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FACILITIES FOR IMPROVING EVALUATIONS OF ELECTROMAGNETIC SUSCEPTIBILITIES OF WEAPON SYSTEMS AND ELECTRONIC EQUIPMENT

M.T. Ma
M.L. Crawford

National Institute of Standards and Technology
U.S. Department of Commerce
Boulder, Colorado 80303-3328

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Electromagnetic Fields Division
Center for Electronics and Electrical Engineering
National Engineering Laboratory
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M. T. Ma and M. L. Crawford
Electromagnetic Fields Division
National Institute of Standards and Technology
Boulder, CO 80303

A preliminary design of an improved testing facility for evaluating the electromagetic susceptibility of weapon systems and electronic equipment is presented. This facility features a combination of the transverse electromagnetic (TEM) cell for low-frequency testing and the reverberating chamber for high-frequency operation. As a system, a coverage of the wide spectrum from 10 kHz to 18 GHz or even to 40 GHz is possible. The TEM/reverberating combination is designed for an input impedance of 50, 75, or 100 Ω to generate a cw electric field up to 200 V/m, or a pulsed electric field up to 50 kV/m with an approximate rise time of 10 ns. The average field for the reverberating mode of operation is described in a statistical sense. Theoretical characteristics for a case study, to meet a given set of requirements, are given.

Key words: EMC test; reverberating chamber; TEM cell; susceptibility.

1. Introduction

The ability to simulate an operating electromagnetic (EM) environment for accurately assessing the cw and pulsed susceptibilities of weapon and electronic systems is fundamental to ensuring the system's compatibility. In recent years, the Fields and Interference Metrology Group of the National Institute of Standards and Technology (NIST) has been developing two facilities, based on sound theoretical understanding of the problem, for this task [1]. They are the transverse electromagnetic (TEM) cell [2] and the reverberating chamber [3, 4, 5]. Each facility has its advantages and limitations.

The TEM cell, shown in figure 1, is an expanded rectangular coaxial transmission line with tapered sections at each end. It provides a shielded environment for measuring both EM susceptibility and emissions of equipment under test (EUT) [6, 7, 8]. Ideally, the TEM cell generates only the TEM mode to simulate the free-space planar field by means of a source supplied at one end with a matched load connected to the other end. To support such a TEM mode, the cell is necessarily a two-conductor system with the region between the inner and outer conductors (either chamber) used as the test zone. Although the center septum (inner conductor) is normally designed to be midway between the outer conductors, its position can be modified to have an offset to allow a larger test zone in one of the chambers [9, 10]. The cell is generally limited to upper frequencies below a few hundred megahertz, depending on the EUT size, to avoid the appearance of the higher order modes [11]. The volume available for testing is inversely proportional to the upper frequency limit. For a given TEM cell size, higher order modes will appear when the operating frequency increases. The cutoff frequencies of the first few higher order modes generated inside a cell with an infinitely long central section can be determined numerically [10, 11]. Since the length of the central section is finite in practice, the transitional sections near the ends will act as a cavity to produce resonant frequencies associated with these cutoff frequencies. In addition, because the polarization of the field generated inside the cell is fixed, systematic rotations of the EUT may be necessary to fully evaluate the EUT's transmitting and receiving characteristics [7, 8].

The reverberating (or mode stirred) chamber, shown in figure 2, is also a shielded room with a rotating stirrer to mix the field generated by a transmitting antenna. This field is very complex, and is described in terms of simple statistics such as maximum and average amplitudes for a large number of different stirrer positions. It is considered uniformly homogeneous and isotropic when averaged. Because of this, the EUT is not required to undergo physical rotations, so this method of testing is very cost effective. However, this facility is restricted to frequencies above a few hundred megahertz, again depending on the chamber size. This restriction is a consequence of requiring the chamber to be electrically large so that there will be enough modes to ensure adequate mode mixing and, hence, spatial uniformity for testing purposes [12, 13].

We are currently investigating the possibility of combining these two measurement concepts to produce a single facility that can be used for EMC testing over a much wider frequency range [14]. Design considerations for a particular model based on this experience, and preliminary results for this model with an assumed set of requirements, are given in Section 2. Other alternative facilities existing elsewhere are suggested in Section 3 and may also be considered for meeting specific measurement needs. Concluding remarks and recommendations are summarized in Section 4.

2. Design Requirements and Sample Results

When evaluating the EMC susceptibility of weapon systems and electronic equipment by a combined TEM cell and reverberating chamber as typically required by a military agency, it is quite common to specify:

(a) frequency of interest from 10 kHz to 18 GHz with a capability of extending to 40 GHz,

(b) cw electric field up to 200 V/m,

(c) pulsed electric field up to 50 kV/m with approximately 10 ns rise time,

(d) possible workable test volume inside the full-scale chamber to be occupied by an EUT as large as 6 m x 9 m x 12 m,

(e) shielding effectiveness of the chamber walls no less than 100 dB, and

(f) different types of modulations (AM or FM).

Based on the tentative requirements listed above, design considerations for the TEM cell consist of a suitable cell size, materials to be selected for constructing the cell, the input impedance as a function of the cell geometry, relative field distribution inside the empty cell, the power required from the signal source, and the cutoff and resonant frequencies of the first few higher order modes. Design parameters for the reverberating mode of operation are the available volume and total surface area of the chamber, the number of possible modes generated inside the chamber as a function of frequency, the mode density necessary to yield uniform fields after averaging, and the quality factor, which is important to determine the trade-off between power requirement and bandwidth for proper operation of the facility.

To provide a large test zone as specified in (d) above and at the same time to require that the original uniform field generated inside the chamber by the TEM mode of operation for lower frequencies not be seriously disturbed by the presence of EUT, it is estimated that the full-scale physical size of the facility will take at least 18 m x 21.34 m x 53 m. A scaled model (1/17.8) will have the dimension of 101 cm x 120 cm x 298 cm, as shown in figure 3. The unique feature is a vertically offset center septum used for the TEM cell to provide a larger usable test volume than the ordinary symmetrical TEM cell for the same overall size.

Any one of the three commonly available metals: aluminum, steel, or zinc-coated steel, may be used in construction. Once a metal with known values of conductivity and permeability is chosen, the skin depth of the chamber walls can be calculated and an adequate thickness for the chamber walls can be determined to provide a shielding protection of at least 100 dB.

The input impedance of the TEM cell may be designed at 50 Ω, 75 Ω, or 100 Ω, depending on the choice of center conductor width [10]. Because of the particular choice of offset for the center conductor shown in figure 3, we propose to use the dimensions given in figure 4 for the cell's cross section. For the full-sized cell with 2a (cell width) = 18 m, 2b (over cell height) = 21.34 m, and h_i (center conductor-to-ground height) = 16 m, we require:

2w (width of the center conductor) in m	Input impedance in Ω
13.5	50
10.8	75
9.0	100

For the scaled cell model, 2a = 101 cm, 2b = 120 cm, h_i = 89 cm, and

2w = 75.8 cm for an input impedance of 50 Ω,
60.6 cm for an input impedance of 75 Ω,
50.5 cm for an input impedance of 100 Ω.

The estimated relative electric-field distribution in the cross sectional testing area, based only on the TEM mode, is similar to that given in figure 5, where V is the voltage between the center and outer conductors. Thus, for a net input power of 1 W supplied to the full-sized cell, we have:

Voltage between center and outer conductors in V	Input impedance in Ω	Electric field generated at midway of the test zone, in V/m
7.07	50	0.44
8.67	75	0.54
10.00	100	0.63

The net power required to produce an electric field of 200 V/m at the midway of the test zone ranges between 0.1 to 0.2 MW, depending on the designed input impedance.

The corresponding electric fields at the midway of the test zone for the scaled model with a net input power of 1 W will be respectively 7.94, 9.74, and 11.24 V/m when the input impedance is designed at 50 Ω, 75 Ω, and 100 Ω. To generate a field of 200 V/m at the test center of the scaled model will, therefore, require a net input power from 300 to 600 W.

The first few higher order modes which may occur inside the TEM cell are TE_{01}, TE_{10}, and TE_{11} modes [1]. The TE_{01} mode will appear at approximately, for the full-sized cell, 5.3 MHz with 50 Ω, 6.5 MHz with 75 Ω, and 7.3 MHz with 100 Ω. For the scaled model, these frequencies become respectively 94.3 MHz, 115.7 MHz, and 130.0 MHz. The TE_{10} mode appears approximately at 8.3 MHz for the full-sized and 148.3 MHz for scaled model, regardless of the input impedance. For the TE_{11} mode, the cutoff frequencies are 11.1 MHz for the full size and 197.6 MHz for the scaled model. Thus, the TEM mode of operation is estimated to be good from dc to 5.3 MHz (50 Ω), to 6.5 MHz (75 Ω), or to 7.3 MHz (100 Ω) for the full-sized model; and from dc to 94.3 MHz (50 Ω), to 115.7 MHz (75 Ω), or to 130.0 MHz (100 Ω) for the scaled model. If, however, some absorbing materials are installed inside the cell, the cutoff frequencies could be increased to 10 MHz for the full-sized and to 180 MHz for the scaled model [15].

In general, a longer width chosen for the center conductor will result in lower input impedance, a more uniform field distribution, a higher input power requirement, and a lower cutoff frequency.

For the mode-stirred operation, the total volume of the full-sized chamber is approximately 14 277 m^3 and the surface area is about 3 170 m^2. The number of modes existing in this volume at 18 MHz is about 25 which is considered a minimum required for producing a statistically uniform average field distribution. The corresponding volume and surface area for the scaled model, and its equivalent frequency to produce a minimum of 25 modes are respectively 2.531 m^3, 10.005 m^2, and 320 MHz. Thus, the transitional frequency regions between the TEM mode operation and the mode-stirred operation are approximately from 10 MHz to 18 MHz for the full-sized and from 180 MHz to 320 MHz for the scaled model. At higher frequencies, the number of modes to be generated inside the chamber will also be increased [12, 13]. In fact, the number of modes is proportional to the third power of frequency.

Another important factor to consider in the design of a reverberating chamber is the mode density [1]. It represents the change in the number of modes in a given frequency interval. The smoothed mode density function for the designed full-sized model is shown in figure 6.

A third design criterion for a reverberating chamber is the quality factor, which helps to determine the power required to generate a desired average field at the test zone. For the full-sized model, the theoretically estimated composite quality factors [1] at 18 MHz are respectively 35.20 x 10^4, 23.27 x 10^4, and 13.95 x 10^4 for the chambers made of aluminum, zinc-coated steel, and steel. This composite factor is considered the upper limit. In practice, because of possible rf leaks and/or absorption by equipment placed inside the chamber, the realistic quality factor will be reduced. At sufficiently high frequencies (≥ 100 MHz), the composite quality factor is reduced approximately by a factor of 2 to 5 [12]. Therefore, the net powers required to generate an average electric field level of 200 V/m at frequencies above 100 MHz are about 27.0 W, 40.9 W, and 68.2 W respectively for aluminum, zinc-coated steel, and steel chambers. This required net power will be increased somewhat for frequencies below 100 MHz and at frequencies above a few gigahertz. For the scaled model, the composite quality factors at 1.7 GHz are estimated to be 1.92 x 10^5, 1.27 x 10^5, and 0.76 x 10^5 respectively for aluminum, zinc-coated steel, and steel. The corresponding required net powers for generating an electric field of 200 V/m are 0.5 W, 0.7 W, and 1.3 W at frequencies above 1.7 GHz.

Because of the space limitation, the stirrer size inside the scaled model as indicated in figure 3 is about 52 cm in length. According to our estimation based on a theoretical study of a one-dimensional stirrer, it will be effective to produce a uniform average field inside the chamber when it is about 2.4λ or greater, where λ is the wavelength [16]. In terms of frequency, this stirrer size is a good design for 1.38 GHz or higher. Since our proposed stirrer is two-dimensional with a narrow width, the lowest frequency for it to be effective is estimated at 1 GHz. For the full-sized chamber, the stirrer is 9.25 m long and 2.85 m wide. It should meet the requirement for frequencies higher than 60 MHz.

To generate an electric field up to 50 kV/m with a 10 ns rise time, we need a pulsed voltage source of 800 kV for the full chamber, or a pulsed voltage source of 50 kV for the scaled model. Each model will require special transitional input sections to prevent high-voltage arcing.

The above preliminary design results are, of course, good specifically for the chamber size (whether full or scaled) we assumed at the beginning of this section. Chamber size and geometry will be adjusted by a similar set of design guidelines when the required workable test volume is changed.

3. Potential Options

The TEM cell configuration proposed above has a section of rectangular coaxial transmission line tapered at each end to adapt to standard coaxial connectors. This design of three different sections is the reason for resonances as mentioned in Section 2. The travelling wave excited by the source does not reach the load simultaneously, thus causing some reflections or even creating some non-TEM modes. An alternative to this is the ABB cell, model 1500 (called GTEM-1500) as shown in figure 7 [17]. This particular model was designed for EUTs up to the size of 1 m x 1 m x 0.5 m in order to ensure a good field uniformity and small load effect. The height of the center conductor is 1.5 m. The overall dimensions are 3 m x 2 m x 6.5 m. The high-power load resistors are installed to allow a maximum cw power of 1 kW, resulting in an electric field of at least 200 V/m. A pulsed voltage of 100 kV can also be applied to generate a pulsed electric field of more than 50 kV/m. The measured reflections are within +2 % and -5 %. The input impedance varies from 45 Ω to 52 Ω. Measured pulsed fields also indicate good fidelity. This model is currently available in the United States. Tests, however, are needed to confirm these figures and may be conducted through an arrangement with the manufacturer. Presumably this model could also be scaled up to accommodate larger test volumes with proportionally greater input powers to generate cw fields up to 200 V/m or pulsed fields up to 50 kV/m.

Another alternative is the symmetrical end-loaded TEM cell shown in figure 8. This facility is available elsewhere [18]. This model offers a reduced length for the tapered section and uses absorbers for wave termination. An arrangment for NIST to make some tests inside this cell for determining its applicability to the task specified in Section 2 is also possible.

A third option is the TEM-driven reverberating chamber currently being designed and investigated at NIST for the U.S. Army [14]. This chamber is also a shielded facility. The TEM cell has three individual orthogonal center conductors (top, back, and end), so that we do not need to rotate the EUT physically inside the cell. The input impedance of this cell is designed at 100 Ω. The test volume in this full-sized chamber, when used in the reverberating mode, is 8 m x 16 m x 30 m. A scaled model (1/10) with the overall size of 1.31 m x 2.41 m x 3.87 m has been constructed for evaluation. The cross section with a top plate as the center conductor has the dimensions of 2a = 3.87 m, 2b = 1.31 m, 2w = 0.46 m, and h_i = 1.06 m (referred to figure 4). The theoretically estimated electric-field amplitude (square root of the sum of the squares of the x- and y-components) distribution inside this cross section, relative to the center value at x = 0 and y = $h_i/2$ may be summarized as follows [19]:

		x = 0	± a/3	± a/2	± 2a/3	± a
y =	$3h_i/4$	1.117	0.983	0.811	0.636	0.438
	$h_i/2$	1.000	0.864	0.706	0.522	0.257
	$h_i/4$	0.931	0.799	0.645	0.459	0.118
	0	0.908	0.779	0.629	0.439	0.000

For the cross section with a back plate as the center conductor, we have 2a = 1.31 m, 2b = 2.41 m, 2w = 0.46 m, h_i = 2.11 m, and the normalized electric-field amplitude distribution as follows:

		x = 0	± a/3	± a/2	± 2a/3	± a
	$3h_i/4$	3.477	3.517	3.550	3.5853	3.610
y =	$h_i/2$	1.000	0.999	0.999	0.998	0.997
	$h_i/4$	0.305	0.295	0.217	0.154	0.026
	0	0.159	0.138	0.113	0.080	0.000

For the cross section with an end plate as the center conductor, we have 2a = 1.31 m, 2b =3.87 m, 2w = 0.46 m, h_i = 3.57 m, and the normalized electric-field amplitude distribution as follows:

		x = 0	± a/3	± a/2	± 2a/3	± a
	$3h_i/4$	8.475	8.489	8.503	8.516	8.530
y =	$h_i/2$	1.000	1.000	1.000	1.000	1.000
	$h_i/4$	0.118	0.118	0.118	0.118	0.118
	0	0.028	0.024	0.020	0.014	0.000

Two stirrers will also be installed in this facility. Each is operated independently under computer control to select appropriate stirrer position and its revolution rate. As a whole, the operation of this chamber will be divided into three distinct regions in frequencies: (1) the TEM mode ranging from 10 kHz to 10 MHz, (2) the transition approximately from 10 to 30 MHz, and (3) the mode-stirred region from 30 MHz to 18 GHz or higher. Test fields will be excited in the chamber at frequencies up to 1 GHz by using either the transmission lines or transmitting antennas such as biconic, log-spiral, or log-periodic antennas. At frequencies above 1 GHz, ridged horn antennas will be used. A 10 kW source should be sufficient to generate a test field up to 100 V/m for the TEM mode of operation, and a 200 W amplifier should generate a test field up to 200 V/m for the reverberating operation.

If test results confirm the theoretical predictions, the chamber may be used directly or modified to meet the need for the hypothetical sample considered in Section 2.

4. Conclusions and Recommendations

A preliminary design of an improved testing facility for evaluating the EM susceptibility of weapon systems and electronic equipment has been presented. The facility consists of a combination of the TEM cell and the reverberating (mode-stirred) chamber. The TEM mode of operation is intended for lower frequency range from 10 kHz to perhaps 10 MHz, and the mode-stirred mode of operation is for higher frequency band from 23 MHz to 18 GHz with a possible extension to 40 GHz. The transitional region is from 10 MHz to 23 MHz, in which the first few higher order modes may be excited but are not sufficient in number for the chamber to reverberate properly. The scaled model specifically discussed in Section 2 should be constructed for evaluating its characteristics. If satisfactory, the full-sized model may then be considered. In the meantime, evaluation and necessary tests with the alternative and supplementary facilities outlined in Section 3 should also be conducted by us to derive a cost-effective and improved EMC testing environment for meeting a given set of specific criteria.

5. Acknowledgments

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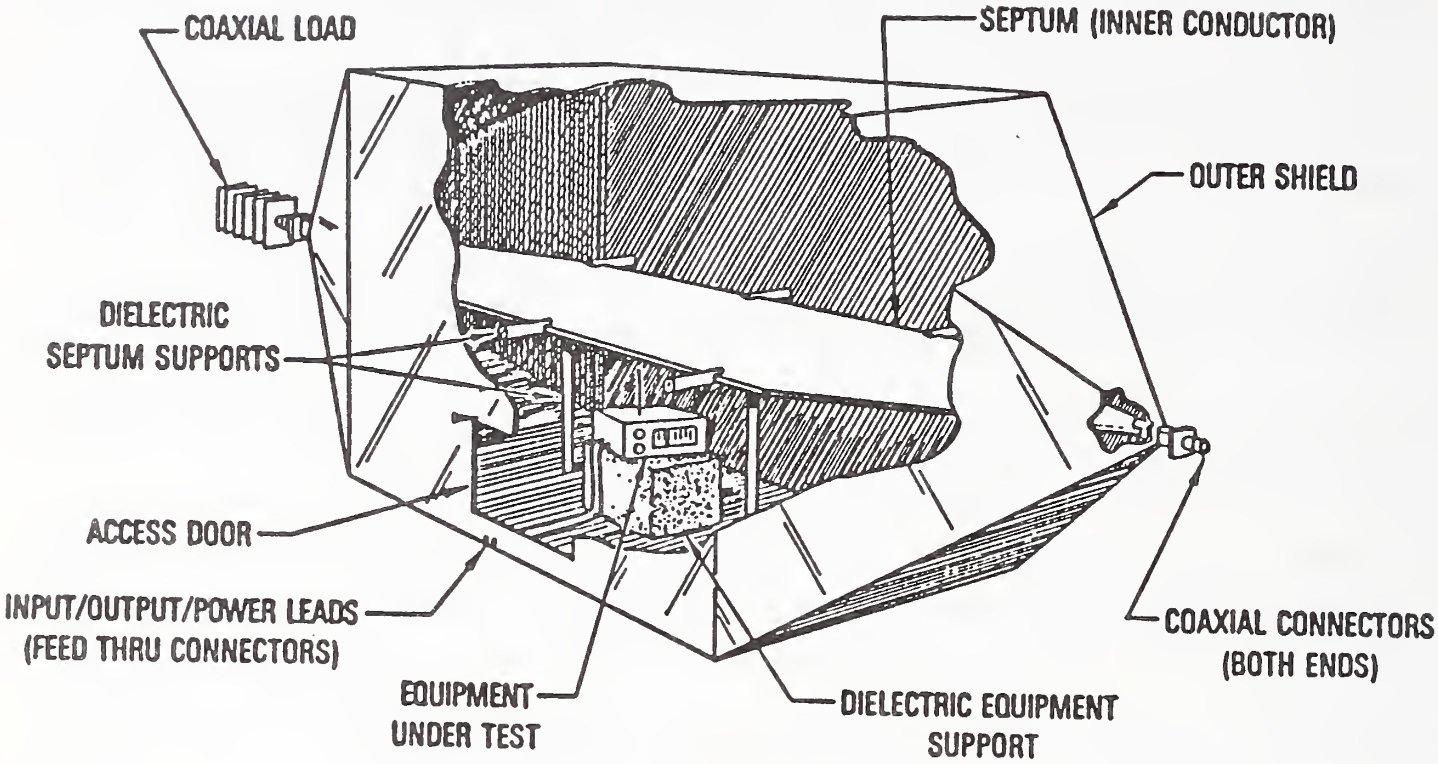


Figure 1. TEM cell for EM susceptibility testing.

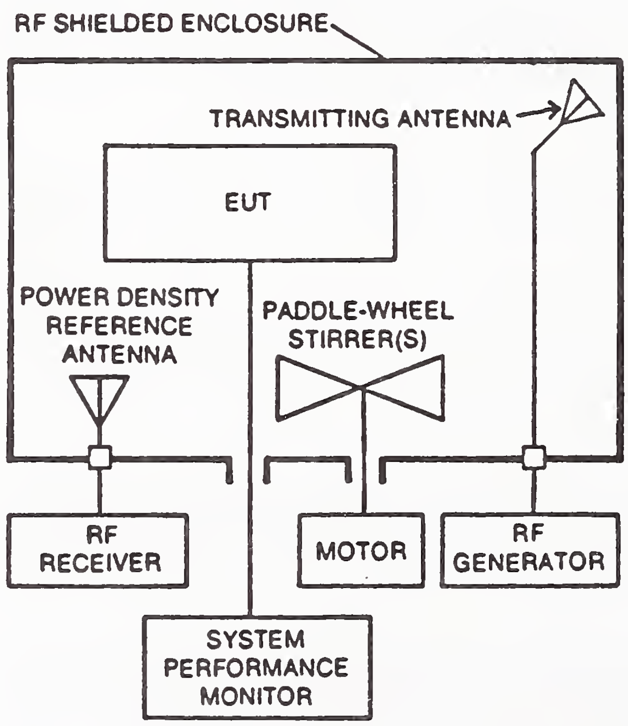


Figure 2. Reverberating chamber for EM susceptibility testing.

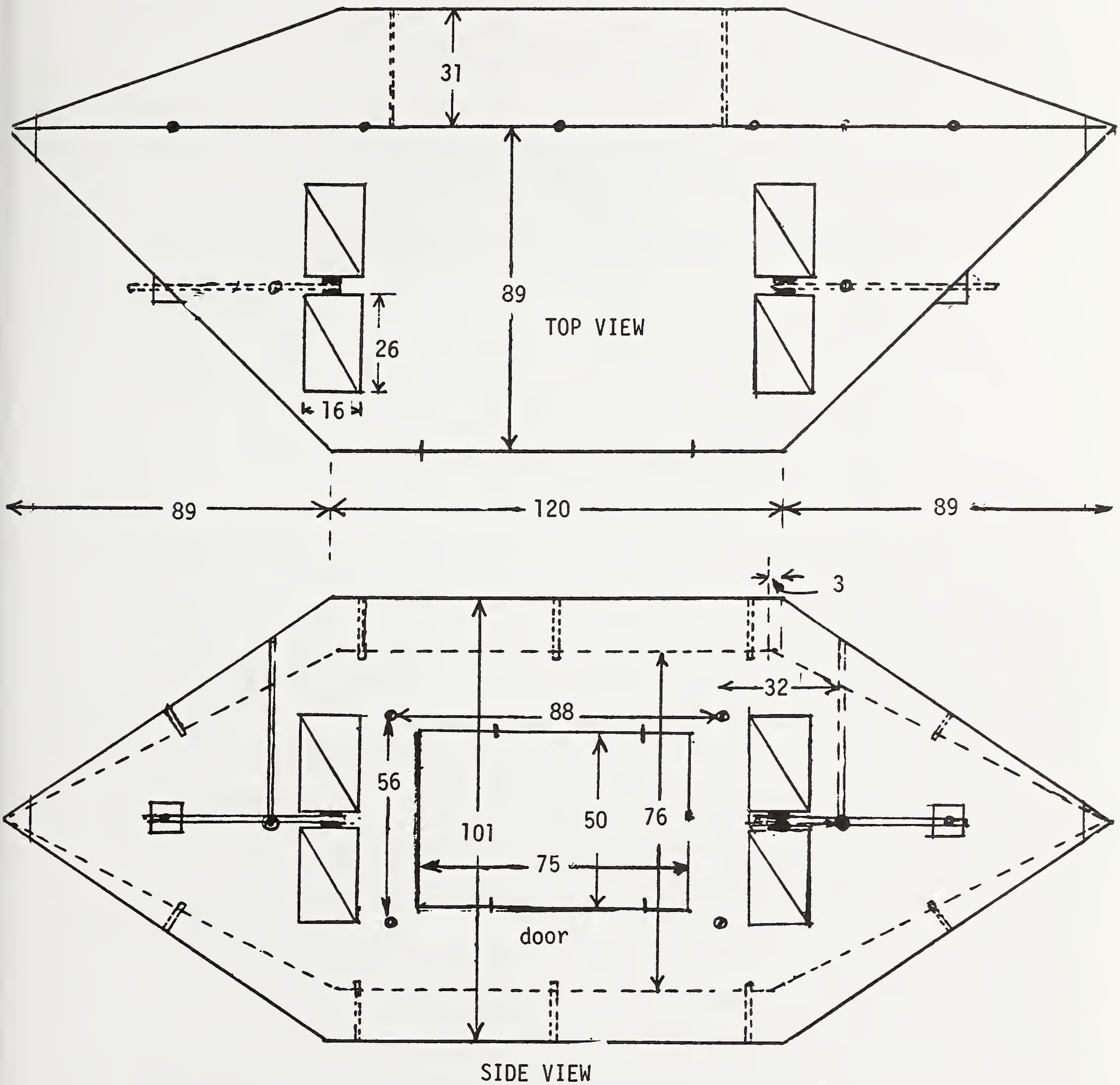


Figure 3. Sketch of the scaled model of a TEM/reverberating chamber as an EMC/EMP testing facility. Dimensions are in cm.

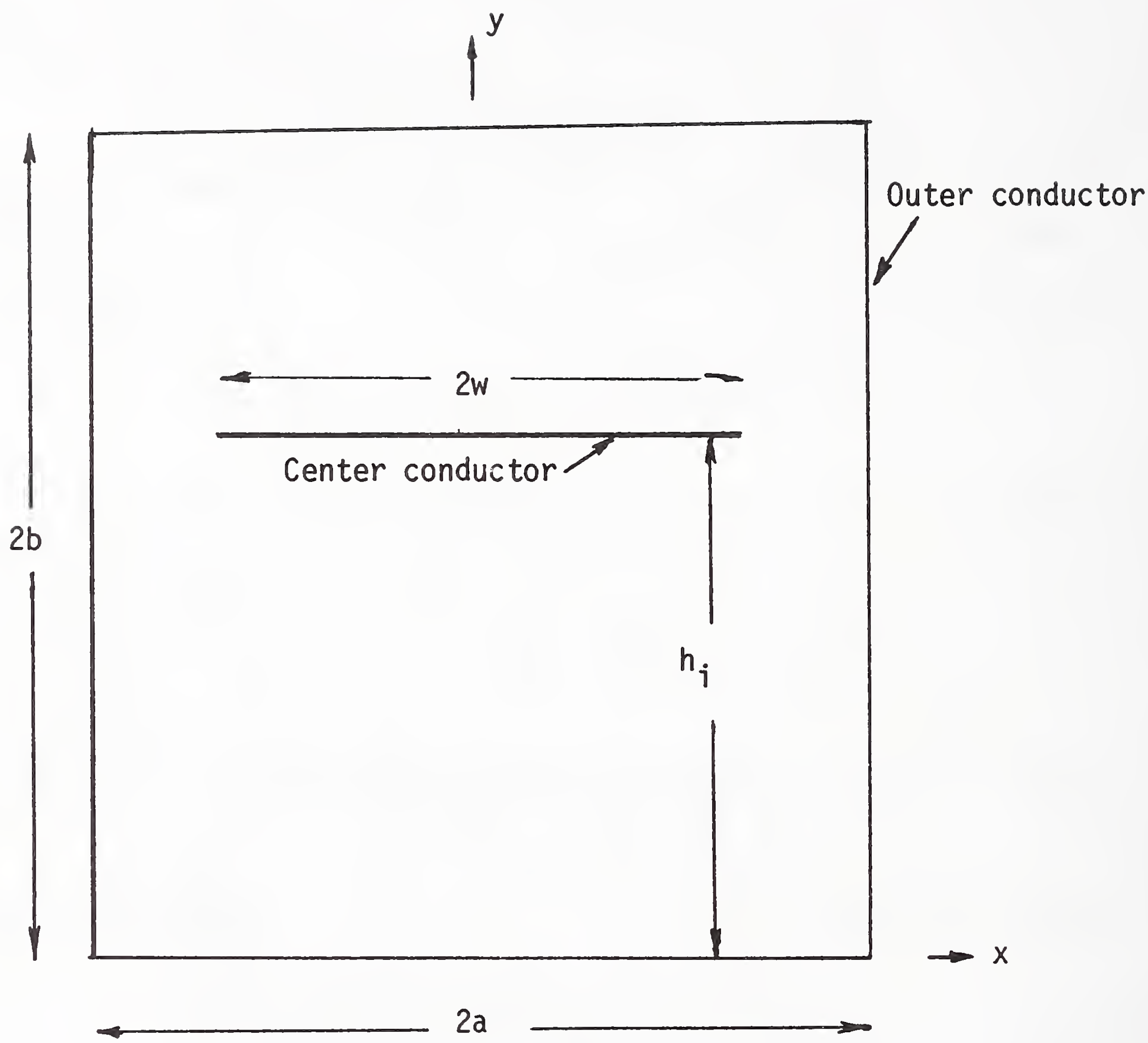
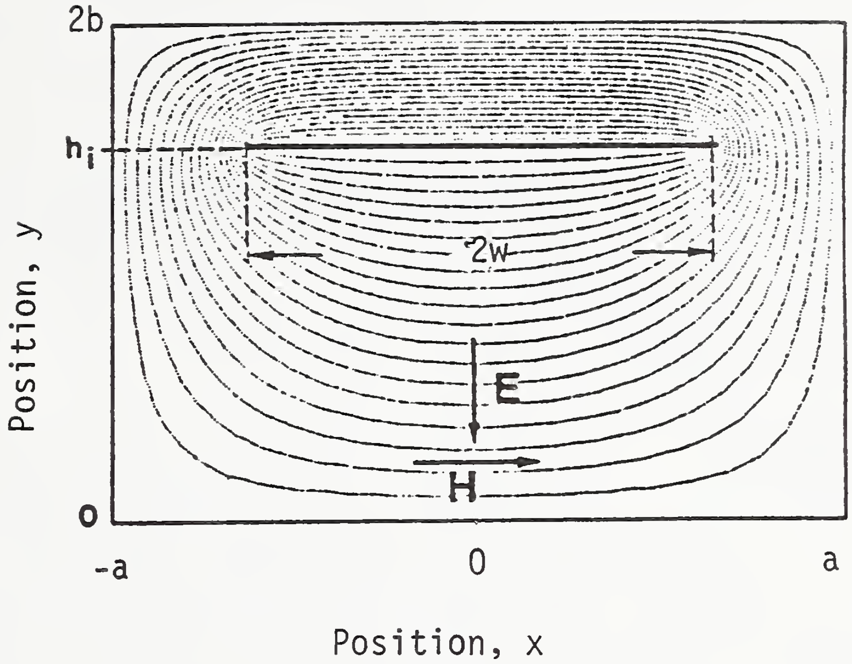
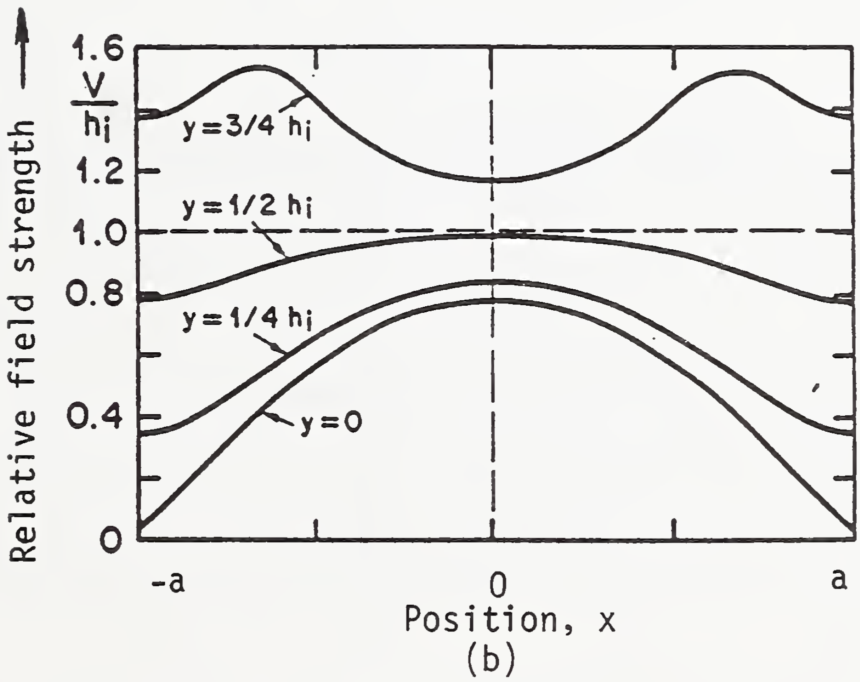


Figure 4. Cross section of the TEM cell.



(a)



(b)

Figure 5. Relative field distribution inside the cross section of a TEM cell, (a) general field orientation, and (b) as a function of heights.

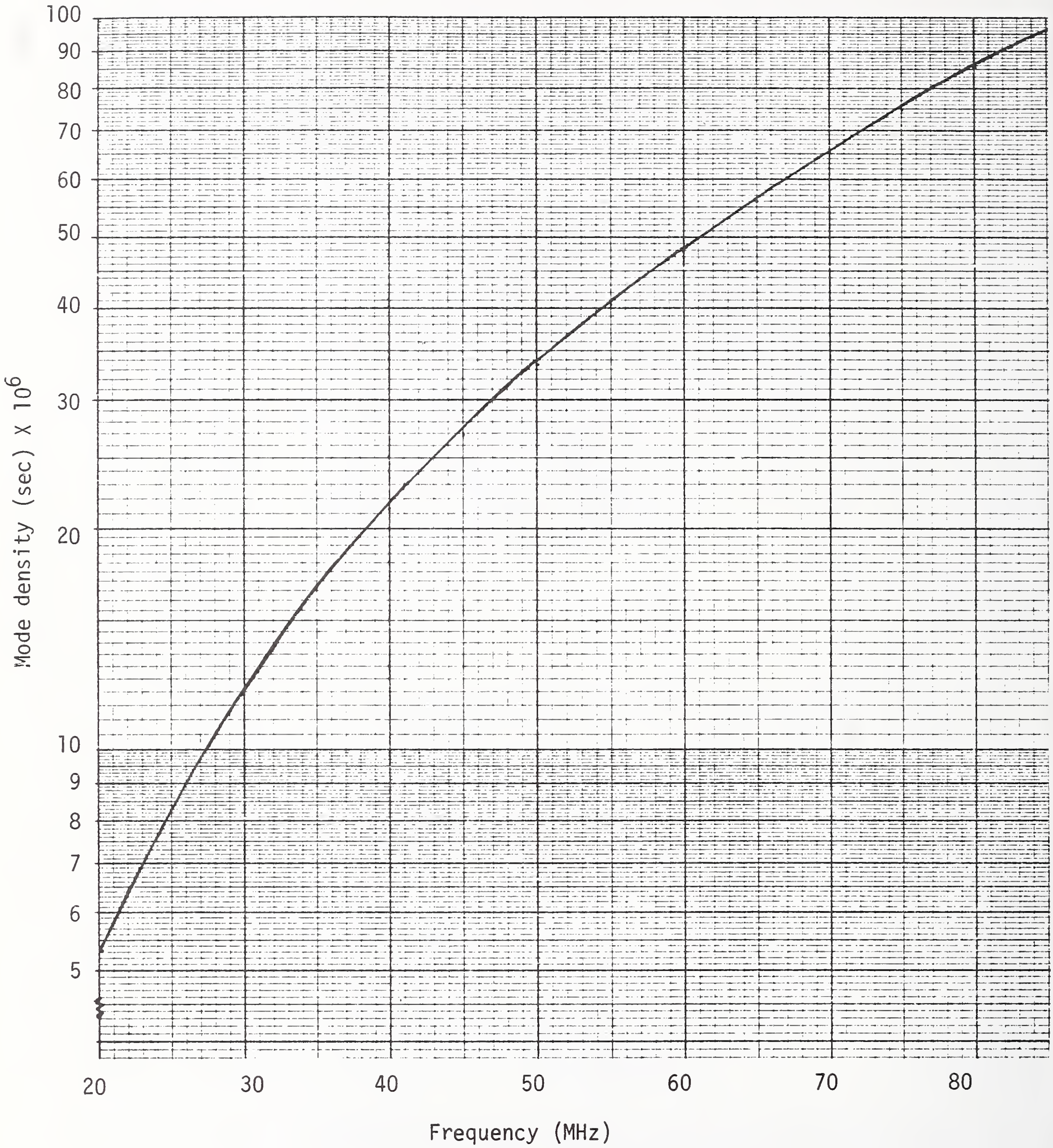


Figure 6. Mode density for the full size reverberating chamber as a function of frequency.

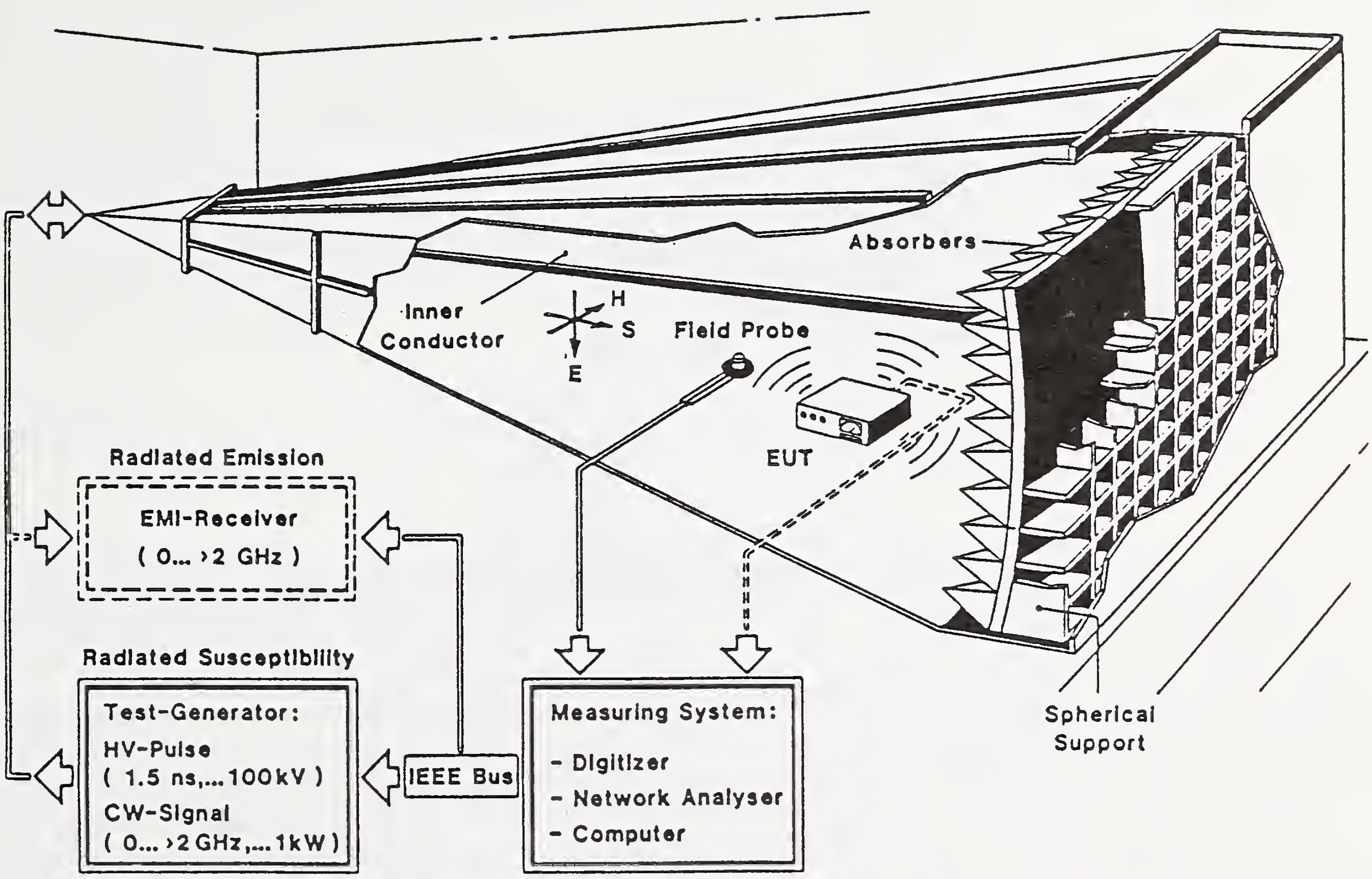


Figure 7. Schematic drawing of ABB gigahertz TEM cell.

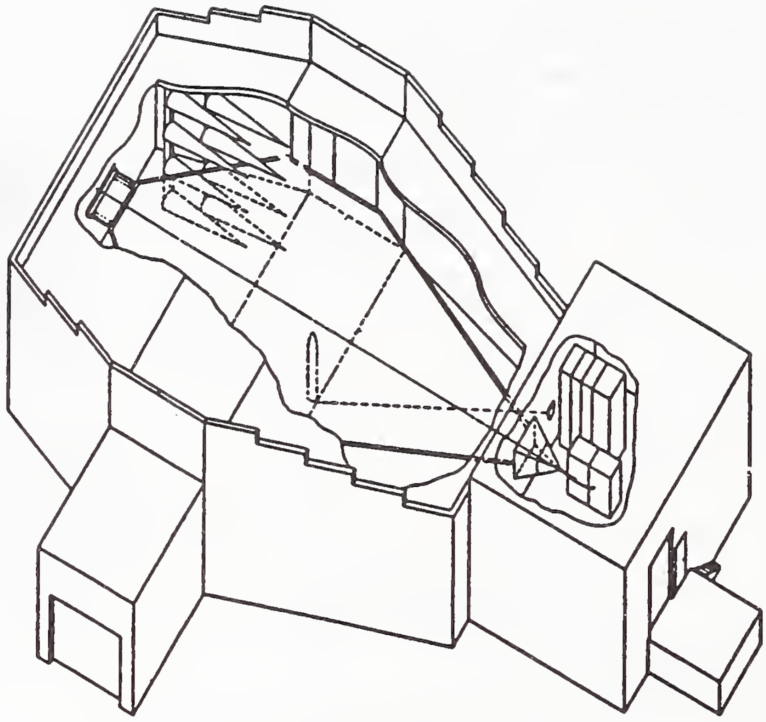


Figure 8. A broadband electromagnetic environment simulator (EMES).

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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.)

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