SHIELDING EFFECTIVENESS MEASUREMENTS OF PLASTICS

John W. Adams
Eric J. Vanzura

National Bureau of Standards
U.S. Department of Commerce
Boulder, Colorado 80303

January 1986

NBSIR 85-3035

SHIELDING EFFECTIVENESS MEASUREMENTS OF PLASTICS

John W. Adams
Eric J. Vanzura

Electromagnetic Fields Division
Center for Electronics and Electrical Engineering
National Engineering Laboratory
National Bureau of Standards
Boulder, Colorado 80303

January 1986

U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, Secretary

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Director

CONTENTS

Page

Shielding Effectiveness Measurements of Plastics

John W. Adams and Eric Vanzura
Electromagnetic Fields Division
National Bureau of Standards
Boulder, Colorado

Measurement of shielding effectiveness (SE) of plastic materials may give serious problems due to the insulating nature of many plastics. A method of making these measurements using a flanged coaxial holder overcomes these limitations.

Key Words: ASTM SE measurements; flanged coaxial holder; SE measurements of plastics; shielding effectiveness measurements

1. Background

A number of methods are either in use or are being developed and evaluated for measuring shielding effectiveness (SE) of materials [1-6]. There are also a number of problems both in making the measurements and interpreting results [1,7]. The main difficulty is to obtain repeatable results on the same material using different techniques and sometimes with the same technique. It is difficult to match the measurement conditions with application conditions. The increased use of plastic binders with insulating characteristics is a substantial change in application technology and also creates additional problems in measurement technology. Federal Communication Commission (FCC) incidental radiation regulations require expensive testing on whole products or systems. Reliable SE measurements may aid design decisions and reduce need for redesign after final FCC testing.

The definition, $SE = 10 \log (P_2/P_1)$, is deceptively easy to state, where P_2 and P_1 are power levels without and with a sample of material present. Conditions that exist during measurement such as angle of incidence and polarization of waves are often omitted or are not known but are essential factors influencing P_2 and P_1.

The five methods of measurement covered in references [1] and [2] are: (1) a variation of MIL-STD 285, (2) a dual transverse electromagnetic (TEM) cell, (3) a flanged coaxial holder, (4) a time domain measurement system in free space, and (5) a time domain measurement system through an aperture of a shielded room. There is substantial disagreement among the measured values of SE on the same material using these five methods. The measured results are shown in figure 1. There is at least a partial understanding of problems causing these variations, and some improvements may allow more repeatable measured results under specific conditions.

There is no practical solution to the use of continuous wave (CW) through an aperture of a shielded room (modified use of MIL-STD 285). The multitude of resonances within the room and the resonances of the aperture cause such a wide range of measured values over short frequency intervals that only by taking a tremendous number of measurements and averaging the data can any meaningful results be obtained. This is prohibitively time consuming and costly.

The dual TEM cell [2,3,4] is useful for measurements with the electric field (E) normal to the surface of the material and for frequencies up to occurrence of modes of higher order than the TEM mode. Thus, the upper frequency is a function of the size of the TEM cell [8]. The major practical problem with this method is the variation in measured data due to contact resistance. Many materials, especially those made of plastic, give considerable variation in contact resistance. This is also a problem for some other measurement systems.

There are various designs of coaxial holders for making SE measurements [1,5,6]. Some require electrical contact with both inner and outer conductors since the measurement relies on conduction current. Others that allow insertion of a sample between flanges of a transmission line can rely on displacement current. This is more effective for measurement on insulating samples, but extra steps must be taken to compensate for the transmission line perturbation caused by this insertion of sample material.

This method seems promising between 10 and 1000 MHz. At frequencies below 10 MHz, compensation for transmission line perturbation becomes increasingly difficult. At frequencies above 1 GHz, higher order modes cause problems. More discussion of the flanged coaxial holder follows since it seems to have the most potential for giving repeatable measured values that compare favorably with theoretically predicted values.

Two time domain techniques under study use subnanosecond pulses to provide SE information from 100 MHz to 4 GHz [9,10]. For both systems, received time domain pulses are first windowed to eliminate unwanted diffracted and reflected signals. After performing Fourier transforms on the received pulse shapes with and without the sample present, a comparison is made of the spectral responses.

The first technique requires samples more than one meter square so the direct path signal can be separated from the diffracted signal coming around the material (see figure 2). The direct difference in spectral responses with and without the material gives SE values. Unfortunately, for SE applications a large sample size is often a limiting factor.

The second method involves placing a small (10 cm diameter) sample over an aperture of either a wall of a shielded room or of a large plane metal sheet (see figure 3). Measured SE values are confounded by effects of aperture loading, contact impedance and aperture resonances at higher frequencies. These effects are not well understood at present.

2. Materials

A proliferation of shielding materials are now available. Metal such as nickel and copper are being plated onto plastic substrates, or conductors such as carbon and graphite are being embedded into a plastic binder. A measurement system should give good measured values regardless of the type of construction or content of a shielding material. This is certainly not a fully accomplished fact as of this writing.

3. Problems

Another problem in interpreting measured data is that specific measurement conditions, usually plane wave incidence with E and magnetic field (H) tangent to the sample surface, are very seldom satisfied in applications. Typically, a source is inside an enclosure, and near field waves impinge on surfaces at a multitude of different angles. Transmission and reflection factors change drastically as angle of incidence and polarization change. There may not be a tractable solution other than the final FCC test [11]; even the measurement of SE of the enclosure material may be a minor factor compared to a large, relatively open aperture such as a video screen. However, decisions must be made to select materials for shielding, and these may be done on a relative basis.

A very enlightening theoretical study [7] of coupling through a small loaded aperture indicates how antenna position, contact impedance and the angle of incidence of an arriving plane wave can significantly affect the measured SE of a material. The specific coupling due to either E or H is shown. Typically, any conductive material severely attenuates the electric field. The magnetic field is, however, shown to penetrate much more strongly through most samples. The particular example shows the shielding of the magnetic field to be 103.6 dB for 0.0 ohm contact resistance, 54.1 dB for 0.01 ohm, and 14.3 dB for 1.0 ohm.

4. Types of Coaxial Holders for SE Measurements

Two types of coaxial transmission line holders will be discussed for SE measurements. Two circuits with lumped elements given in figures 4a and 4b are shown to illustrate the problem caused by contact resistance.

Figure 4a shows a sample represented by Z_L connected to the inner and outer conductors of a coaxial transmission line by a parallel resistor and capacitor. The resistor represents contact resistance (conduction current) and the capacitor represents capacitive coupling (displacement current).

This may simulate the case of the American Society for Testing Materials (ASTM) coaxial holder. Figure 4b shows the same sample Z_L connected to similar parallel R and C circuits which are now in series with the coaxial line. This may simulate the case of the flanged National Bureau of Standards (NBS) holder. Although measured numbers may be used to analyze these circuits, the concepts are illustrative and distributed circuits or field analysis should be used for rigorous calculations. Erratic and erroneous measurements are caused when both susceptance and conductance are too small (poor coupling). For conductive samples, conductance will be large and either circuit will give good data. For insulating materials, conductance will be small and variable, and displacement current through capacitive coupling must be greater than conduction current in order to obtain repeatable data. This may be achieved by increasing capacitance by enlarging the capacitive coupling area by use of flanges as shown in figure 4b. Thin samples will also increase this capacitance. The ratio of displacement to conduction current will determine how low in frequency the coaxial fixtures may be used. For insulating materials, the conductance will be very low, and the more stable capacitance will carry the dominant portion of the current. Unfortunately, as frequency decreases the susceptance also decreases to the point that the relatively unrepeatable conductance carries the larger proportion of current. Measured data at low frequencies show this instability. The "corner" frequency may be calculated by $f=1/2\pi RC$; the range of instability is below this corner frequency.

The holder proposed by ASTM committee D-9.12.14 in Emergency Standard ES 7 - 83 is described by Simon [6] and shown in figure 5. The coaxial line has continuous inner and outer conductors of diameter 4.35 and 9.9 cm, respectively (see figure 4a). The sample should be an annular disk with matching dimensions to fit between the inner and outer conductor. The sample must make resistive contact with the walls. Silver paint is suggested, but even with a good quality silver paint, any variation in the contact resistance causes substantial change in measured SE values. Samples with imperfectly conducting edges inherently give unrepeatable results. The capacitive coupling for thin samples is so small that it is insufficient to overcome poor contact resistance, especially for samples which are basically good insulators. Two runs are needed; one is taken with an empty holder, while the second is taken with the sample present.

NBS has a coaxial transmission line holder with flanges in the midsection and with inner conductor diameter of 3.2 cm and outer conductor diameter of 7.6 cm. See the Appendix for engineering drawings of this holder. The flange has an outer diameter of 13.3 cm, as shown in figure 6. The sample should be a solid disk with diameter of 13.3 cm. The transmission line is perturbed by this sample since it adds series admittances to both inner and outer conductors (see figure 4b). This perturbation depends on dielectric constant, conductivity, and thickness of the test sample. The perturbation caused by these series admittances may be isolated by making a reference annular disk that matches the dimensions of the outer conductor and a solid disk that matches the dimensions of the inner conductor. This leaves the space between inner and outer conductor open. These reference disks are the same thickness as the sample disk to be used for the load. Measured transmission values with these reference disks give insertion loss caused by the series admittances. These values are then used as reference values to be compared with values obtained when the solid disk of the sample material is clamped between the flanges. Nylon screws should be used to clamp the flanges together to minimize erratic conductive contact with edges of samples. This means that each set of measurements must be made twice, first with the reference and then with the sample.

With an automated measurement system, the time required to make the needed measurements is still reasonable. The values obtained with the NBS sample holder are repeatable and agree with calculated values, except for inhomogeneous samples. Many of the insulating plastic samples give erratic data when measured in the ASTM holder; conductive samples give more consistent results if contact resistance is minimized with silver paint. Inhomogeneous samples give more difference in capacitance due to positioning and pressure variations than do homogeneous samples.

5. Automated Measurements with the NBS Coaxial Holder

Figure 7 shows the test configuration of the NBS shielding effectiveness measurement system. The NBS system uses a computer-controlled data acquisition setup which measures incident, reflected and through powers at any number of frequencies in the 1 MHz to 1 GHz range. The operator controls the measurement through the computer by answering prompts. First the signal generator power level and desired frequencies are input to the computer. The computer sets the signal generator to the specified power level and frequency. It also sets the digital spectrum analyzer to this same frequency. Power from the signal generator then goes through a 10 dB attenuator to reduce reflections going back into the generator. A calibrated bidirectional coupler gives the incident and reflected powers at the 50-ohm coaxial sample holder input port (port 1). When the rf reaches the surface of the test sample, the incident power is partially reflected due to impedance mismatch and partially enters the sample. Once inside the sample, rf power is absorbed as it passes through. On the other side of the test sample the incident power is again partially re-reflected back into the sample and partially coupled through as transmitted power. This transmitted power passes through a calibrated 9 dB attenuator and a set of automated coaxial rf switches. The computer controls a relay actuator that configures the rf switches so that either incident, reflected or through power passes to the spectrum analyzer. The two rf lines that are not being measured are terminated in 50 ohm loads. Power from the switches goes through a calibrated 3 dB attenuator and is then measured by the spectrum analyzer.

Under computer control the spectrum analyzer performs many functions. To provide a good measurement range the spectrum analyzer is first set to 10 dB/division and its reference level is set 13 dB higher than the highest possible signal level that could get through. This reference level is usually the signal generator level minus the total attenuation of the three pads (22 dB) plus 13 dB. Then, at each frequency, the spectrum analyzer sets the frequency span to the current center frequency divided by 100. For example, if the frequency were 500 MHz the frequency span would be 5 MHz.

The spectrum analyzer then takes eight sweeps using the "max hold" function, and uses the "peak search" to measure the frequency and power level. It then moves off the center frequency and measures the noise floor of the spectrum analyzer. If this measured signal-to-noise ratio is less than 10 dB, the computer will make the spectrum analyzer go through a high resolution subroutine in which the reference level, frequency span, resolution bandwidth and video bandwidth are reduced to pull the signal out of the noise as much as possible. If the signal is still too small, a flag is set indicating that the measured value is too near the noise floor. The computer then resets the spectrum analyzer to its normal operation. Once the incident, reflected and transmitted powers are measured, the computer sets the spectrum analyzer and signal generator to the next frequency and the measurement process is repeated through the specified number of frequencies.

The computer stores and displays data in different ways. As each measurement is taken, the power level is displayed on the computer's CRT. If the signal is sufficiently higher than the noise, that level is stored in an array. When the three power levels at any particular frequency have been made, the computer sends the information to the printer where it is written along with any other information about that measurement. When a run is completed the computer prompts the user to store the information on disk and asks for a filename. The frequencies and corresponding power levels are then written to disk, and measurements which were too small are marked appropriately. As discussed earlier, both reference and load runs are needed to calculate shielding effectiveness of the sample. Once information from both runs have been collected, the computer calculates the difference between the through power of the load and reference runs, using incident power measurements to normalize both runs to the same input power level. This difference is then written to disk where it can later be plotted. Some of these plots are shown in figures 8 and 9.

Automating the shielding effectiveness measurement system not only speeds up the measurement procedure but also decreases human error and makes data processing and presentation effective and easy. A typical run measuring incident, reflected, and through powers at 41 different frequencies usually takes about 15 minutes. The same run before automation took more than eight hours. The information may be stored directly to floppy disks and retrieved and plotted.

The dynamic range achieved by the NBS system is about 95 dB. This is more than adequate for measuring the SE of most materials. This number can be pushed beyond 100 dB, but additional care is needed for measurements that require more than 90 dB of dynamic range to avoid contamination of data by leakage. The repeatability of measured SE values is within 2 dB from 10 MHz to 1 GHz. The low frequency end will vary depending on the sample and is determined by the ratio of conduction to displacement currents for the particular sample.

Current investigations at NBS are to determine the accuracy of these and other types of shielding effectiveness measurement techniques.

6. Observations and Implications of Data Shown in Figures 8 and 9

The three curves shown in figure 8 are indicative of several potential problems. The sample is a thin gold film on a plastic substrate. Even if the edges are silver painted before the sample is inserted into the ASTM holder, poor conductive contact gives grossly pessimistic values of SE as shown by the silver-painted-before-insertion curve. Silver painting in place assures good contact, but some mismatch and resulting standing wave are caused by a combination of variations of characteristic impedance of the transmission line holder and by reflections from the silver paint along the edges of the sample. The flanged NBS holder which relies on displacement current at frequencies above 30 MHz gives the expected flat response. At the low frequencies it too gives erratic values as conduction current becomes dominant.

Figure 9 shows results of an insulating sample. Even though the edges were silver painted in place, the results in the ASTM holder are grossly erroneous. The flanged coaxial holder gives reasonable results down to about 30 MHz where displacement current falls off.

7. Conclusions

There are serious pitfalls for the unwary caused by measurement-system limitations in making SE measurements on insulating materials. This paper shows that flanged coaxial holders offer a viable means of making plane wave, normal incidence SE measurements on insulating materials as well as on conducting materials.

8. Acknowledgments

Mark Ma, A. R. Ondrejka, and Perry Wilson have made numerous helpful suggestions which are greatly appreciated.

9. References

[1] Ondrejka, A. R.; Adams, J. W. Shielding effectiveness (SE) measurement techniques. 1984 IEEE National Symposium on Electromagnetic Compatibility; San Antonio, Texas: 1984 April 24-26. 249-256.

[2] Wilson, P. F.; Ma, M. T. Small aperture analysis of the dual TEM cell. 1984 IEEE National Symposium on Electromagnetic Compatibility, San Antonio, Texas; 1984 April 24-26. 365-369.

[3] Wilson, P. F.; Ma, M. T. Small aperture analysis of the dual TEM cell and an investigation of test object scattering in a single cell. Nat. Bur. Standards (U.S.) Tech. Note 1076; 1984 October.

[4] Faught, A. N., Jr.; Dowell, J. T.; Scheps, R. D. Shielding material insertion loss measurement using a dual TEM cell system. 1983 IEEE International Symposium on Electromagnetic Compatibility; Washington, DC; 1983 August 23-25. 289-290.

[5] American Society for Testing and Materials Emergency Standard ES 7-83, Electromagnetic shielding effectiveness of planar materials. Philadelphia, PA; 1983 December.

[6] Simon, R. M. High accuracy in EMI measurement. Modern Plastics; 1983 August. 78-80.

[7] Wilson, P. F.; Ma, M. T. Factors influencing material shielding effectiveness measurements. 1985 IEEE International Symposium on Electromagnetic Compatibility; Wakefield, MA, 1985 August. 29-33.

[8] Tippet, J. P.; Chang, D. C.; Crawford, M. L. An analytical and experimental determination of the cutoff frequencies of higher-order modes in a TEM cell, Nat. Bur. Stand. (U.S.) NBSIR 76-841, 1976 June.

[9] Lawton, R. A.; Ondrejka, A. R. Antennas and the associated time domain range for measuring impulsive fields. Nat. Bur. Stand. (U.S.) Tech. Note 1008; 1978 April.

[10] Kanda, M. The effects of resistive loading of TEM horns. IEEE Transactions on Electromagn. Compat. EMC-24, No. 2: 245-255; 1982 May.

[11] FCC Rules, Part 15, Subpart J (47 CFR 15.801-15.840), Federal Register at 45 FR 42347, U.S. Government Printing Office, 1980 June 24.

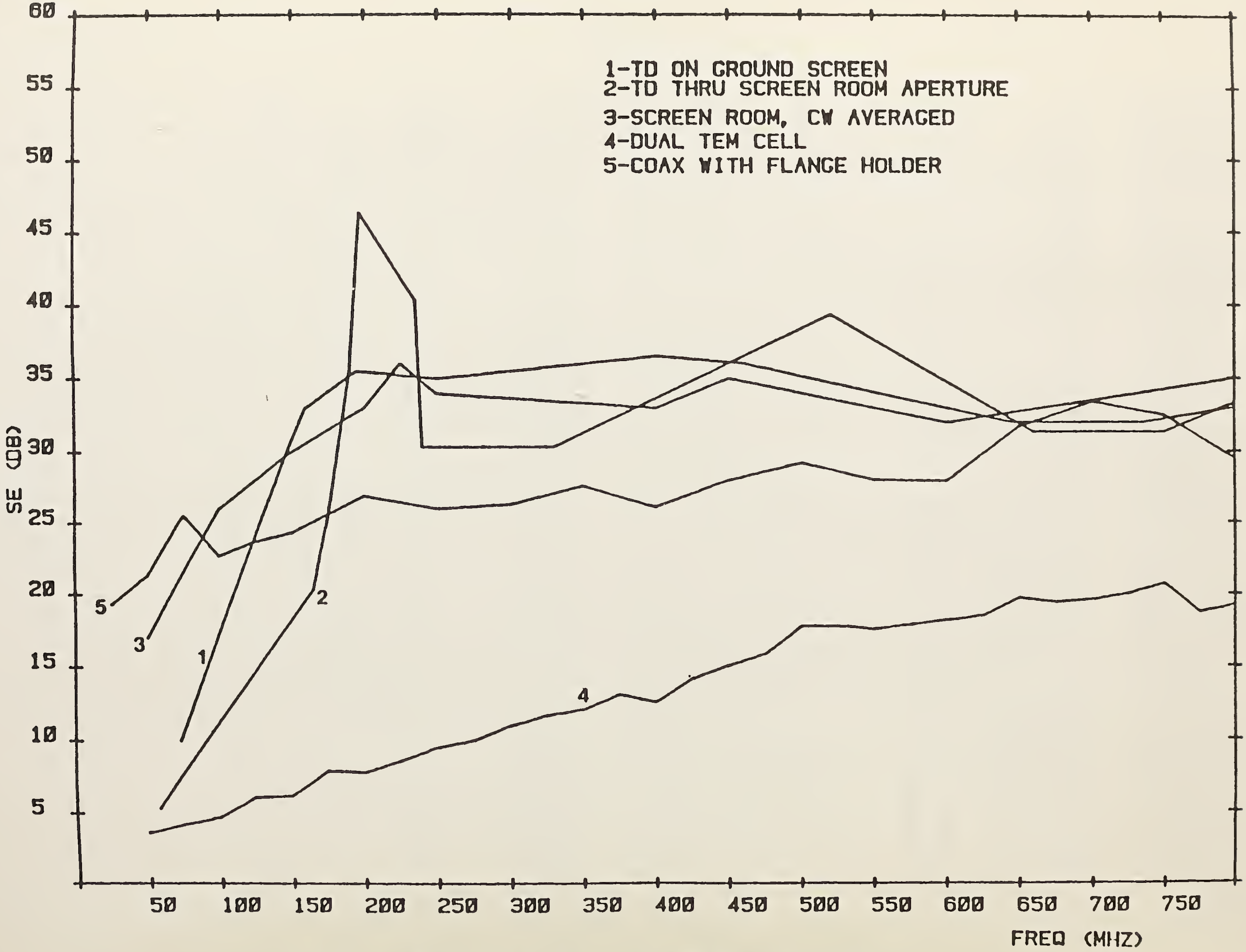


Figure 1. Measured SE data of the same material using five different measurement techniques.

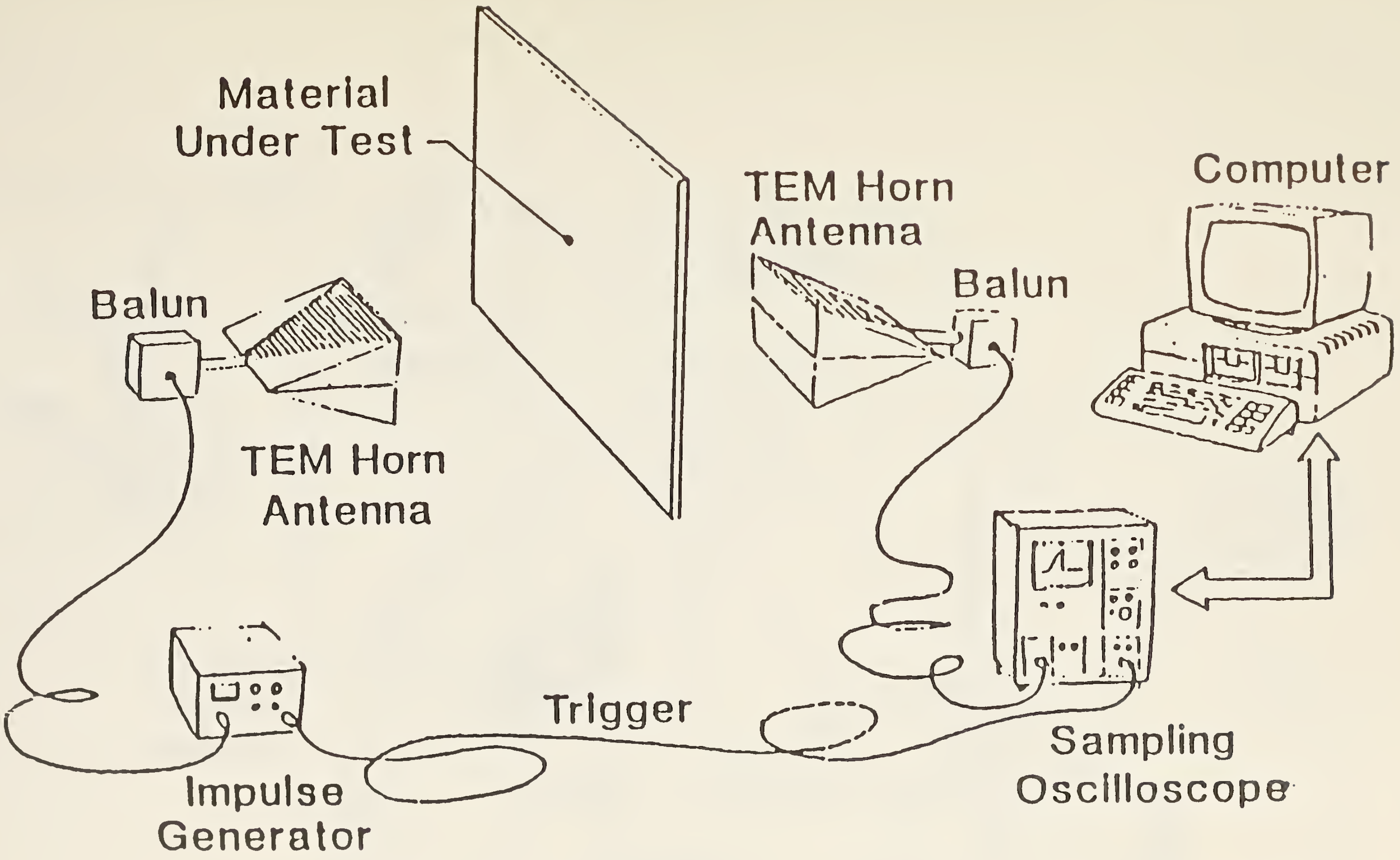


Figure 2. Open-space time domain measurement system.

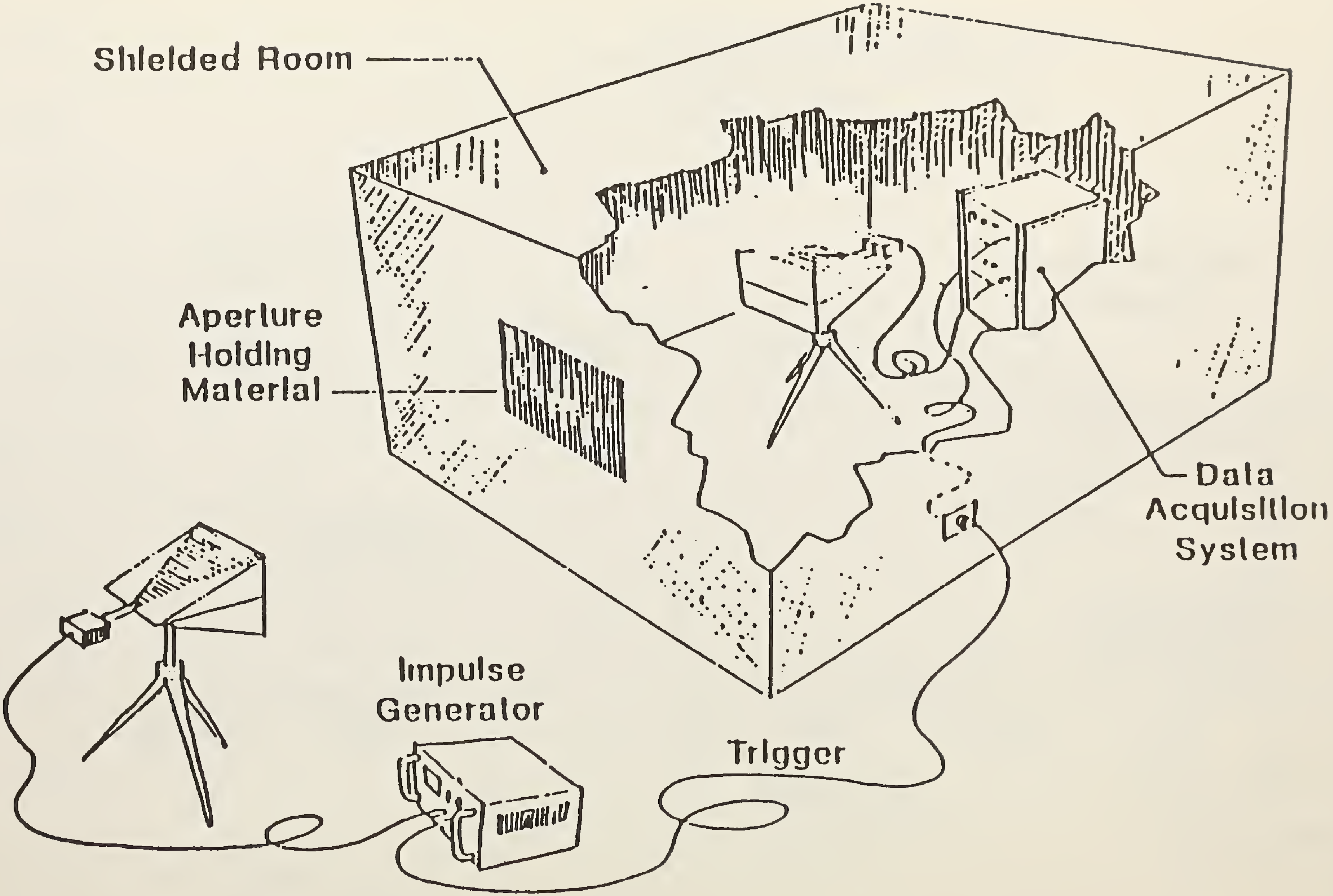


Figure 3. Aperture time domain measurement system.

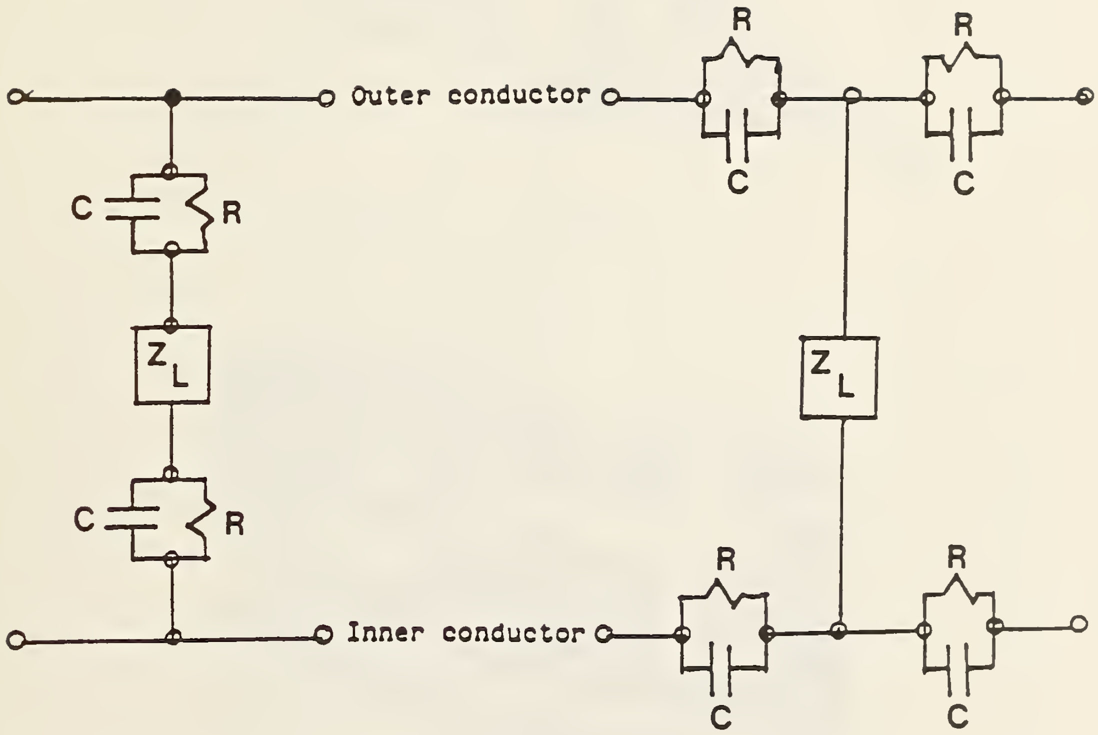


Figure 4a

Figure 4b

Figure 4. Circuit models for showing effect of contact resistance.

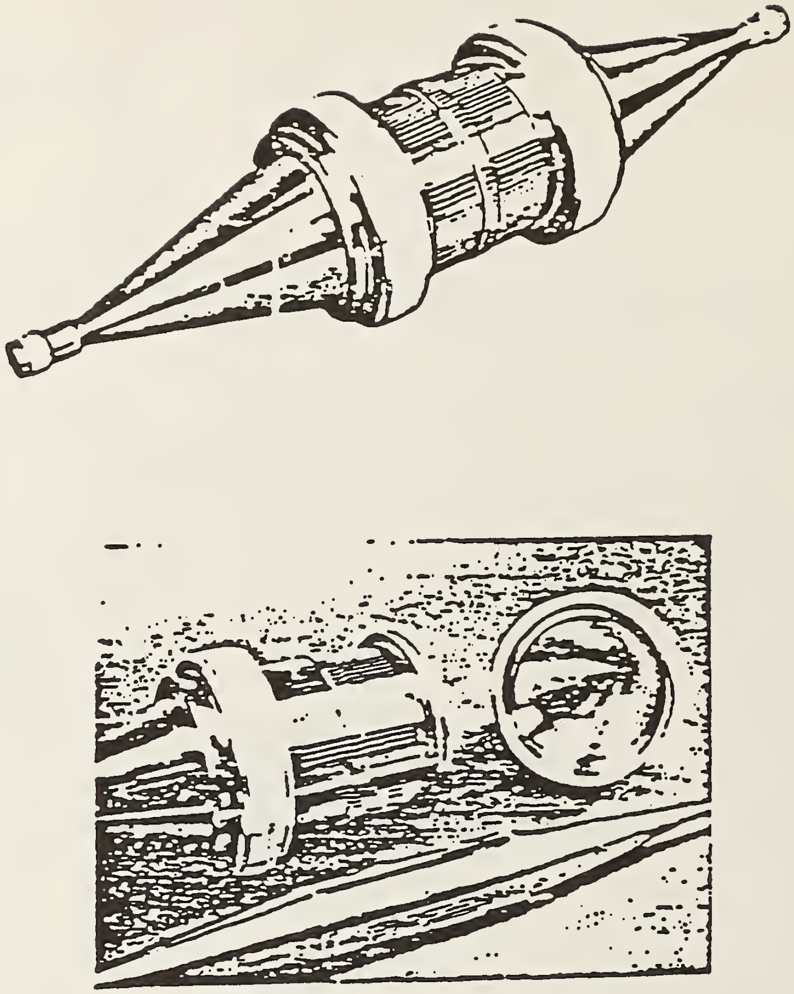


Figure 5. ASTM coaxial holder for SE measurements.

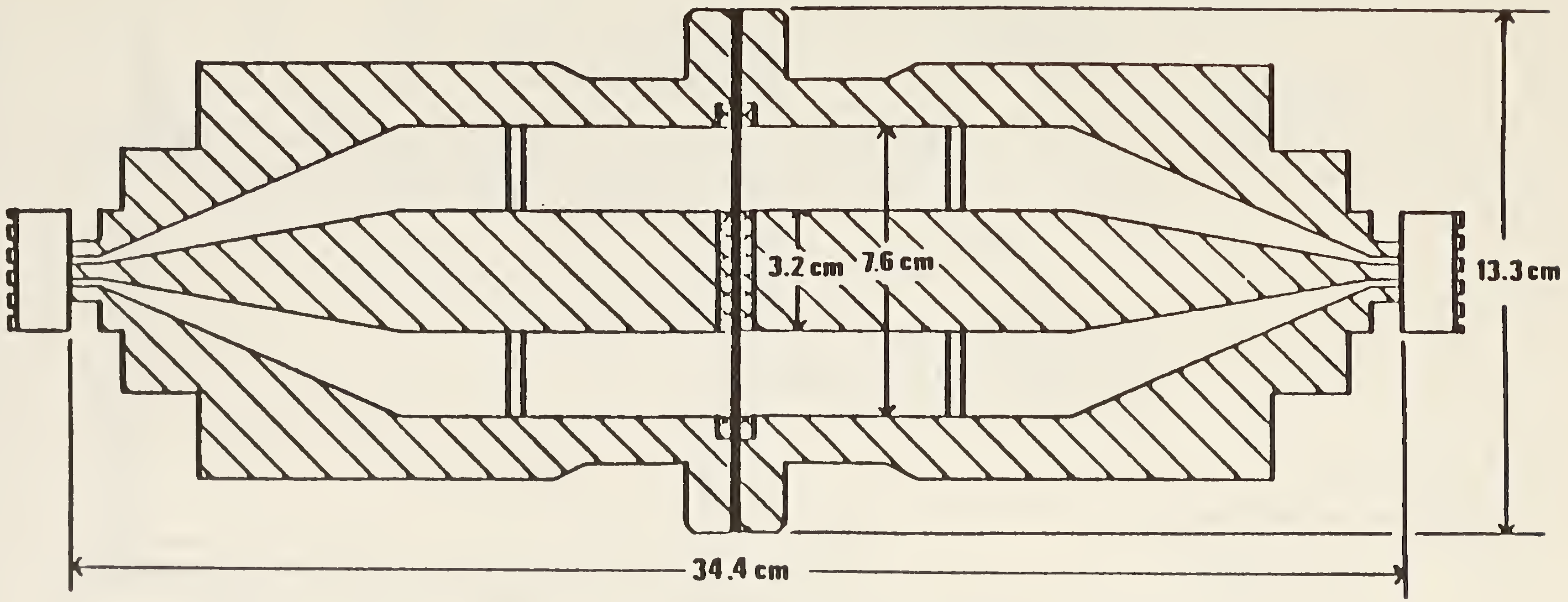


Figure 6. Flanged coaxial holder for SE measurements.

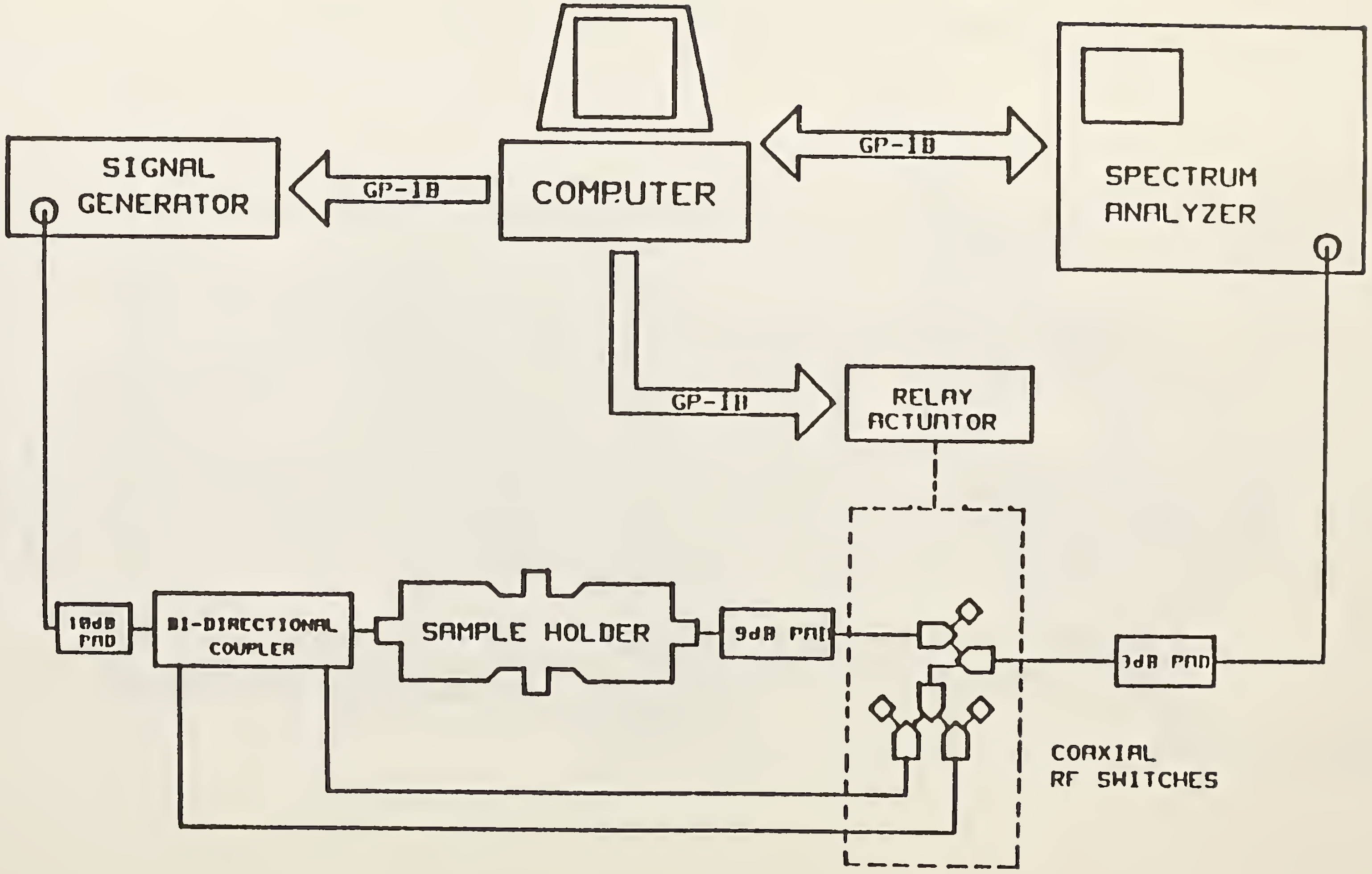


Figure 7. Block diagram of automated SE measurement system that uses coaxial holders.

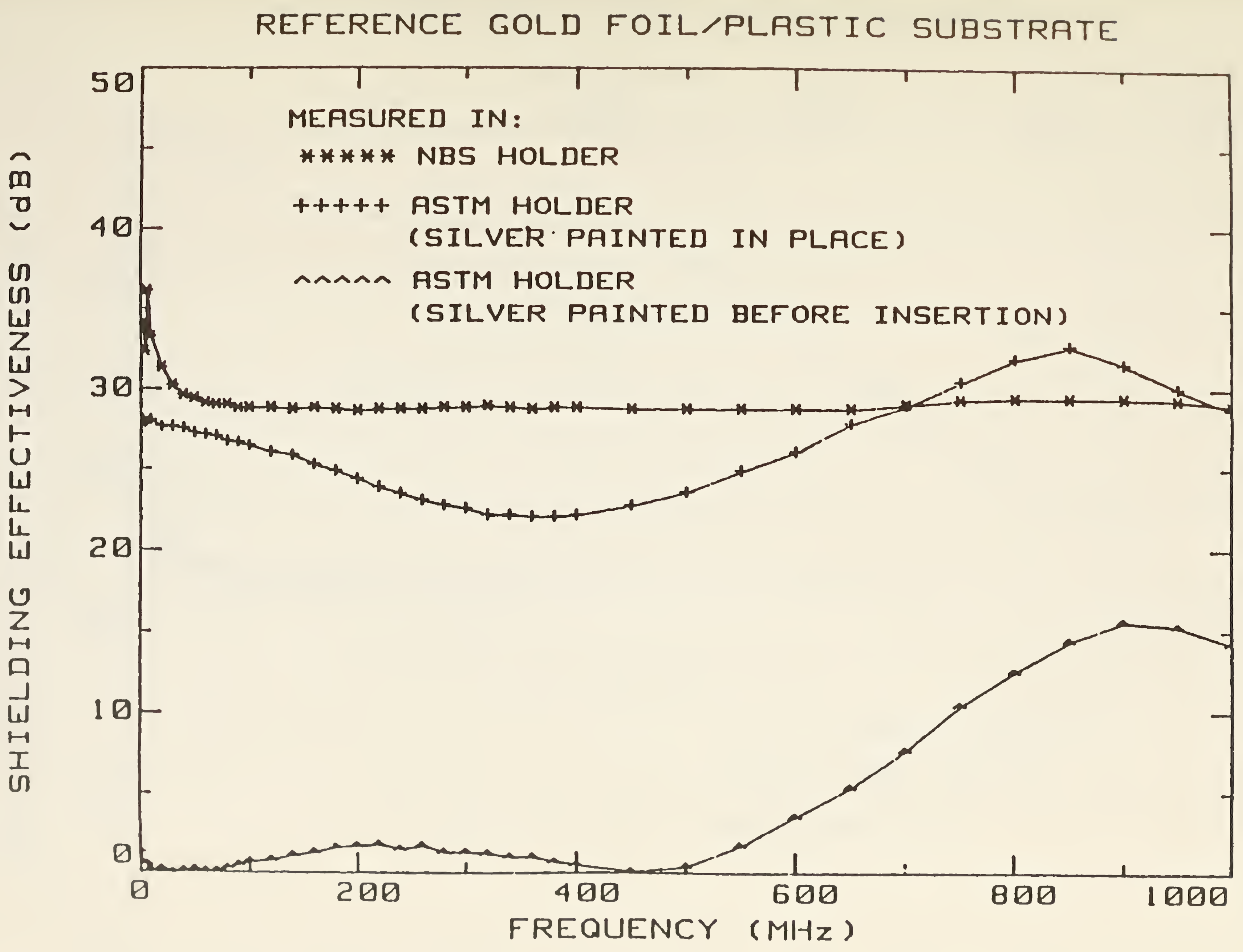


Figure 8. Measured data of gold-film (conducting) sample using flanged and ASTM holder.

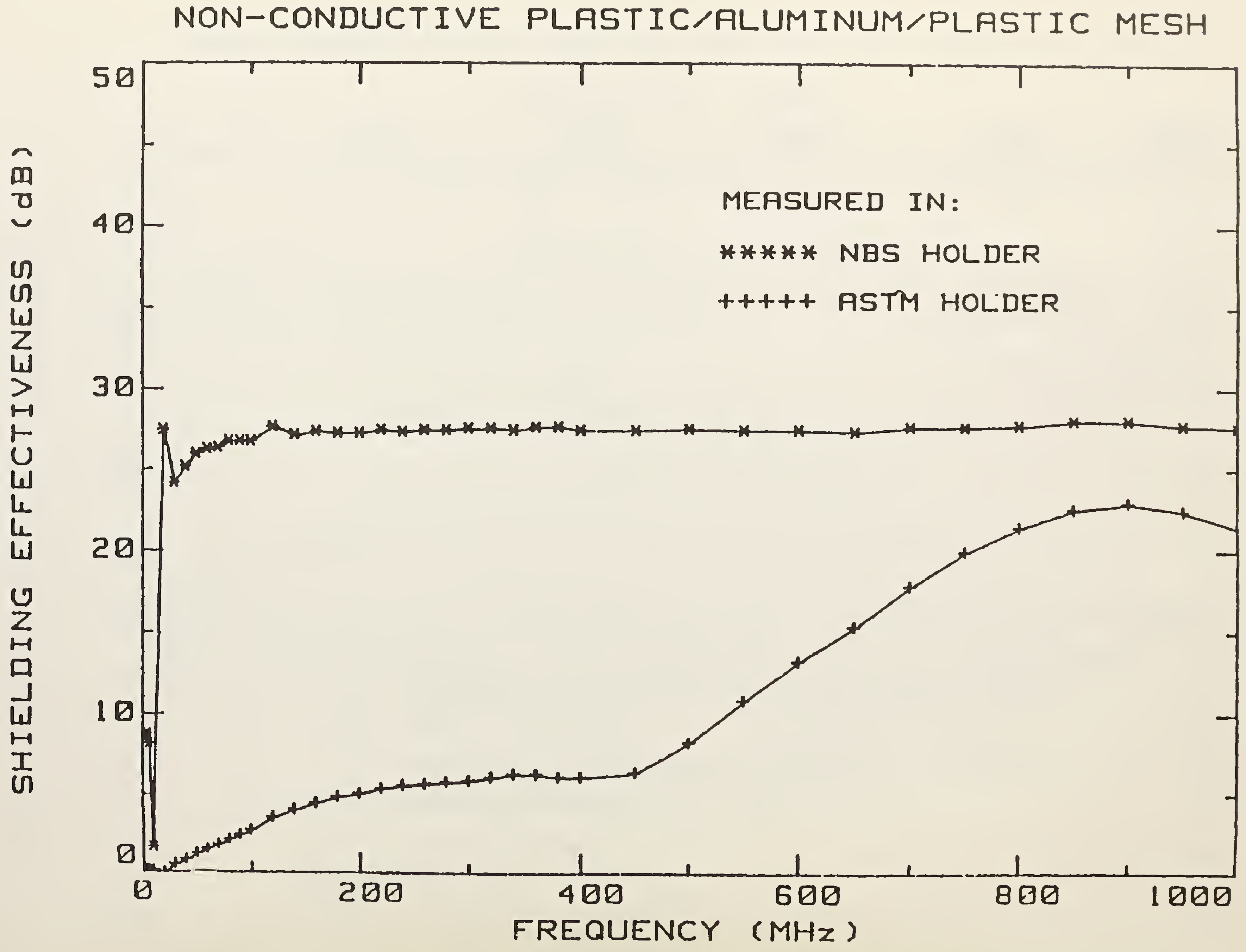
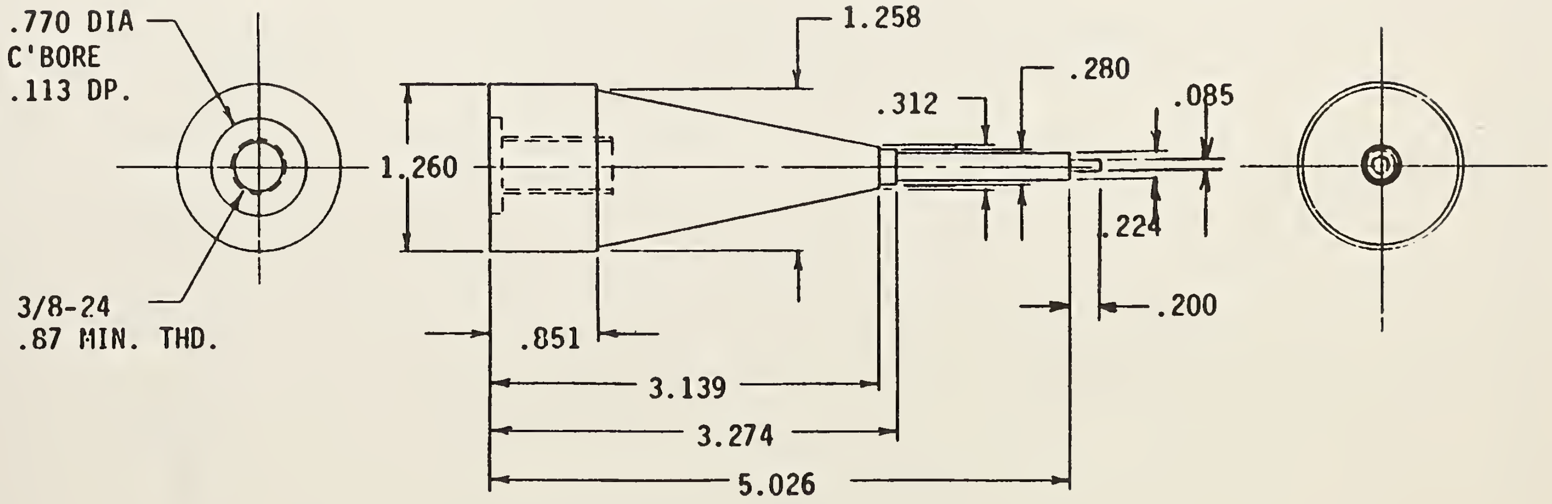


Figure 9. Measured data of laminated (insulating) sample using flanged and ASTM holder.

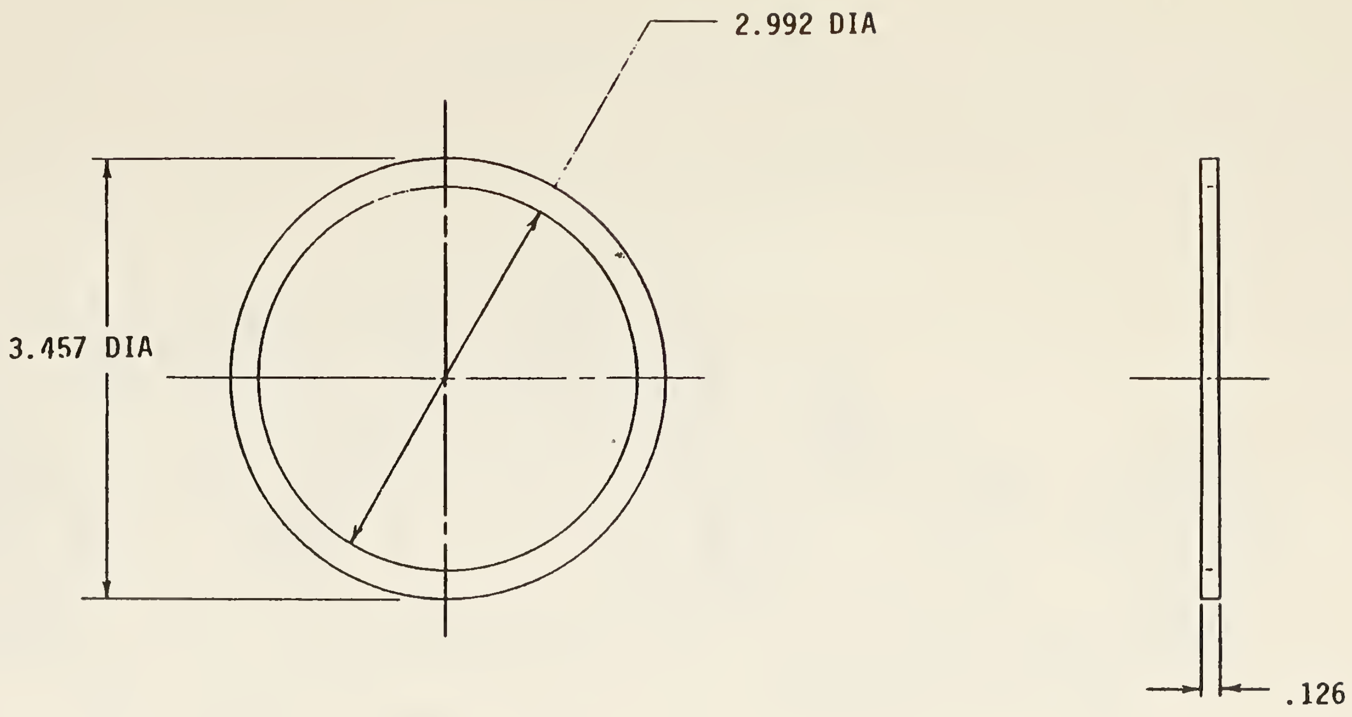
Appendix

Engineering Drawings of Flanged Coaxial Holder



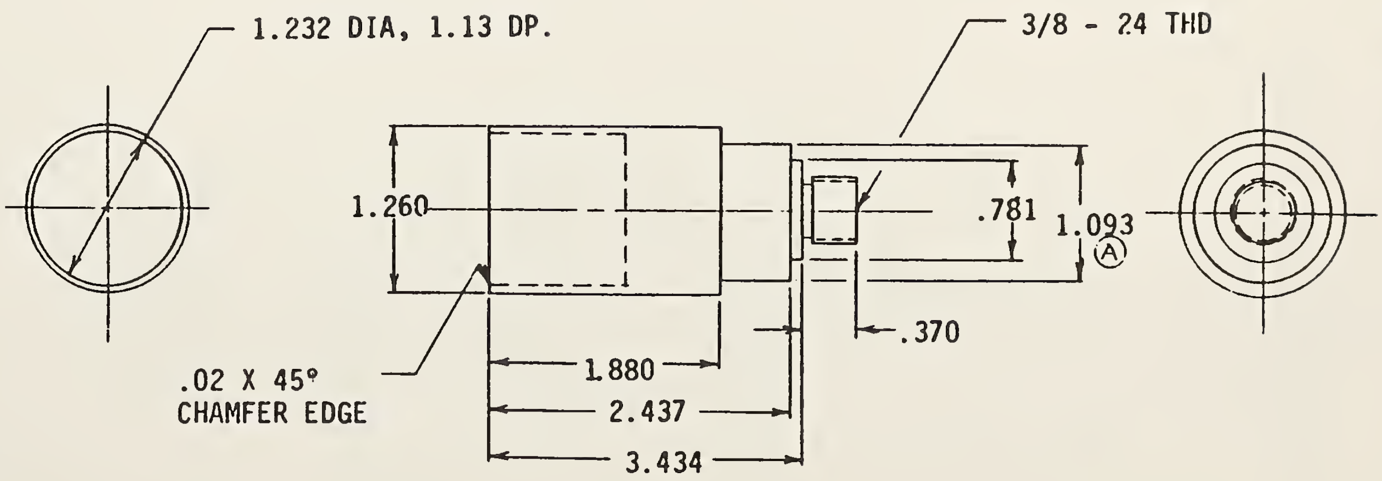
.XXX ±.005
MATERIAL: BRASS

PART A



.XXX ±.005
MATERIAL: BRASS

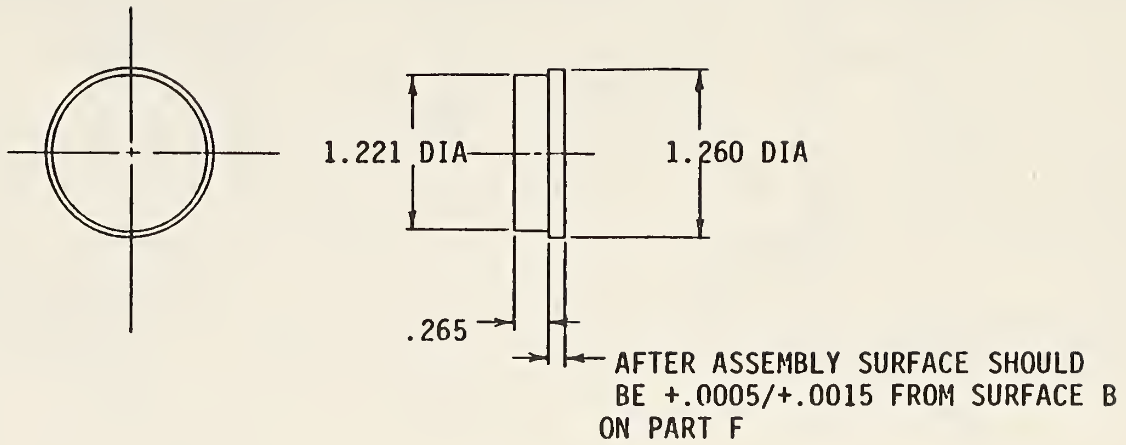
PART B



(A) PRESS FIT WITH PART E

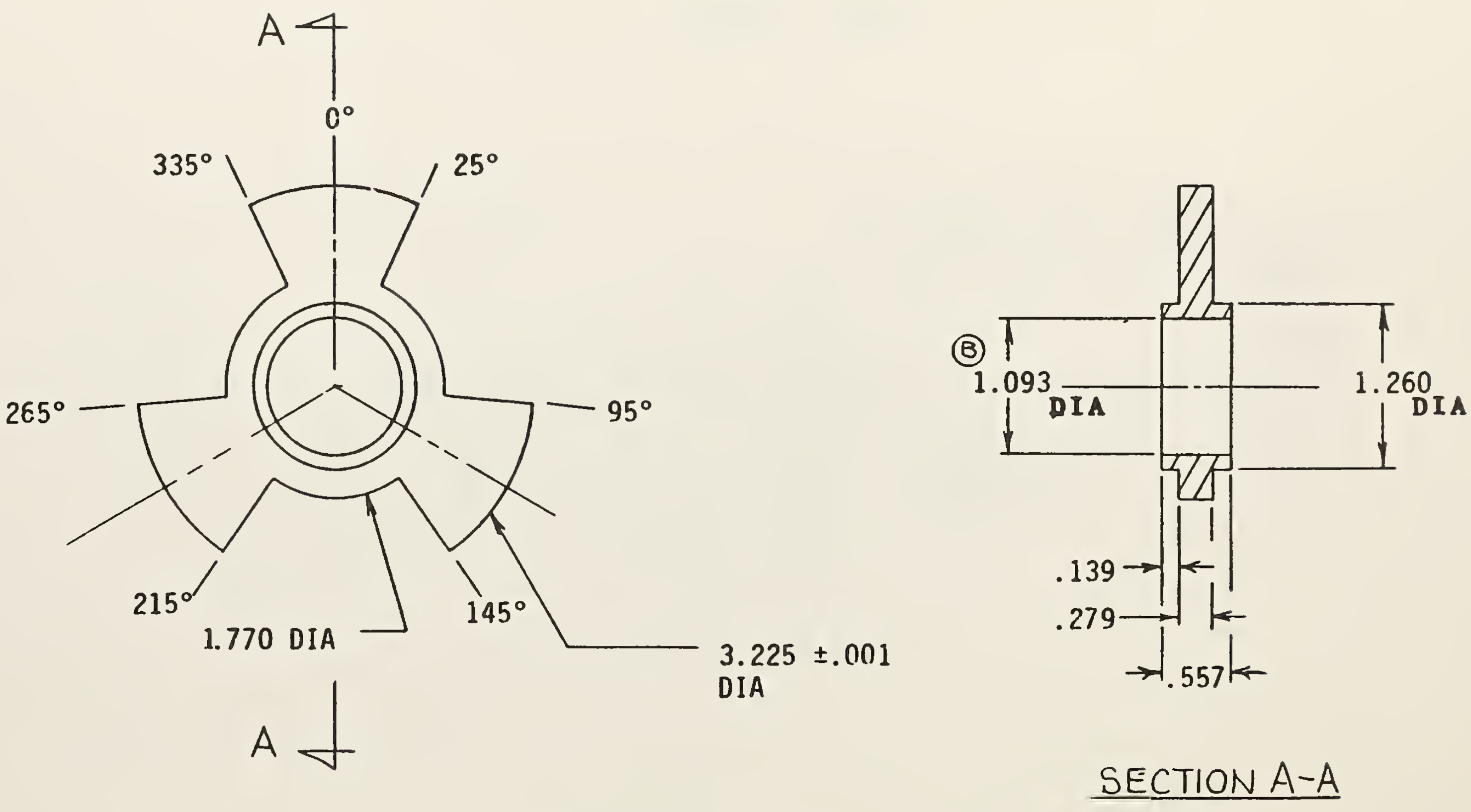
.XXX ± .005
MATERIAL: BRASS

PART C



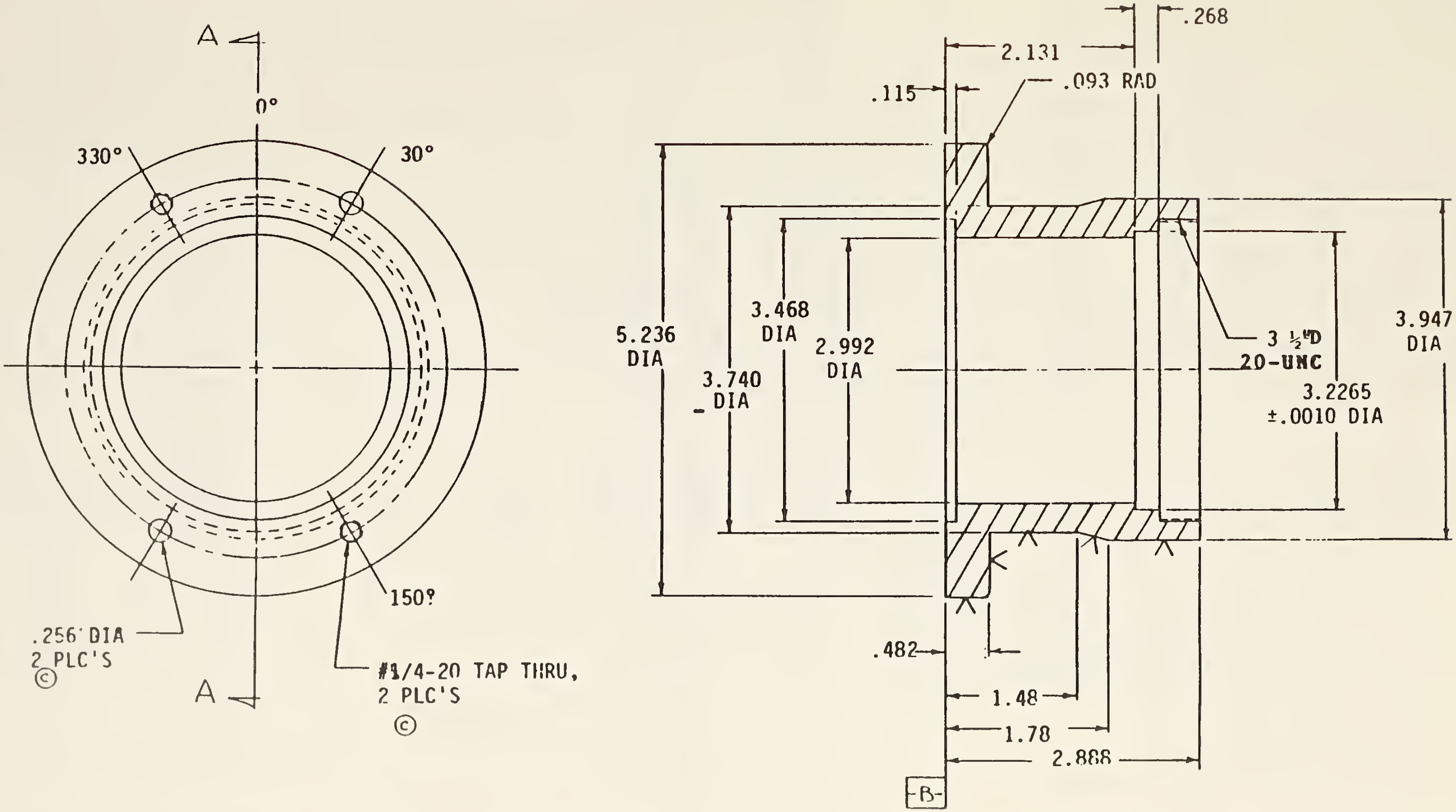
.XXX ± .005
MATERIAL: BRASS

PART D



(B) PRESS FIT WITH PART C

PART E
.XXX ± .005
MATERIAL: NYLON



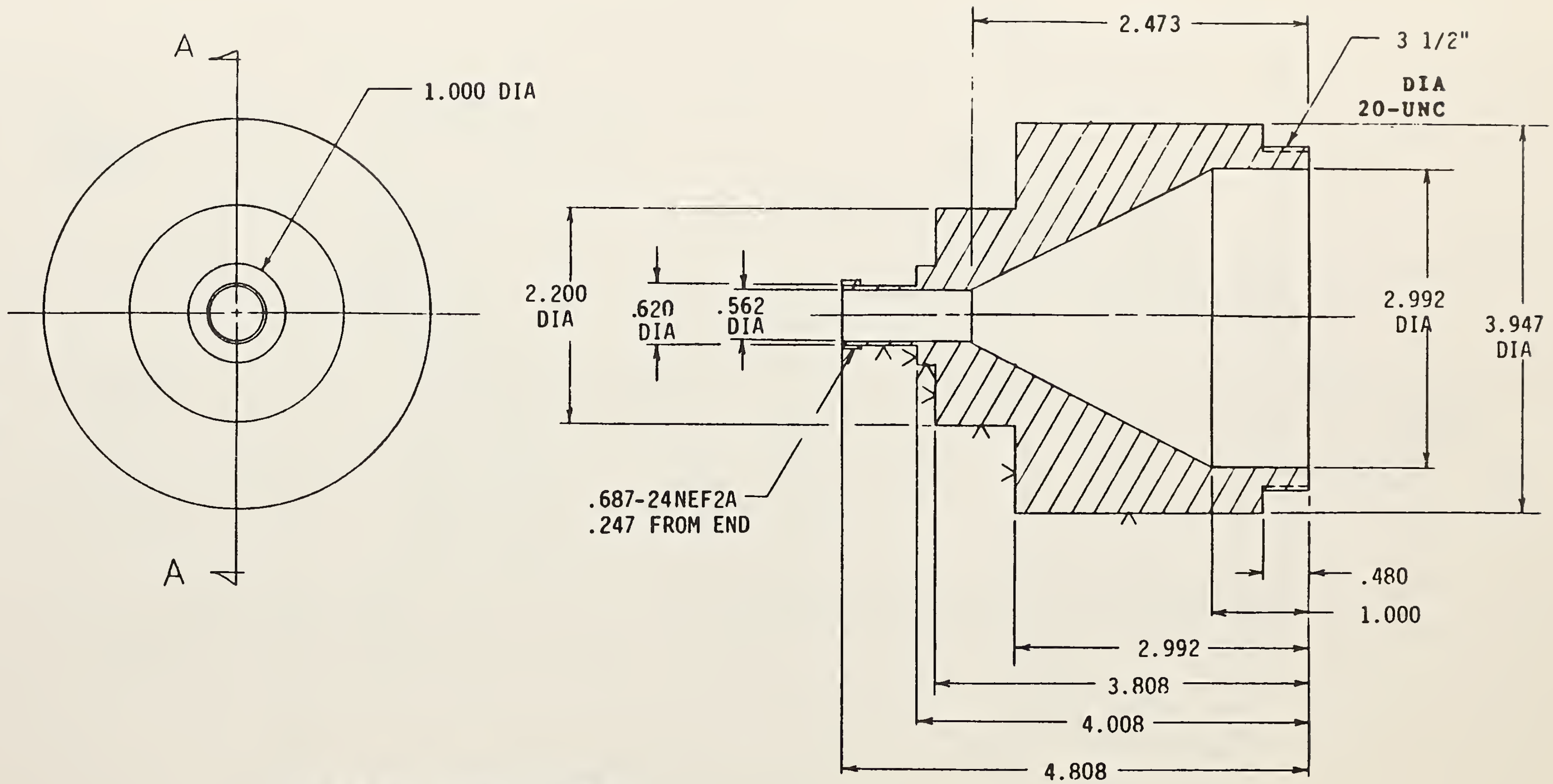
© REVERSE TAPPED HOLE AND THRU HOLE ON MATING PART

SECTION A-A

FINISH ON DESIGNATED
SURFACES TO BE NICKEL
PLATED.

.XXX ±.005
.XX ±.01
MATERIAL: BRASS

PART F



FINISH ON DESIGNATED SURFACES
TO BE NICKEL PLATED

.XXX ±.005
MATERIAL BRASS

SECTION A-A

PART G

NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBSIR 85-3035	2. Performing Organ. Report No.	3. Publication Date January 1986

4. TITLE AND SUBTITLE

Shielding Effectiveness Measurements of Plastics

5. AUTHOR(S)

John W. Adams and Eric Vanzura

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

10. SUPPLEMENTARY NOTES

☐ 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)

Measurement of shielding effectiveness (SE) of plastic materials may give serious problems due to the insulating nature of many plastics. A method of making these measurements using a flanged coaxial holder overcomes these limitations.

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

ASTM SE measurements; flanged coaxial holder; SE measurements of plastics; shielding effectiveness measurements

13. AVAILABILITY

- [X] Unlimited
- [ ] For Official Distribution. Do Not Release to NTIS
- [ ] Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.
- [X] Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES

36

15. Price