# CONDUCTIVE COATINGS/GASKETS FOR EMI SHIELDING: THEORY AND PRACTICE

Design engineers should be aware of discrepancies between theoretical expectations of component shielding effectiveness and actual performance.

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## INTRODUCTION

The establishment of FCC rules on the permissable levels of noise emission (Part 15, Subpart J) has made EMI a major concern for both the design and manufacturing engineers of electronic devices. The penalty for non-compliance with the FCC rules is serious enough that new service industries have been created for the much needed knowledge on compliance.

The use of conductive coatings is one method to achieve EMI/RFI suppression for molded plastic enclosures.[1,2] This article will differentiate conductive coatings from gaskets/sealants and adhesives according to the following criteria: Coatings include those materials with less than 10-mils in thickness, whereas gaskets/sealants/adhesives will be defined as materials with thicknesses of at least 50 mils or more. The thickness is defined as the minimum distance through the shielding material the EM wave must travel to affect the enclosed device.

In addition to the thickness relationship, there are differences in the types of signals that must be shielded. These can be primarily divided into three categories: Near-field (dominated by the magnetic component), far-field (plane-wave which has both electric and magnetic components in more or less the same magnitude), and electromagnetic pulse (EMP). EMP signals consist of both magnetic and electric components of very large magnitude between 10 kHz and 100 MHz.

In the case of shielding against far-field emissions using coatings, the theory of plane-wave applies and exact analytical solutions exist. This theory shall be applied to the case of pure metal coatings, as well as conductive plastic coatings, with volume resistivities of 2 to 0.0005 ohm-cm, which are common characteristics of typical carbon, nickel, copper, and silver paints. In addition, a silver coating with 0.00005 ohm-cm resistivity has been developed. Calculations based on plane-wave theory with the assumption of coating resistivity covering this range of conductivity will be reported. This predicted shielding effectiveness will be compared with an EMI/RFI paint of which typical shielding effectiveness is enhanced by means of its magnetic properties.

In the case of gasket/adhesive/sealant applications, the plane-wave theory is also applicable when the shielding requirement is in the far-field regime. However, the thickness dependence would be very different from that of coating. Such a drastic difference will have strong effects on the design of electronic cabinets as well as aerospace enclosures. An understanding of these basics will save time and money.

In the near-field application, where magnetic field is an important factor, the theory is not so straightforward. While some prediction based on theoretical analysis can be performed, the general usefulness of such analysis is very limited. Careful analysis is of particular importance for those frequencies below 10 MHz. Some of the military applications call for shielding effectiveness of up to 60dB at 10 kHz. Shielding against the magnetic component is of extreme importance at this frequency. This article shall be limited to discussions of common experiences in this application area.

## EMI/RFI SHIELDING THEORY

The shielding effectiveness of a homogeneous medium, suchas coatings/sealants/adhesives and gaskets, is directly related to the propagation of electromagnetic (EM) field through that medium. The propagation of the EM wave is, however, directly related to the electronic and magnetic property of the media and the interfaces between the media. In almost all cases, one of the media is normally air. In this analysis, it is sufficient for all practical purposes that air is taken to be equivalent to vacuum.

For a truly continuous medium, the propagation of a travelling EM wave from one medium to another can be analytically solved with Maxwell's equations if the medium is infinitely remote from the electromagnetic source. In this particular case, the travelling EM wave can be considered as a plane-wave. Whether a particular case can be considered or approximated as plane-wave or not will depend on the specific situation. In principle, at the higher frequencies (>10 MHz), an approximation using plane-wave can be assumed when the source is more than 100 meters away from the medium. A plane-wave approximation is usually accurate, therefore, for shielding in computer, TV and radar (6 MHz to 1 GHz).

In the case of plane EM wave travelling through an infinitely large conductive medium with finite thickness, the analytical solution is easily obtained by merely matching the boundary conditions at the interface. Typical solutions are available from various text books. The following equation on power transmittance also includes multiple internal reflections within the shielding medium.

$T$ = Transmittance Coefficient
= Transmitted Power/Incident Power

$$= \frac{4(\omega\epsilon/\sigma)\exp(-2t/\delta)}{\sinh^2(2t/\delta)\cos^2(2t/\delta) + \cosh^2(2t/\delta)\sin^2(2t/\delta)} \qquad (1)$$

where

$\delta$ = skin depth and is defined in equation (3)

$\omega = 2\pi$ f where f is frequency in Hz

$\sigma$ = volume conductivity ($\text{ohm}^{-1} \cdot \text{cm}^{-1}$)

$\mu_r$ = relative magnetic permeability

$\epsilon$ = vacuum electric susceptibility

t = medium thickness (micron)

$$\text{Shielding Effectiveness} = -10 \log T \qquad (2)$$

The unit for measuring shielding effectiveness of the normal medium is normally quoted in decibel units (dB). Their physical meanings are illustrated in Table 1.

**Table 1. Shielding Effectiveness Measurements.**

| Power Ratio | Voltage Ratio | Attenuation om dB |
|---|---|---|
| 1/2 | $(1/2)^{1/2}$ | −3 |
| 1/4 | 1/2 | −6 |
| 1/10 | $(1/10)^{1/2}$ | −10 |
| 1/100 | 1/10 | −20 |
| 1/10,000 | 1/100 | −40 |
| $10^{-6}$ | 1/1,000 | −60 |
| $10^{-8}$ | 1/10,000 | −80 |

Thus, attenuation by 40dB would mean the voltage output is reduced to one percent of the input voltage. This shielding effectiveness is considered adequate for most commercial applications. Most of the military applications require shielding effectiveness of over 80dB, which would mean a reduction to 0.01 percent of the original voltage.

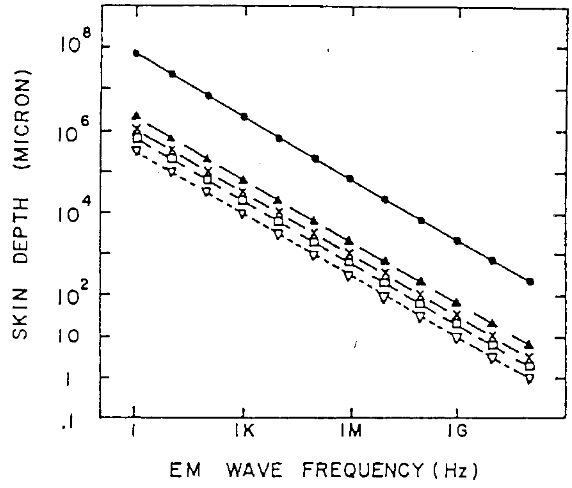
In order to understand the physical meaning of Equations (1) and (2) better, the function of skin depth in both the qualitative and quantitative senses must be understood.

$$\delta = 50.33 \times 10^6 (1/f\mu_r\sigma)^{1/2} \qquad (3)$$

where f is frequency in Hz, $\mu_r$ is relative magnetic permeability, and $\delta$ is conductivity in $\text{ohm}^{-1} \cdot \text{cm}^{-1}$.

From Equation (3), skin depth is decreased at a higher frequency when the material is magnetic and is more conductive. That the factors that determine the skin depth also determine the overall shielding effectiveness at a fixed frequency means that it will be best to construct a shielding material with both high relative magnetic permeability as well as high electrical conductivity.

Skin depth based on the bulk volume conductivities of 0.5, 20, 200, 2,000, and 20,000 is plotted in Figure 1. In the cases of 20 and 200, a relative magnetic permeability of 25 has been introduced instead of 1. It can be easily seen that material with conductivity of 200 $\text{ohm}^{-1} \cdot \text{cm}^{-1}$ actually has a shallower skin depth than the more conductive material of 2,000 $\text{ohm}^{-1} \cdot \text{cm}^{-1}$. This phenomenon is manifested in the frequency dependence of skin depth. For convenience, the magnetic permeability was assumed to be constant in calculation although it is usually not true. It tends to approach unity at a higher frequency.



Key (in bulk volume resistivity)

▽ = Pure Metal-based

X = Silver-based 2000 $\text{ohm}^{-1}\text{cm}^{-1}$, $\mu_r = 1$

□ = 200 $\text{ohm}^{-1}\text{cm}^{-1}$, $\mu_r = 25$

△ = Nickel-based, 20 $\text{ohm}^{-1}\text{cm}^{-1}$, $\mu_r = 25$

● = Carbon-based, 0.5 $\text{ohm}^{-1}\text{cm}^{-1}$, $\mu_r = 1$

Figure 1. Skin Depth vs. Frequency.

The relative magnetic permeability of most magnetic metals, such as iron, nickel and their alloys, has a strong frequency dependence and approach unity at the MHz range. Thus, assuming frequency independent magnetic permeability will result in the overestimation of shielding effectiveness in the higher frequency for magnetic metals such as nickel paints. In general, however, volume resistivity does not change with frequency until it approaches the optical frequency of $>10^{12}$ Hz. This applies to all highly filled conductive materials.[3,4]

## EMI/RFI COATING

EMI/RFI coating has become an integral part in manufacturing communication and information processing equipment, particularly when using a plastic housing or a metallic enclosure that requires an interfacial conductive coating. Different approaches can be used to achieve conductivity in a plastic enclosure. The commonly used methods are: direct metal deposition (zinc arc, evaporation, electroless plating, etc.), conductive polymer coating, and molded conductive composite.[5,6,7] The theoretical treatment of shielding effectiveness is essentially the same in all cases when difference in conductivity is considered.[8]

The basic difference between conductive polymeric coating and metal deposition is that, when done correctly, metal deposition will form a continuous film with no pores. Thus the theory described by equations (1) and (2) will apply almost exactly.

In the case of conductive coating, the size of the conductive particulates is somewhat limited. The coating can be construed as essentially overlaying metallic meshes with the mesh-size opening dependent on the average particle size. When the wavelength of the EMI signal is close to the dimension of the conductive particulate, the mechanism of quantum transmission probability becomes significant. Since 30 GHz corresponds to a wavelength of one cm and 3 GHz corresponds to a wavelength of 10 cm, from a practical viewpoint, this mechanism of EMI transmission is relatively insignificant. Problems arise only when one is using unusually large conductive particulates, or when the coating is so thin that local non-uniformity makes the pore size appear close to the dimension of the wavelength.

Coating for EMI/RFI suppression is generally insufficient in the lower frequency range of below one MHz. This is true even if the coating is pure silver because of the relatively large skin depth and the occasionally important magnetic component contribution. To provide low frequency shielding, thickness in the range of one cm is required for 40 to 60dB shielding for the purely conductive metals.

The source of EMI leakage at the high frequency end is primarily due to interface openings of the enclosure, insufficient compression on the conductive gaskets, corroded interfacial coating, oxidized interfaces, and delamination.

The typical thickness of a conductive polymer coating is one to 3 mils, whereas that of metallic deposition could be as low as 0.5 mil. Figure 2 is a plot of shielding effectivenesses of silver conductive coating of 2,000 and 20,000 $\text{ohm}^{-1} \cdot \text{cm}^{-1}$, a proprietary coating of 200 $\text{ohm}^{-1} \cdot \text{cm}^{-1}$, and relative magnetic permeability($\mu_r$)equals 20, and nickel-based coating of 20 $\text{ohm}^{-1} \cdot \text{cm}^{-1}$. Magnetic permeability is assumed to be 1 throughout the frequency domain except where noted. It is known that magnetic permeability will decrease to one at the MHz range; thus the shielding effectiveness in this calculation will tend to be high at that region.

The shielding effectiveness of nickel paint is approximately 45dB for a 2-mil coating, while a proprietary paint approaches that of pure silver paint at 70 to 75dB. It should be emphasized that shielding effectiveness increases rapidly at the 100 MHz range due to the fact that skin-depth is approaching that of the coating thickness. The difference between a one-mil and 3-mils coating is less than 10dB. Such a prediction is well proven for most of the practical applications.[9,10]

Recently, copper-based EMI/RFI coating has gained momentum over the conventional nickel-based coating in terms of usage volume. One reason is concern for the potential health hazard related to the nickel-based materials, such as nickel fine powder and solution. This is particularly true during the coating application processes, since the fine spraying mist contains nickel as well. Another factor is the stability of conductivity and thus the shielding effectiveness. It is commonly assumed that conductivity of nickel is relatively stable based on experiences with nickel plating in electronic applications. Nickel may be more stable than copper when in continuous film form from a metal deposition process and when in unmodified particulate form. However, many modified and stabilized copper coatings are also available. From heat aging studies performed on the existing copper-based and nickel-based paints, the authors concluded that both of the copper-based and nickel-based paints degraded rapidly at temperatures of 60 to 100°C in a relatively short time. Also, most of the "stabilized" copper-based paints showed a more stable conductivity than that of the nickel paints. Among all of the copper-based conductive paints, a great degree of variation in conductivity stability existed.

Figure 3 plots shielding effective-

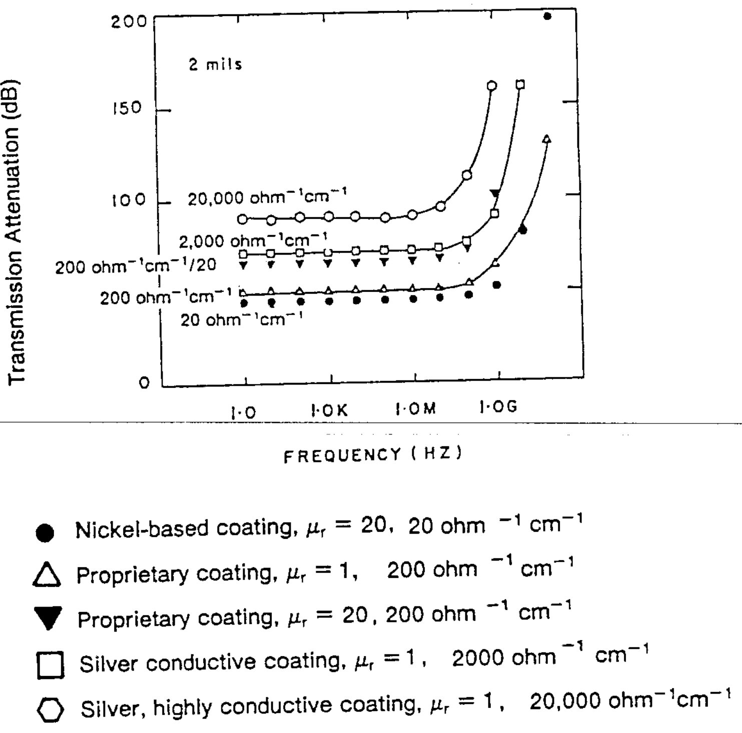


Figure 2. Shielding Effectiveness of Selected Conductive Coatings.

ness of some of the paints evaluated for aging studies at 100°C. A more stable material at this temperature does offer longer life at temperatures of 25 to 40°C. More detailed kinetic studies on the conductivity degradation mechanism will be necessary to evaluate the functional shielding effectiveness requirement.

The relative cost of achieving EMI/RFI shielding by different coating methods has been analyzed by many authors.[9] The various methods of coating, such as spray polymer coating, electroless plating, zinc arc-spraying, and evaporation differ in both the cost of application and the material cost. Overall, spray coating of conductive polymer yields the best cost-effectiveness.

However, evaporation and electroless coating do provide a more effective conductive metal layer for the same thickness. With the advance of highly conductive silver coatings of 0.00002 ohm-cm, a metal-like conductivity can be achieved with the paint-spraying method. This may someday allow large structural shielding where metallization is not practical.

## EMI/RFI GASKET / SEALANT / ADHESIVE

Because the application of gaskets, sealants, and adhesives tends to require relatively thick sections of material typically in the range of one mm or higher, they shall be treated in the same category.

In the case of a thick EMI barrier, the skin depth is of the same order of magnitude as the thickness of the barrier in most of the frequency range of interest. Thus, the skin depth plays a major role in shielding against EMI. Figure 4 is a plot of shielding effectiveness for conductive materials with a thickness of one cm for each of the materials. In this type of shielding application, the thickness of the material is very critical. Thus when one is designing an enclosure using a specification of an EMI/RFI gasket which is primarily based on one-inch thickness, it will be quite erroneous to assume that a gasket of one mm thickness will also provide the same shielding level as provided for in the specification.

## EMP SURVIVABILITY

Electromagnetic pulse survivability is another aspect of electromag-

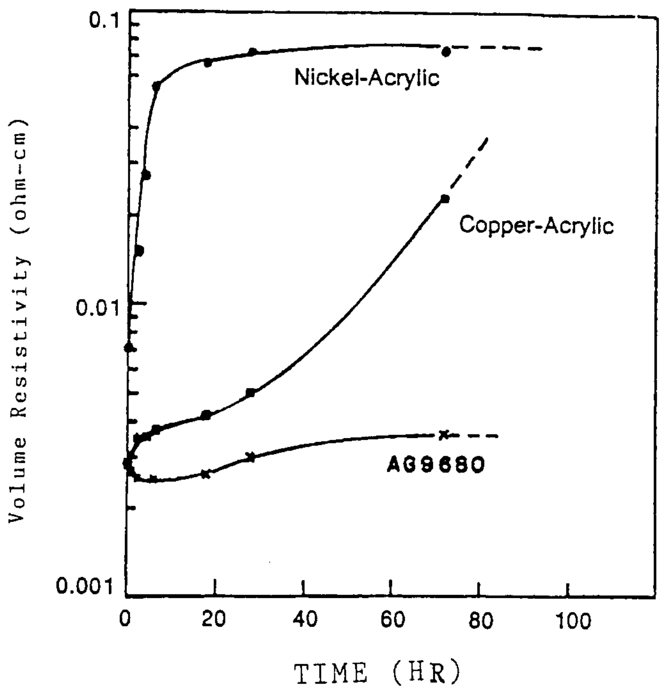


Figure 3. Accelerated Heat Aging of Commercial EMI Paints at 100°C.

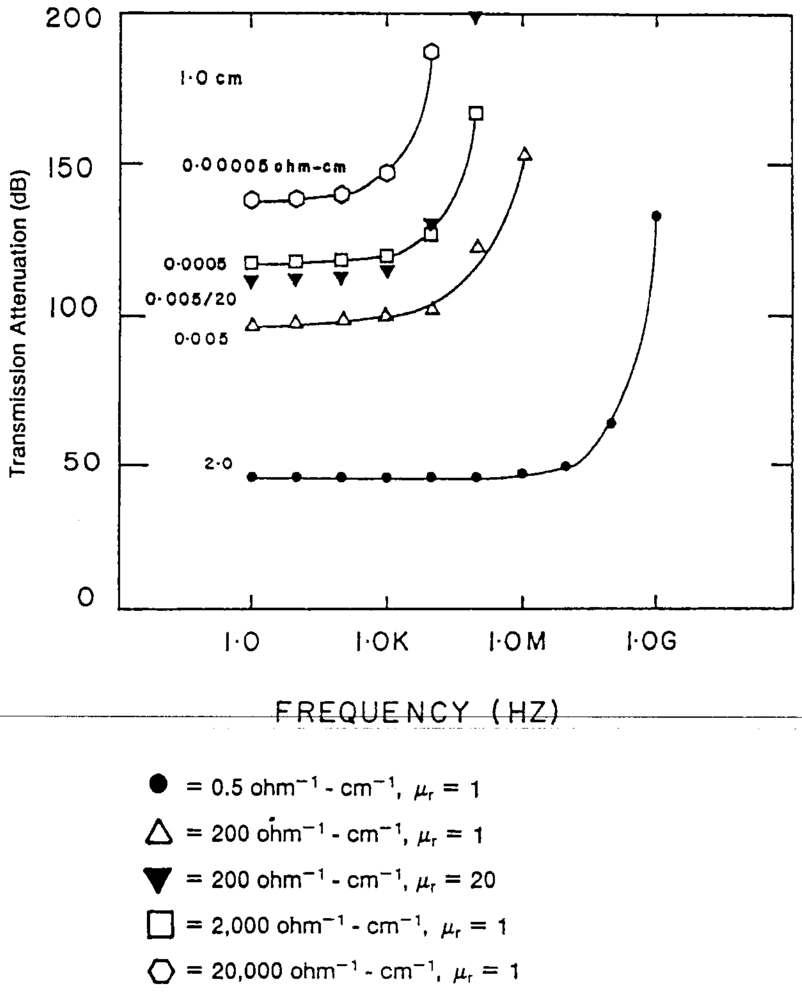


Figure 4. Gasket/Adhesive/Sealant Shielding.

netic compatibility that has attracted a lot of attention in recent years. EMP primarily refers to the electromagnetic energy that is released in the process of a nuclear explosion. Since the current generated in this situation is a spike, the Fourier transform of the spike can represent a distribution of energy with its maxium at around one MHz.[10] In other words, a maximum level exists in the frequency spectrum because the spike is not infinitely sharp. The frequency spectrum covers from very high frequency down to dc.

There are two important aspects in EMP survivability: the *energy level and the frequency* involved. To be effective in surviving the EMP environment, a shielding material has to be able to carry a large amount of energy at and around one MHz. The current density carrying capability of the material is of utmost importance for this aspect. In one of the most recently issued military specifications on conductive gaskets, the material is required to withstand instantaneous current density of 3 amperes per square millimeter at one MHz with decay time similar to field situation. Thus if a material is able to survive a dc current density of 3 amp/mm$^2$ continuously at room temperature, it will also survive the EMP requirements. Material that has a dc current capability lower than 3 amp/mm$^2$ might still be able to survive that current spike, since it is impressed on the material for only microseconds.

Current density measurements have been performed on some of the most common conductive materials with resistivity from 0.01 to 0.00002 ohm-cm. It was found that the current density carrying capability is directly related to the intrinsic conductivity of the material as expected; the Joules heating effect is also proportional to the ohmic resistance of the conductor. Material with resistivity of 0.001 ohm$^{-1}$ - cm$^{-1}$ was able to survive a current density of 3 amp/mm$^2$. In the case of a silver-loaded material with 0.00002 ohm-cm resistivity, the current density carrying capability was increased up to 50 amp/mm$^2$. For gasket materials such as those filled with silver-plated copper, resistivities are in the range of 0.01 ohm-cm. However, it is imperative that the material be tested with the described EMP testing method. Even though the material survives one simulated test, it does not automatically mean that it will survive the second time. The current density of some of the silver loaded epoxies for the study are plotted in Figure 5.

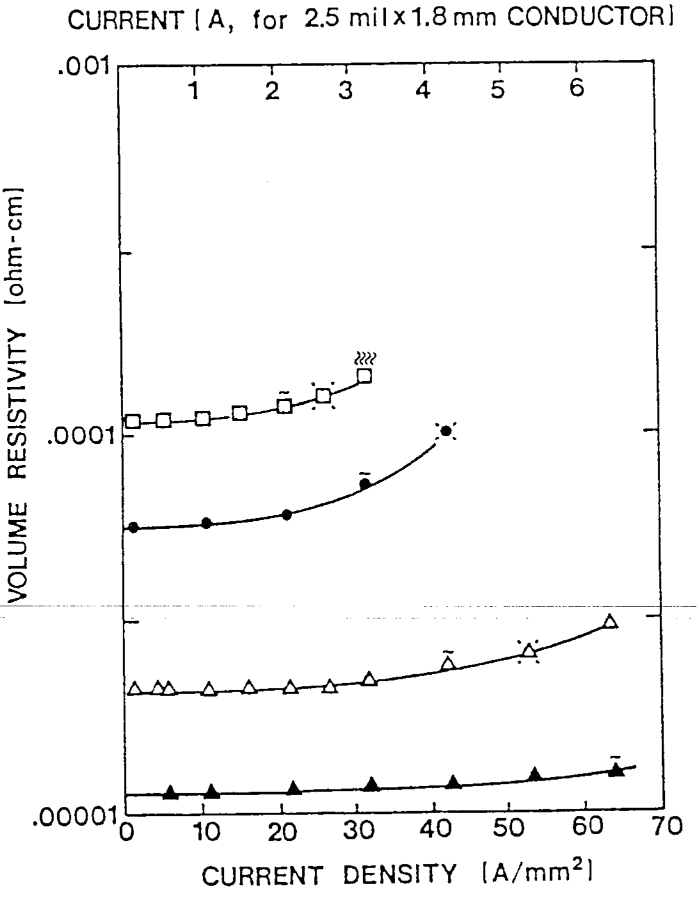


Figure 5. Current Density Properties of Silver-Loaded Epoxies.

## FLEXIBILITY AND ELASTICITY

For shielding an enclosure from both the environmental effects and EMI, a highly flexible and elastic conductive gasket is essential to assure complete electrical continuity. When environmental effects are the major concern, a combination of conductive EMI shield with a non-conductive environmental shield can be used. In cases where the conductive gasket is to be bonded onto the substrate, a compatible conductive adhesive should be used. Some of the conductive adhesives on the market, however, are not conductive unless they are compressed. It is recommended that a conductive adhesive that is intrinsically conductive without compression and has a value close to the conductivity of the gasket be used. The reason is that one can never assure the uniformity of clamping pressure in an enclosure because of the intrinsic dimensional distortion of aluminum structures.

Almost all of the conductive elastomers that are used for EMI/RFI shielding application are made of silicone and fluorosilicone elastomers. They are selected for their wide temperature range of application and their resistance to fungus, ozone, etc. The properties of the resulting conductive gaskets usually are reflections of the material properties of the elastomeric matrix.

When properly cured, both the silicone and fluorosilicone resins yield excellent elastomeric properties with elongation in the range of 100 to 500 percent and compression set of less than 20 percent. After the matrix elastomer is loaded with the conductive filler, the elongation and compression set properties tend to degrade substantially. The elongation normally drops to 100 to 300 percent; the compression set increases to approximately 30 to 60 percent.

There are fundamental differences in *surface energy* between silicone and fluorosilicone rubber when a bonding operation is required. The silicone resins are non-polar in nature with the molecular structure highly symmetrical and non-polar. Therefore, the adhesive material will also have to be highly non-polar. In fact, the only adhesive that was found satisfactory with silicone rubber is conductive silicone adhesive. In the case of fluorosilicone, the material is somewhat polar in nature because of the polar fluoride groups attached to the silicon backbone. A corresponding fluorosilicone adhesive will be a good choice. The fluorosilicone gaskets can also be bonded with some other conventional polar adhesives.

When two metal structures have to be permanently joined together mechanically, the conductive sealant will be essential for assuring electrical continuity to account for the unavoidable thermal excursion. In most cases, a conductive RTV will be chosen because of its flexibility and reasonable adhesion. In this case, the silicone or fluorosilicone sealant should be highly conductive. The only drawback to silicone sealants is the fact that there is nothing that will adhere to them short of another silicone. Thus, a decorative coating, moisture barrier coating, or chemical protection coating of another sort will be almost out of the question.

Conductive silicone and fluorosilicone are also used as flexible conductive coatings. These silicone coatings adhere very well to most substrates and also provide excellent flexibility. In cases where flexible polyester is used as the structural support, a flexible coating such as the silicone coating can be used. In a more conventional application, polyurethane is normally chosen. The highly conductive epoxy elastomer discussed in the sealant application was also used with outstanding results. The advantages of epoxy as coating are its ease and insensitivity to moisture. It is also relatively non-toxic in comparison with the polyurethane family. In fact, these novel epoxy materials have been used with excellent success in many missile programs as coating, adhesive, and sealant.

## RELIABILITY OF EMI/RFI/EMP MATERIALS

The problem of reliability in EMI shielding applications is rather complex and is highly dependent on the modes of application. Traditionally, the sources of problems are: compatibility in adhesion, scratch resistance, thermal cycling and shock, moisture resistance, elasticity, etc. This discussion focuses on the EMI-related intrinsic material problems. They are identified as (1) electrical stability under thermal aging and (2) corrosion-related problems at the interfacial joint of dissimilar metals (galvanic).

### *THERMAL AGING (OXIDATION)*

It is well known that the electrical properties of most of the metallic particulates used in EMI application are highly temperature sensitive. They are: nickel, copper, steel, silver-plated copper, silver-plated glass, silver-plated nickel, silver-plated aluminum, and noble metal particulates.

All of the non-noble metal-filled compounds tend to be sensitive to oxidation. This is also true for those silver-plated metals and inorganics. In the case of such a filled polymer, insulating oxide of 20 to 100 angstroms in thickness around the conductive particulate will be detrimental to the conductivity of the material system. The tunneling mechanism responsible for conductivity in such a filled polymer system is essentially an exponential decreasing function to the thickness of the insulating barrier between the conductive particulates. Most of the applications in both the military and commercial fields call for testing such a conductive material as applied at the maximum rated temperature for 1,000 hours. For example, a silver-plated-copper-based gasket will be tested at 125°C for 1,000 hours. Although such test results are useful in weeding out some unstable materials, it is not very useful in actually predicting the long-term stability behavior over a period of time such as 75°C for 20 years (for some military applications) or 40°C for 10 years (for commercial applications). In order to predict the long-term behavior correctly, one should examine the degradation kinetics.

A prediction can be established by testing the same material at a minimum of four different temperatures. An Arrhenius plot is made up of plotting the time to reach a certain degradation (e.g., 10 times increase in resistivity) versus the inverse of temperature. The time to reach the same level of degradation at a lower temperature (such as the application temperature) can be projected from higher temperature results. It is used to gauge the usefulness of the material under those temperature extremes. It is noted in our theoretical prediction that every 10-times increase in resistivity will cause a degradation of over 20dB in shielding effectiveness for both the coating and gasket-adhesive-sealant applications. Therefore, if the original coating has a volume resistivity of 0.005 ohm-cm, at 2-mils coating thickness it will yield a shielding effectiveness of approximately 50dB. However, when the resistivity is increased to 0.05 ohm-cm, the shielding effectiveness will be dropped to 30dB and below. It will not then provide enough shielding even for most commercial applications.

Figure 6 is an Arrhenius plot of some of the commercially available silver-plated copper materials. Comparing the two materials which both survived the 1,000 hours test, the hypothetical material (solid line) will project to survive more than 20 years at 75°C while the experimental product (dash line) will fail in less than 5 years. It is obvious from the figure that the kinetic of degradation as signified by the slopes of the data can be very different. It is imperative that at least three to four data points are collected in order to give any clue on whether the material will survive the long-term application.

At this point, a data bank or information source for predicting long-term EMI reliability for both the military and commercial applications does not exist. The only material with documented aging characteristic for long-term military application is pure silver-filled materials. We have performed experiments based on pure silver-filled silicone and epoxy systems with thermal aging at 150°C, 175°C and 200°C. The electrical resistivity of these materials, however, decreases with aging at high temperatures.

Tests on conductive epoxy based on commercially available silver-plated copper and nickel were also performed. Epoxy was used because of its thermal stability so that one may accumulate data at a higher temperature regime. It was found that the performance of silver-plated copper depends strongly on manufacturers. None of the silver-plated coppers tested were able to survive

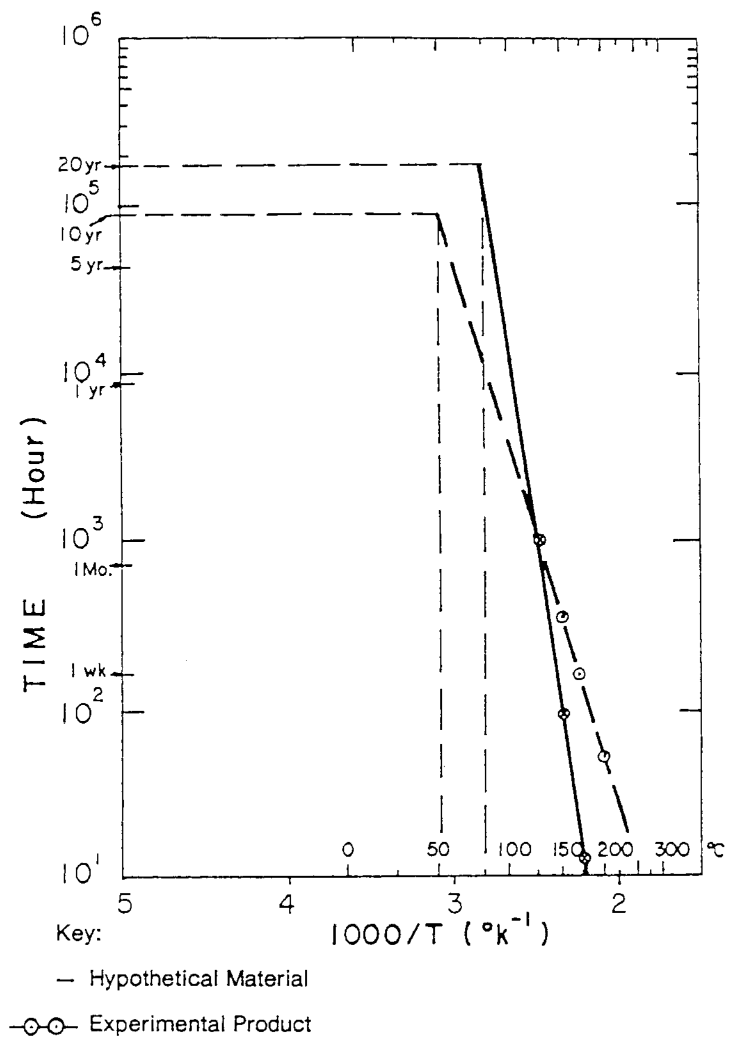


Figure 6. Time-Temperature Relationship of Resistivity Degradation.

more than 5 years at 75°C. Some of the better silver-plated coppers can survive for more than 20 years at 50°C, while some fail in less than 2 years. It was also found that silver-plated copper manufactured by different vendors tends to give different time/temperature curves and thus different degradation rates.

In the case of nickel-based epoxies, the results are extremely erratic. Conductivity of the same batch of material when freshly purchased and after stored for one year has a conductivity range from $10^6$ ohm-cm to 0.05 ohm-cm. Even at best, conductive nickel did not seem likely to last more than 5 years at 50°C. As a conclusion, unless there is a means of preventing nickel from oxidizing, it is unlikely that it can be made to serve with long-term stability.

In the case of gasket application, the degradation of silver-plated copper is not only reflected in the loss of electrical conductivity, it is also reflected in the loss of the rubber properties. The degradation of silver-plated copper arises from the fact that the surface of the copper particulates is not completely covered by the silver, which in practice is almost unavoidable. Therefore, it is only a matter of the degree to which the oxidative-prone particulate can be covered with silver. Organic compounds are also used in deterring oxidation in copper. Their results in these applications have not been proven.

### *CORROSION AND ITS PREVENTION*

Corrosion due to moisture, particularly under a salt-spray environment, is another important reliability problem that requires more study. The problem is extremely material- and substrate-dependent. There are no data banks on the effects of long-term exposure due to salt-spray, extremely ionic active environments. This type of problem is especially important for gaskets/adhesives/sealants applications that involve metal-filled silicone rubber.

It is quite clear that silver-coated metals intrinsically are different in electronegativity from the substrate (usually aluminum). Therefore, the potential for corrosion exists at all times. The task is primarily on how to obtain a more corrosion-resistant conductive coating so that the corrosion mechanism can be curbed within the limit over a long period of exposure time. Another possible solution is to obtain a better corrosion-resistant filler. Yet another approach is to provide a moisture barrier over the conductive coating or gasket.

### INTERFACIAL CONDUCTIVE COATING

Most of the metallic structural materials that are used to house or to shelter the electronic devices are made of aluminum. Aluminum is extremely easy to oxidize. After oxidation, it retains a thin layer of non-conductive aluminum oxide on top of the substrate. Under salts and moisture, aluminum corrodes rapidly; thus EMI leakage results at the interface between the gasket and the oxidized and non-conductive substrate. The aluminum surfaces are therefore normally coated either with a conversion-coating, a metallic coating of a different metal, or with a conductive polymer coating. The conventional wisdom is that since tin oxide is semi-conductive in nature, tin should therefore be useful for such interfacial application. Another common approach is to use a silver-filled epoxy coating to protect the aluminum interface. It is well known in the industry that tin-coated aluminum, when used in conjunction with wire-mesh gasket, will give excellent shielding effectiveness when initially assembled together. Once the system is exposed to the outside environment, the shielding effectiveness degrades drastically.

### CORROSION-RESISTANT FILLERS AND MATRIX

It is conceivable that some fillers are more corrosion resistant than others in terms of galvanic corrosion and their intrinsic corrosion resistance properties. In the case of aluminum substrate, the best filler will obviously be aluminum, but due to its intrinsic oxidation problem, it cannot be made conductive without using silver or other precious metal as a protective coating. Silver-plated aluminum has been claimed to have good compatibility with conversioncoated aluminum. However, experimental results from many users did not show concurring results. The fact that bare aluminum and converted aluminum surfaces are not very stable themselves and have to be coated with some protective coatings such as tin or silver epoxy for long-term durability indicates that the use of such matched potential materials is very limited.

An experiment was performed using different conductive fillers such as silver-plated copper, silver-plated nickel, and silver particulates in an elastomer matrix. All of the materials were cured under the same conditions on a silver-epoxy-coated aluminum substrate and on a bare, freshly abraded aluminum substrate. These test coupons are then submerged in a 10 percent brine solution at 40°C for long-time exposure. The coupons were then taken out at every 24 hours for evaluation in terms of the intrinsic conductivity of the rubber, the silver-epoxy coating, and the interfacial conductivity between the rubber and the substrate. It was found that the silver-plated, metal-filled rubbers lost their intrinsic conductivity in a matter of days. The unprotected interface between the rubber and the bare aluminum substrate also degraded rapidly. The one with the best corrosion-resistant properties is the silver-loaded elastomer on the silver-epoxy coated aluminum substrate. Very little degradation in their intrinsic and interfacial conductivity was observed.

## MOISTURE BARRIER APPROACH

Another approach to prevent degradation due to corrosion is by means of a moisture barrier with more corrosion-resistant conductive fillers and matrix. It was demonstrated recently in one laboratory that such a combination of technology is successful in providing protection for a conductive joint under 1000 hours of salt-spray environment. Two metal plates are bonded together by the conductive adhesive under test. The joint surfaces that are exposed to the environment were protected with a coating. Many different material systems were tested under the same conditions. The fillers used in this application include: conventional silver-plated copper, silver-plated aluminum, and a proprietary filler. After 1000 hours under salt-spray environment, the proprietary filler system, which is paintable and features rubber-like flexibility, was the only one that was able to retain its electrical continuity. It should be noted that all of the silicone and fluorosilicone compounds are difficult to paint over with corrosion-protection coating because of their low surface energy. The fact that most of the silicone compounds are not good moisture barriers means that they are vulnerable to corrosion.

## BEST MODE OF CORROSION PROTECTION

The best mode of corrosion prevention is obviously a combination of good engineering design and proper choice of materials. Using a combination of all the aforementioned approaches will provide the best corrosion protection. The oxidation and corrosion of the substrate surface can definitely be improved with a conductive coating. The use of conductive fillers which potentially match those used in the conductive coating, the gasket, and adhesive will provide a more durable conductive interface. If a moisture barrier is subsequently applied, EMI shielding in the system level will also be markedly improved. ■

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