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US Army Corps
of Engineers
Construction Engineering
Research Laboratory

USACERL Technical Report FM-92/06
September 1992
Electromagnetic Pulse (EMP) Validation and
Design Recommendations for C3I Facility

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Effectiveness of Low-Cost Electromagnetic Shielding Using Nail-Together Galvanized Steel: Test Results

by
Peter F. Williams
Eric L. Kennedy
Ray G. McCormack

The sensitivity of modern electronic equipment has increased the need for costly electromagnetic shielding. To reduce this cost, the U.S. Army Construction Engineering Research Laboratories (USACERL) has developed a new concept for shielding design that uses 28-gauge galvanized steel and standard galvanized nails.

In this study, an electromagnetically shielded structure using the concept was designed, built, and evaluated for shielding effectiveness. The galvanized material was mounted to the standard USACERL test aperture and nailed to the wooden module frame, and the shielding effectiveness of the new construction design was measured using radio frequency antennas and receivers.

Evaluations showed that the nail-together structure proved adequate for many shielding applications. However, while the galvanized steel met most shielding application requirements, this process added multiple seams to the structure, which decreased shielding in many instances by as much as 40 dB.

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U.S. G.P.O. 1992-746-414

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE
September 1992

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
Effectiveness of Low-Cost Electromagnetic Shielding Using Nail-Together Galvanized Steel: Test Results

5. FUNDING NUMBERS
PE 4A162734
PR AT41
WU MA-C62

6. AUTHOR(S)
Peter F. Williams, Eric L. Kennedy, and Ray G. McCormack

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Construction Engineering Research Laboratories (USACERL)
P. O. Box 9005
Champaign, IL 61826-9005

8. PERFORMING ORGANIZATION REPORT NUMBER
TR FM-92/06

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
HQUSACE
ATTN: CEMP-ET
20 Massachusetts Avenue, NW
Washington DC, 20001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

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In this study, an electromagnetically shielded structure using the concept was designed, built, and evaluated for shielding effectiveness. The galvanized material was mounted to the standard USACERL test aperture and nailed to the wooden module frame, and the shielding effectiveness of the new construction design was measured using radio frequency antennas and receivers.

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14. SUBJECT TERMS
Electromagnetic Shielding
Electromagnetic pulse
C3I Facilities

15. NUMBER OF PAGES
56

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT
SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std Z39-18
298-102

FOREWORD

This study was conducted for Headquarters, U.S. Army Corps of Engineers (HQUSACE), under Project 4A162734AT41, "Military Facilities Engineering Technology"; Work Unit MA-C62, "Electromagnetic Pulse (EMP) Validation and Design Recommendations for C^3I Facility." The HQUSACE technical monitor was Mr. George Evans, CEMP-ET.

This research was performed by the Engineering and Materials Division (FM), of the Infrastructure Laboratory (FL), of the U.S. Army Construction Engineering Research Laboratories (USACERL). The USACERL principal investigator was Mr. Peter Williams. Mr. Ray G. McCormack was the Electromagnetic Technologies (FMT) Team Leader. Dr. Michael J. O'Connor is Chief, CECER-IF. Dr. Paul Howdyshell is Chief, CECER-FM. The USACERL technical editor was Mr. William J. Wolfe, Information Management Office.

COL Daniel Waldo, Jr., is Commander and Director of USACERL, and Dr. L.R. Shaffer is Technical Director.

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EFFECTIVENESS OF LOW-COST ELECTROMAGNETIC SHIELDING USING NAIL-TOGETHER GALVANIZED STEEL: TEST RESULTS

1 INTRODUCTION

Background

The sensitivity of modern electronic equipment has created an increased need for electromagnetically shielded structures because such equipment plays many critical roles: controlling energy usage, assisting command and control, maintaining vital communication, etc. As the quantity and importance of electronic information grows, there is a greater demand for electromagnetic security. Electromagnetic shielding can provide the needed safety and security, but at a high economic cost. Electromagnetic shielding can become a large percentage of the cost of construction or retrofit of a facility, since most designers tend to use proven, conservative, expensive shielding designs.

In most security communication facilities, however, the specific level of shielding required by TEMPEST* is based on many factors, such as the distance to the nearest unsecured area, the level of emanations from the secured equipment, and the intelligibility of the information being transferred.[1] In such facilities, the low level of radiated emanations from the protected equipment and the large distances from the nearest unsecured area can reduce the required level of shielding. When these factors are taken into account, the required shielding can in some cases be relatively small, sometimes as low as 30 dB.[2]

Although electromagnetic shielding has evolved through many years of research, development, and innovative design, there continues to be a need for low-cost, generally acceptable designs. New designs should use standard, inexpensive construction materials, should be simple in design, and should be quick and easy to build. This study was part of an effort to test new materials in the form of a permanent enclosure, and to test a new concept of seam-joining

Objectives

The objectives of this study were to design, build, and evaluate the electromagnetic shielding effectiveness of a simple, low-cost, galvanized steel shielding design, using no special materials, composites, or assemblies.

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* TEMPEST is a code name generally applied to secure communication networks where compromising emanations must be maintained at a suitably low level.

[1] Peter F. Williams, Kevin K. Heyen, and Ray G. McCormack, *Low-Cost Electromagnetic Shielding Using Drywall Composite*, Technical Report (TR) M-88/02/ADA190374 (U.S. Army Construction Engineering Research Laboratory [USACERL], October 1987).

[2] Ray G. McCormack and Peter F. Williams, *Development, Design, Construction, and Testing of a Copper-Arc-Sprayed Shielded Enclosure*, TR M-86/11/ADB106252 (USACERL, July 1986), p 28.

Approach

A design using galvanized steel as shielding material, nailed to a wooden frame was chosen because this design combines the economy of relatively inexpensive, off-the-shelf materials, with the simplicity of a nail-together construction technique. All materials were chosen for their effectiveness, low cost, and ready availability. A shielded module was constructed of 28-gauge galvanized steel panels nailed onto a wooden frame. Test procedures specified in Military Standard (MIL-STD) 285[3] and the Institute and Electronic Engineers (IEEE) Proposed Standard Procedures 299[4] were used to measure the shielding effectiveness (SE) of the module and panel. (The standard procedures were modified slightly to allow for more modern equipment and for testing at more frequencies.) A panel of the galvanized material was mounted on a 4.5-ft x 2.5-ft aperture of a shielded room to measure the shielding effectiveness of the modular shielding material. This aperture was part of a modular plate steel room that shields against radio-frequency interference (RFI) up to 120 dB. The tests were analyzed manually and were graphed using a personal computer and graphics plotter.

Scope

This study evaluated the performance of a test panel and a shielded module. Transient effects were not measured, nor were the materials evaluated for their ability to withstand the rigors of weather or the passage of time.

Mode of Technology Transfer

It is anticipated that the results of this study will be included in a future revision of the Army Technical Manual (TM) 5-855-5 *Nuclear Electromagnetic Pulse Protection* (Department of Army [DA], 15 February 1974). It is recommended that the U.S. Army Corps of Engineers (USACE) develop a design guide on the construction of permanent electromagnetically shielded structures, which will include the information gained from this study.

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[3] Military Standard 285, *Attenuation Measurements for Enclosure, Electromagnetic Shielding for Electronic Test Purposes, Method of* (Department of the Army [DA], 25 June 1956).

[4] Institute of Electrical and Electronic Engineers (IEEE) Proposed Standard Procedures 299, *Trial-Use Recommended Practice for Measurement of Shielding Effectiveness of High Performance Shielding Enclosures* (Institute of Electrical and Electronic Engineers, Inc., 1969).

2 MODULE CONSTRUCTION

Attachment of Galvanized Material

ASTM A366 cold-rolled steel, galvanized using ASTM 525-type process galvanized sheets with a thickness of 18.7 mils (28 gauge), was selected as the material for the module. The galvanized sheets were cut into 2- and 4-ft widths for the side walls, while the rear and front walls were cut into 3- and 4-ft widths to match the stud spacing of the wooden frame. Figure 1* shows a diagram of test point locations, including the galvanized panel layout. The diagram in Figure 1 gives an exploded view looking from the outside of the shelter. Many of the panels were corroded and were mechanically cleaned using a wire and buffing wheels attached to construction-grade electrical drills to ensure better electrical connections between panels. Any corrosion along the edges of the material may cause some shielding degradation at most frequencies.

On the left and right sides of the structure, two 4-ft panels and one 2-ft panel were nailed to the wooden frame with a 2-in. overlap in the wall seams. The 2-ft section was attached to the frame on the sides in the center. The top and the bottom sections were constructed the same way as the sides, with 2- and 4-ft widths of the galvanized material. A 1-in. wide, 14-gauge galvanized steel flat strip was fabricated to join the two pieces of metal at all seams. Figure 2 shows the flat strip on a wall seam and Figure 3 shows the edge seam design. Figure 4 gives a plane view of the corner seam design. Figure 5 shows a cutout of the corner seam design. Figure 6 depicts the corner seam design.

Each of the sheets and flat strips were predrilled with a 2-in. hole spacing. The corners and edges were joined similarly, with 4-in. strips of 28-gauge galvanized sheet bent in half at 90-degree angles to be used as galvanized corners, electrically connecting the seams of the two faces. Each of the sheets were nailed together with 1-1/2 in. 4d galvanized nails. Figures 7 and 8 show the completed module with and without the copper-clad hatch door, respectively. Figure 9 shows a corner detail of the double mesh gasket surrounding the module hatch. Figure 10 shows a cutout view of the wall seam design.

Construction of Wooden Frame

A wooden frame for the module, and a cart were constructed of 2 x 4's and 3/4-in. plywood. The cart aided in moving the module. The outer dimensions of the wooden frame were 7 ft wide by 10 ft deep by 7 ft high. The dimensions of the cart were 7 ft wide by 10 ft deep.

The personnel and equipment entry hatch for the modules was of a basic design. An EMI/RFI gasket was placed along the edge of a 28 x 28-in. copper-clad board. The copper was 21.6 mils thick. The copper-clad board was bolted to the side of the module over a 24 x 24-in. hole. For ventilation, five 5.75 in. long, 1/2-in. inside diameter, type M copper pipes were inserted through the hatch and soldered peripherally to the copper. Figures 11 and 12 give close-up views of the copper-clad hatch and the hatch copper tubing, respectively. The 1/2-in. inside diameter copper tubing has a cutoff frequency of 13.8 GHz.

Figure 13 shows a plane view diagram of the seam design. It can be seen that the overlap of the 28-gauge galvanized sheets are sandwiched together with a 14-gauge flat strip and galvanized nail.

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* All figures are included at the end of their corresponding chapters.

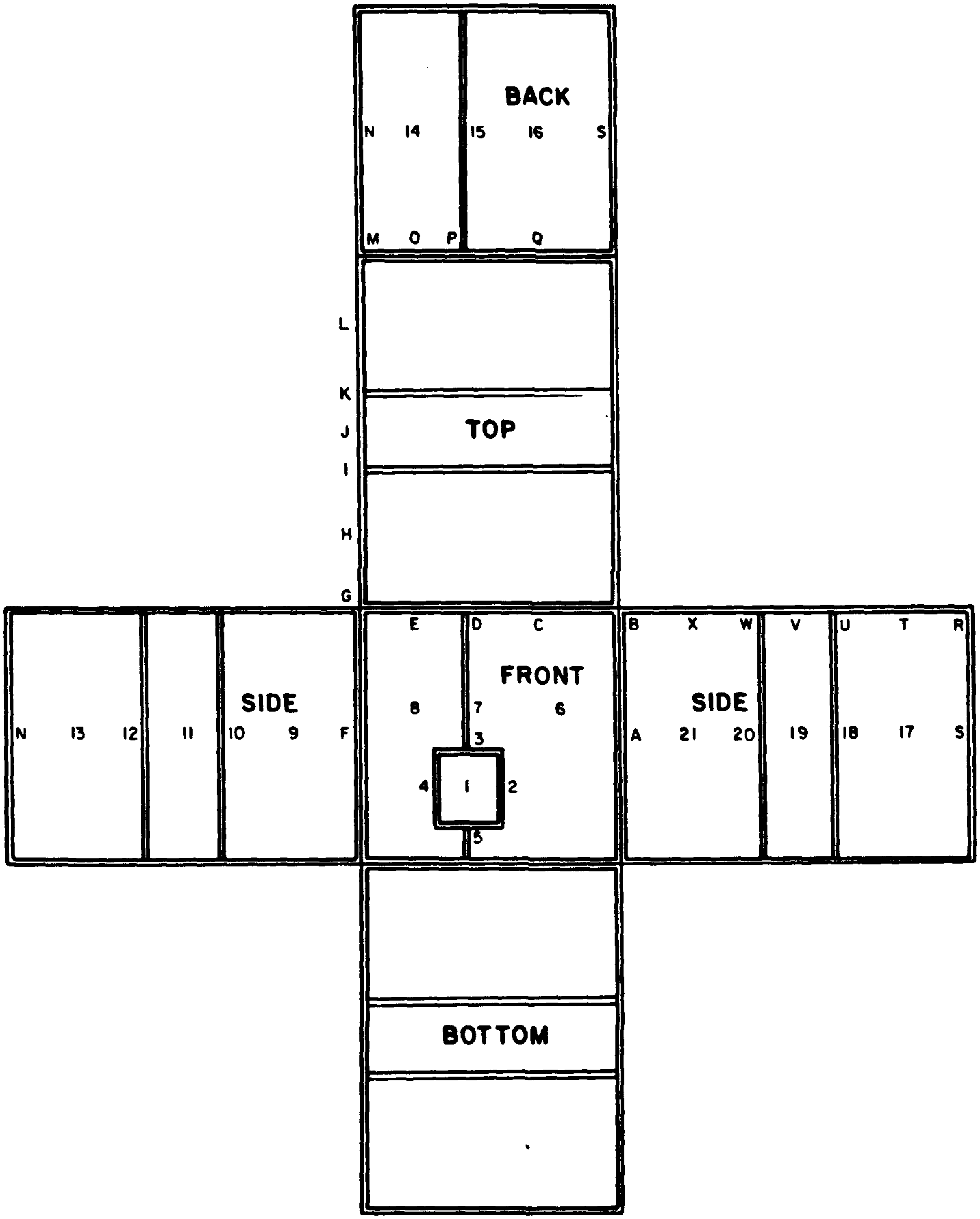

Figure 1. Diagram of Test Point Locations.

Figure 2. Flat Strip on Wall Seam.

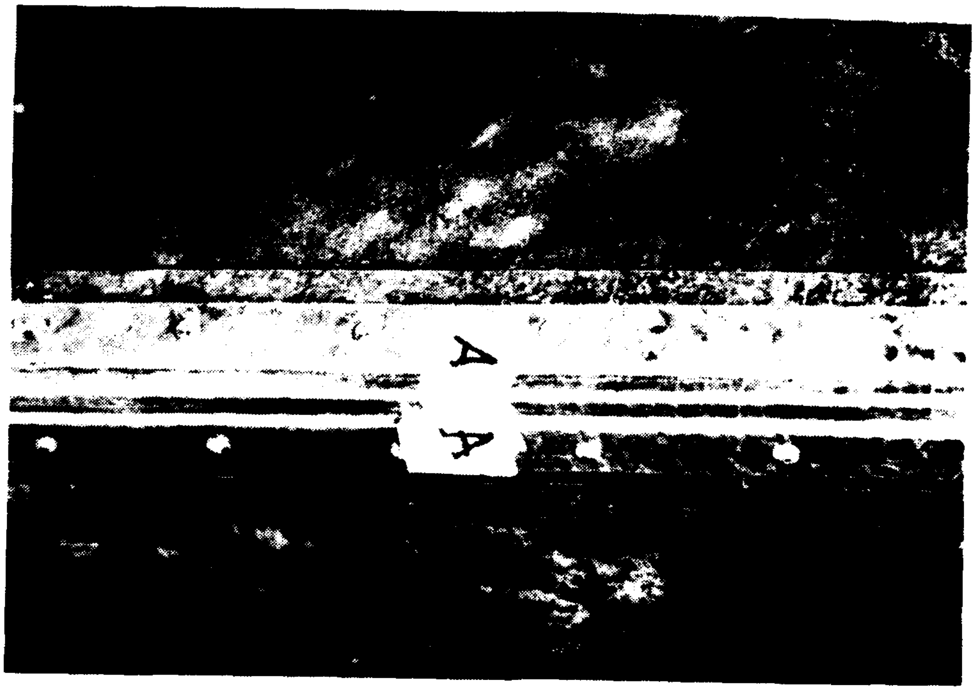

Figure 3. Edge Seam Design.

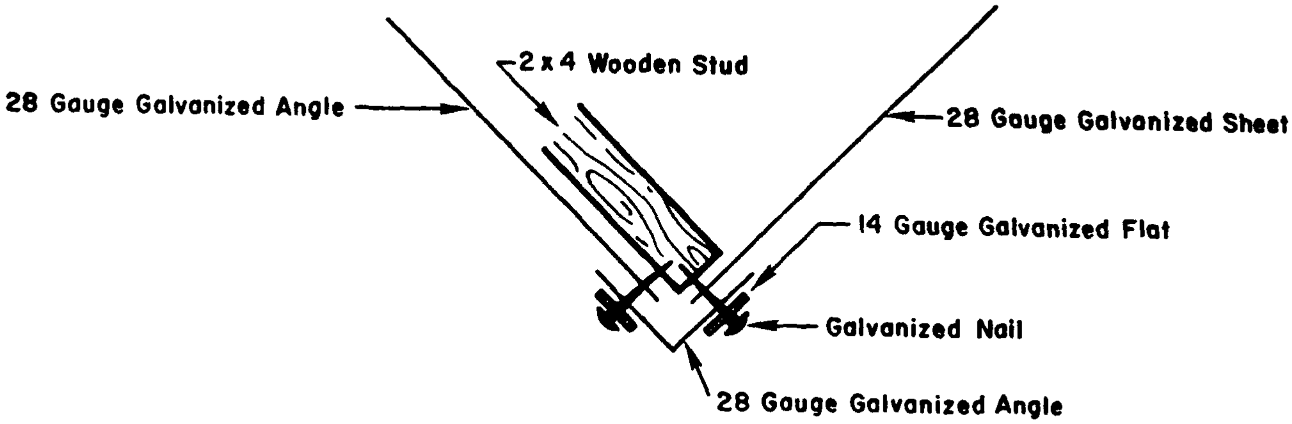

Figure 4. Plane View of Corner Seam Design.

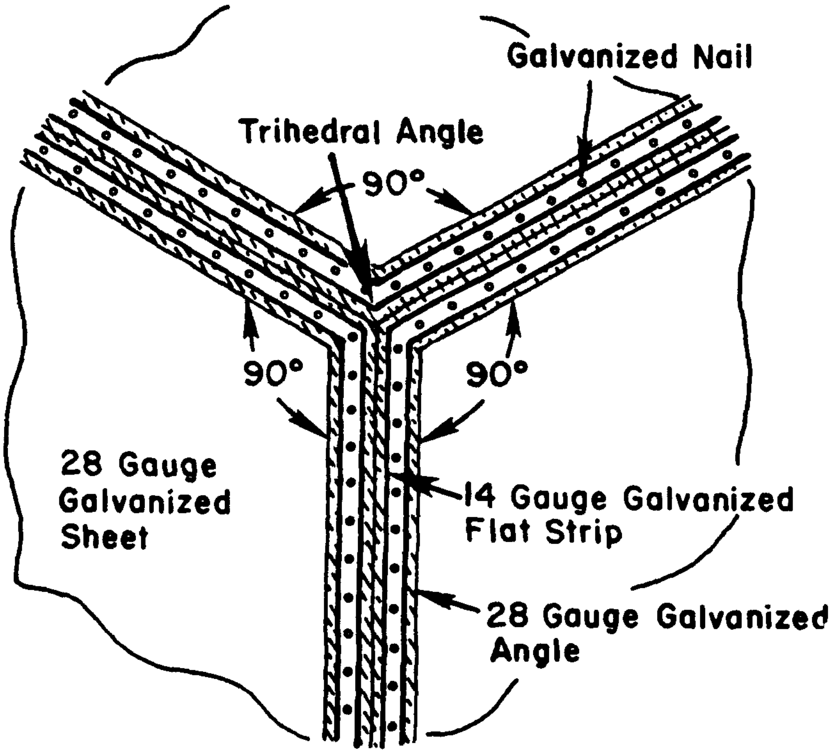

Figure 5. Cutout of Corner Seam.

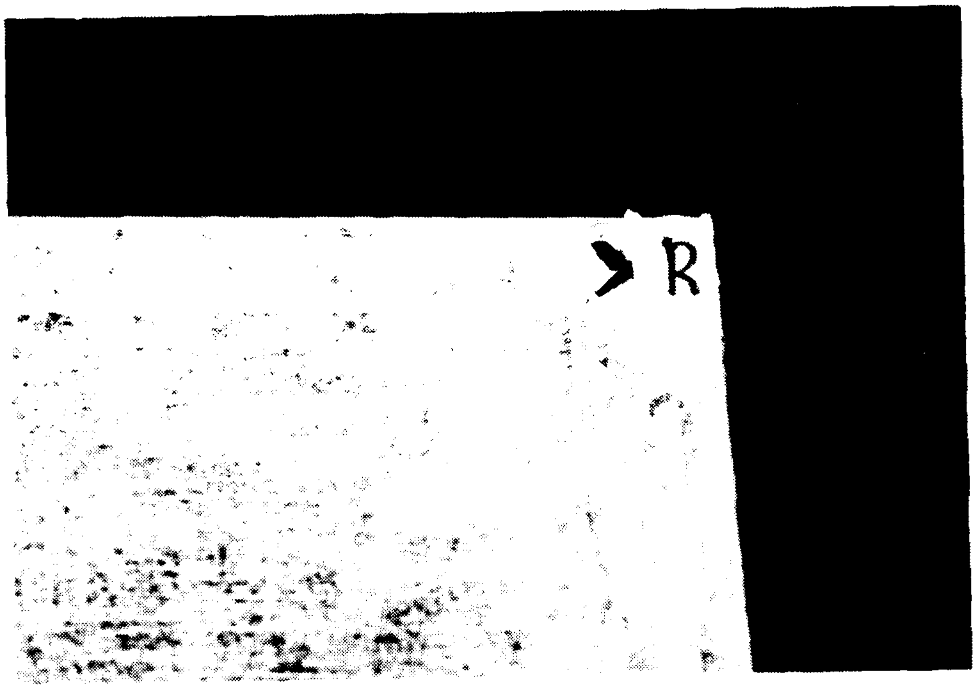

Figure 6. Corner Seam Design.

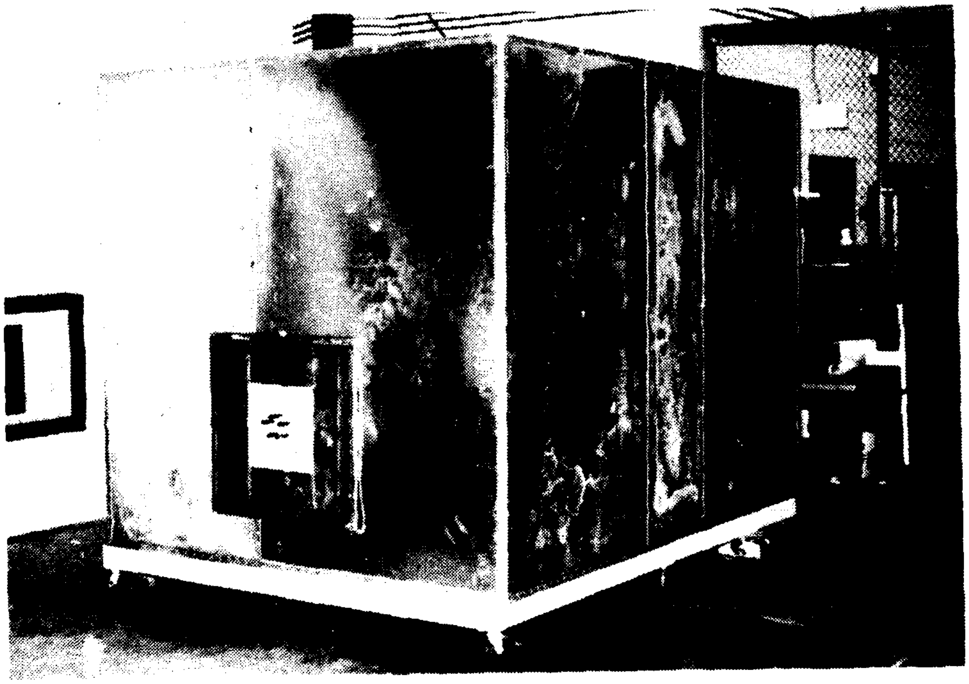

Figure 7. Completed Module With Hatch Mounted.

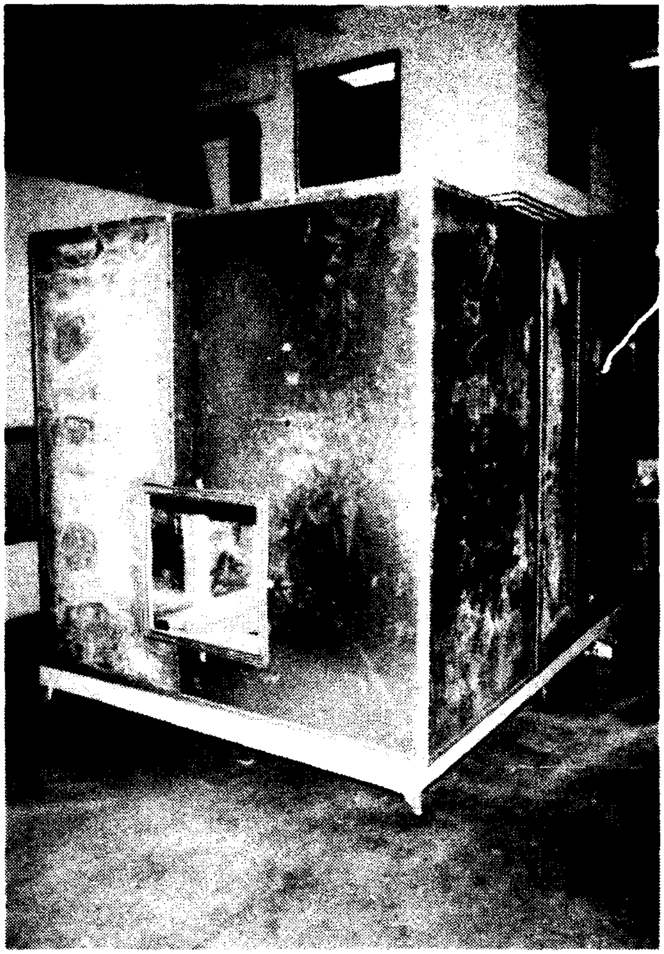

Figure 8. Completed Module Without Hatch Mounted.

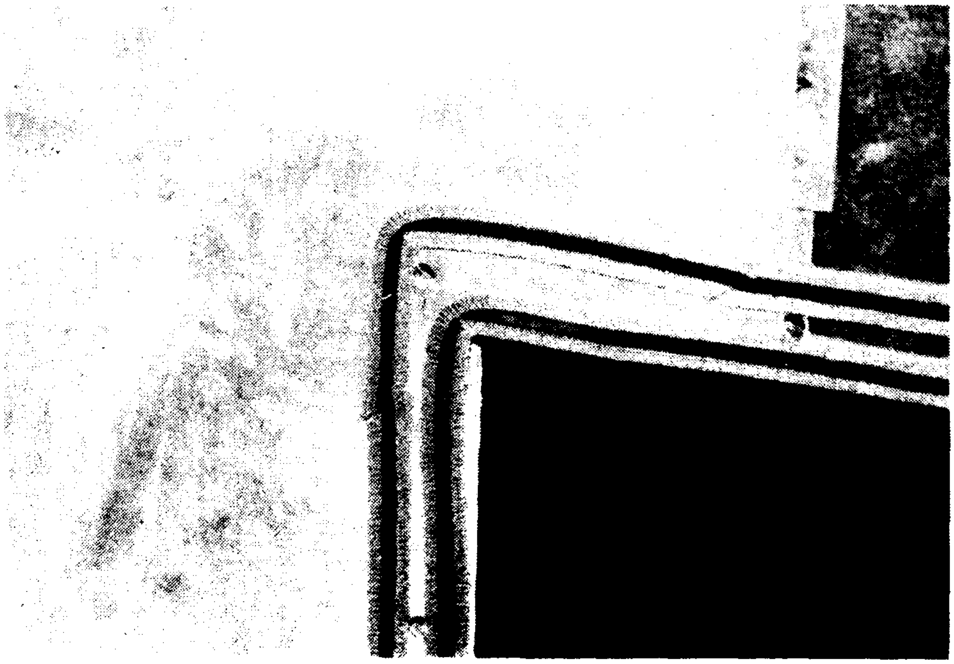

Figure 9. Double Mesh Gasket on Module Hatch.

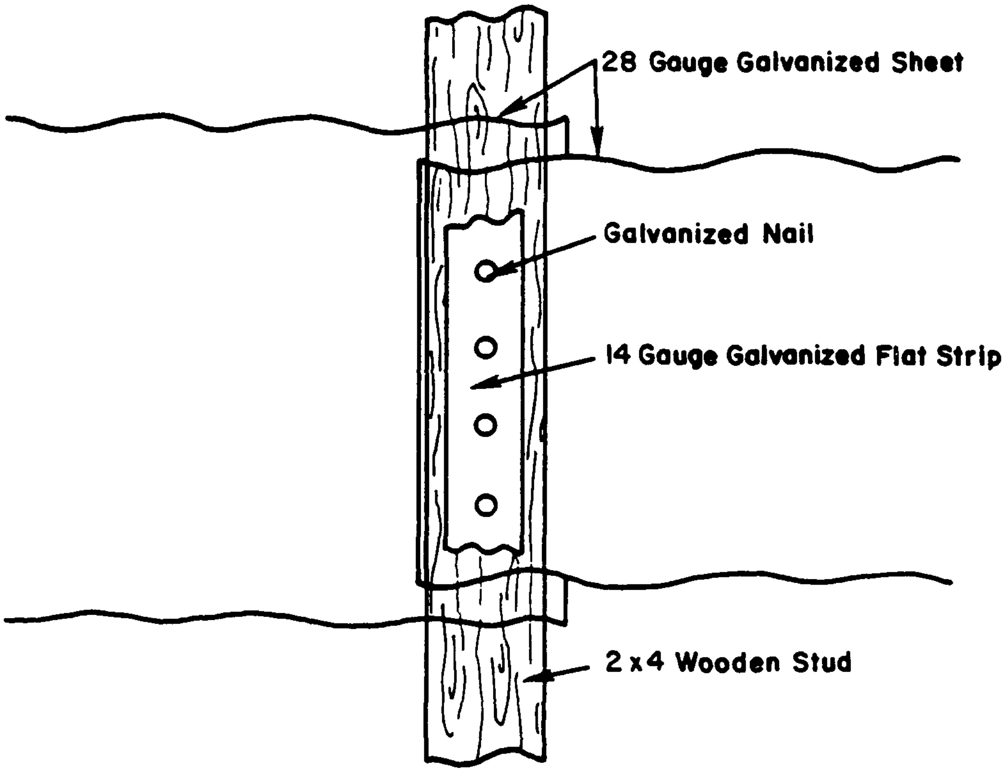

Figure 10. Cutout View of Wall Seam Design.

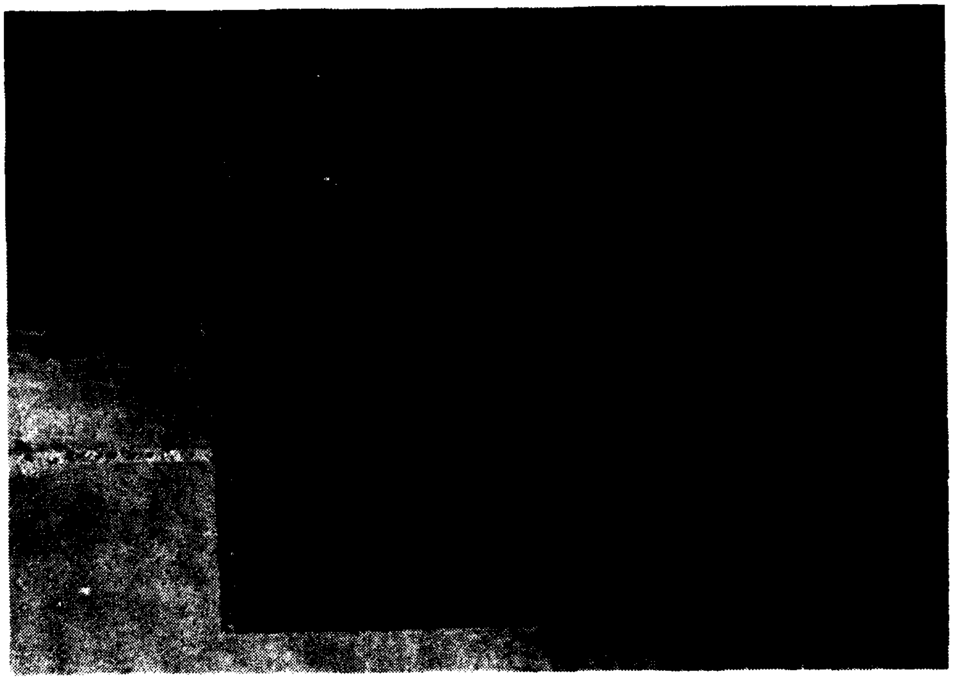

Figure 11. Close View of Hatch.

Figure 12. Hatch Copper Tubing.

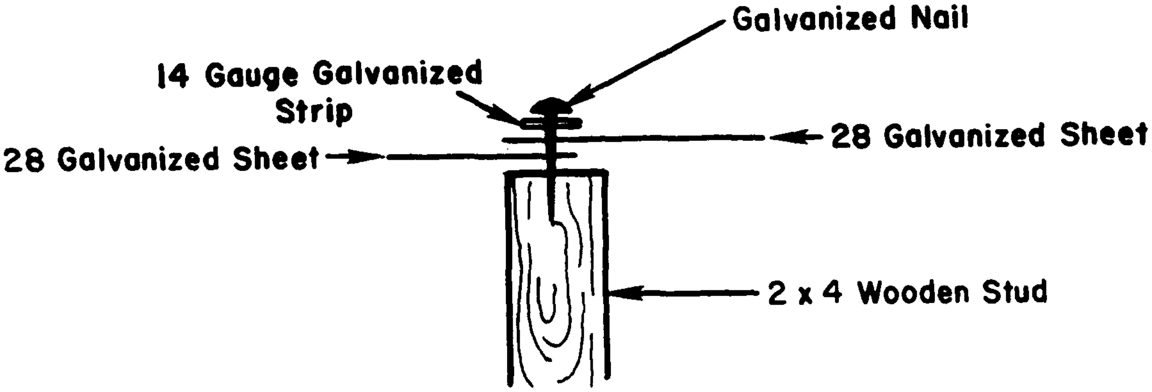

Figure 13. View of Module Seam Design.

Cost Considerations

Table 1 shows a breakdown of the module's total cost including labor and materials ($2775.81). The total cost of this module is small compared to typical shielded rooms costing as much as $18,000 for a shelter of the same size. The cost of the module will be reduced even further if the module is put into mass production. For example, all predrilling of strips could be accomplished in a single stroke and mass produced by appropriate tooling. Corner joining hardware can be standardized and mass produced. The $1015 for cutting, bending, and drilling the metal would also be significantly reduced.

The labor required for construction could be significantly reduced after the assembly technicians are appropriately trained and experienced. The test structure was a one-of-a-kind prototype; the required hardware would cost much less if it were purchased in production quantities. The introduction of a door and electrical power, however, would increase the cost of the shelter considerably.

The average shielded door will cost anywhere from $4000 to $7000. A moderately good shielded door (with a shielding effectiveness in the range of 60 to 100 dB) would probably cost about $5000.[5] Typical enclosures with welded seams and a good quality door shielded in excess of 100 dB are very expensive. Bolt-together and modular enclosures are less expensive, but the advertised shielding of such structures is normally less than 90 dB; modular enclosures generally provide much less shielding than the welded-seam shelters. The cost of a typical bolt-together modular type enclosure with a good door is about $11,000.

With the addition of a shielded door, an air vent, and connector panel, this type of module would cost about $7500. Putting this module into mass construction would reduce the price considerably. Even before mass production, this module costs about 30 percent less than comparable welded modules. Note, however, that many modular and bolt-together shielded enclosures do not provide the shielding that their manufacturers claim. Reported shielding effectiveness often falls as low as zero dB at some frequencies.[6]

Table 1

Breakdown of Module Cost

Wooden Frame and Cart		Galvanized Skin	
Item	**Cost**	**Item**	**Cost**
Materials	$67.50	Materials	$286.81
Labor	$86.50	Cut and bend material	$175.00
		Clean and drill metal	$840.00
		Place metal on building	$1320.00
Total	$154.00	Total	$2775.81

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[5] Phonecons between Peter F. Williams of USACERL and: Robert Lindgreen of RF Enclosures, Addison, IL; and Peter Deal of Lectro-Magnetics, Inc., Los Angeles, CA, January 1992.

[6] Ray McCormack, *EMI/RFI Shielding Effectiveness Evaluation of Bolt-Together Shielded Rooms in Long-Term Aging*, TR M-296/ADA102754 (USACERL, June 1981).

3 SHIELDING EFFECTIVENESS MEASUREMENTS

Aperture Tests

The inherent shielding effectiveness of the galvanized sheet steel was found by performing measurements on a test sample in the standard USACERL test aperture, located in a 120 dB-shielded enclosure (an 11-gauge steel box with welded seams and a 3-1/2 x 7-ft shielded entry door). The outside aperture dimensions are 4-1/2 by 2-1/2 ft, while the inside dimensions are 4-ft, 1 in. x 2-ft., 1 in. Figure 14 shows the two layers of double-mesh gaskets that surround the aperture and electrically connect the test sample to the shielding aperture. Figures 15 and 16 show photographs of the inside and the outside of the USACERL test aperture, respectively.

Table 2 lists test frequencies for each field and antenna type used when the test material was mounted in the standard test aperture.

Table 2

Test Frequencies

Magnetic Field (12-in. Loops)	Electric Field (41-in. Mono-Pole)	Plane Wave (1-m Conical)	Plane Wave (X-Band Horn)
150 kHz	150 kHz	200 MHz	1000 MHz
200 kHz	200 kHz	300 MHz	2000 MHz
300 kHz	300 kHz	400 MHz	3000 MHz
700 kHz	700 kHz	450 MHz	4000 MHz
1 MHz	1 MHz	600 MHz	5000 MHz
3 MHz	3 MHz	700 MHz	6000 MHz
7 MHz	7 MHz	800 MHz	7000 MHz
10 MHz	10 MHz	1000 MHz	8000 MHz
15 MHz	15 MHz		9000 MHz
	20 MHz		10,000 MHz
	25 MHz		
	50 MHz		
	200 MHz		
	300 MHz		
	350 MHz		
	400 MHz		
	500 MHz		

The shielding effectiveness of the module's galvanized material was measured by using procedures similar to those outlined in IEEE Standard 299 and MIL-STD-285; the modifications to those standards (made to take advantage of current technology) were:[7]

- A logarithmic spiral (conical) antenna replaced the dipole antenna.
- The transmission line connector went through the shelter instead of through the test material.
- Tests were conducted at more frequencies than outlined in the standards.
- For the intermediate wave measurement test setup, IEEE 299 requires that the dipole antennas be 1.3 wavelengths from the shield. The distance used in the test was 36 in.
- The antenna-to-shield distances differed for the 400 MHz test. MIL-STD-285 requires, for the reference test, that the source antennas be 72 in. from the shield, with the receiving antenna 2 to 24 in. from the shield on the same side as the source. It requires the source antenna for the signal test to be at the same distance from the shield as for the reference test, with the receiving antenna 2 in. from the shield on the opposite side. For this reference test, both source and receiving antennas were separated by 72 in., plus shield thickness. For the signal test, each antenna was placed 1 yd from the shield.

Measurements were taken in the reference as well as in the signal measurement orientation. The same equipment was used for both reference and signal measurements.

Nail-Together Module

The nail-together module was tested near the 120 dB shielded enclosure in the USACERL Electromagnetics Laboratory. Due to space limitations, the room was physically rotated to test the various sides to assure minimal standing waves between the 120 dB room and the nail-together module. The nail-together module was tested according to IEEE-299.

Shielding effectiveness measurements were performed on the front, rear, and sides of the module only. No tests were performed on the top or bottom of the module, due to the difficulty and inaccessibility of these faces. It is assumed that the data for the top and bottom of the shelter will be similar to the data for the sides of the shelter.

Measurements were taken in the reference as well as in the signal measurement orientation for the low-frequency magnetic test, the plane-wave dipole test, and the X-band horn test. To take the reference measurements, the antennas were placed in the laboratory with specific antenna spacing with no obstruction (air only) between the antennas, as outlined in IEEE-299. To take the signal measurement, the material tested was placed between the two antennas and a signal strength in decibels was recorded. For the low-frequency loop test at 15 kHz, 150 kHz, and 15 MHz the antenna spacing was 24 in. plus material thickness. For the signal measurement system, each antenna was placed 12 in. from the shield, with the transmitting antenna on the outside of the shelter and the receiving antenna on the inside of the shelter. Figures 17, 18, and 19 show the open reference measurement, transmitting antenna, and signal measurement antennas for the low-frequency magnetic loop test, respectively.

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[7] Williams et al., p 12.

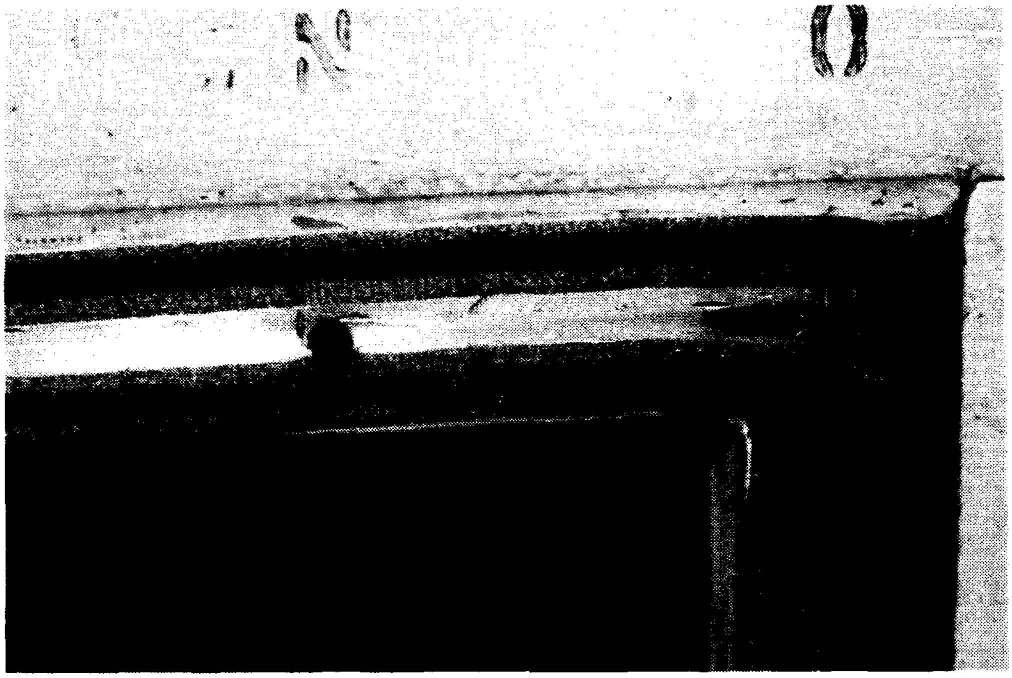

Figure 14. Double Mesh Gasket on Test Aperture.

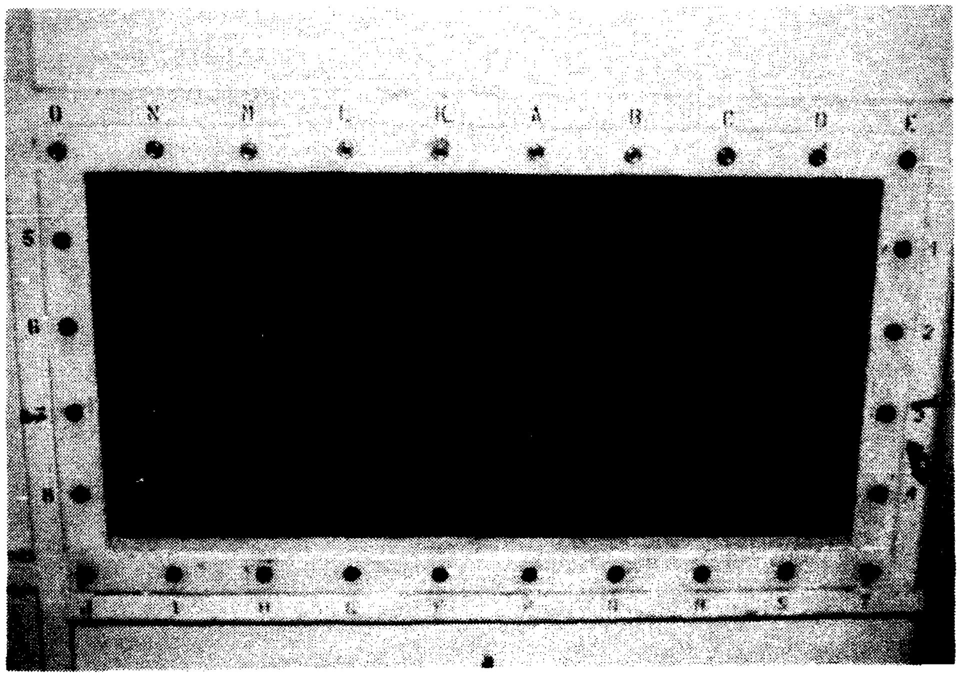

Figure 15. Inside of Test Aperture.

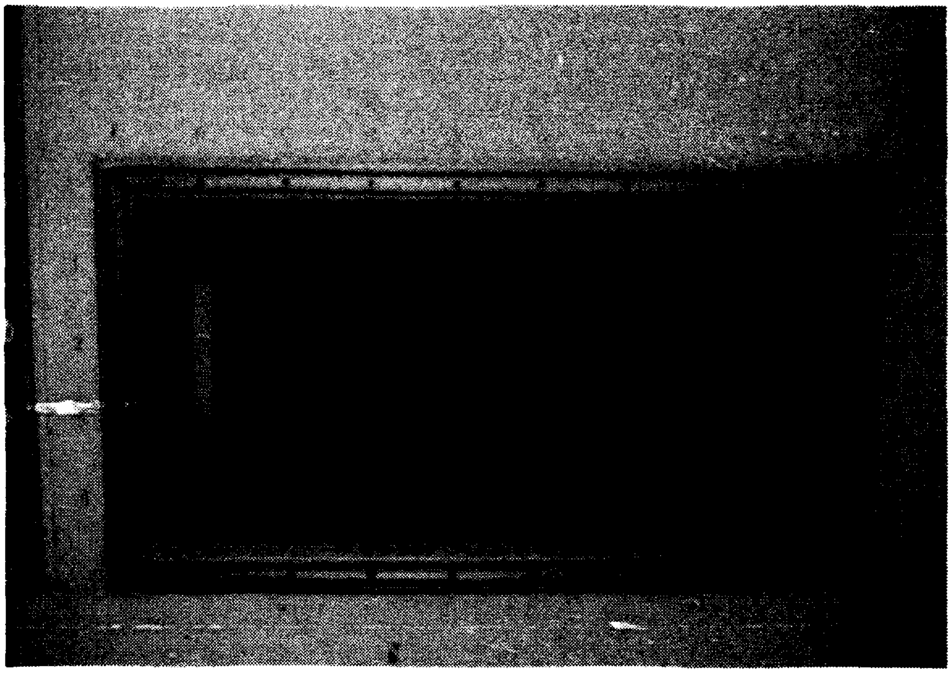

Figure 16. Outside of USACERL Test Aperture.

Figure 17. Open Reference Setup for the Magnetic Loop Test.

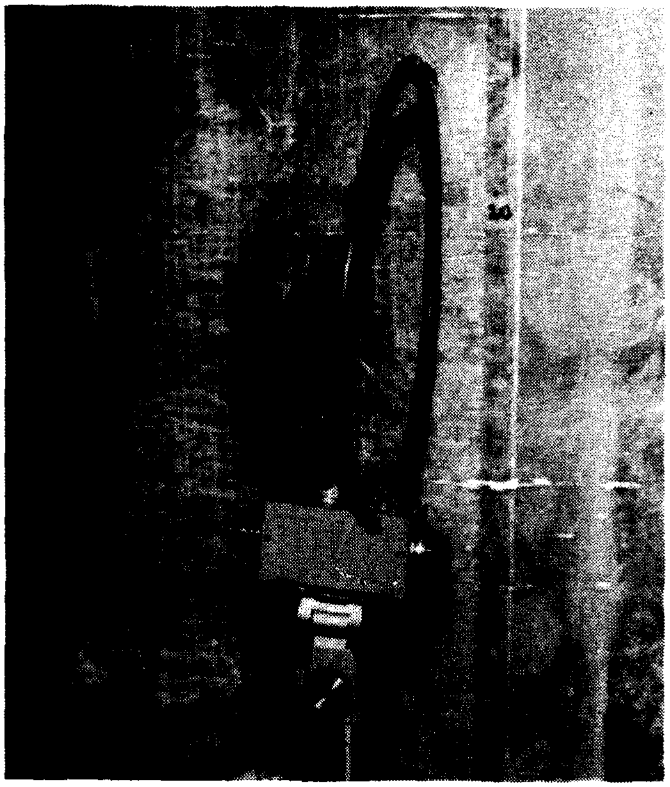

Figure 18. Signal Measurement Transmitting Antenna for the Magnetic Loop Test.

Figure 19. Signal Measurement Receiving Antenna for the Magnetic Loop Test.

For the plane-wave dipole test at 400 MHz and 1000 MHz to simulate the free-field signal amplitude, the transmitting antenna was placed the specified distances from the module wall in both the vertical and horizontal antenna orientations. The receiving antennas were moved up and down until a maximum reading was reached on the field strength meter. After this maximum was reached, the antenna was moved towards and away from the transmitting antenna at least one half the distance to the next point, where the maximum and minimums were recorded. To obtain a signal strength with the shelter in place, the transmitting antenna was placed the specified distance from the test point. The receiving antenna was placed on the inside, and moved up and down, and back and forth, until a maximum and minimum were reached and recorded. Figures 20, 21, and 22 show the open reference measurement, transmitting antenna, and signal measurement antennas in the vertical orientation for the high-frequency plane-wave dipole test, respectively.

For the plane-wave horn test at 10,000 MHz to simulate the free-field signal strength, the transmitting antenna was placed the specified distance from the shielded module in both the vertical and horizontal antenna orientations. The receiving antennas were moved up and down until a maximum reading was reached on the field strength meter. At this point, the antenna was moved towards and away from the transmitting antenna at least 1/2 the distance to the next point, where the maximum and minimum were again recorded. To obtain a signal strength with the shelter in place, the transmitting antenna was placed the specified distance from the test point. The receiving antenna was placed on the inside and moved up and down, and back and forth, until a maximum and minimum were reached and recorded. Figures 23, 24, and 25 show the open reference measurement, transmitting antenna, and signal measurement antennas in the vertical orientation for the high-frequency plane-wave X-band horn test, respectively.

Figure 20. Open Reference Setup for the Plane-Wave Dipole Test.

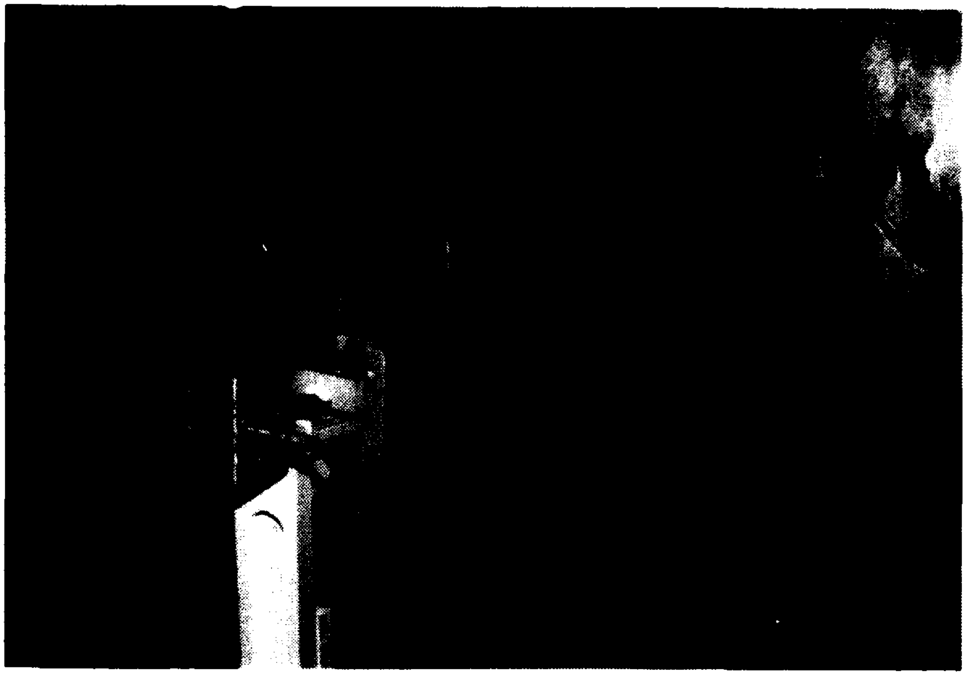

Figure 21. Signal Measurement Transmitting Antenna for the Plane-Wave Dipole Test.

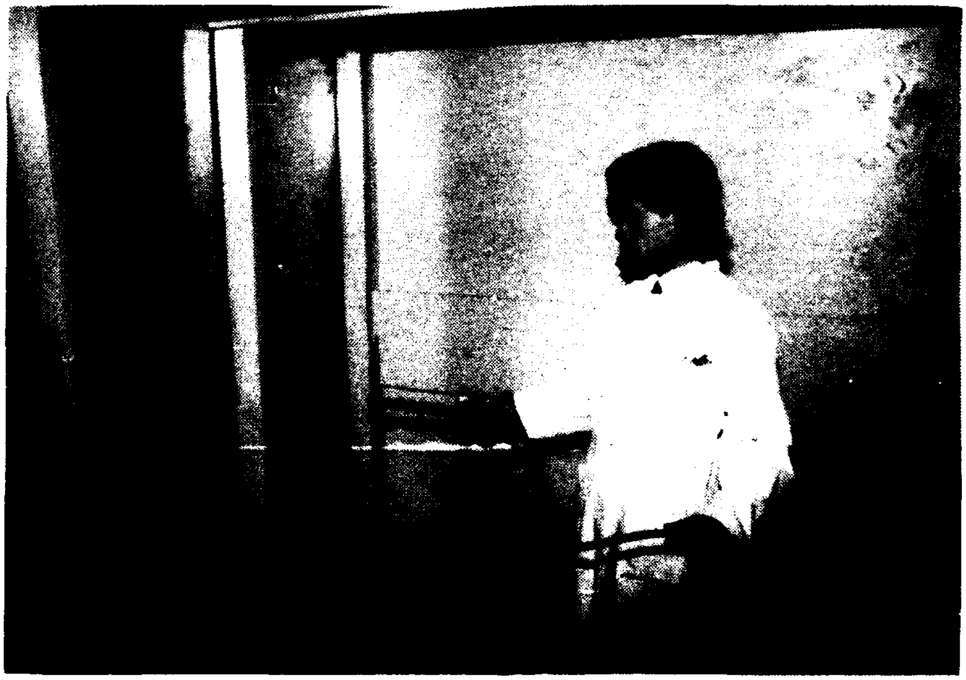

Figure 22. Signal Meaasurement Receiving Antenna for the Plane-Wave Dipole Test.

Figure 23. Open Reference Setup for the Plane-Wave Horn Test.

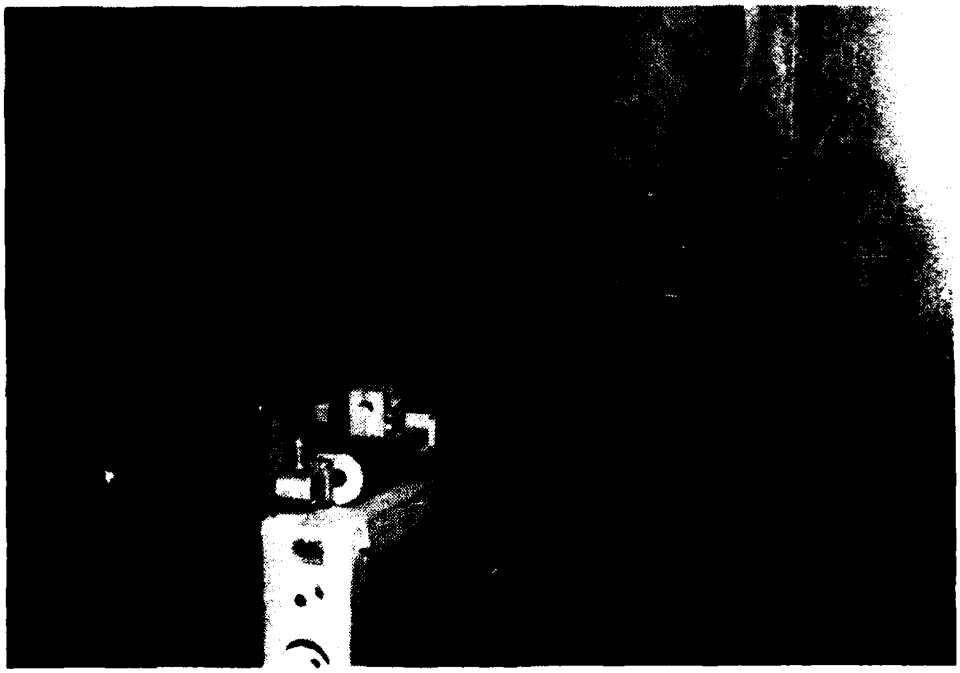

Figure 24. Signal Measurement Transmitting Antenna for the Plane-Wave Horn Test.

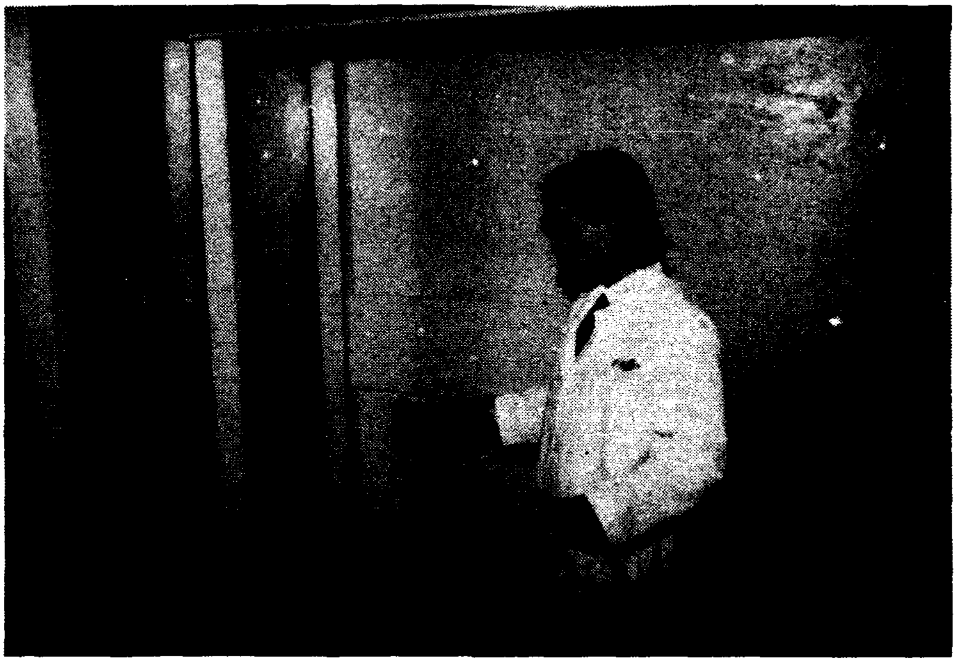

Figure 25. Signal Measurement Receiving Antenna for the Plane-Wave Horn Test.

4 DISCUSSION OF TEST RESULTS

Aperture Data

The exact shielding effectiveness of the test aperture data for the most part could not be determined because all but one point had shielding beyond the measurement capabilities of the test system. The purpose of this test, however, was to show that the 28-gauge steel could provide a high quality shield and this can still theoretically be shown to be true. Note that the shielding at 15 kHz is 55 dB. (All tabular and graphical data are included in Appendix A.) Figure A11 shows the graph of the aperture SE data. Information from this graph shows the SE of a constructed module to be above 85 dB for all frequencies above 150 kHz. Practice shows that the electrical quality of the seams determines the performance of the enclosure, with low-seam resistance being important.[8] Therefore, the metal mating surfaces between panels must be clean, corrosion-free, galvanically similar, and have uniform contact pressure to maintain the SE.

Theoretical Data

To calculate the theoretical SE of the galvanized material, a shielding program was written (Appendix B), based upon theoretical shielding equations.[9] The equations used are only mathematical approximations, valid only under the following assumptions: (1) a constant permeability, (2) planar material, (3) perpendicular wave incidence, (4) infinitely large sheet material, (5) finite antenna, (6) displacement currents are ignored, and (7) conductivity of sheet material greater than zero.[10]

The manufacturer of the sheet steel states that the pregalvanized material had a permeability of 18.6 millihenrys/meter, which gives a relative permeability of well above 2000. Using this value in the shielding program produces a calculated shielding above 300 dB at 15 kHz magnetic. This value of SE disagrees with the aperture data by a factor of 5 or 6. The permeability from the manufacturer's value was varied down to a relative permeability of 207, such that the Low Impedance Magnetic Loop test shielding effectiveness at 15 kHz was the same as the test aperture SE of the sheet steel at this frequency. The manufacturer's value of permeability disagrees with the experimental finding by a factor of 10.

Figure A12 shows the theoretical values of shielding for the Low Impedance Magnetic field loop test that are less than 160 dB. Figure A13 depicts the theoretical values of shielding at all considered frequencies using a relative permeability of 207 with a thickness of material of 18.7 mils. Figure A14 shows the theoretical values of shielding below 160 on the same graph as the test aperture data. This figure shows that a better method of calculating theoretical shielding effectiveness for multiple shields should be used. The test aperture data based upon the theoretical data as seen in Figures A11, A12, and A13 should be 95 dB. The actual data shows the shielding to be in excess of 120 dB at 150 kHz.

It should be noted however, that this galvanized sheet steel actually has three thicknesses of metal. As per the manufacturer and ASTM standard 525 there are two thickness of zinc from the galvanized coatings, each about 7 mils thick, along with a thickness of 1006-grade low-carbon steel of about 4.7 mils. The shielding effectiveness equations used in the shielding program listed in appendix B do not consider multiple material thicknesses. As stated, these equations cannot make accurate predictions for these materials.[11] Appendix C discusses how to calculate theoretical shielding effectiveness.

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[8] McCormack, p 9.

[9] Donald R. White, *A Handbook on Electromagnetic Shielding Materials and Performance* (Don White Consultants, Inc., Gainsville, FL, 1980)

[10] White, p 1.19.

[11] White, p 2.1

It could be assumed that the SE of each of the three coatings could simply be summed. It has been shown that SE of multiple materials do not "add".[12] While absorption losses of multiple material do add, reflection and re-reflection losses do not. If the calculated values of SE of these three materials were added, then the theoretical value of shielding at 15 kHz would be only 35 dB. The actual shielding of these composite materials is not equal to the sum of the SE of the parts. (In this case, they were less.)

Module Data

The shielding effectiveness of the nail-together module data is better than expected. The actual shielding for the module is expected to be much less than the theoretical and test aperture data, due to introduction of the personnel entry hatch and seams. The nail-together concept is previously untested, and seam shielding is the primary factor that determines overall shielding in all frequencies of interest in the low-frequency magnetic and high-frequency plane wave tests. Figures A1 and A2 show that the shielding is as high as 89 dB at 15 MHz magnetic on a side wall panel center, and as low as 32 dB at 15 kHz magnetic on the hatch. In Figure A3, the average module overall shielding is as high as 62 dB at 15 MHz magnetic and 10 GHz plane wave and as low as 52 dB at 15 kHz magnetic.

A typical seam on a module of this type has been shown to have, on the average, a minimum of 58 dB (Figure A4). The average shielding of all wall seams exceeded 58 dB and was as high as 83 dB. A typical corner seam (Figure A5) has a minimum of 42 dB on the average, and a shielding as high as 59 dB (Figure A5). A typical panel center has the highest values of shielding, on the average, a minimum of 56 dB and a maximum of 85 dB (Figure A6). A typical side wall has a minimum of 52 dB and a maximum SE of 77 dB (Figure A7).

The maximum and minimum SE of the hatch center are 77 and 35 dB respectively (Figure A8). The SE of the hatch sides is less than the SE of the hatch center (Figure A9), which is to be expected. The SE of the hatch sides is about 72 dB maximum and 35 dB minimum. The hatch overall SE, taking all points into consideration, is 72 dB maximum and 35 dB minimum (Figure A10).

The overall module SE was more than expected, and with improvements in the seam design etc., the values of shielding can be increased. It is expected that the horizontal antenna orientation will have the lowest values of shielding, on an average, for vertical seams. The data shows this to be true. It is expected that the SE of the horizontal and vertical antenna orientations at the panel center would be very similar, as shown in Figure A6. If the values were not close, then the horizontal values should be less than the vertical due to the many vertical seams on the shelter. Again the data shows this to be true.

It is anticipated that the personnel entry hatch data would show the horizontal and vertical antenna orientations SE to be similar to each other due to the hatch's two vertical and two horizontal seams. The graphed data generally bears this out; however, in the few instances where this does not occur, the event may be due to some experimental or operator error.

Many of the discrepancies in the data are within the experimental errors of the tests. For the magnetic field region between 15 kHz and 15 MHz, the anticipated experimental error is equal to ± 1 to 2 dB, and for the plane wave region, the anticipated experimental error is equal to ± 3 to 6 dB.

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[12] Peter F. Williams, et al., Tables A2, A4, and A7.

5 CONCLUSIONS AND RECOMMENDATIONS

From the data taken in this study, it is concluded that the shielding effectiveness of the nail-together module is adequate for many communications security applications. In most security communication facilities, the specific level of shielding required by TEMPEST is based on many different factors, such as distance to nearest unsecured area, the level of emanations from the secured equipment, and the intelligibility of the information being transferred. When each of these factors is taken into account, the shielding requirement is in some cases as low as 30 dB, a level of shielding considerably lower than the values of SE obtained with the tested nail-together module. With better mechanical and electrical connections at the interfaces of the seams, the shielding effectiveness overall for the module could be further increased by as much as 20 to 30 dB. Nail-together shielded enclosures can be built at about one-third the cost of conventionally shielded structures. The use of standard, construction-grade materials incorporating this seam design offers a very high quality shield at a relatively low price.

It is important to test the shielding effectiveness of any new module design in the field as well as in a controlled laboratory environment. Field testing according to standard procedures should confirm the data from this study in more detail. With this in mind, the following recommendations are made:

- Long-term aging effects (including environmental and field deployment) should be examined, because the shielding effectiveness of the module could change due to oxidation, corrosion, and wear of the seams. The addition of heat, cold, and moisture could corrode the module panels, could buckle the substrate material, etc., thus degrading the overall shielding effectiveness of the nail-together module.

- The edges of each 28-gauge panel and each piece of 14-gauge flat strip should be cleaned extensively according to ASTM standards for the preparation of metal specimens. This extra mechanical cleaning will enhance the electrical conductivity along seams, increasing the overall shielding of the module.

- An experiment should be performed to evaluate thermal-sprayed zinc. Each panel edge of the 120 dB-shielded enclosure door should be flame- or arc-sprayed with zinc. The addition of the zincked edges could provide better electrical and mechanical connections along the seams, which would, in turn, increase the shielding effectiveness of the nailed module.

- A second piece of 14-gauge galvanized flat strip should be added to the inside seams of the galvanized module. The 14-gauge flat strip is less likely to form itself to the contours of the wooden 2x4. This flat strip is much stronger and more uniform than the wooden 2x4, and will help give uniform pressure along the seams, and double protection for each seam. The cost increase of this process will be negligible, while the increase in the module shielding could be substantial.

- Experiments should be performed to compare the use of nails with that of screws. The 1-1/2 in. 4d galvanized nails should be replaced with 1-1/2 in. 4d galvanized screws. The use of screws may produce a more consistent electrical connection along the seams. The nail concept produces relatively good seam connections; however, in some cases, the nailed seams were not as tight as anticipated. The screws are somewhat harder and more time-consuming to apply, but they would increase the cost of the shelter by only a small fraction of the original module cost.

- This second galvanized module should be constructed with screw connections, and its performance tested and documented, including comparisons to previous construction designs.

Broader issues regarding the galvanized module using standard construction materials need to be addressed, particularly whether such construction design can be generalized to other shielding applications, like electromagnetic pulse protection. It is recommended that further study be done to determine:

- Whether this type of galvanized construction concept and seam design is adequate for an electromagnetic pulse (EMP) environment
- What kind of maintenance will be required to ensure that this material and concept will have minimal shielding degradation with aging
- Whether thinner gauge material will be better suited for lower shielding applications
- Whether thicker materials will perform better in an EMP environment.

APPENDIX A: Tables and Graphs

Table A1

Nail-Together Module Data Set 1 (Sidewalls)

Test Point	Vertical 0.015	Horiz. 0.015	Vertical 0.15	Horiz. 0.15	Vertical 15	Horiz. 15
Reference	54	54	81	81	73	73
Noise	-29	-29	-38	-38	-29	-29
1	-10	-13	4	4	7	21
2	-14	-15	3	6	7	22
3	-5	-12	16	8	10	12
4	-18	-21	4	5	7	23
5	-9	-4	12	14	6	13
6	-14	-6	15	8	5	9
7	-14	-7	33	9	12	15
8	-4	-12	24	17	11	12
9	-8	-4	2	1	11	9
10	-8	-7	9	-8	3	11
11	-7	-7	7	1	2	8
12	-7	-7	8	-7	18	10
13	-6	-6	2	3	14	19
14	-15	-7	16	15	22	9
15	11	-2	28	5	17	11
16	-15	-15	15	11	13	4
17	-9	-5	13	5	16	3
18	-15	-5	10	-5	16	5
19	-9	-5	8	3	18	12
20	-19	-5	11	-6	7	5
21	-7	-5	4	4	6	18
Ave.	-9.62	-8.10	11.62	4.43	10.86	11.95
Ave. SE	63.62	62.10	69.38	76.57	62.14	61.05

Table A1 (Cont'd)

Nail-Together Module Data Set 1 (Sidewalls)

Test Point	Closed Hatch		Open Hatch		Closed Hatch		Open Hatch		Closed Hatch		Open Hatch	
	Vertical 400	Horiz. 400	Vertical 400	Horiz. 400	Vertical 1000	Horiz. 1000	Vertical 1000	Horiz. 1000	Vertical 10,000	Horiz. 10,000	Vertical 10,000	Horiz. 10,000
Reference	116	116	116	116	113	114	113	114	96	96	96	96
Noise	-13	-13	-13	-13	-3	-3	-3	-3	5	5	5	5
1	81	76	107	106	68	64	81	76	32	38	94	95
2												
3												
4												
5												
6	76	78	93	96	65	63	92	92	23	28	67	61
7												
8	54	49	94	90	42	45	84	79	31	34	53	51
9												
10	54	49	87	92	48	58	83	76	33	36	56	55
11												
12												
13	80	45	88	86	38	45	82	76	33	31	53	53
14												
15	49	41	81	86	44	53	82	77	32	38	52	50
16												
17	60	62	82	83	51	52	83	81	32	29	51	49
18												
19	61	62	82	85	55	53	85	82	33	38	51	49
20												
21	55	63	86	85	54	58	85	86	35	43	51	55
Average	63.33	58.33	88.89	89.89	51.67	54.56	84.11	80.56	31.56	35.00	58.67	57.56
Average SE	52.67	57.67	27.11	26.11	61.33	59.44	28.89	33.44	64.44	61.00	37.33	38.44

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*All data values are in dB microvolts

Table A2

Nail-Together Module
Data Set Number 1 (Corners)

Corner	Horiz. 0.015	Horiz. 0.15	Horiz. 15
A	3	29	20
B	3	33	23
C	15	2	11
D	15	32	16
E	22	37	9
F	5	20	12
G	5	25	19
H	14	33	8
I	6	26	9
J	20	34	10
K	15	29	8
L	20	28	20
M	8	15	20
N	15	22	24
O	19	33	13
P	15	28	15
Q	18	30	14
R	12	22	16

Table A3

Galvanized Sheet Steel Test Aperture Data

Freq (MHz)	Ref dB	Signal dB	SE dB*	
Magnetic field (12-in. Loops)				
0.0150	50.0	-5.0	55.0	
0.15	81.0	-39.0	120.0	+
0.20	80.0	-39.0	119.0	+
0.30	78.0	-7.0	85.0	+
0.70	75.0	-35.0	110.0	+
1.00	74.0	-35.0	109.0	+
3.00	68.0	-29.0	97.0	+
7.00	70.0	-29.0	99.0	+
10.00	75.0	-30.0	105.0	+
15.00	75.0	-29.0	104.0	+
Electric field (mono-pole antennas)				
0.15	93.0	-39.0	132.0	+
0.20	94.0	-39.0	133.0	+
0.30	98.0	-37.0	135.0	+
0.70	106.0	-35.0	141.0	+
1.00	105.0	-35.0	140.0	+
3.00	115.0	-29.0	144.0	+
10.00	120.0	-29.0	149.0	+
10.00	110.0	-30.0	140.0	+
15.00	111.0	-29.0	139.0	+
20.00	99.0	-28.0	139.0	+
25.00	102.0	-26.0	125.0	+
50.00	83.0	-12.0	114.0	+
200.00	110.0	-10.0	93.0	+
300.00	113.0	-9.0	119.0	+
350.00	105.0	-13.0	126.0	+
400.00	95.0	-13.0	118.0	+
500.00	78.0	-3.0	98.0	+
Plane wave (conical antennas)				
200.00	93.0	24.0	69.0	
300.00	106.0	29.0	77.0	68.0
400.00	104.0	35.0	69.0	68.0
450.00	104.0	39.0	65.0	68.0
600.00	80.0	7.0	73.0	68.0
700.00	78.0	-5.0	83.0	68.0
800.00	76.0	8.0	68.0	68.0
1000.00	75.0	7.0	68.0	68.0
2000.00	90.0	22.0	68.0	68.0

* A "+" indicates that shielding effectiveness was beyond USACERL test equipment capability.

Table A3 (Cont'd)

Galvanized Sheet Steel Test Aperture Data

Freq (MHz)	Ref dB	Signal dB	SE dB[*]	
Plane wave (large horn antennas)				
2000.00	75.0	2.0	73.0	+
3000.00	111.0	2.0	109.0	+
4000.00	114.0	2.0	112.0	+
5000.00	110.0	4.0	106.0	+
6000.00	114.0	4.0	110.0	+
Plane wave (small horn antennas)				
4000.00	52.0	2.0	50.0	+
5000.00	109.0	4.0	105.0	+
6000.00	107.0	4.0	103.0	+
7000.00	105.0	4.0	101.0	+
8000.00	101.0	3.0	98.0	+
9000.00	100.0	3.0	97.0	+
10000.00	99.0	3.0	96.0	+

[*] A "+" indicates that shielding effectiveness was beyond USACERL test equipment capability.

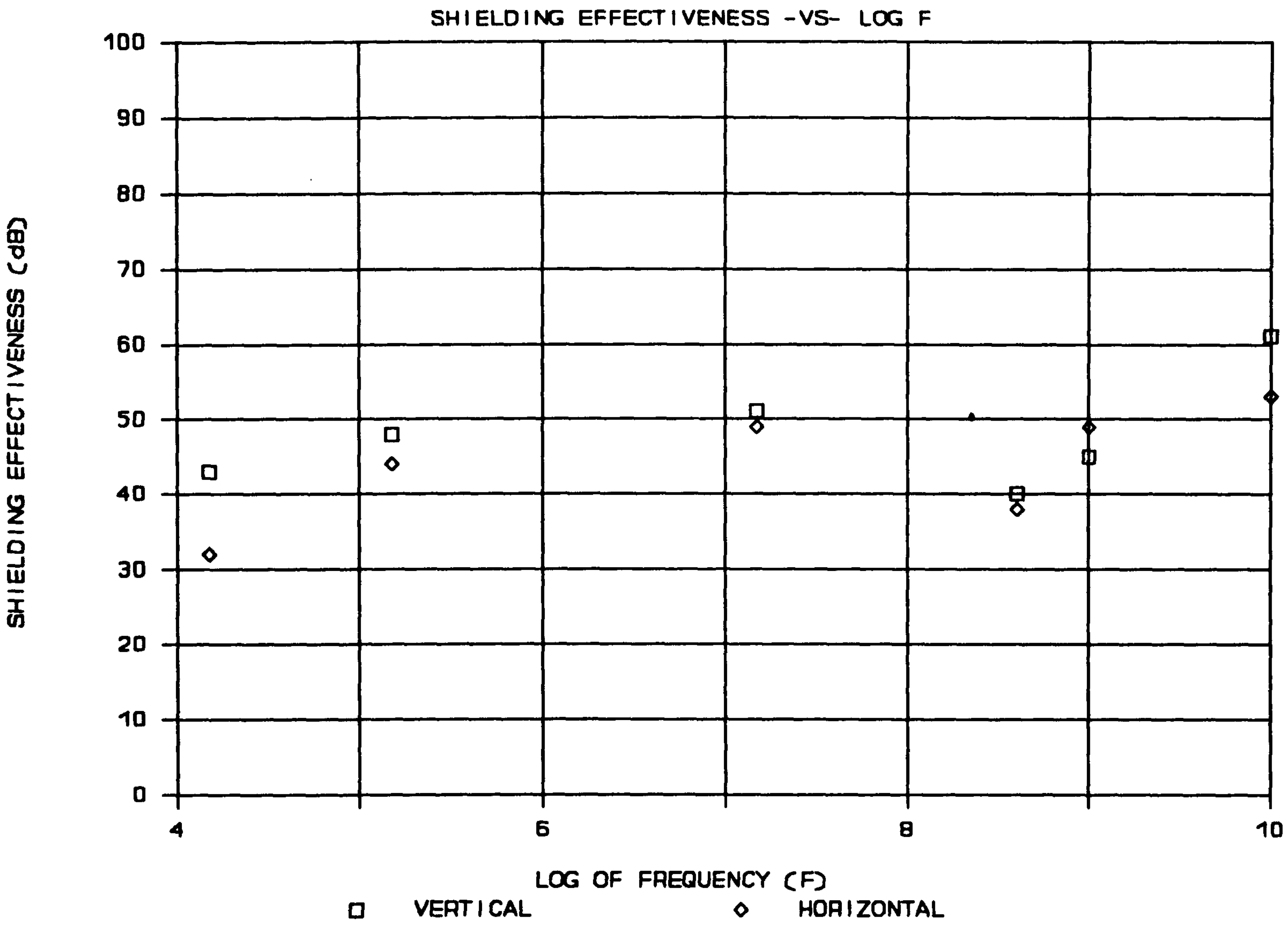

Figure A1. Nail-Together Module Low Shielding Effectiveness.

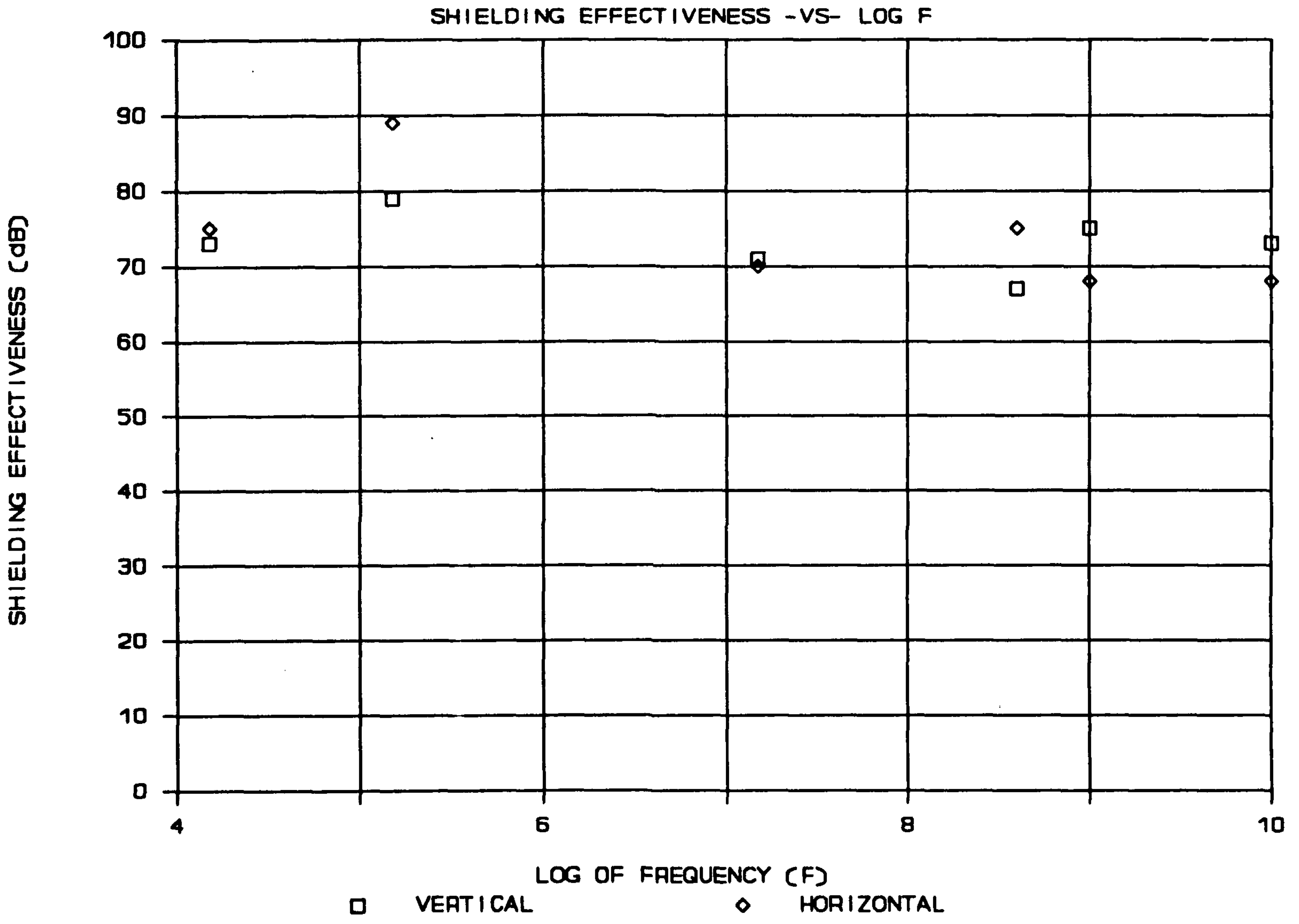

Figure A2. Nail-Together Module High Shielding Effectiveness.

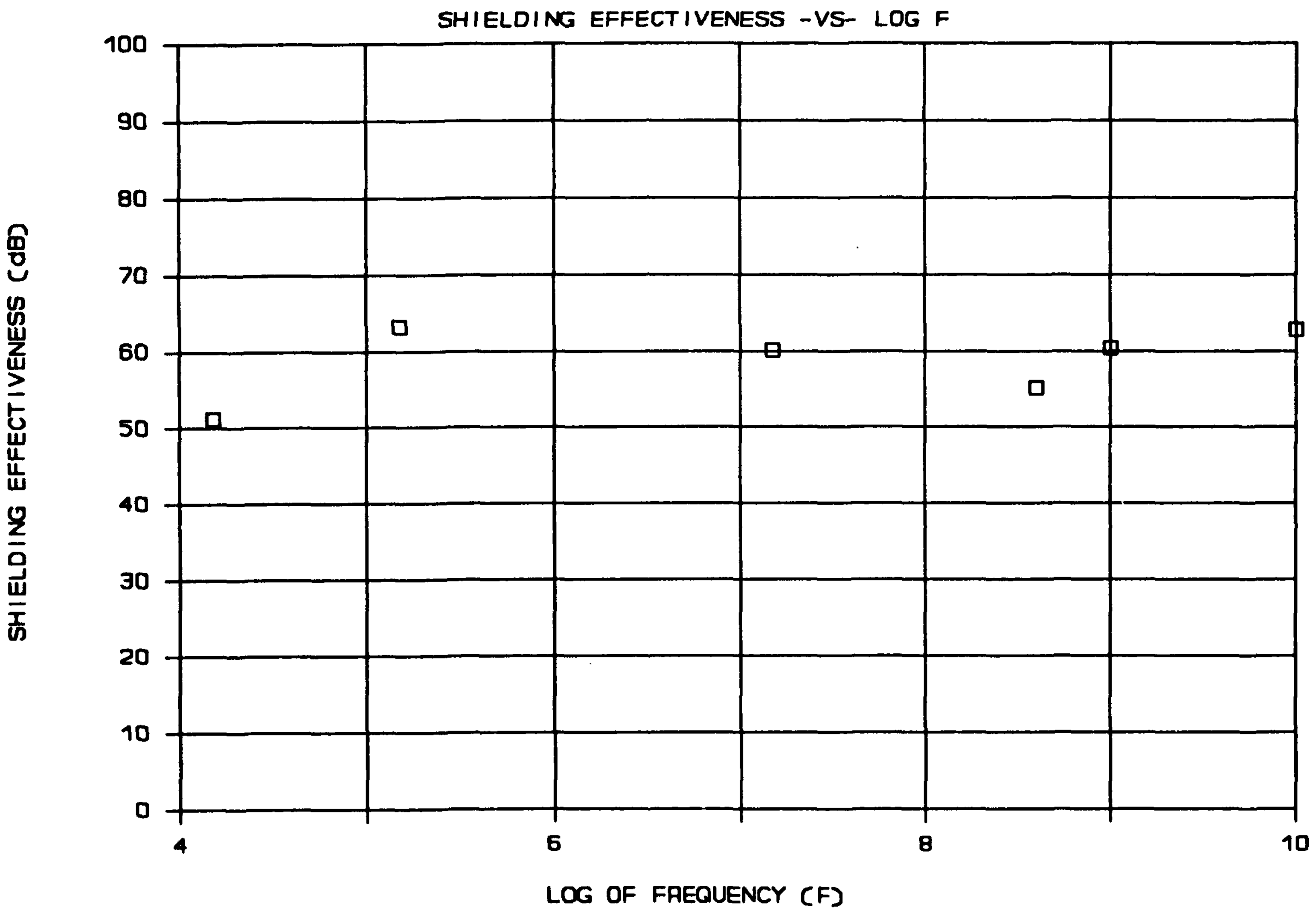

Figure A3. Nail-Together Module Overall Average Shielding.

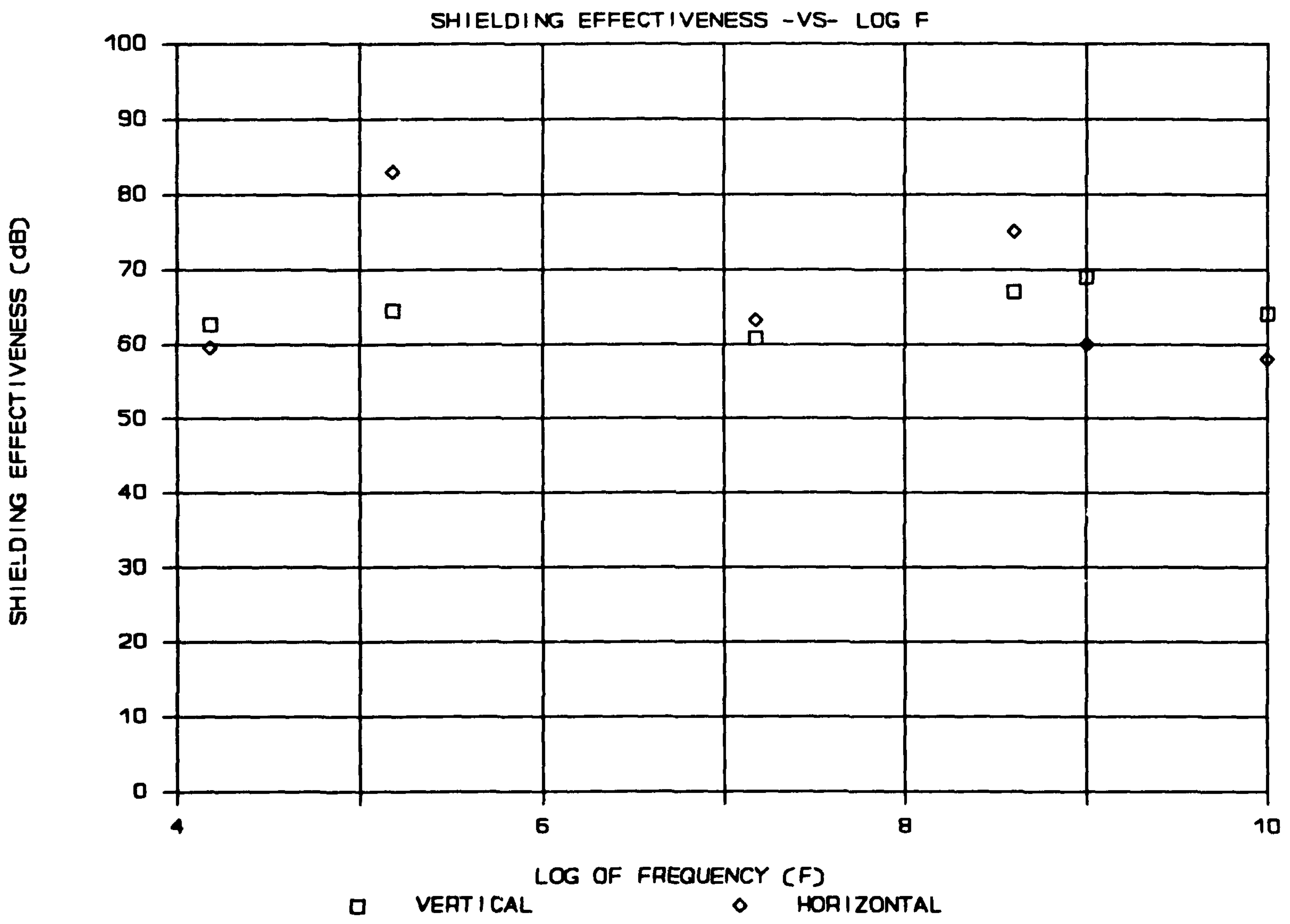

Figure A4. Nail-Together Module Typical Seam Shielding Effectiveness.

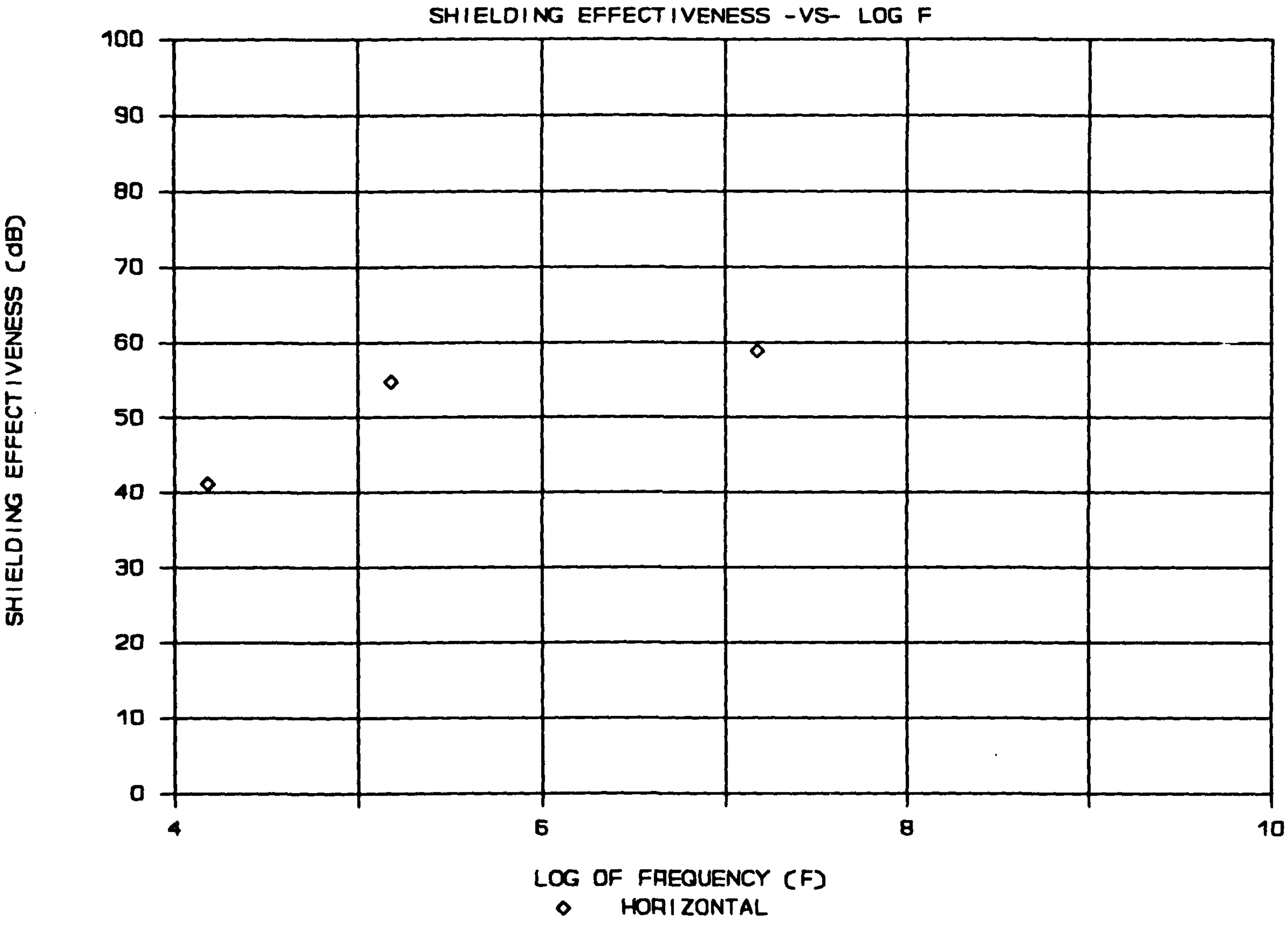

Figure A5. Nail-Together Module Typical Corner Shielding Effectiveness.

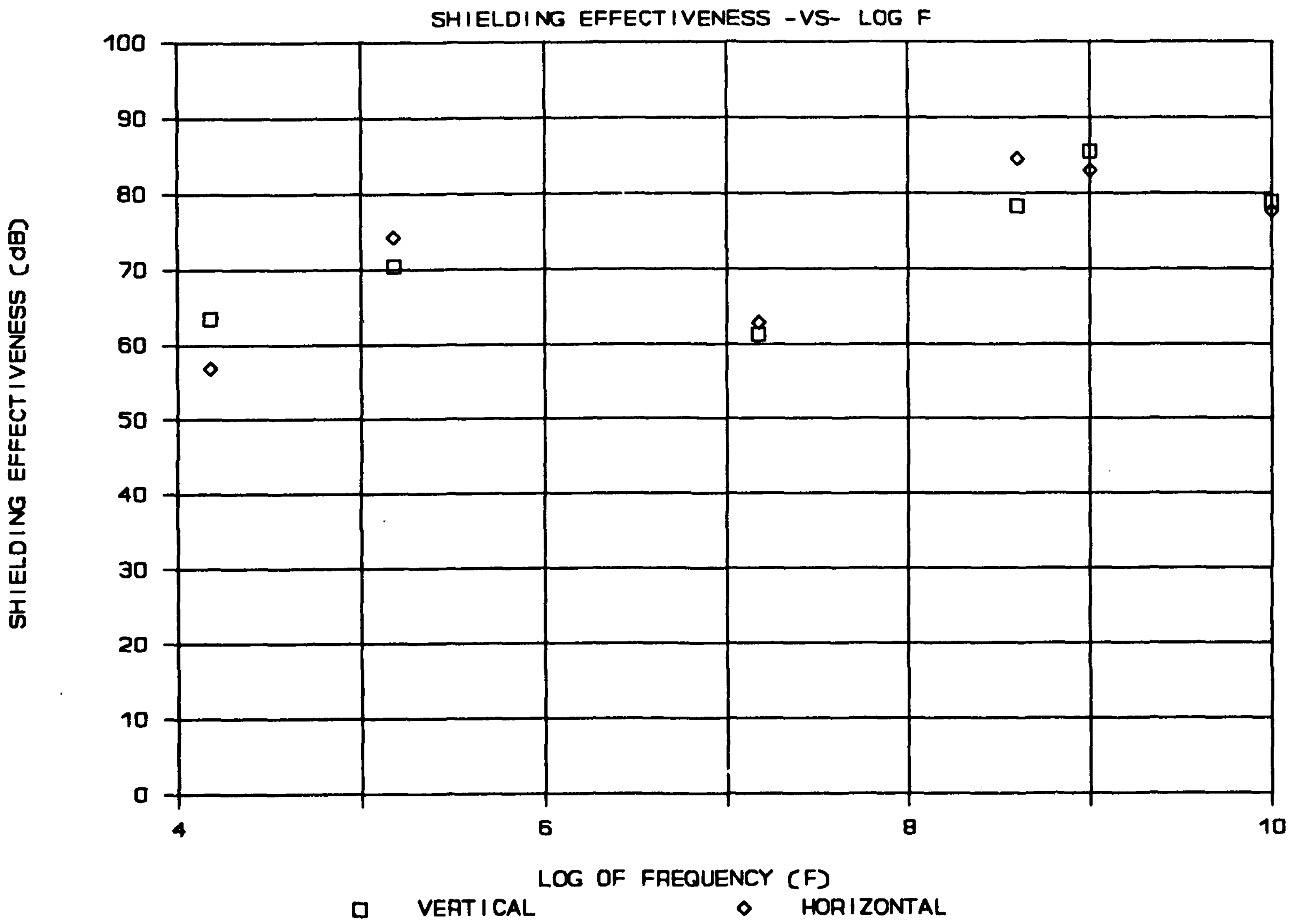

Figure A6. Nail-Together Module Typical Panel Center Shielding Effectiveness.

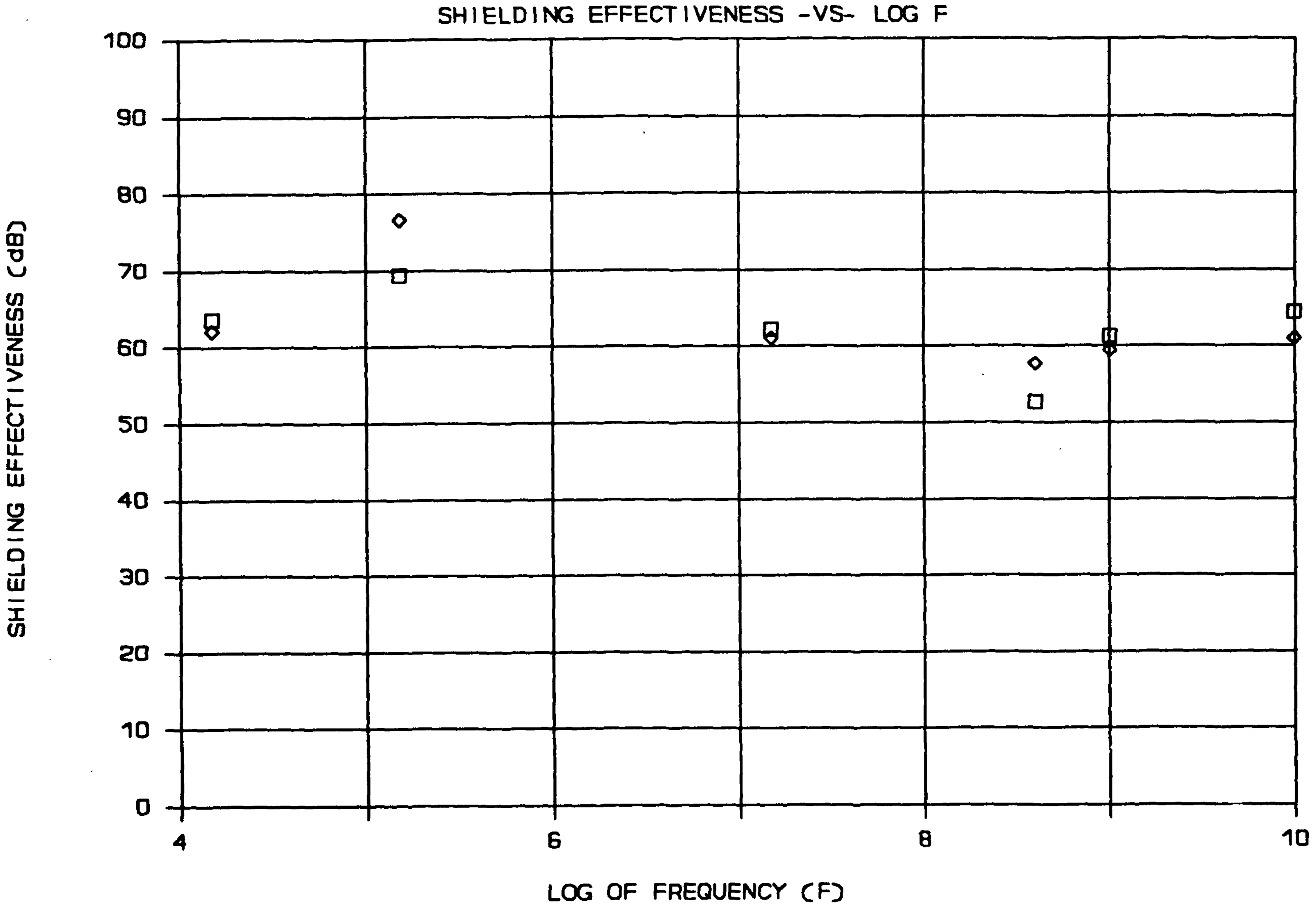

Figure A7. Nail-Together Module Average Side Wall Shielding Effectiveness.

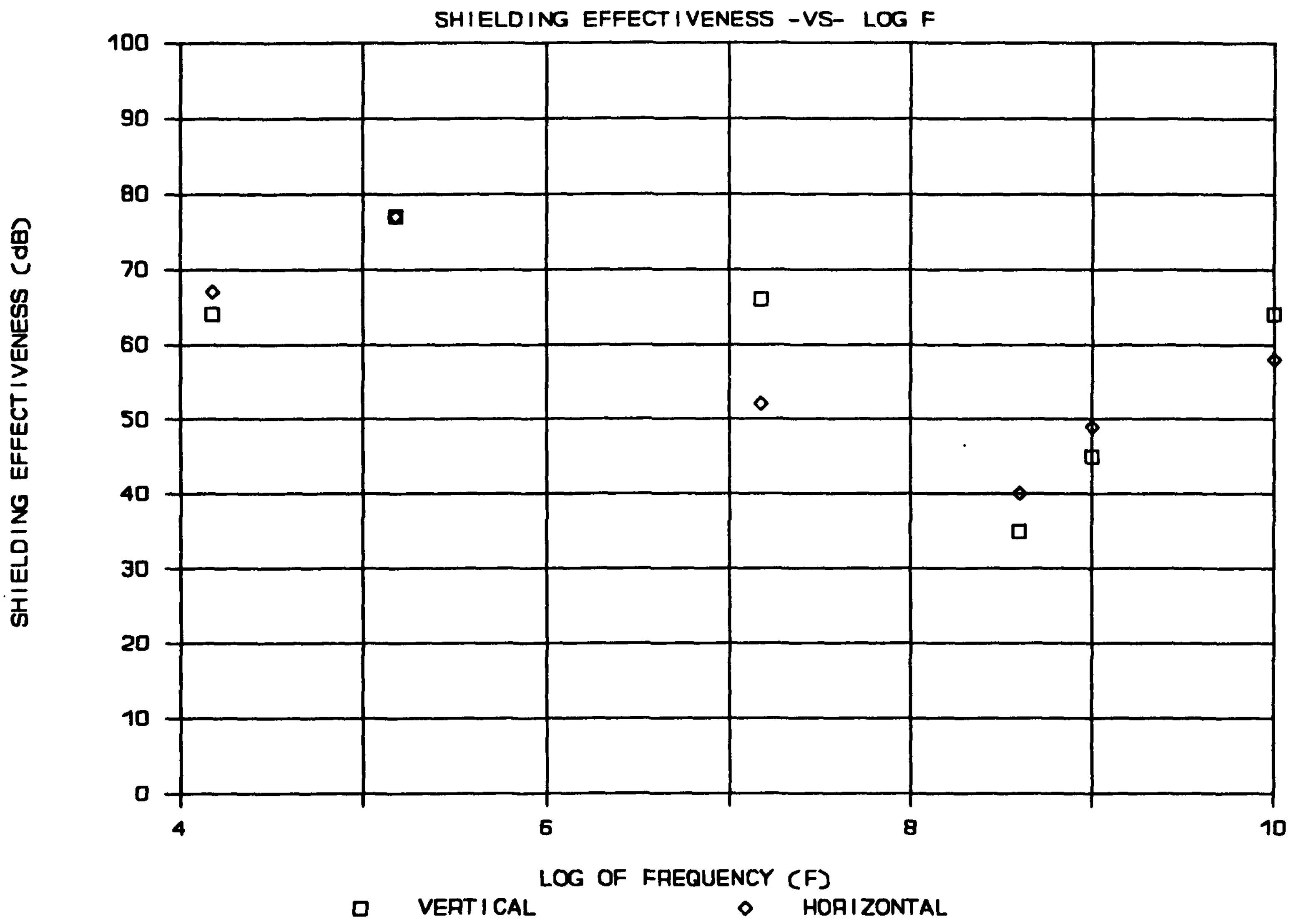

Figure A8. Nail-Together Module Hatch Center Average Shielding Effectiveness.

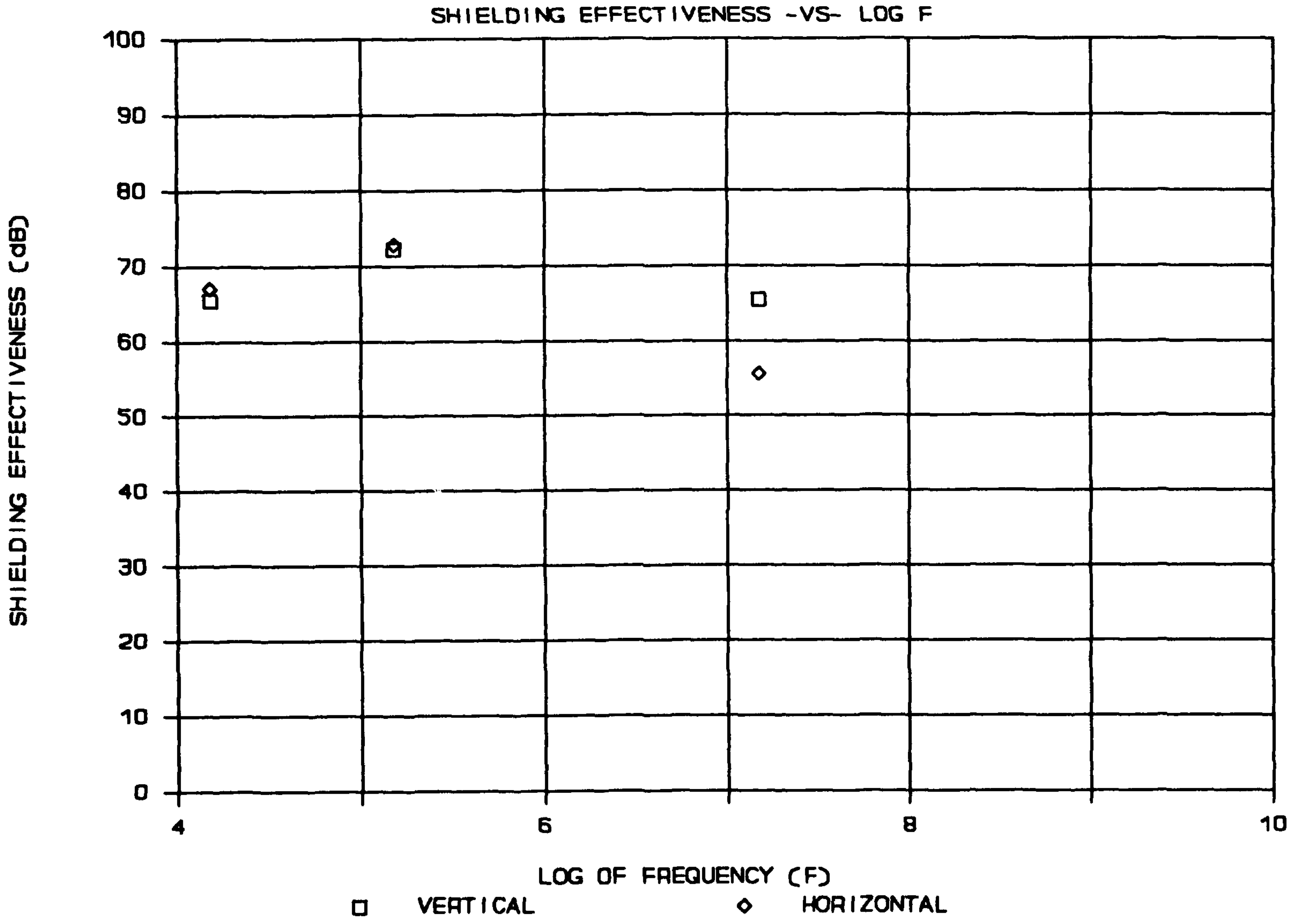

Figure A9. Nail-Together Module Hatch Sides Average Shielding Effectiveness.

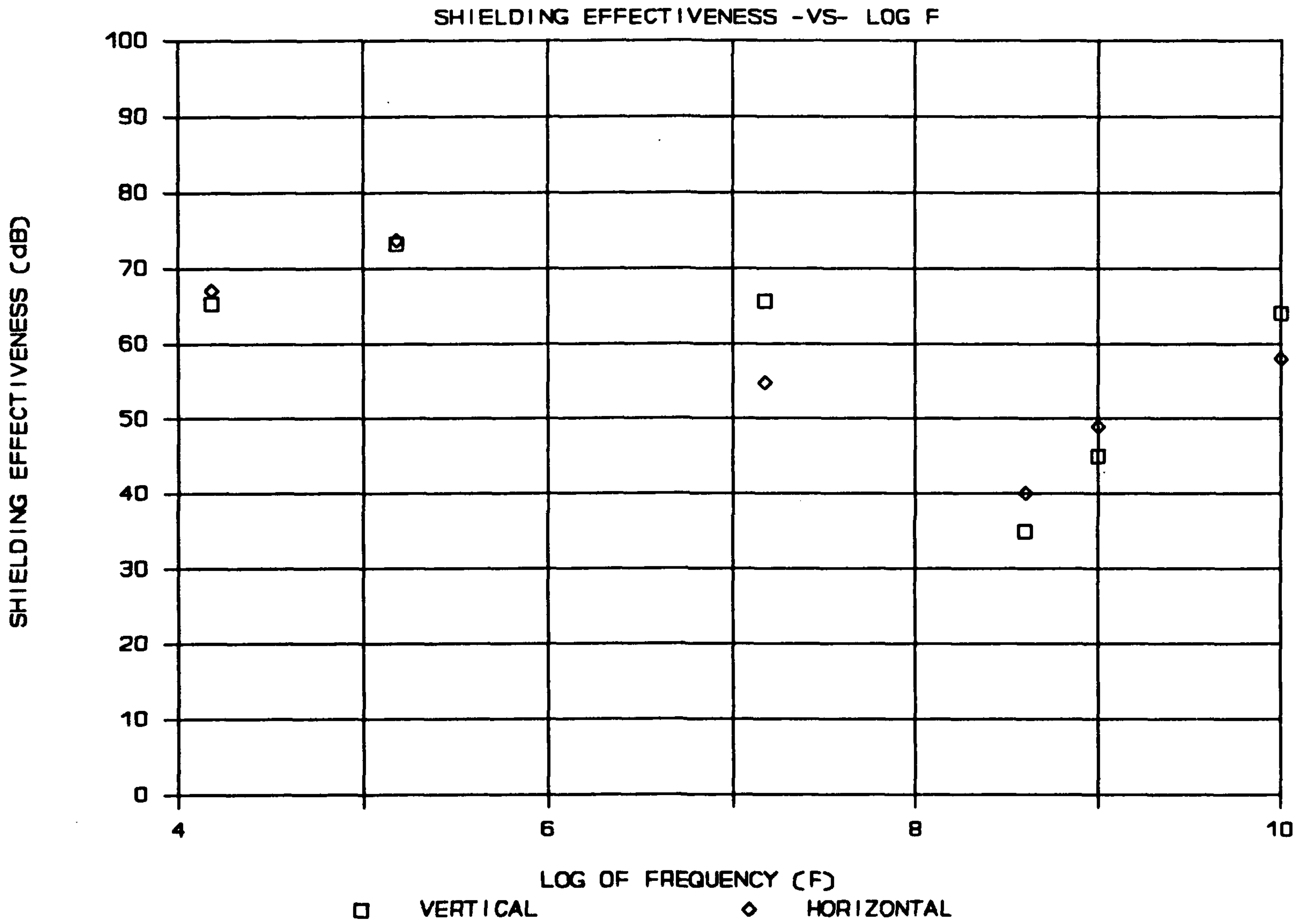

Figure A10. Nail-Together Module Hatch Overall Average Shielding Effectiveness.

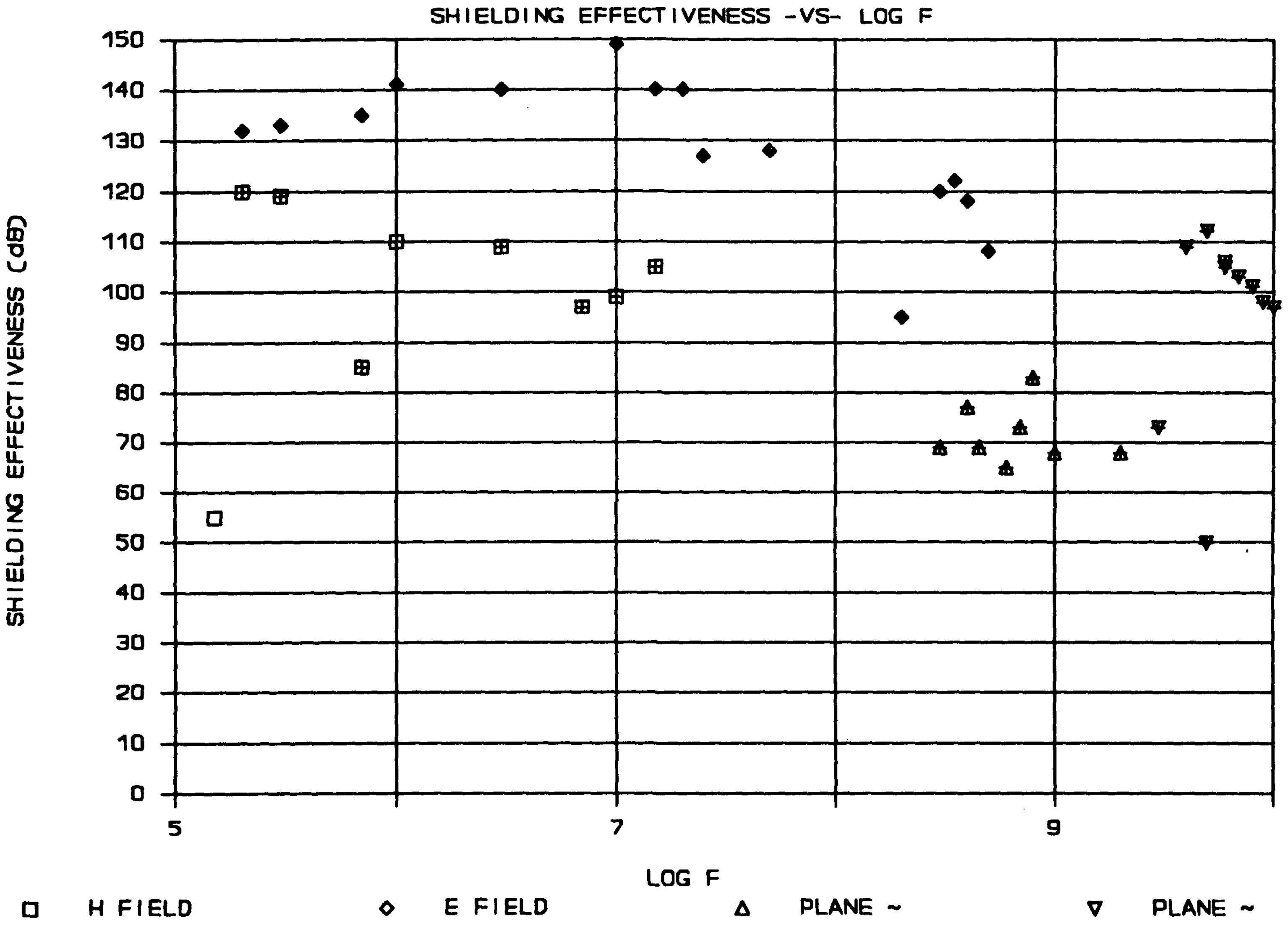

Figure A11. Galvanized Sheet Steel Aperture Shielding Effectiveness.

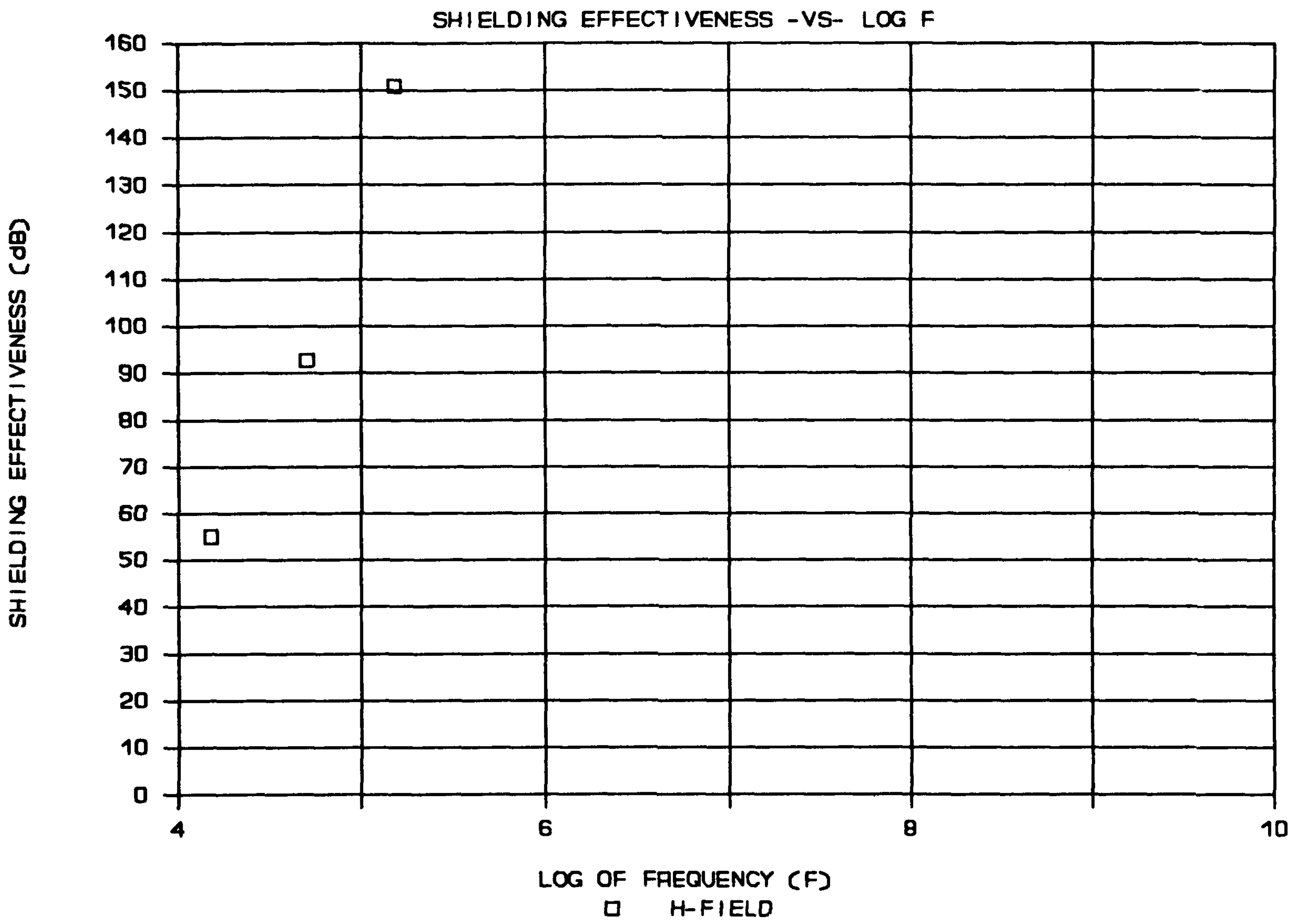

Figure A12. Galvanized Sheet Steel Theoretical Data < 160 dB.

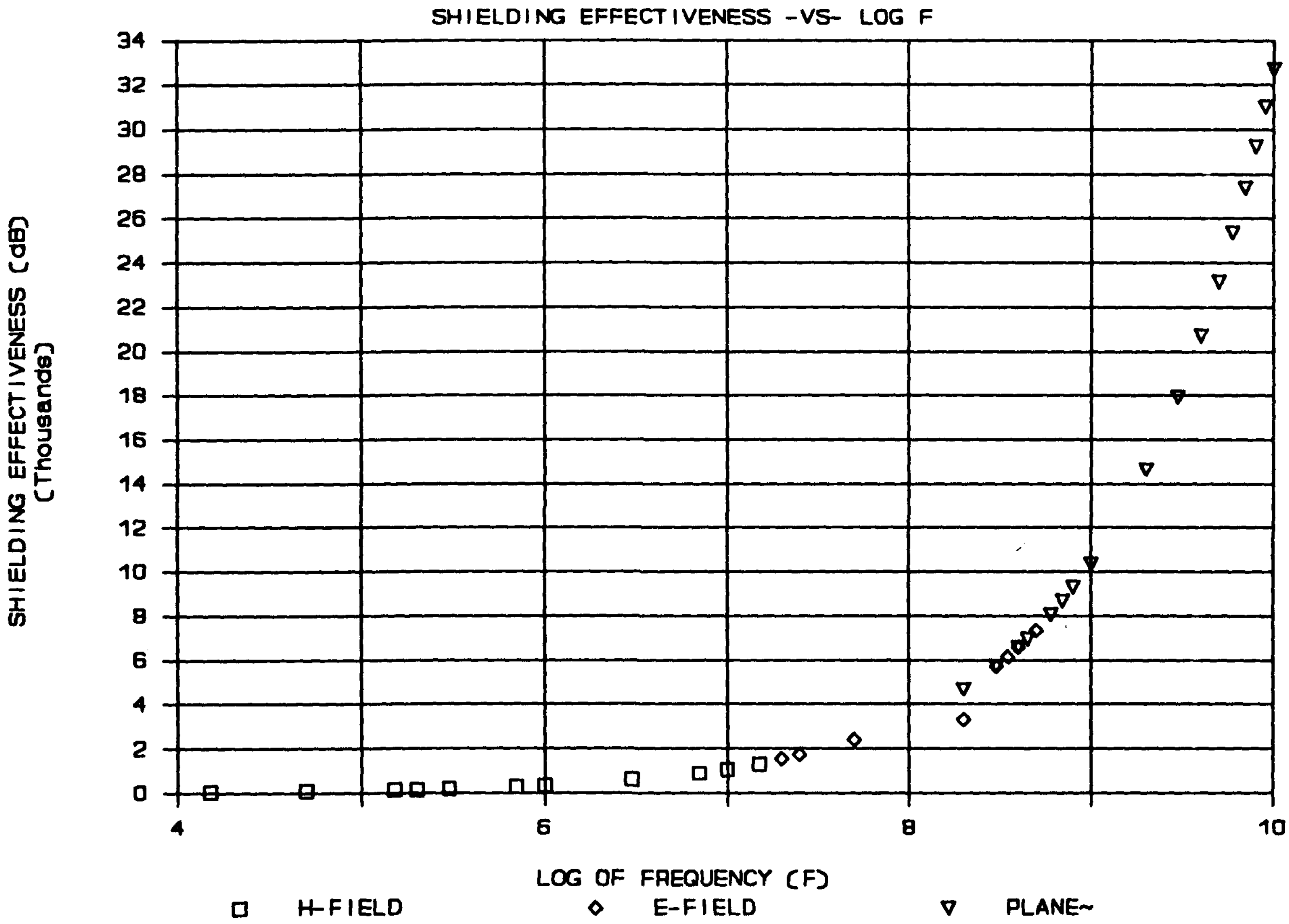

Figure A13. Galvanized Sheet Steel Theoretical Shielding Effectiveness.

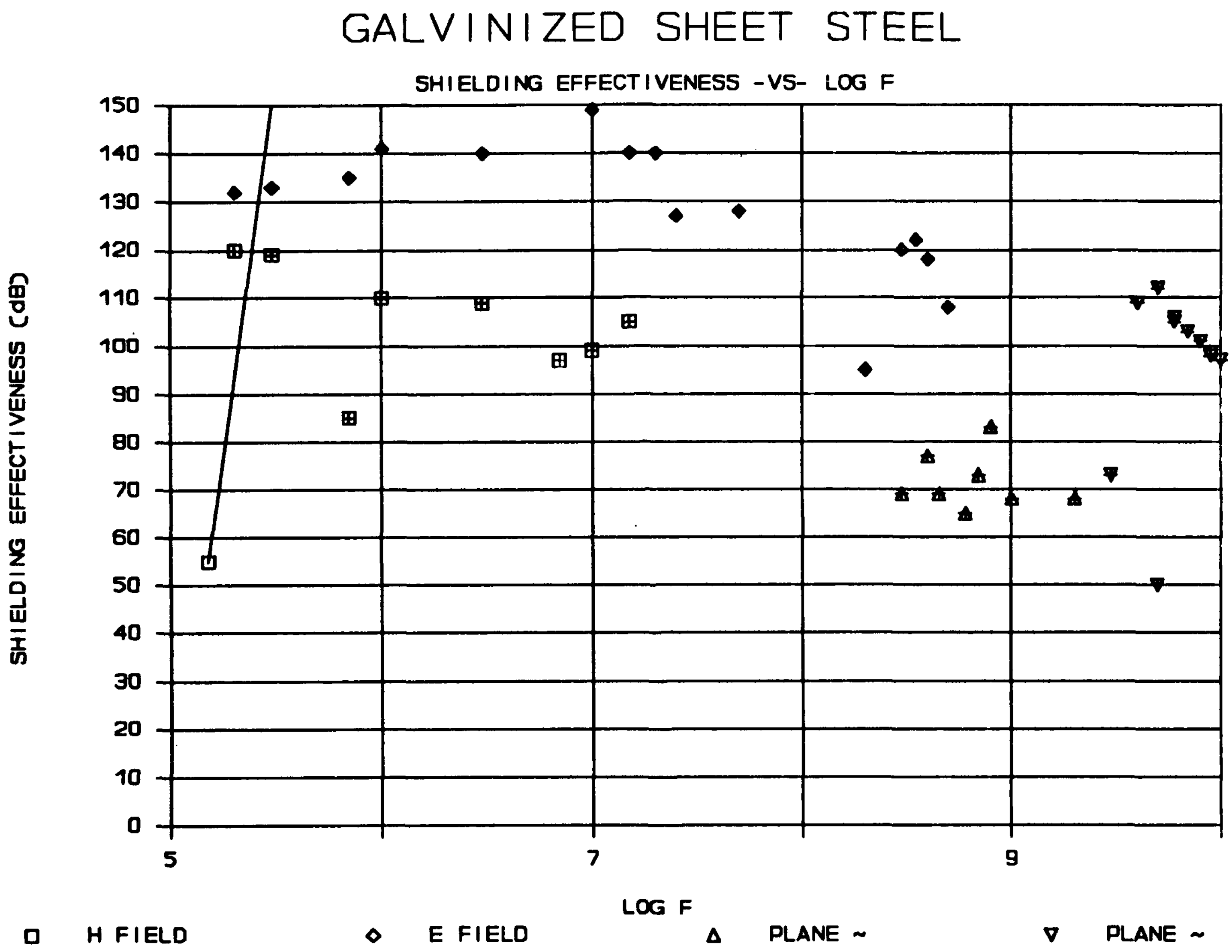

Figure 14. Galvanized Sheet Steel Aperture SE Compared to Theoretical Data < 160 dB.

APPENDIX B: BASIC Program for Calculating Theoretical Shielding Effectiveness

```
10    REM  This program calculates theoretical shielding
20    REM  effectiveness.
30    REM
40    REM  Written by Peter Williams    March 1984
50    REM
60    REM  Modified by Mike McInerney    May 1984
70    REM
80    REM  Modified by Peter Williams    March 1988
90    REM
100   CLS
110   DIM AB(23),RE(23),RR(23),SH(23),F(23),K(23)
120   DATA .015,.050,.150,.200,.300,.700,1.00,3.00,7.00,10.00,15.00,20.00
130   DATA .015,.050,.150,.200,.300,.700,1.00,3.00,7.00,10.00,15.00,20.00
140   DATA 25.00,50.00,100.00,200.00,250.00,300.00,350.00,400.00,500.00
150   DATA 200.00,300.00,400.00,450.00,600.00,700.00,800.00,900.00
160   DATA 1000,2000,3000,4000,5000,6000,7000,8000,9000,10000
170   CLS
180   PRINT "INPUT RELATIVE PERMEABILITY OF METAL"
190   INPUT Y
200   PRINT "INPUT CONDUCTIVITY RELATIVE TO COPPER"
210   INPUT G
220   PRINT "INPUT RELATIVE PERMITIVITY OF METAL"
230   INPUT ER
240   PRINT "INPUT TYPE OF METAL"
250   INPUT M$
260   PRINT "INPUT METAL THICKNESS IN INCHES"
270   INPUT T
280   CLS
290   PRINT: PRINT :PRINT "Calculating Shielding Effectiveness."
300   FOR L = 1 TO 3
310   IF L = 1 THEN E$="low"
320   IF L = 2 THEN E$="high"
330   IF L = 3 THEN E$="plane"
340   IF L = 1 THEN NN = 12
350   IF L = 2 THEN NN = 21
360   IF L = 3 THEN NN = 18
370   P=3.1415927#
380   N=1.257E-06
390   CC=5.8E+07
400   E=8.854E-12
410   D=.3048
420   C = G * CC
430   U = N * Y
440   EE = ER * E
450   FOR I=1 TO NN:READ F(I)
460   IF (ASC(E$)=80) OR (ASC(E$)=112) THEN 500
470   IF (ASC(E$)=72) OR (ASC(E$)=104) THEN 490
480   K=D*SQR(2*P*F(I)*1000000!*C*N/Y):GOTO 510
490   K=1/(2*P*.3048*F(I)*1000000!*E*SQR(2*P*F(I)*1000000!*U/C)):GOTO 510
500   K=1/SQR(2*P*F(I)*1000000!*Y*E/C)
510   Z=(1+K)^2/(4*K)
520   RE(I)=20*(LOG(Z)/LOG(10))
530   AB(I)=3.338*T*SQR(F(I)*1000000!*Y*G)
540   X=((K-1)/(K+1))^2*10^(-.1*AB(I)):K(I)=K
```

```
550  W=(1-X*COS(.23*AB(I)))^2
560  V=(X*SIN(.23*AB(I)))^2
570  S=SQR(W+V)
580  RR(I)=20*(LOG(S)/LOG(10))
590  SH(I)=RE(I)+AB(I)+RR(I)
600  NEXT I
610  IF (ASC(E$)=72) OR (ASC(E$)=104) THEN 640
620  IF (ASC(E$)=80) OR (ASC(E$)=112) THEN 650
630  LPRINT"                    ","LOW IMPEDANCE FIELD":LPRINT "        ","  (LOOP TEST)":GOTO 660
640  LPRINT"        ","HIGH IMPEDANCE FIELD":LPRINT "              ","  (DIPOLE TEST)":GOTO 660
650  LPRINT"                        ","PLANE WAVE FIELD":LPRINT "          ","                (HORN TEST)"
660  LPRINT:LPRINT"                         ";T*1000;"  MILS OF ";M$:LPRINT
670  LPRINT"    CONDUCTIVITY=   ";C,"  RELATIVE CONDUCTIVITY=   ";G
680  LPRINT:LPRINT"    PERMITIVITY=    ";EE,"  RELATIVE PERMITIVITY=   ";ER
690  LPRINT:LPRINT"    PERMEABILITY=   ";U,"  RELATIVE PERMEABILITY=   ";Y
700  LPRINT
710  LPRINT"  FREQUENCY";"       ABSORPTION";"       REFLECTION";"       REREFLECTION";"
     SHIELDING"
720  LPRINT"   (MHZ)  ";"       (dB)   ";"       (dB)   ";"       (dB)    ";"       (dB)   "
730  LPRINT"------------------------------";"------------------------------";"---------------":LPRINT
740  FOR J=1 TO NN
750  LPRINT USING "######.####      ";F(J);
760  LPRINT USING "####.####       ";AB(J);RE(J);RR(J);SH(J)
770  NEXT J
780  LPRINT CHR$(12)
790  NEXT L
800  CLS:RESTORE
810  PRINT:PRINT"WANT TO DO MORE CALCULATIONS FOR A NEW THICKNESS"
820  INPUT Y$
830  IF (ASC(Y$)=89) OR (ASC(Y$)=121) THEN 260
840  IF (ASC(Y$)<>78) AND (ASC(Y$)<>110) THEN 810
850  PRINT"WANT TO DO CALCULATIONS FOR A DIFFERENT METAL"
860  INPUT D$
870  IF (ASC(D$)=89) OR (ASC(D$)=121) THEN 170
880  IF (ASC(D$)<>78) AND (ASC(D$)<>110) THEN 850
890  END
```

APPENDIX C: CALCULATION OF THEORETICAL SHIELDING EFFECTIVENESS

Equations

The shielding effectiveness (SE) is a figure which descrbes the performance of a shield in reducing electromagnetic energy. Thus, the shielding effectiveness can be described as a loss in field strength. The shielding effectiveness can be modeled by several equations,[13] the first of which is:

$$SE_{dB} - A_{dB} + R_{dB} + B_{dB} - \text{Leakage Effects} - \text{Standing Waves} \qquad \text{[Eq B1]}$$

where A_{dB} = the absorption loss, R_{dB} = the reflection loss, and B_{dB} = the re-reflection loss. Each of these terms can be defined by various equations.

The absorption term can be defined in terms of thickness (t) in mils (thousandths of an inch) and frequency (f) in MHz in english units as:

$$A_{dB} - 3.338 t_{mils} \sqrt{f_{MHz}\, \mu_r\, \sigma_r\, dB} \qquad \text{[Eq B2]}$$

where μ_r and σ_r are the permeability and the conductivity of the shield material relative to copper.

The reflection loss relations are predicated upon an impedance mismatch at the metal-barrier interfaces. The reflection term can be defined as:

$$R_{dB} - 20 \log_{10} [(1 + K)^2/4K]_{dB} \qquad \text{[Eq B3]}$$

where K is defined as the ratio of the wave impedance to the metal-barrier impedance:

$$K - \tfrac{1}{2}\, \pi r f \varepsilon_o \sqrt{2\pi f \mu/\sigma} \text{ for high impedance (magnetic) fields} \qquad \text{[Eq B4]}$$

$$- r\sqrt{2\pi f \sigma \mu_o/\mu_r} \text{ for low impedance (electric) fields} \qquad \text{[Eq B5]}$$

$$- 1/\sqrt{2\pi f \mu \varepsilon_r/\sigma_o} \text{ for plane waves} \qquad \text{[Eq B6]}$$

---

[13] Donald R.J. White, *A Handbook on Electromagnetic Shielding Materials and Performance* (Don White Consultants, Inc., 1980), pp 1.14-1.35.

The re-reflection term can be described in terms of the wave and metal-barrier impedance:

$$B_{dB} = 20 \log_{10} \{ 1 - [(K - 1)/(K + 1)]^2 \times 10^{-0.1A_{dB}} (\cos 0.23A_{dB} - \sin 0.23A_{db}) \} \qquad \text{[Eq B7]}$$

where A_{dB} is defined in Equation B2.

Symbols and Abbreviations

dB = decibels

f = frequency

m = meter(s)

mils = thousandths of an inch

r = source to shield distance

t = thickness

A = absorption loss

B = re-reflection loss

MHz = megahertz or millions of hertz

R = reflection loss

SE = shielding effectiveness

ε_0 = permittivity of free space and copper

μ = permeability of shield material = $\mu_o\mu_r$

μ_o = absolute permeability of air = 4×10^{-7} henrys/m

μ_r = permeability of shield material relative to copper

π = 3.14159

σ = conductivity of shield material in mhos/m

σ_r = conductivity of shield material relative to copper

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