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Shielding Effectiveness Test Report for a TI-Shield™ Enclosure

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An electromagnetic (EM) shielding effectiveness test was conducted to evaluate the performance of 10-mil-thick TI-Shield™ applied to an Army tactical shelter. TI-Shield™ is a clad metal composite of copper/alloy49/copper which is typically available bonded to 1/4-in. particle board. Gaven Industries installed the TI-Shield™ panels to the interior of a plywood shelter mockup using continuously soldered seams. This shielded enclosure was then tested according to IEEE-STD-299-1991, with some modifications. The shelter mockup and EM testing are discussed with the results presented as recommended by the standard. These results demonstrate that application of TI-Shield™ to a shelter would satisfy the EM shielding requirement of MIL-STD-907B.

14. SUBJECT TERMS

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1. Introduction

An electromagnetic (EM) shielding effectiveness (SE) test was performed as an evaluation of a relatively lightweight, cost-effective material that may be used for EM shielding of an equipment enclosure, such as the Standardized Integrated Command™* Post Shelter (SICPS). This EM testing was done to support the U.S. Army Research Laboratory (ARL) Composite Shielding Initiative [1] and to collect data for a demonstration of composite shielding technology. This report focuses on an evaluation of 10-mil-thick TI-Shield™, one of the currently available advanced-technology shielding materials. This roller-bonded, clad metal composite of copper/permalloy49/copper (Cu/A49/Cu) is manufactured by Texas Instruments, Inc., and distributed by Gaven Industries, Inc., in 2-ft-wide rolls (approximately $8/ft^2).

2. Background

The ARL has established a program of applied research to acquire, develop, and apply EM shielding technology to ensure the survivability of Army resources to EM threats. The program has a strong focus on characterizing, understanding, predicting, and controlling the interaction of EM fields with composite materials. The environment we consider is nonionizing EM radiation, including electromagnetic pulse (EMP), high-power microwave (HPM), EM interference (EMI), and lightning. The program proposes to provide an evolutionary development of the EM shielding technology to enhance survivability performance and system effectiveness.

As part of this program we evaluate and test practical and cost-effective shielding techniques that can be applied to composite structures used in Army systems. Our emphasis is to acquire, install, and test several available advanced EM-shielding materials that could be used in Army tactical shelters so that we can evaluate the EM performance of the shielded enclosure. The size and physical configuration of the enclosure we selected for this demonstration represent the SICPS designed for the Heavy High Mobility Multipurpose Wheeled Vehicle (HMMWV).

As part of a Natick Research, Development, and Engineering Center program, a Hardened Standard Shelter (HSS) has been proposed as the next generation Army tactical shelter [2]. One version of the HSS is an approximately 25-mil-thick welded aluminum skin inside a filament-wound, graphite/epoxy (G/E) composite structure. For a conductivity relative to copper, $\sigma_r = 0.5$, the magnetic (H-) field SE of this liner is estimated as 52 dB at 20 kHz and 80 dB at 200 kHz [3]. Although Al provides lightweight EM shielding (5.6 oz/ft^2), installation can be expensive because of the difficulties of welding aluminum.

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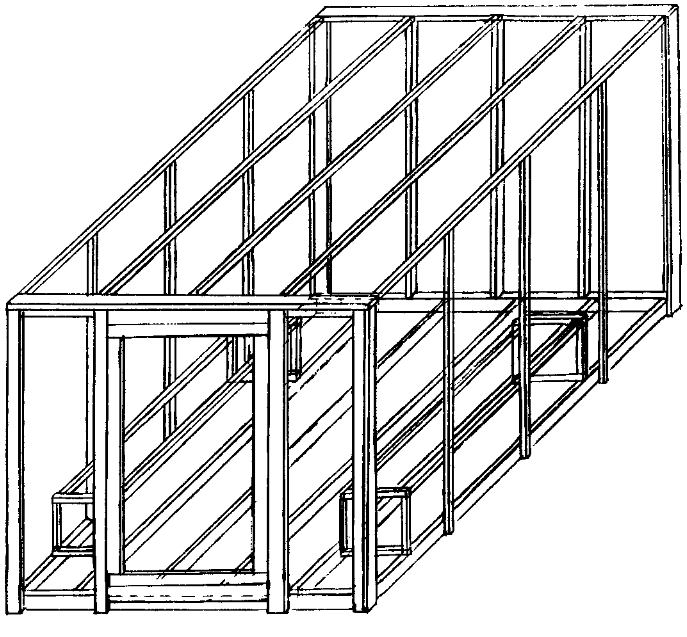
A49 is a 49-percent nickel, 50-percent iron alloy (no anneal), which has a typical relative permeability of 2,500 to 90,000 [4]. We use the conductivity of a 50-percent nickel, 50-percent iron alloy, $\sigma_r = 0.0384$, relative to Cu [3]. According to Gaven Industries, Inc., the proportional layer structure of the clad metal is 20-percent Cu, 60-percent A49, and 20-percent Cu, so the relative thickness is approximately 2 mils of Cu, 6 mils of A49, and 2 mils of Cu. The material density is 8.3 g/cm^3, so for a thickness of 10 mil, the weight is about 7 oz/ft^2. TI-Shield™ seems to satisfy a basic requirement for shielding composite structures, as it does not significantly add to the system weight. Further, it is easily applied with standard construction and soldering techniques. The SE measurement results indicate that TI-Shield™ can have a better SE than the welded Al liner.

3. System Description

The enclosure we chose for this series of tests is a plywood mockup of the HSS that would be used with the Heavy HMMWV. The HSS can be manufactured of fiber-reinforced plastics; it provides protection against blast overpressure, fragmentation rounds, chemical/biological attack, and EM environment effects (E^3). This composite HSS provides EM shielding by an aluminum liner that is welded together and used as a form for the filament-wound G/E. This aluminum liner is expensive to install and adds weight to the HSS. Electric (*E*-) and *H*-field intensity measurements inside the mockup are compared to the unperturbed or “free field” intensity. Once the shield material is installed, any difference in field intensity is defined as the SE for this size enclosure.

Figure 1 is a sketch of the wood structure (8 ft l × 6.8 ft w × 5.3 ft h) used for the HSS mockup. We built the shelter 8 ft long so that standard lengths of wood could be used (the HSS is actually 8.5 ft long). This 6-in.-shorter shel-

Figure 1. Framing structure for HSS mockup.



ter will not affect the EM field attenuation measurements, since the test frequencies chosen are not near the fundamental cavity resonance. The mockup did not include the inside compartment in the front of the shelter, normally used to enclose the generator unit; its absence will not affect the EM field-attenuation measurements of the shelter's shielding material. The inside compartments for the wheel wells were included in the mockup (fig. 1).

We glued the entire frame structure together so that temporary metal fasteners could be removed and would not affect the EM measurements. The mockup was made from 1/4-in. plywood except the floor, which was made of 1/2-in. plywood. The interior (including the wheel wells) was then covered with 1/4-in. particle board that had TI-Shield™ bonded to it. This resulted in 1/2-in.-thick walls and ceiling and a 3/4-in.-thick floor. Gaven Industries installed the particle board and soldered the seams using standard techniques. Seams were overlapped at least 1 in. and continuously soldered. The TI-Shield™ panels were glued to the mockup so that temporary metal screws could be removed. The holes left by the temporary fasteners were covered with TI-Shield™ patches and soldered, as were the triple corners (i.e., corners which include the floor or ceiling).

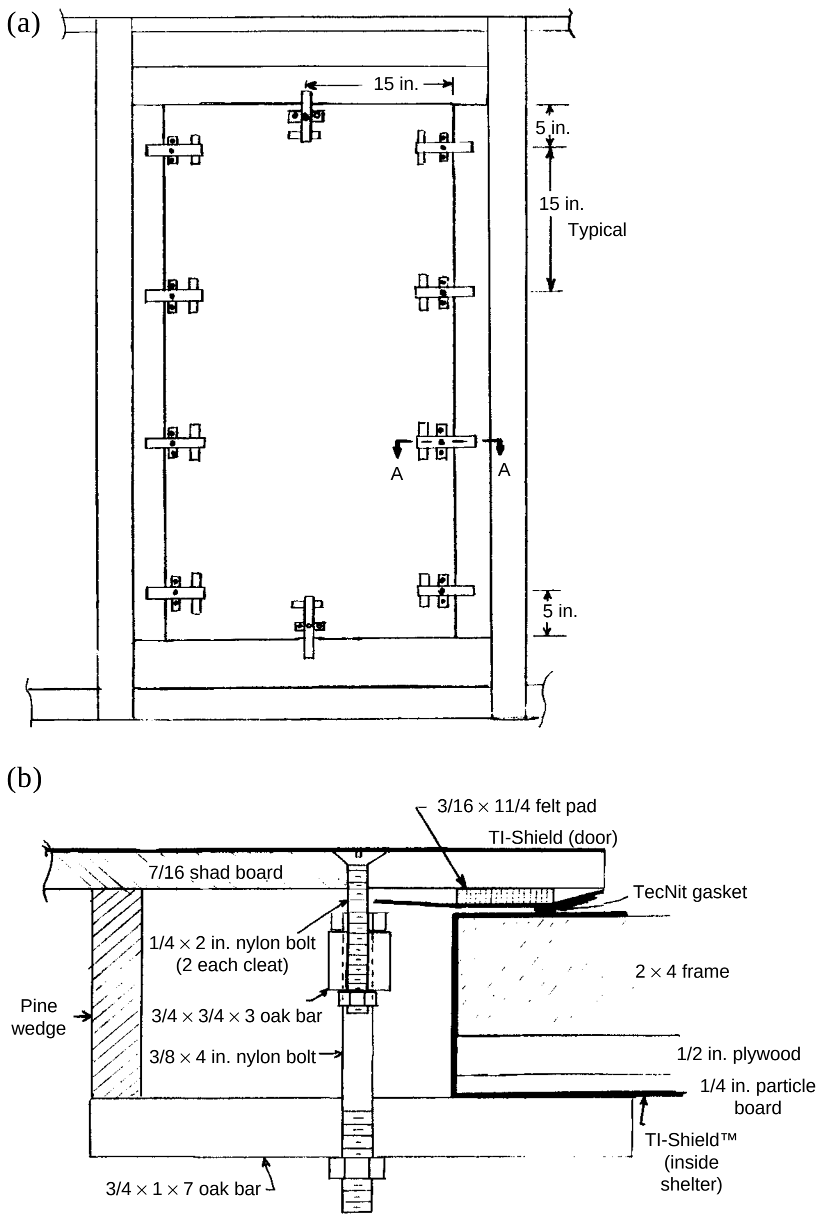
A plywood panel was covered with TI-Shield™ and used as a door. Nonmetallic fasteners were designed to hold the door in eight places (fig. 2(a)). The cleat arrangement using nonconductive bolts and spacer blocks is shown in figure 2(b). The door panel was sized so that there would be at least a 2-in. overlap of shielding material around the door perimeter. A wire-mesh gasket was installed between the door and shelter wall to provide more uniform contact between the eight cleats (fig. 2(b)). The shimmed spacer blocks are adjusted to provide high-pressure contact. The resulting door arrangement, though not as good as an rf fingerstock door, could be adjusted to provide reasonably uniform electrical contact.

4. Test Objectives

The objectives of this series of EM tests are

1. to perform an SE evaluation of 10-mil TI-Shield™ when installed in a mockup of the HSS, in accordance with MIL-STD-907B [5];
2. to use the SE test procedures of IEEE Std 299-1991 [6], which supersedes MIL-STD-285 [7], to obtain sufficient data to evaluate the shielded mockup; and
3. to collect baseline SE data that can be used for comparison to analytical results, other shielding material test data, and for an evaluation of intentional and/or unintentional shield degradations.

Figure 2. Door cleat: (a) locations and (b) detail.



5. Test Approach

The test approach is to follow IEEE Std 299-1991 using the equipment listed in table 1. Equipment that requires calibration had been appropriately certified within the past year. IEEE Std 299-1991 calls for SE tests at seven frequencies in three ranges (high, mid, and low), along with a preliminary spatial scan to disclose serious defects. The high-range measurements (1.7 to 18 GHz) were not possible because equipment was not available. The mid-range measurements (300 MHz to 1 GHz) were in accordance with IEEE Std 299-1991, except log-periodic (LP) antennas were used instead of dipole antennas. The directional gain of these antennas provides good dynamic range but the physical size requires some deviation from the recommended test procedures. The low-range measure-

Table 1. Equipment for shielding effectiveness measurements.

Instrumentation	Description
Tektronix 492P	spectrum analyzer
Hewlett Packard 8660C	synthesized signal generator
Hewlett Packard 86602B	rf section (1–1300 MHz)
Hewlett Packard 86601A	rf section (0.01–110 MHz)
ENI 240L	rf amplifier (200 W, 0.02–10 MHz)
ENI 510L	rf amplifier (9.5 W, 1.7–500 MHz)
Tripp Light PV-500FC	dc to ac invertor
3-turn, 12-in.-diameter loop	transmit antenna
1-turn, 12-in.-diameter loop	receive antenna
(2) Emco 3146	log periodic antennas

ments (14 kHz to 20 MHz) were in accordance with IEEE Std 299-1991 except that the three test frequencies were somewhat higher than the recommended values, due to equipment limitations. At all frequencies, the substitution technique is used to quantify the measured SE.

5.1 Low-Range Calibration Procedures

The configuration for the low-range free-field calibration consists of coplanar loops with the edges 24.5 in. apart in the absence of the shield. The free-field calibration and test procedures are in accordance with IEEE Std 299-1991. At each frequency the antenna current is recorded, and the maximum received signal represents the calibration level for this current. The receiver bandwidth is set at the same value used for the SE measurements, which is 1 kHz in all cases. The antenna height is 36 in. above the ground. The test frequencies were selected, based on the available equipment, to be 20 kHz, 200 kHz, and 20 MHz. The lowest cavity resonant frequency for this enclosure is, F_r = 107 MHz, so the chosen frequencies are consistent with the requirements of IEEE Std 299-1991.

5.2 Mid-Range Calibration Procedures

The test configuration for the mid-range free-field calibration (fig. 3(a)), is more complicated. The distances specified in IEEE Std 299-1991 are modified to account for the larger antennas (roughly 2 ft in length) used in these tests. The center of the receive antenna is located 2 ft from the outside shelter wall, while the center of the transmit antenna is located 6 ft from this wall. The antenna separation (center to center) for calibration is then 4 ft (1.3 m), and the recommended scanning procedure is used. The antenna separations are consistent with IEEE Std 299-1991; however, the length of the longest LP elements violates the electrically small antenna length (one-eighth wavelength) specified to avoid variations in the antenna input impedance owing to the shield proximity. The recommended calibration procedures were used in addition to a true free-space calibration (i.e., in the absence of the shelter). The variations observed during these calibration procedures were 1 to 3 dB.

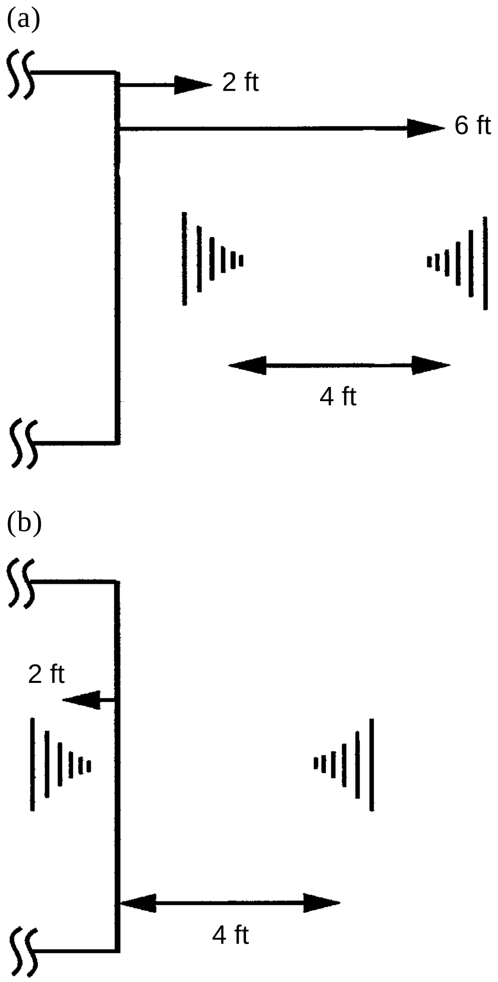


Figure 3. Top views of (a) mid-range calibration procedure (not to scale) and (b) mid-range measurement procedure (not to scale.)

At each frequency the transmit antenna current is recorded. The average of the maximum and minimum received signal is the calibration level for this input current. The receiver bandwidth is set at the same value used for the SE measurements, which is 1 kHz in all cases. The antenna height is 36 in. above the ground. The selected test frequencies are 350 and 850 MHz, which are greater than $3F_r$. During the SE measurements, the receive antenna center is kept at 2 ft from the inside wall surface while the transmit antenna center is kept at 4 ft from the outside wall surface. The center-to-center antenna separation is then 6 ft (fig. 3(b)). The wall thickness (0.5 in.) and the difference between calibration and measurement antenna separations are neglected as recommended in IEEE Std 299-1991.

Variations of the recommended procedures were investigated, such as calibrations in free-space versus near the shelter, and variations in the antenna separation. These experiments resulted in a 1- to 3-dB difference in received signal between the calibration and measurement configurations. This small difference is also typical of the variations observed during the calibration and measurement scanning procedures. Using an average of the calibration measurements and recording the maximum received signal for the SE measurements, as recommended in IEEE Std 299-1991, minimizes the importance of these small variations. The mid-range SE results would not compare directly to measurements taken with electrically small dipole antennas, but the difference should be less than 6 dB.

6. Preliminary Measurements

The preliminary scanning measurements recommended in IEEE Std 299-1991 were conducted at 20 MHz, which is much less than F_r, and at 350 MHz, which is much greater than F_r. The results indicated no significant problem areas except the door. Test points near the door showed SE reductions of several decibels, which depended on the pressure applied to the door's contact points. Since the HSS mockup has no other penetrations, the preliminary measurements indicated that all seams had been adequately soldered. The nonlinearity tests recommended in IEEE Std 299-1991 were not possible because of an insufficient measurement dynamic range. However, since the magnetic material is sandwiched between Cu sheets, no saturation effects would be expected at the field intensity levels used for testing [4].

7. Measurement Procedures

The low-range measurement procedure was in accordance with IEEE Std 299-1991, so the edge-to-edge antenna separation is 24.5 in. In all cases, the coplanar orientation of the loop antennas was used. We chose multiple test points to evaluate the SE of each shelter face, the corners, and around the door. However, the number of seams required for the installation of TI-Shield™ precluded the test locations specified in IEEE Std 299-1991. One test point (TP) at the center of each side was chosen as a representative panel measurement, and we scanned the nearby seams using the recommended technique. The TP locations relative to the soldered seams are indicated in figure 4 (where only the major seams soldered during installation are shown for clarity). The transmit antenna remained at the required polarization (horizontal (H) or vertical (V) with respect to the ground) while the receive antenna was displaced and rotated. The largest reading was recorded for each TP at each frequency. The TP nomenclature, antenna polarization, and location are described in table 2. The TP locations in the corners (C1 and C2) are accessible and were tested as recommended in IEEE Std 299-1991 with horizontal polarization of the coplanar loop antennas.

The mid-range measurement procedure is consistent with IEEE Std 299-1991, but the physical size of the LP antennas required the distances shown in figure 3(b). Each TP was tested using both polarizations of the matched antennas and the recommended scanning technique. In the scanning procedure the transmit antenna remained at a fixed polarization while the receive antenna was displaced and rotated. The largest reading was recorded for each TP at each frequency and polarization. This measurement (the minimum SE) was typically 2 to 3 dB larger and was observed near the solder locations.

Figure 4. Test point and seam locations.

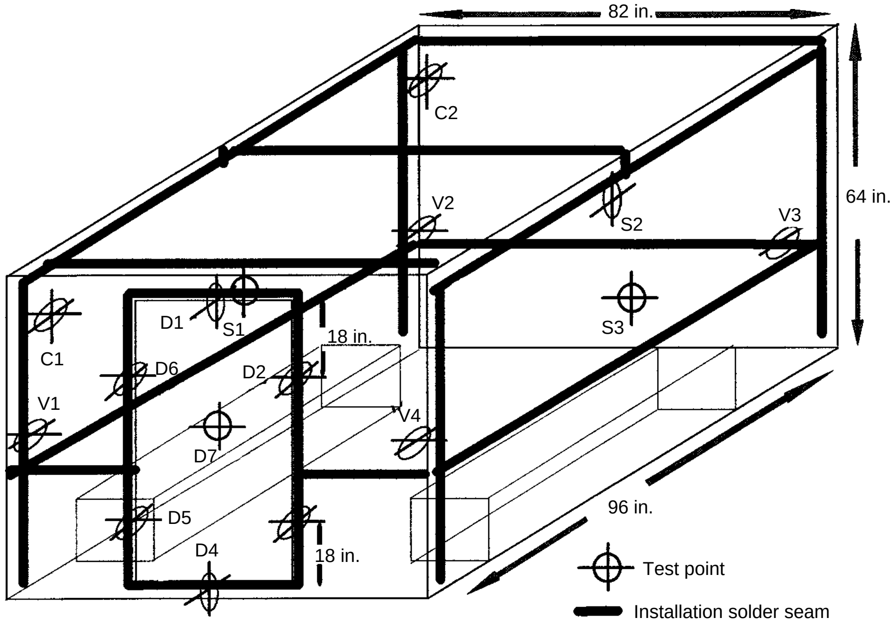


Table 2. Test point locations and antenna polarizations.

TP	Description	Location on HSS (see fig. 4)	Loop plane[a,b]	Log-periodic plane[a,b]
C1	Rear triple corner	Upper rear roadside corner	H	Diagonal
C2	Front triple corner, top	Upper front roadside corner	H	Diagonal
D1	Door top	Top door seam	V	H, V
D2	Right door seam, next to top	Curbside door seam	H	H, V
D3	Right door seam, next to bottom	Curbside door seam	H	H, V
D4	Door bottom	Bottom door seam	V	H,V
D5	Left door seam, next to bottom	Roadside door seam	H	H,V
D6	Left door seam, next to top	Roadside door seam	H	H, V
D7	Door center	Center of door	H, V	H, V
S1	Roadside wall	Center of roadside wall	H, V	H, V
S2	Front wall	Center of front wall	H, V	H, V
S3	Curbside wall	Center of curbside wall	H, V	H, V
V1	Vertical seam 1	Center of rear-roadside vertical seam	H, V	H, V
V2	Vertical seam 2	Center of front-roadside vertical seam	H, V	H, V
V3	Vertical seam 3	Center of front-curbside vertical seam	H, V	H, V
V4	Vertical seam 4	Center of rear-curbside vertical seam	H, V	H, V

[a] *With respect to the ground plane.*

[b] *Perpendicular orientation of receive antenna also used during the scanning procedure.*

Note: H = horizontal; V = vertical

8. Results

The results for each TP are based on the largest received signal in the scanning procedure for that TP. The substitution technique quantifies the measured SE, and the average of all measurements was calculated according to IEEE Std 299-1991. This average is included even for the *H*-field SE measurements as shown in table 3. According to IEEE Std 299-1991, the shelter SE should actually be reported as shown in table 4. For a local source, the lowest measured value is reported as the enclosure SE; for a distant source, the average of all measurements is reported as the enclosure SE. The lowest measured value and the average of all measurements excluding the door test points (TP D1 to D7) are also shown and characterize the enclosure SE without the door. The measured SE in the door area of the shelter indicates the quality of the door closure rather than the SE performance of the material. Thus, a good indication of the TI-Shield™ performance, when not limited by penetrations, is shown in table 4 by the standard results excluding the door test points.

Table 3. Shielding effectiveness test results.

Measurement location		Nominal shielding level (dB)				
		H-field at 24.5 in.			Plane wave at 72 in.	
Test point	Polarization	20 kHz	200 kHz	20 MHz*	350 MHz	850 MHz
D1	V	42	64	65	—	—
D2	H	44	63	64	—	—
D3	H	50	70	64	—	—
D4	V	43	60	65	—	—
D5	H	48	68	64	—	—
D6	H	45	62	64	—	—
D7	H	52	71	64	103	98
D7	V	53	71	65	100	89
S1	H	63	74	64	103	100
S1	V	63	75	65	105	104
S2	H	63	71	64	101	105
S2	V	63	71	65	102	104
S3	H	63	71	64	113	105
S3	V	63	71	65	106	104
V1	H	63	74	64	104	106
V1	V	—	—	—	103	101
V2	H	63	74	64	102	96
V2	V	—	—	—	103	104
V3	H	63	71	64	103	105
V3	V	—	—	—	105	104
V4	H	60	71	64	103	101
V4	V	—	—	—	103	100
C1	H	63	74	64	—	—
C2	H	63	75	64	—	—
	Average	59	71	64	104	102

**Exceeds measurement dynamic range at this frequency.*

Table 4. Shielding effectiveness of an HSS mockup.

		Standard results (dB)			
		Local source		Distant source	
Frequency	Type of measurement	With door	Without door	With door	Without door
20 kHz	H-field	42	60	59	63
200 kHz	H-field	60	71	71	73
20 MHz*	H-field	64	64	64	64
350 MHz	E-field	100	101	104	105
850 MHz	E-field	89	96	102	103

**Exceeds measurement dynamic range at this frequency.*

For comparison, the calculated *H*-field SE for 10-mil-thick Cu is about 50 dB at 20 kHz and 70 dB at 200 kHz. The calculated SE for 6-mil-thick A49 (μ_r = 2500) is about 28 dB at 20 kHz and 100 dB at 200 kHz [3]. If the exact construction and EM properties of the layered material are known, the effective media approximation (i.e., a weighted average according to layer thickness) can be used to estimate the average electrical parameters [8]. For a roller-bonded material, such a model is difficult to determine exactly, as the interface between layers is not well defined. This model does not include the additional reflective losses at the Cu / A49 interfaces. This impedance mismatch must be included [9] and explains why the TI-Shield™ structure performs better than A49 / Cu / A49 or steel five times as thick [10].

The measured enclosure SE is expected to be less than that predicted for an infinite planar slab, since the field diffusion through the soldered seams typically limits the SE in practice. This is true even for well-formed seams where the field leakage (aperture coupling) is small but the field diffusion through the seam is still larger than that through the shield material. The measured SE also depends on the enclosure size and increases proportionally to the ratio of volume to surface area, so larger structures demonstrate a higher SE [11]. For TI-Shield™, magnetic contact is not maintained across the soldered seam and a slot model can be used to estimate the *H*-field transmission per meter of slot length. For soldered seams (90-percent In / 10-percent Sn) with a 1-cm overlap and 25-µm solder thickness, the *H*-field SE of a 1-m slot is on the order of 57 dB at 20 kHz [9]. According to Gaven Industries the solder thickness is typically 25 µm, so the TI-Shield™ seams should have better performance since the overlap is at least 2.5 cm.

The data indicate that the *H*-field SE (neglecting door leakage) is limited to about 70 dB at 20 kHz by this *H*-field diffusion through the nonmagnetic solder joints. This limiting effect can be somewhat improved by using fewer seams, a larger overlap, different solder, etc, but the *H*-field diffusion through the seams is expected to be greater than that through the TI-Shield™ material at frequencies below about 100 kHz. The measured data indicate that a TI-Shield™ structure can readily meet the EM shielding requirements of MIL-STD-907B, MIL-STD-188-125 [12], or the National Security Agency Specification No. 65-6 [13].

9. Conclusions

The HSS mockup constructed for these tests represents a nonconductive (i.e., nonmetallic) command-post-size shelter. Gaven Industries did the TI-Shield™ installation using standard construction and soldering techniques. The door design provided the most practical means of frequent shelter access while maintaining good electrical contact. Thus, the shielded HSS mockup represents an EM-hardened tactical shelter where the SE performance is somewhat limited by the lack of an rf fingerstock door. TI-Shield™ applied to conducting (or poorly conducting) shelters should demonstrate an even larger SE, which is typically limited by the performance of the door and penetrations.

The results demonstrate that 10-mil TI-Shield™ can satisfy the EM-shielding requirements of MIL-STD-907B in the frequency range 150 kHz to 10 GHz. The verification testing specified in MIL-STD-907B is in accordance with MIL-STD-285, which has been superseded by IEEE Std 299-1991. The tests were thus conducted according to IEEE Std 299-1991 except as specifically indicated. The results are compiled and reported according to IEEE Std 299-1991, except that the standard results neglecting the door measurements are included for comparison. Even without an rf fingerstock shielded door, the HSS mockup has good EM performance and would pass the SE requirement of MIL-STD-907B. The material is extremely cost effective, lightweight, and can be readily installed using standard techniques. Discounting the reduced SE of the door, 10-mil TI-Shield™ is an effective solution to meet (or exceed) typical SE requirements. New standards are currently being developed for shielded enclosures where the low-frequency SE requirement will be reduced [14]. In this case, even a very thin clad metal would be an attractive alternative for EM shielding compared to welded Al shields.

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