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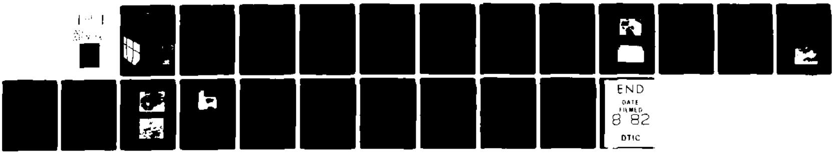

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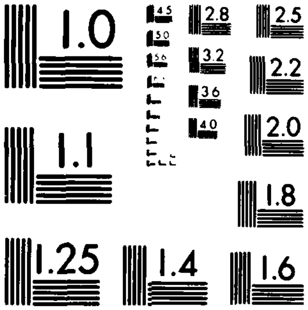

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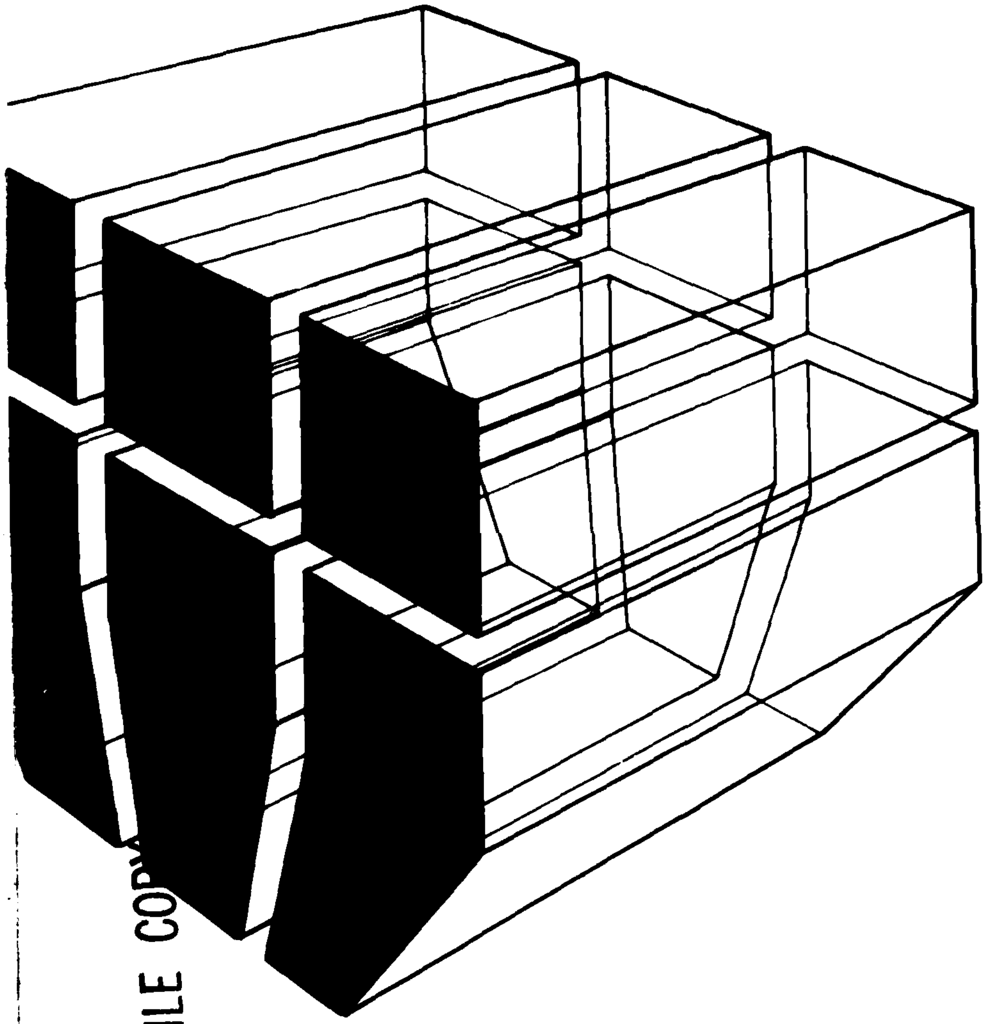
TECHNICAL REPORT M-316
June 1982
Laboratory Evaluation of EMP/EMI Shielded
Enclosure Performance and Design Standards

ARC-SPRAYED METALS FOR STRUCTURAL ELECTROMAGNETIC SHIELDING



by
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CERL

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Electromagnetic shielding tests of small samples (2 ft by 4 ft or 0.61 m by 1.22 m) of arc-sprayed metals on typical construction materials were conducted to determine the feasibility of using arc-spray technology to provide a low-cost method of shielded construction. Test results indicate that such panels can provide significant shielding and that this technology may be useful for applications having a low shielding requirement. In an additional study, it was determined that arc-spraying of leaky seams of conventional modular shielded construction can provide increased electromagnetic shielding.

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FOREWORD

This investigation was performed for the Directorate of Military Programs, Office of the Chief of Engineers (OCE), under Project 4A762719AT50, "Mobility, Soils, and Weapons Effects"; Technical Area A0, "Weapons Effects and Protective Structures"; Work Unit 015, "Laboratory Evaluation of EMP/EMI Shielded Enclosure Performance and Design Standards." The applicable QCR is 1.03010. The OCE Technical Monitor was Mr. Paschal Brake, DAEN-MPE-E.

This investigation was performed by the Engineering and Materials Division (EM), U.S. Army Construction Engineering Research Laboratory (CERL). Dr. Robert Quattrone is Chief of CERL-EM.

COL Louis J. Circeo is Commander and Director of CERL, and L. R. Shaffer is Technical Director.

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ARC-SPRAYED METALS FOR STRUCTURAL ELECTROMAGNETIC SHIELDING

1 INTRODUCTION

Background

Structures are usually electromagnetically shielded by placing a sheet metal skin around the volume to be shielded. Ideally, for maximum shielding performance, this skin must be electrically and mechanically continuous. Typically, shields are constructed of bolted modular systems or welded metal sheets. In general, the shielding performance of bolted construction will be less than that of welded construction because of surface oxides, surface and shape imperfections, and differences in bolt torque. Either construction technique is relatively expensive.

Electromagnetic shielding of Corps of Engineers-related construction may be necessary wherever Army Technical Manual (TM) 5-855-5, NSA No. 65-6 (secure communications), or other electromagnetic compatibility or interference reduction requirements exist.[1] To help the Army cut its shielding costs, the U.S. Army Construction Engineering Research Laboratory (CERL) proposed and conducted an investigation of the performance of arc-sprayed metals for structural electromagnetic shielding. Molten metal spraying is a recently developed technology which may offer an economical alternative to bolt and welded construction for upgrading modular shielded construction, converting nonshielded metallic construction to shielded construction, or supplying a metal shielding skin.

Objective

The objective of this study was to determine whether it was feasible to use arc-sprayed metals as an economical means of (1) providing electromagnetic shielded construction by depositing metals on typical construction materials, and (2) upgrading existing modular shielded construction by sealing radio frequency leaks in seams.

Scope

This study only determined electromagnetic shielding effectiveness and related parameters of arc-sprayed metals on test panels of construction materials. No full-scale structure tests or long-term durability tests were conducted.

Approach

Test panels of construction materials covered by arc-sprayed metals were prepared and shielding effectiveness tests conducted. The thickness of the deposited metal was estimated by weighing the sample before and after arc spraying using densities determined at CERL. Electrical conductivity and density measurements were made on strips of arc-sprayed metal deposited on mylar and then peeled off. Adhesion to concrete was measured using especially prepared samples with a 1-sq-in. (645.2-mm^2) surface. Special care was taken to ensure a deposited metal thickness that was as uniform as possible for all tests.

Mode of Technology Transfer

The information presented in this report will be used for updating TM 5-855-5.

2 TECHNICAL DISCUSSION: METAL SPRAYING PROCESSES

There are two commercial processes for spraying molten metals to produce a metal coating: flame-spraying and arc-spraying. The flame-spraying process uses an acetylene flame to melt the metal, which is then propelled to the surface being sprayed by a compressed air stream. The arc-spraying process uses metal wires as consumable electrodes. An arc is drawn between two wires; as the wires melt, a compressed air steam propels molten metal droplets to the surface being sprayed. Wire feed rate, arc current, and air flow rate are adjusted to control droplet size and coating quality.

CERL chose the arc-spraying process for its laboratory studies because:

1. The arc-melted metal droplets are at a higher temperature than flame-melted metal droplets when sprayed, giving greater bond strength.

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[1] *Nuclear Electromagnetic Pulse (NEMP) Protection*, Army Technical Manual (TM) 5-855-5 (Department of the Army, February 1974); and *RF Shielded Enclosures for Communication Equipment*, NSA No. 65-6 (National Security Agency, October 30, 1964).

2. The arc-spraying process can deposit metal three to five times faster than the flame-spraying process.[2]

3. No combustion heat is present in the arc-spray process, and the generated heat is confined primarily to the metal droplets. Thus, less heat is transferred to the surface being sprayed, making it safer to spray plastics and other combustible materials.

The arc sprayer used by CERL for this study was an Arcsprayer 375, manufactured by TAFA Metalization, Inc., of Concord, NH. This machine feeds wire from spools through an electrode assembly, which transfers current to the wire. The wire then is vaporized in the arc formed between the wires. Figure 1 shows the arc-spraying process in operation. (The arc in Figure 1 was adjusted for good visibility, and not necessarily for good coating properties.)

Sample Preparation

CERL has a high-performance, shielded room with a "window" 4-1/2-ft long by 2-1/2-ft wide (1.37-m long by 0.76-m wide). Sample panels are bolted over this window to test their shielding effectiveness. Figure 2 shows a test sample in place on the shielded room window along with a magnetic field loop antenna used for shielding tests. The shielding test samples for this study were all 4-1/2 by 2-1/2 ft (1.37 by 0.76 m). They consisted of different arc-sprayed metals and different metal thicknesses deposited on a base material of 1/8-in. (3.175-mm) hardboard. In addition, a concrete panel was coated with steel. In general, it was found that a thin layer of arc-sprayed zinc had to be placed on the hardboard before steel would adhere to it. This was also true for the concrete test sample. The concrete panel was 4-1/2- by 1-1/2-ft by 1-in. thick (1.37- by 0.76-m by 25.4-mm thick). Mesh wire reinforcement was used only around the bolt holes in the concrete.

The test samples used for this study were all relatively thin layers, although there is no practical reason to limit the deposited metal thickness—other than material cost and application time.

Samples for density and conductivity measurements were arc-sprayed onto mylar sheets; the adhesion between the metal and the mylar is such that the deposited metal can be removed intact from the mylar.

Arc Spraying a Buckled Seam

A test sample consisting of a slotted base panel covered with a smaller panel was constructed to test various seam configurations (Figure 3). The two panels were made of aluminum and attached using screws spaced 2 in. (50.8 mm) apart. For this test, 0.042-in. (1.06-mm) plastic spacers were placed between the screws to simulate buckling (Figure 4). The test sample was sandblasted to remove oxidation from the aluminum surface. The seam was then arc-sprayed with zinc so that the sprayed metal completely covered the gaps caused by the buckling. Shielding effectiveness tests were made by mounting the sample on the window of the shielded room. The results of the shielding tests are plotted in Figure 5. Since the shielding effectiveness increased considerably, it appears that arc-spraying seams can be a very effective method for improving the shielding performance of a bolted seam structure.

Dissimilar metals used for such repair of leaky seams may be subject to galvanic induced corrosion. This can be eliminated, however, by protecting the sprayed area from moisture.

Bond Strength of Arc-Sprayed Materials on Concrete

Bond strength or adhesion between arc-sprayed metals and concrete was measured in accordance with American Society for Testing and Materials (ASTM) Standard C 633-79.[3] The basic technique can be understood by looking at Figure 6. One face of a concrete substrate is coated with the metal to be tested (Figure 7), then bonded to the face of a loading fixture. Next, this assembly is subjected to a tensile load normal to the plane of the coating. Ten zinc, 15 tin, and 10 low-carbon steel samples were tested. The concrete surface was sandblasted before arc-spraying to ensure that the metals would adhere to the concrete.

The test results are summarized in Table 1. Although only a limited number of tests were conducted, the bond strength appears to be a function of surface roughness, porosity of the material substrate, and arc parameters such as stand-off distance, air atomization pressure, electrode feed rate, and arc current.

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[2] D.R.J. White, *A Handbook on Electromagnetic Shielding Materials and Performance* (Don White Consultants, 1975), p 216.

[3] *Standard Test Method for Adhesion or Cohesive Strength of Flame-Sprayed Coatings*, ASTM C 633-79 (American National Standards Institute [ANSI]/American Society for Testing and Materials [ASTM], 1979).

Figure 1. Arc-spraying steel onto a panel surface.

Figure 2. Test panel in place on CERL's shielded room.

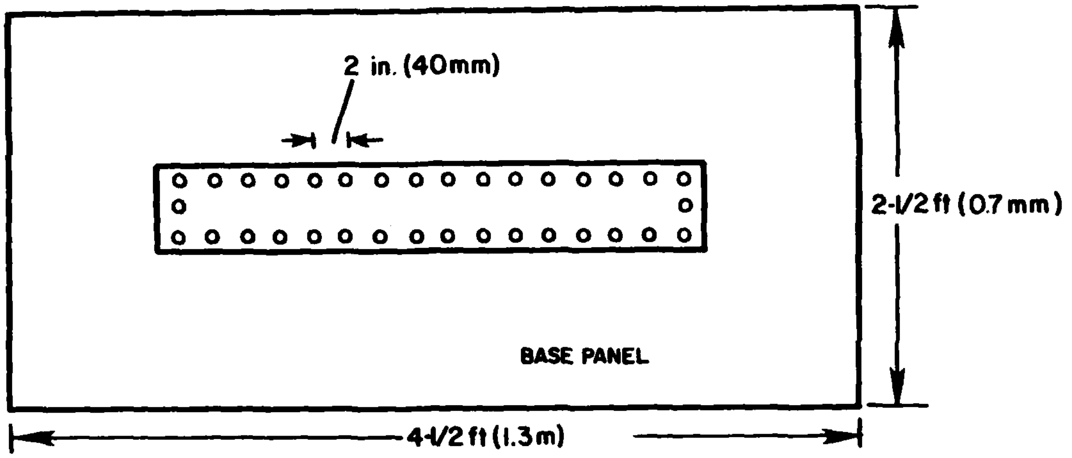

Figure 3. Test panel with buckled seam.

Density Measurements

The dimensions and weight of the zinc, tin, and steel samples arc-sprayed at CERL were used to determine the samples' density. The metals first were deposited on a mylar substrate, then 2- by 2-in (50.8- by 50.8-mm) samples were removed from the mylar. The samples were weighed and their thicknesses measured. The density of the deposited metals is a function of the atomizing air pressure. For this test, the air pressures ranged from 70 to 80 psi (480 to 550 kPa). The results of the density measurements are given in Table 2. In the table, CERL's values are compared with the densities of arc-sprayed material measured by TAFA Metalization, Inc., and the densities of the bulk metal.[4] CERL's density values were somewhat less than those obtained by TAFA Metalization, Inc., but both were less than the density values of the bulk metal.

Table 1

Bond Strength Between Arc-Sprayed Metals and Concrete

Zinc

Range: 50-275 psi*
n = 10**
$\bar{x}$ = 154.5 psi
s = 95.2 psi

Tin

Range: 95-485 psi
n = 15
$\bar{x}$ = 270.3 psi
s = 121.9 psi

Low-Carbon Steel

Range: 280-450 psi
n = 10
$\bar{x}$ = 360 psi
s = 85.4 psi

*Metric conversion: 1 psi = 6.89 kPa.
**Where: n = number of samples
$\bar{x}$ = mean
= the standard deviation

Concrete Panel Tests

For the concrete panel test, a 1-in.-thick (25.4-mm-thick) concrete panel was poured 2-1/2 by 4-1/2 ft (0.76 by 1.37 m); bolt holes were drilled to match those of CERL's all-welded shielded room window. Mesh wire reinforcement was placed around the periphery of the panel to reinforce the bolt holes. (The center of the panel did not contain reinforcement.) A thin undercoat of zinc was placed so the steel would adhere to the concrete. The arc-sprayed steel coating on the concrete was about 30-mils (0.0645-mm) thick. The thickness was estimated by controlling the duration of the arc-spraying operation. The panel was mounted on the shielded room, and shielding tests were conducted. The results are shown in Table 3 and plotted in Figure 8.

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[4] *TAFA Arc-Spray Zinc Wire-02E*, File 1.9.1.2-02E; *TAFA Arc-Spray Tin Alloy Wire-02C*, File 1.9.1.2-02C; and *TAFA Arc-Spray Low-Carbon Steel Wire-30E*, File 1.9.1.2-30E (TAFA Metalization, Inc., June 1981 and September 1980).

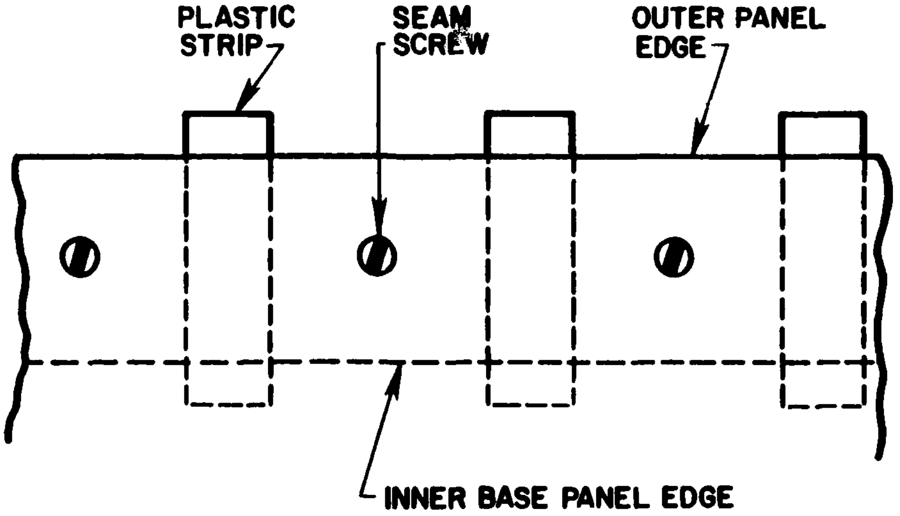

Figure 4. Detail of buckled seam simulated by plastic inserts.

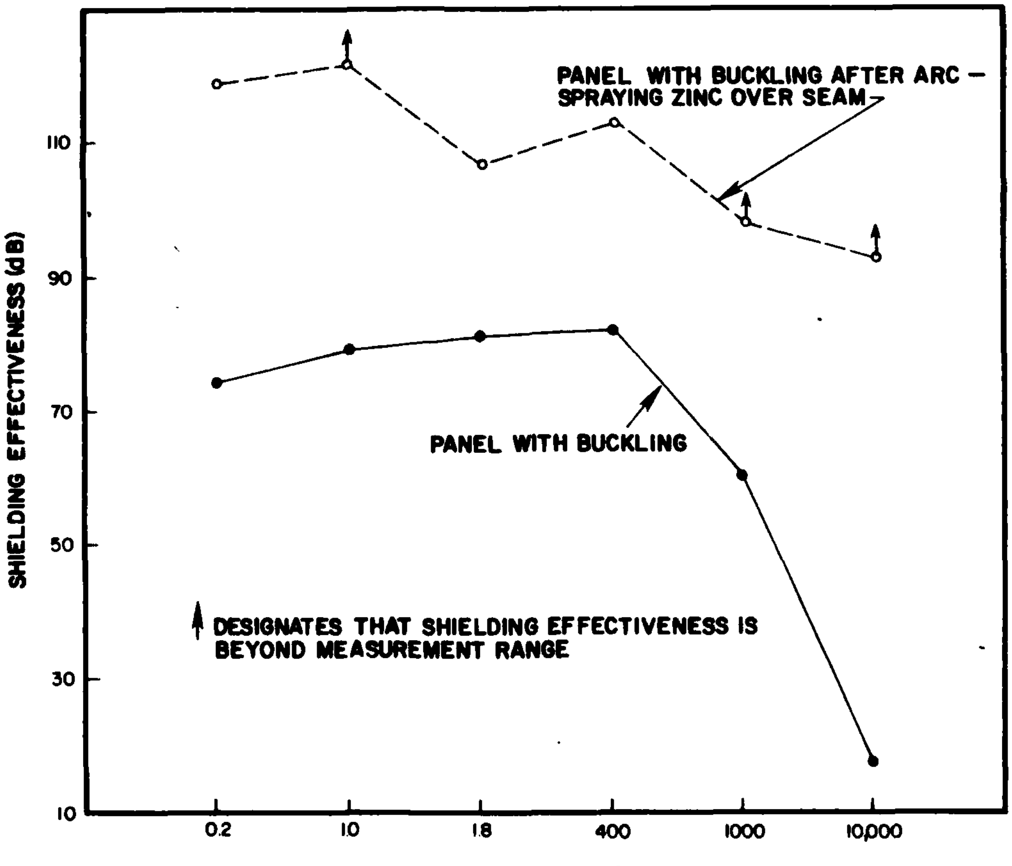

Figure 5. Shielding effectiveness changes caused by arc-spraying a buckled seam.

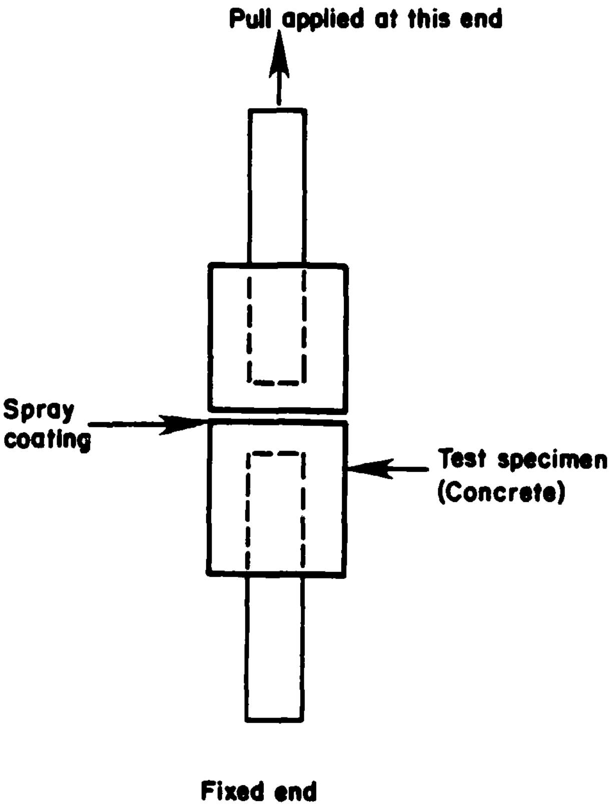

Figure 6. Adhesion test for flame-sprayed materials (ASTM C 633).

Figure 7. Test samples for adhesion of arc-sprayed metal to concrete.

Table 2
Densities of Arc-Sprayed Metals

Metal	CERL Density	TAFA Density	Bulk Metal
Zinc	0.335 gm/mm^3	0.636 gm/mm^3	0.714 gm/mm^3
Tin	0.546 gm/mm^3	0.65 gm/mm^3	0.731 gm/mm^3
Steel	0.432 gm/mm^3	0.678 gm/mm^3	

Conductivity Determination

Samples of arc-sprayed tin and zinc were produced by arc-spraying the material onto a mylar sheet and cutting a 1.97- by 0.39-in. (50- by 10-mm) strip from the sample. The metal could be peeled easily from the mylar without damage, simplifying thickness measurements. The conductivity was determined by measuring the resistance of the metal strip with a Keithley Model 502A milliohmeter. The resistivity of the material is then:

$$\rho = \frac{RA}{L} \qquad \text{[Eq 1]}$$

where: ρ is the resistivity in ohm mm

R is the measured resistance in ohms

A is the cross-sectional area of the strip in millimeters

L is its length in millimeters.

The results of these measurements are given in Table 4. In the table, resistivity values for bulk materials are listed for comparison; the same measurements were made on a sample of aluminum foil. In each case, it was found that the resistivity of the metal strips was considerably higher than published values for the resistivity of the bulk metal.

Table 3
Shielding Effectiveness of Arc-Sprayed Steel on a Concrete Panel

Frequency	Shielding Effectiveness
10 kHz	9 dB
50 kHz	20 dB
200 kHz	31 dB
1 MHz	46 dB
10 MHz	64 dB
30 MHz	76 dB
450 MHz	70 dB
2.5 GHz	58 dB
9.5 GHz	52 dB

Electron Microscope Photographs of Arc-Sprayed Metals

Electron microscope photographs of arc-sprayed zinc and steel were taken at magnifications of 140x and 1400x (Figure 9). These photographs were taken to examine the microstructure of the deposited metals. The 1400x photograph shows an area of 3.20 X 10^{-3} by 2.53 X 10^{-3} in. or 8.14 X 10^{-2} by 6.43 X 10^{-2} mm. The typical estimated thickness of the deposited metal on the test panels produced for this study was on the order of 2.0 X 10^{-3} to 5.1 X 10^{-3} in. (7.9 X 10^{-5} to 2.0 X 10^{-4} mm). Thus, the dimensions of the 1400x photograph are on the same order of magnitude as the thickness of the deposited metal. From these photographs, it appears that nonuniformities may extend through a good percentage of the deposited metal thickness. Metals with such a microstructure will have a lower conductivity than the bulk material. Thus the maximum achievable shielding effectiveness obtainable from the arc-sprayed metal will be decreased from the theoretical value for a given thickness. Annealing of the arc-sprayed metal may help in obtaining a higher shielding effectiveness from the material.

Shielding Tests

The arc-sprayed test samples were mounted on the window of CERL's shielded room and electromagnetic shielding effectiveness tests conducted over a range of frequencies (Figure 10). Table 5 lists the samples on which these tests were conducted. (The samples listed as Panels 1 through 6 were tested as part of a previous study.)[5]

The test results are plotted in Figures 11 through 14. The plots indicate that all sprayed metals produce significant shielding (considerably more than would result from conductive paint, but somewhat less than might be expected from sheet metal). The data in Figures 13 and 14 show that the shielding effectiveness increases with increasing thicknesses of deposited

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[5] *Study of EMI/RFI Shielding of Tactical Shelters*, ESL-TR-80-24 (U.S. Air Force Engineering and Service Center, April 1980).

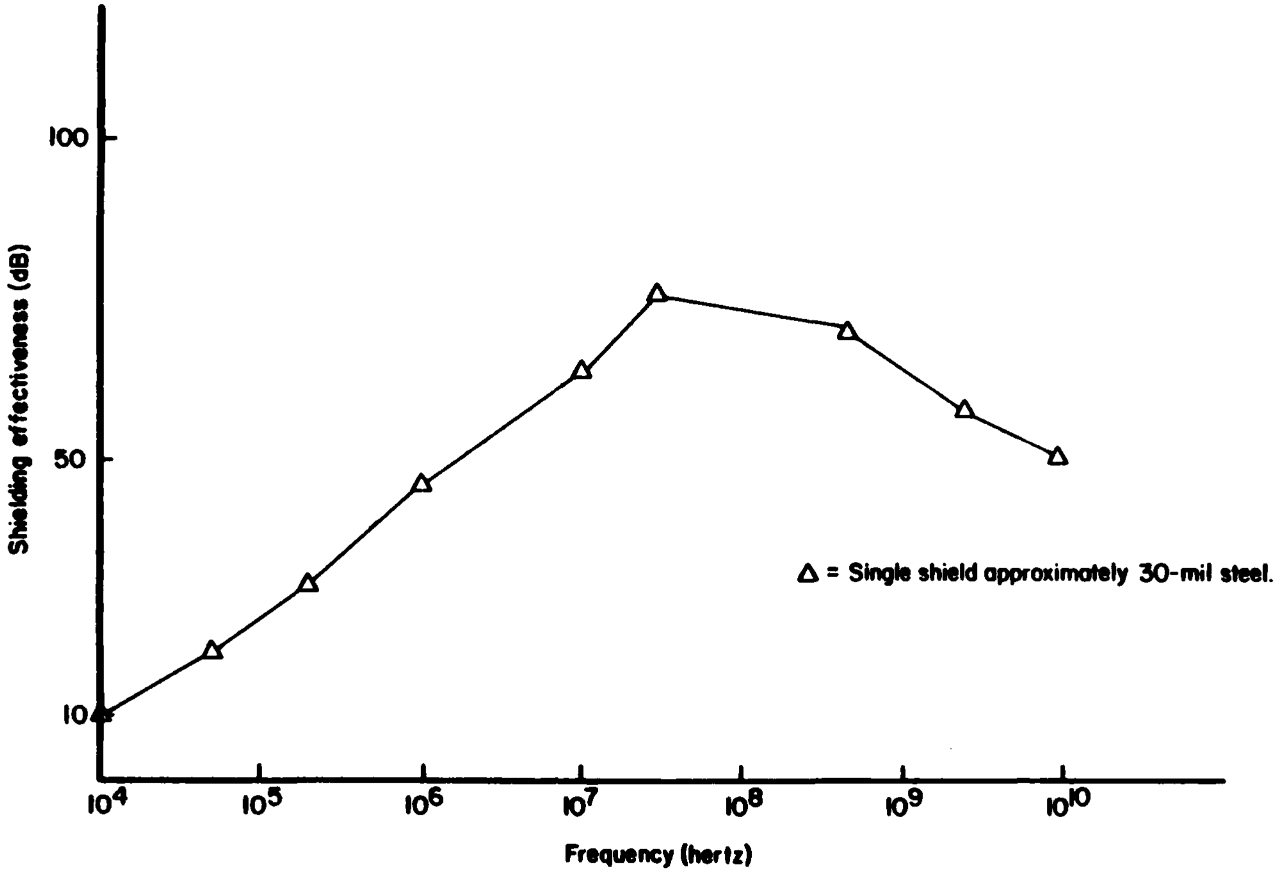
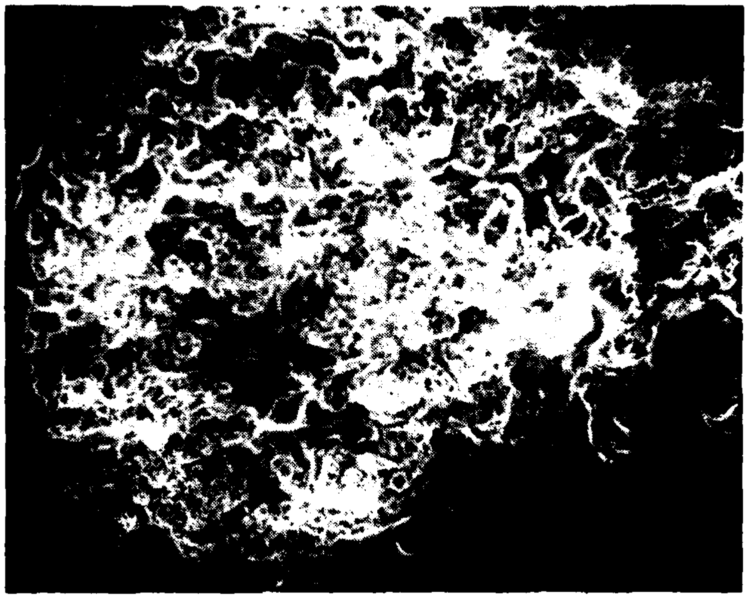


Figure 8. Shielding effectiveness of arc-sprayed steel on concrete.

Table 4
Electrical Conductivity and Resistivity of Arc-Sprayed Metals

Material	Dimensions (mm) (l × w × t)	Resistivity (ohm-mm)	Conductivity (mho/mm)	Resistivity of Bulk Material (ohm-mm)
Zinc	50 × 10 × 0.33	2.31×10^{-6}	4.33×10^{5}	6×10^{-7}
Tin	50 × 10 × 1.65	3.3×10^{-6}	3.03×10^{5}	11.4×10^{-7}
Aluminum foil	50 × 10 × 0.254	4.42×10^{-6}	2.26×10^{5}	2.62×10^{-7}



a. 140x

b. 1400x

Figure 9. Electron microscope photographs of arc-sprayed steel.

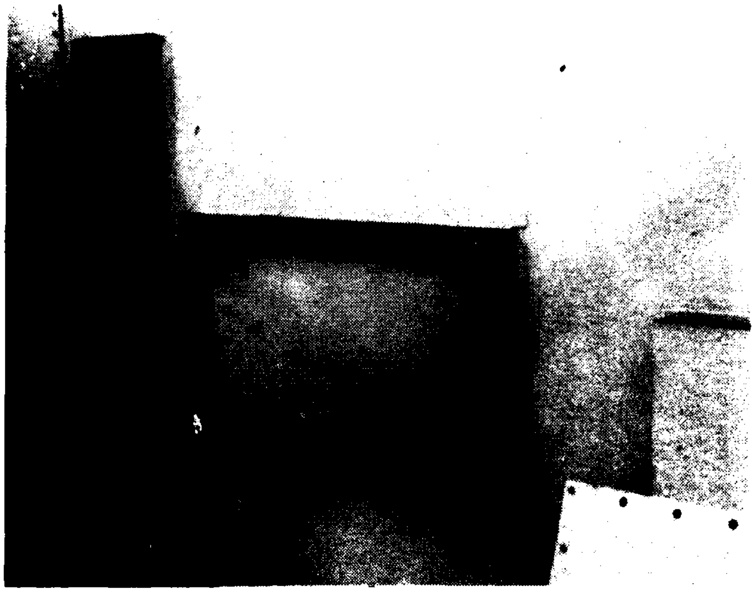


Figure 10. Panel mounted on shielded room for shielding effectiveness tests.

Table 5
Arc-Sprayed Test Panels Subjected to Electromagnetic Shielding Tests

Sample	*Material*	*Substrate*	*Thickness (inches)**
Panel 1	Nickel over zinc	Hardboard	Ni = 0.00091, Zn = 0.002
Panel 2	Steel over zinc	Hardboard	Steel = 0.001, Zn = 0.002
Panel 3	Nickel-steel mix over zinc	Hardboard	Ni-Steel = 0.0024, Zn = 0.002
Panel 4	Zinc	Hardboard	0.0024
Panel 5	Zinc-nickel-steel	Hardboard	Zn = 0.003, Ni = 0.0091, Steel = 0.0012
Panel 6	Zinc-steel-nickel	Hardboard	Zn = 0.0026, Steel = 0.0012, Ni = 0.001
Panel 7	Zinc	Hardboard	0.0054
Panel 8	2 coatings zinc	Hardboard	0.019
Panel 9	2 layers zinc	Hardboard (both sides)	0.012
Panel 10	Tin	Hardboard	0.0028
Panel 11	2 coatings tin	Hardboard	0.0084
Panel 12	2 layers tin	Hardboard (both sides)	0.018
Panel 13	Steel over zinc	Concrete	≈0.030

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*Metric conversion: 1 in. = 25.4 mm.

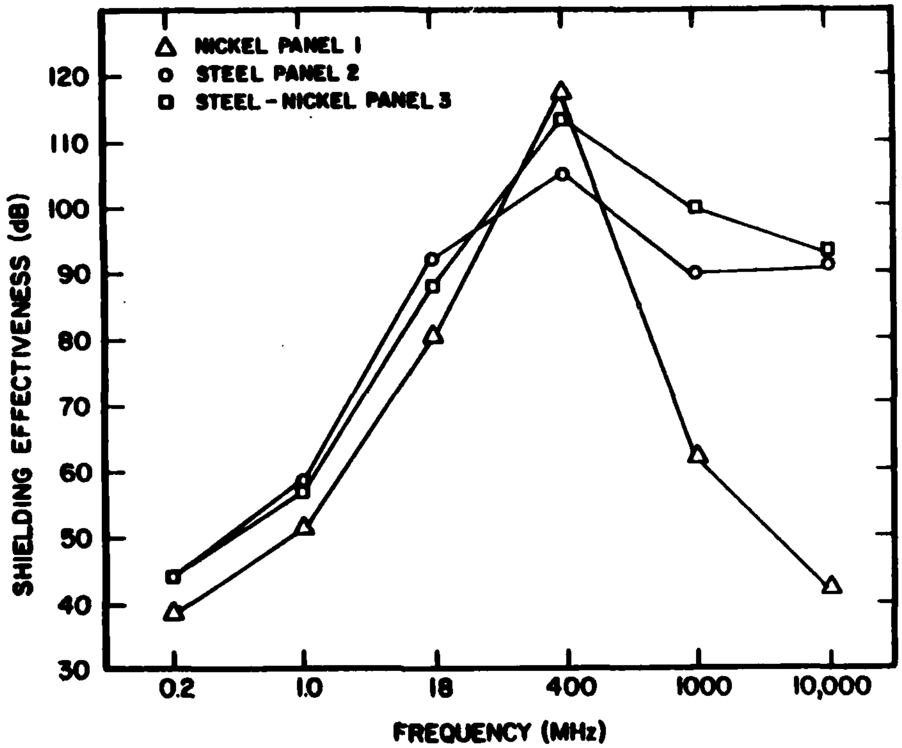

Figure 11. Shielding effectiveness comparison between arc-sprayed nickel and steel layers, and homogeneous mix.

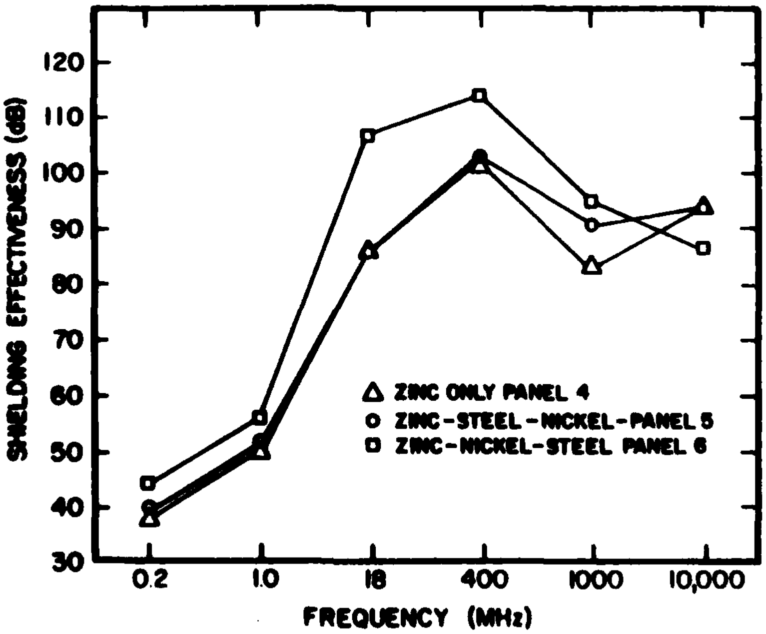

Figure 12. Shielding effectiveness comparison between composite arc-sprayed metals.

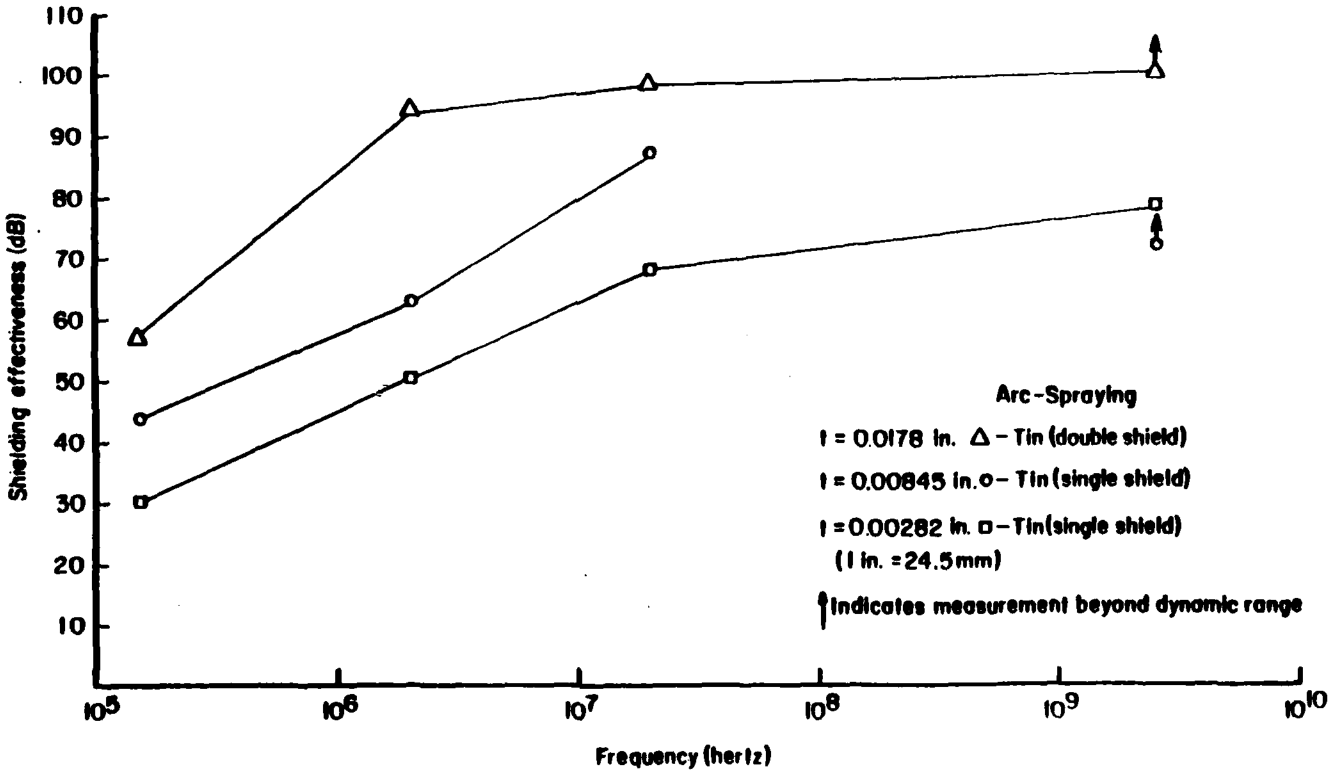

Figure 13. Shielding effectiveness of arc-sprayed tin.

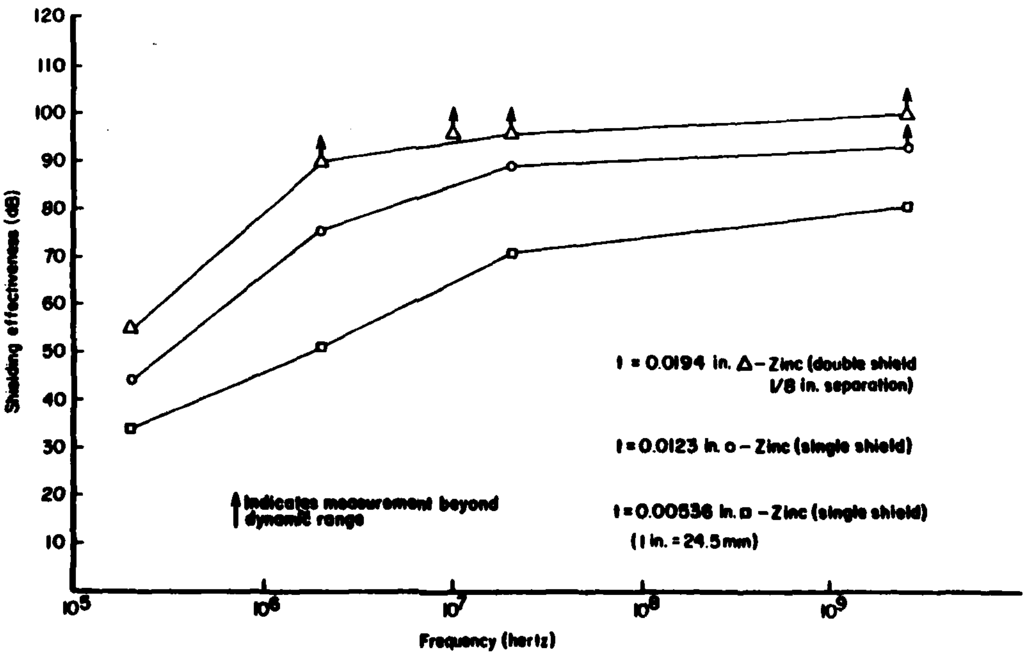

Figure 14. Shielding effectiveness of arc-sprayed zinc.

metal. Unfortunately, it is not possible to isolate the effects of separating the layers of metal from the effects of additional metal thickness in these plots. While it is difficult to compare the relationships of shielding effectiveness vs metal type from these data, it appears that, in general, the shielding effectiveness is proportional to the conductivity of the arc-sprayed metal.

Theoretical Shielding Effectiveness

The measured values for sample thicknesses used for the conductivity measurements, and the values of conductivity for arc-sprayed tin, zinc, and aluminum foil, were used in a CERL computer program to determine theoretical values for shielding effectiveness. The results of these calculations are plotted in Figure 15. While direct comparison with measured values is difficult because of the differences in thicknesses, the test results compare favorably with the theoretical values, with the exception of the high-frequency measurements. Shielding values at the high-frequency end appear low, either because of equipment dynamic range limits or because the actual shielding is lower due to reduced electrical conductivity of the metal caused by the irregular microstructure of the arc-sprayed metal. Most of the measured shielding effectiveness of the thin layers of metal tested at CERL is probably due to reflection losses caused by the impedance mismatch at the air-metal interface. Absorption losses through the material are probably negligible.

Arc-Spray Cost Analysis

TAFA Metalization, Inc., estimates it would cost \$1.09/sq ft (\$11.75/m^2) to arc-spray zinc over plastic and fiberglass equipment enclosures to provide EMI/RFI shielding. This cost estimate assumes that the process is conducted at a plant location.[6] Field location arc-spraying costs may be somewhat different, but

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[6] *Application Data*, File 2.4.3.1 (TAFA Metalization, Inc., November 10, 1980).

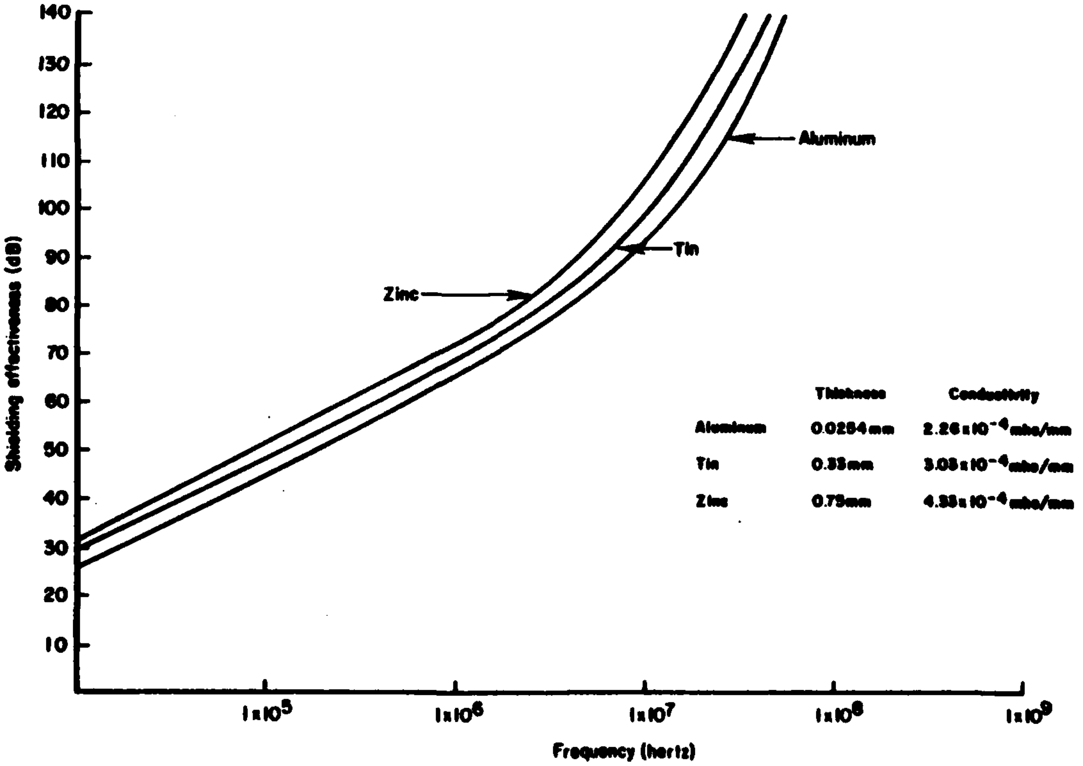

Figure 15. Theoretical shielding effectiveness of thin metal layers.

probably would be on about the same order of magnitude. Additional costs for shielded structures would include the same items required for conventional shielded construction, e.g., doors, electrical filters, and air vent filters. While the feasibility of providing electromagnetic shielding by arc-spraying metals has been established, a complete experimental shielded room has not yet been constructed. It may be more practical to provide modular panels arc-sprayed off-site and limit on-site arc spraying to seams. The cost of off-site and on-site preparation should not be significantly different.

Current cost estimates (new construction) for clamp-together, or modular, and welded construction are approximately $10 to $15 per square foot of surface area (walls, floor, and ceiling). Costs for doors and electrical filters are additional.

Summary

The results of these studies indicate that arc-spraying of leaky seams of modular shielded construction is a feasible technique for upgrading the shielding of these structures. The sprayed metals should be picked so that galvanic corrosion will not occur, or the sprayed seams should be protected from moisture.

The arc-sprayed metals placed on the construction materials provided significant shielding. These results should justify full-scale testing on room-sized structures. The concept may be especially useful for retrofit shielding in existing construction, especially if the shielding requirement is relatively low. Conventional shielded construction for retrofit application can be quite expensive.

Higher shielding levels than those observed should be possible by depositing thicker layers of metal.

3 CONCLUSIONS

This study was conducted to determine the feasibility of using metal arc-spray technology as an economical technique for providing electromagnetic shielded construction, or for upgrading shielded structures. Test results indicate the process can find application in both areas. Improved shielding in conventional modular shielded construction can be provided by arc-spraying the seams until all the gaps are bridged. Zinc appears to be a satisfactory material for this application. Zinc, tin, and steel can provide significant shielding when deposited on construction materials. The measured conductivity of the arc-sprayed materials is a function of the arc parameters and is somewhat less than the conductivity of the bulk materials. This means that the shielding provided by attenuation through the metal is less than the attenuation which would be expected from an equivalent thickness of the bulk metal. However, most of the shielding for thin layers is probably due to reflection losses. The differences in conductivity will have less relative effect in reducing reflection losses. The impedance mismatch between air and metal interfaces, which is responsible for the reflection loss, is not changed significantly by the difference in conductivity.

Specifically, this study concluded that:

1. Arc-spraying metals on construction materials can provide significant shielding at reasonable material and labor costs.

2. Arc-spraying metal over a leaky seam provides a considerable improvement in shielding effectiveness, effectively sealing the leak.

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