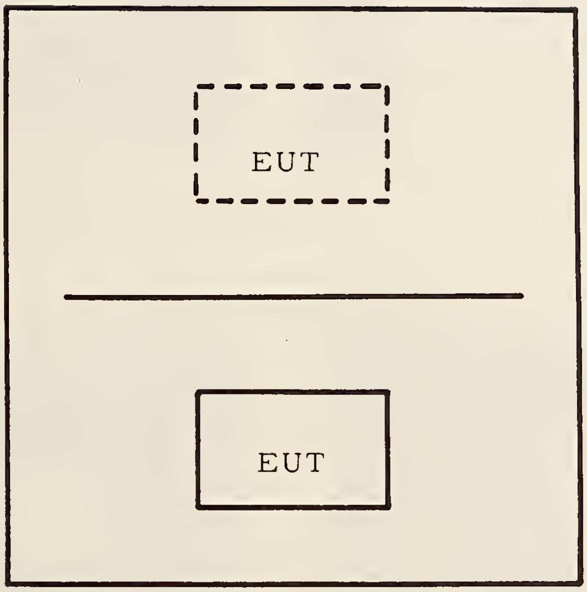


Figure A-1. Placement of EUT and its image (second identical EUT) in cell for measurement of loaded impedance, Z_0'.

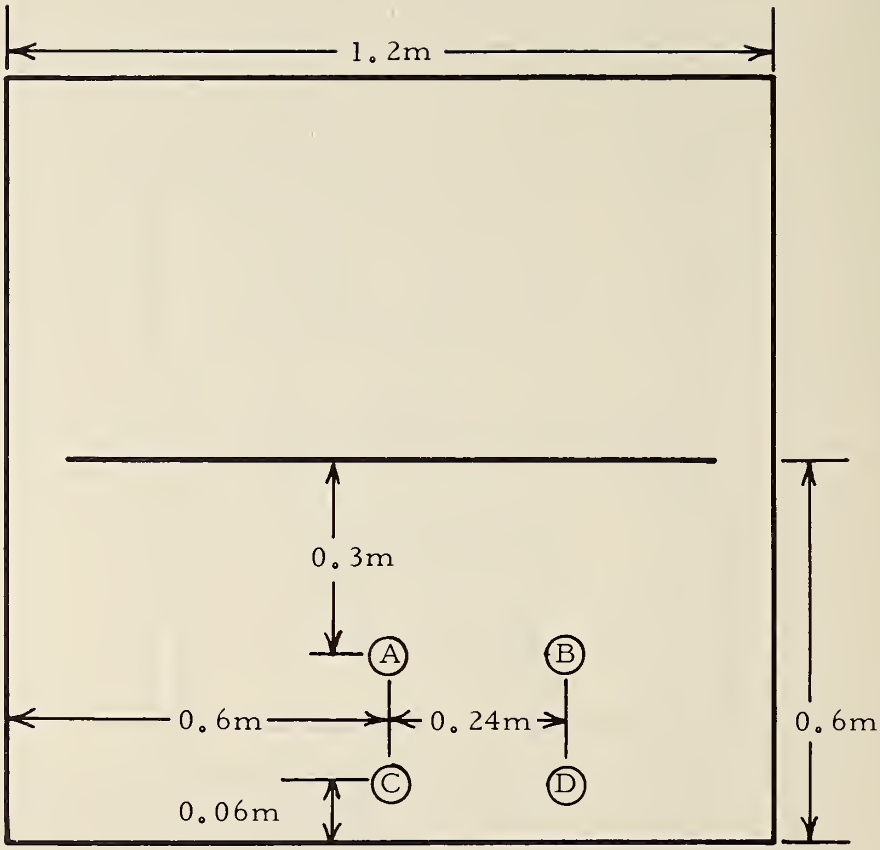


Figure B-1. Placement locations of the spherical dipole radiator inside the 1.2m x 1.2m x 2.4m symmetric TEM cell for radiated emissions measurements.

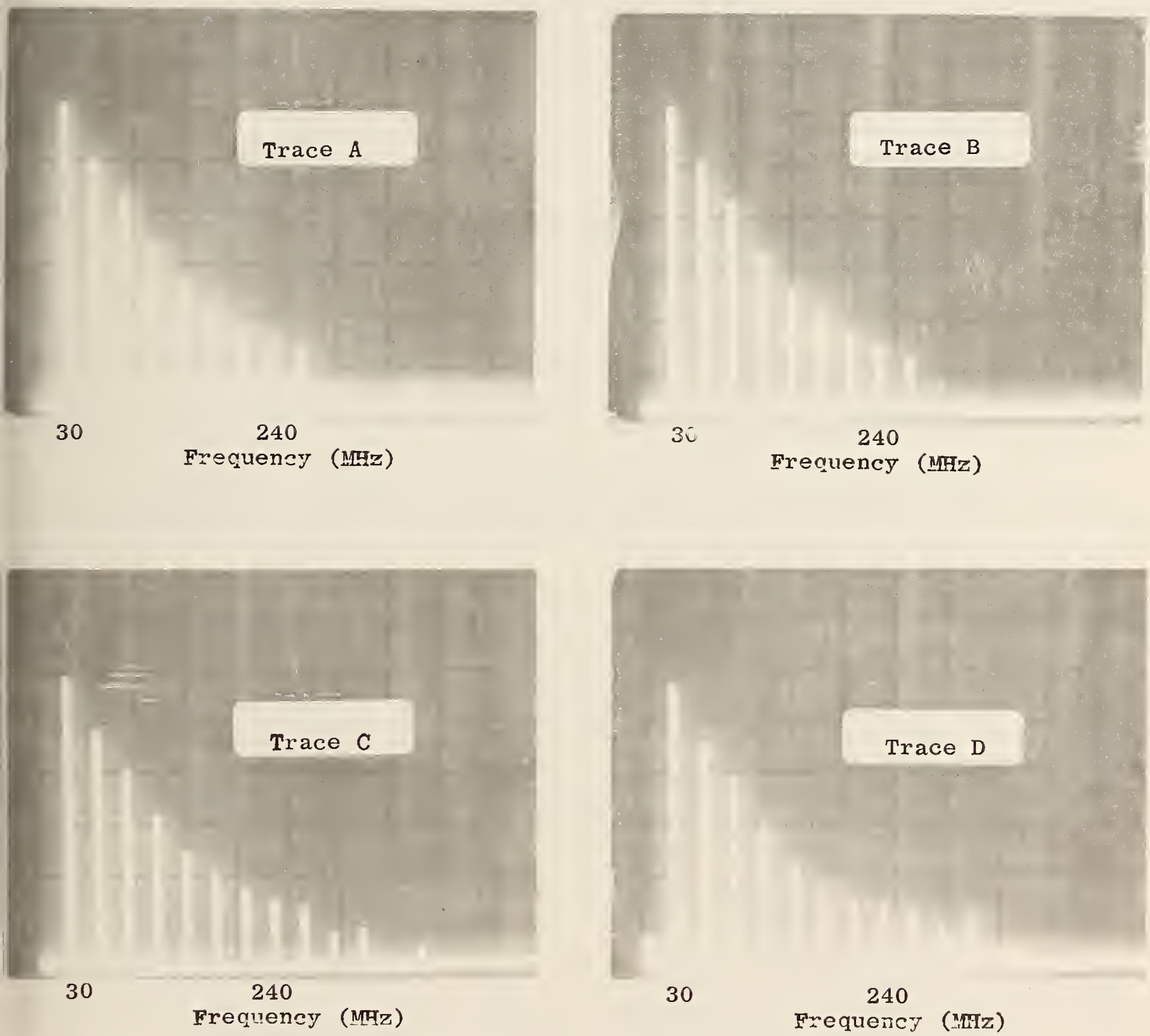


Figure B-2. Radiated emissions from 10cm spherical dipole measured inside a 1.2m x 1.2m x 2.4m TEM cell. Spectrum analyzer display (0-500)MHz. 50MHz/div. Reference level = -10dBM, 10 dB/div. Trace A obtained with dipole centered in test zone midway between septum and outer walls. Trace B same as trace A, except dipole was moved to 36cm from door side, Trace C same as trace A except dipole lowered to 6cm from floor. Trace D obtained with dipole 6cm above floor and 36cm from door side. (Location measurement referred to center of spherical dipole.)

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M. L. Crawford and J. L. Workman

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Supersedes NBS TN-1013 dated April 1979

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

This publication describes the physical design and electrical evaluation of pertinent parameters which influence the use and operation of a transverse electromagneti (TEM) cell. Detailed, step-by-step procedures are given for using a TEM cell for performing either radiated EM susceptibility testing or for measuring radiated EM emissions from electronic/electro-mechanical equipment. These measurement procedure provide guidelines to potential users and also indicate precautions to observe to minimize problems often encountered when performing EMC measurements and hence to enhance the cell's usefulness. Where available, a brief error analysis associated with the measurement technique is included.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

measurement procedures; susceptibility and emission measurements; transverse electromagnetic cell.

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